Development of new synthetic strategies exploiting an unexpected rearrangement of vinylcyclopropanes

Arnaud DELBRASSINNE

Supervisor: Prof. R. Robiette

Louvain-la-Neuve, 2023

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Prof. Michael SINGLETON, Université catholique de Louvain

Supervisor:

Prof. Raphaël ROBIETTE, Université catholique de Louvain

Acknowledgements

J'aimerais, par ces quelques lignes, adresser mes remerciements aux personnes suivantes, ayant contribué directement ou indirectement à la réalisation de cette thèse de doctorat.

Mes premiers remerciements s'adressent au Professeur Raphaël Robiette pour m'avoir acceuilli au sein de son équipe pendant les 5 dernières années, pour sa disponibilité et son aide lors de la réalisation de ce travail.

Je remercie les Professeurs Berionni, Elias, Lecourt et Singleton d'avoir accepté d'évaluer ce travail et pour toutes les remarques lors de la défense privée qui ont permis au manuscrit de devenir meilleur. Merci au Professeur Garcia d'avoir accepté de présider mon jury. Merci également au Professeur Riant d'avoir fait partie de mon comité d'accompagnement.

Merci aux personnes qui ont travaillées avec moi sur ce projet; Boris, Brice, Julien, Madeline, Maximilien, Pierre-Louis et Thomas pour avoir contribué aux résultats de cette thèse et/ou de m'avoir permis d'expérimenter l'encadrement. Merci également aux autres membres du labo que j'ai cotoyé pendant cette thèse ; Axel, Cécile, Judith, Juhans, Julien, Julien, Julinda, Maxence, Ousam, Simon et Ugo pour la bonne ambiance au labo pendant ma thèse.

Je remercie Stéphanie pour le côté organisationnel au labo et pour les analyses effectuées. Merci également à Laurent pour les analyses de masse et HPLC.

Un grand merci à Audrey pour toute l'aide administrative pendant cette thèse, surtout sur la fin de celle-ci.

Le bon déroulement d'une thèse ne se joue pas uniquement au laboratoire, j'aimerais donc remercier chaleureusement Camille pour tout le soutien reçu pendant ces 4 années ainsi pour tous les excellents moments partagés.

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Abstract

Vinylcyclopropanes are key intermediates in organic chemistry which undergo several important rearrangements. The group of Prof. Robiette recently discovered a new rearrangement of vinylcyclopropanes into skipped dienes proceeding at room temperature and with a high selectivity. Based on this transformation, we developed a synthetic strategy towards skipped dienes using benzylic sulfonium ylides and 1,3-dienes.
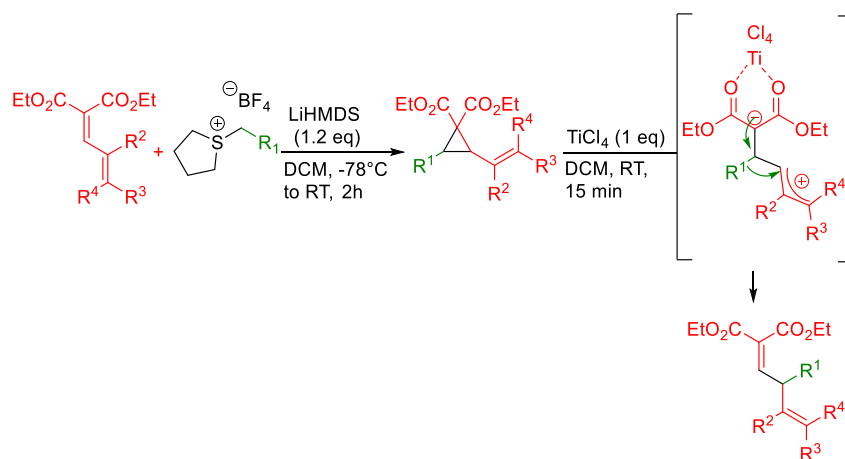
Some limitations concerning the rearrangement step were found during the extension of the scope of this methodology. Additionally, we have conducted a computational investigation of the mechanism of this rearrangement. Obtained results enabled us to gain a better understanding of the factors controlling reactivity and stereoselectivity in this process.

We have then capitalised on this new transformation to develop related methodologies involving a 1,2-migration step promoted by Lewis acids. We developed two one-carbon homologation methodologies; the first is the homologation of α,β-unsaturated aldehydes to β,γ-unsaturated aldehydes and the second consists of the homologation of activated olefins. Additionally, combined experimental and computational mechanistic studies were

performed. Finally, enantioselective versions of both methodologies were investigated using chiral sulfonium salts.
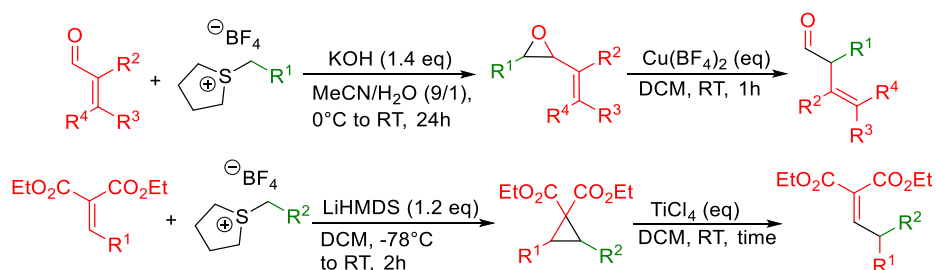
Finally, our attention turned to divinylcyclopropanes. After investigating their rearrangement to 1,4,4'-trienes *via* a 1,2-migration promoted by a Lewis acid, we started the optimisation of their Cope rearrangement to cycloheptadienes. This work only provides proof of concept as this transformation still requires more investigation to find optimised reaction conditions.
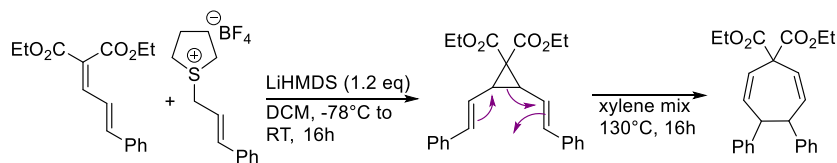
Résumé

Les vinylcyclopropanes sont des intermédiaires clefs en synthèse organique pouvant être impliqués dans des réarrangements importants. Récemment, le groupe du Prof. Robiette a découvert un nouveau réarrangement de VCPs en diènes-1,4 se déroulant à température ambiante et se voulant hautement sélectif. Nous avons développé une nouvelle stratégie de synthèse permettant d'obtenir des diènes-1,4, basée sur cette reaction de migration-1,2, utilisant des diènes-1,3 et des ylures de sulfonium benzyliques comme substrats.
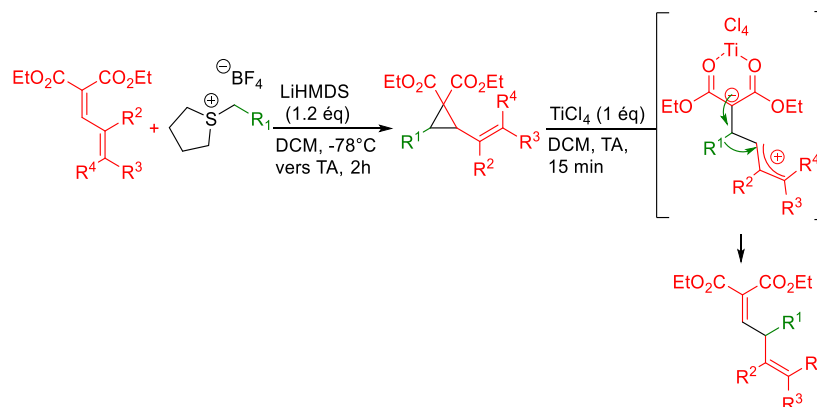
Lors de ce travail, le champ d'application a été élargi et certaines limitations au niveau de l'étape de réarrangement ont pu être mises en évidence. Nous avons également étudié cette étape à l'aide de l'outil computationnel. Les résultats obtenus ont permis une meilleure compréhension des facteurs impliqués dans la réactivité et la stéréospecificité du réarrangement.

Forts des connaissances acquises lors de l'étude de cette méthodologie, nous avons ensuite développé deux nouvelles stratégies d'homologation d'un carbone incluant une étape de migration-1,2. La première concerne la transformation des aldéhydes α,β-insaturés en leurs homologues β,γ-insaturés, la seconde est, elle, une homologation d'oléfines activées. Des études mécanistiques expérimentales et théoriques concernant les étapes de réarrangement de ces stratégies ont été réalisées. Les versions énantiosélectives de

ces méthodologies ont également été étudiées en utilisant des sels de sulfonium chiraux.
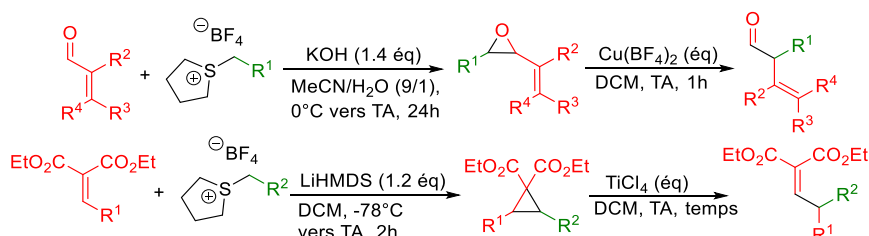
Pour terminer, notre attention s'est tournée vers les divinylcylopropanes. Après la mise au point de la formation des triènes-1,4,4' induite par les acides de Lewis, nous avons commencé à optimiser leur réarrangement de Cope afin d'obtenir des cycloheptadiènes. Le travail sur cette réaction constitue une preuve de concept et le processus d'optimisation mériterait d'être approfondi afin de trouver les conditions opératoires idéales.
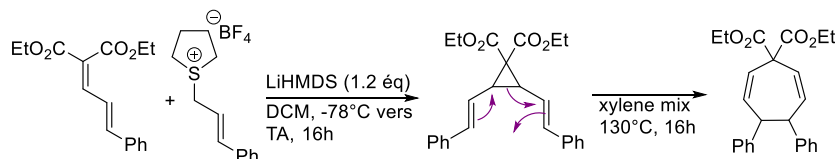
Foreword

This Ph.D. thesis is part of a research program carried out in our laboratory. The interested reader may also read the following references:

- M. Richald, *Divergent and Selective Rearrangements of Vinylcyclopropanes into 1,4-Diene and Cyclopentenes*, PhD thesis UCLouvain, **2019**.
- A. Delbrassinne, *Synthèse de diènes-1,4 à partir d'ylures de sulfonium et diènes-1,3*, Master's thesis UCLouvain, **2018**.

This PhD thesis led to the publication of three articles:

- M. Richald, A. Delbrassinne, R. Robiette, *Eur. J. Org. Chem.*, **2019**, 3779-3782.
- A. Delbrassinne, M. Richald, J. Janssens, R. Robiette, *Eur. J. Org. Chem.* **2021**, 2862-2868.
- A. Delbrassinne, B. J. Takam Mba, R. Robiette, to be submitted.

Abbreviations list

^{13}C NMR: Carbon-13 nuclear magnetic resonance

^{1}H NMR: Proton nuclear magnetic resonance

2-Py: 2-pyridyl

Å: Angström

Ac: Acetyl

AcOEt: Ethyl acetate

AcOH: Acetic acid

APCI: Atmospheric Pressure Chemical Ionisation

Ar: Aryl

cat: catalyst

BINAP: 2,2'-bis(diphenylphosphino)-1,1'-binaphtyl

Cbz: Carboxybenzyl

COD: Cycloocta-1,5-diene

COSY: Correlation spectroscopy

CP: Cyclopentene

Cy: cyclohexyl

δ: Chemical shifts

d: doublet (spectral)

d.r.: Diastereoisomeric ratio

DACP: Donor-acceptor cyclopropane

dba: Dibenzalacetone

DBU: 1,8-Diazabicyclo[5.4.0]undec-7-ene

DCM: Dichloromethane

DEPT: Distortionless Enhancement by Polarisation Transfer

DIBAL-H: diisobutylammonium hydride

diVCP: Divinylcylopropane

DMF: *N,N*-Dimethylformamide

DMSO: Dimethylsulfoxide

DMT: Dimethyl terephtalate

dmpe: 1,2-Bis(dimethylphosphino)ethane

E: Electrophile

e.e.: Enantiomeric excess

e.r.: Enantiomeric ratio

EDG: Electron donating group

eq.: equivalents

ESI: Electro spray ionisation

Et: Ethyl

Et$_2$O: Diethylether

EtOH: Ethanol

EWG: Electron withdrawing group
HetAr: Heteroaryl
HMBC: Heteronuclear multiple-bond correlation spectroscopy
HMDS: Hexamethyldisilazane
HMQC: Heteronuclear multiple-quantum correlation
HPLC: High performance liquid chromatography
HRMS: High resolution mass spectroscopy
Hz: Hertz
i-Bu: Isobutyl
i-Pr: Isopropyl
IR: Infrared
L = Ligand
L.A.: Lewis acid
LiHMDS: Lithium bis(trimethylsilyl)amide
LiTMP: Lithium tetramethylpiperidide
m: multiplet (spectral)
m-: meta
M: Molarity (mol/L)
Me: Methyl
MeOH: Methanol
MeCN: Acetonitrile
MHz: MegaHertz
mmol: millimole
m/z: mass to charge ratio
MS: Molecular sieves
n-BuLi: *n*-Butyllithium
NEt$_3$: triethylamine
NHC: N-heterocyclic carbene
Nu: nucleophile
o-: ortho
Oct: Octyl
p-: para
p-ABSA: 4-Acetamidobenzenesulfonyl azide
Piv: Pivaloyl
Ph: Phenyl
PTSA : *para*-toluenesulfonicacid
pyBOX: pyridine-2,6-bis(oxazolidines)
q: quadruplet (Spectral)
quant: quantitative
RT: Room temperature
s: singlet (spectral)
t: triplet (spectral)

TBAF: Tetrabutyl ammonium fluoride
TBAI: Tetrabutylammonium iodide
TBHP: *tert*-Butyl hydroperoxide
TBS: *tert*-butyldimethylsilyl
t-Bu: Tertiobutyl
Tf: Triflate
TFA: Trifluoroacetic acid
THF: Tetrahydrofuran
THT: Tetrahydrothiophene
TMS: trimethylsilyl
TS: Transition state
VCP: Vinylcyclopropane

Chapter 1: Introduction

1.1. Donor-acceptor cyclopropanes

1.1.1. Introduction

The cyclopropane is the smallest and the most strained of the cycloalcanes. The formation of this carbocycle necessitates the association of three methylene groups, setting C-C-C angles at the value of 60°, which is lower than the typical angle of 109.5°C for the sp^3 hybridised orbitals. Accordingly, C-C bonds in the cyclopropane molecule are bent bonds with a nonoptimal overlap of the orbitals (Figure 1.1).
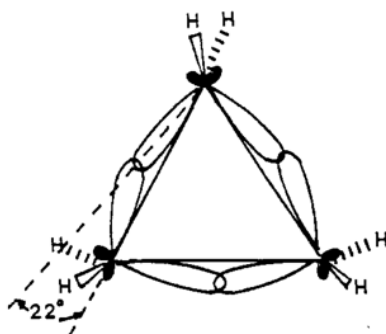
Figure 1.1: Bent bonds in the cyclopropane molecule

The opening of the cycle liberates *ca.* 27 kcal/mol of strain energy.[1] This ring strain energy can be used as the driving force behind a chemical process.[2] However, the polarisation of the C-C bonds of the unsubstituted cyclopropane is low and the barrier for its homolytic ring-opening is thus significant (*ca.* 60 kcal/mol).[2] The general method for increasing the reactivity of cyclopropanes is the addition of substituents (electron-donor or -withdrawing) to the three-carbon cyclic alkane (Scheme 1.1).
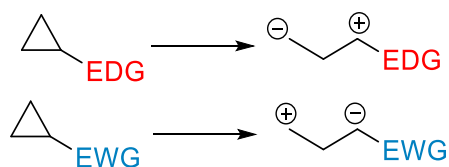
Scheme 1.1: Heterolytic cleavage of cyclopropanes with electron-donor (EDG) and -withdrawing (EWG) groups

The substituents have no significant impact on the ring-strain of these substituted cyclopropanes[3] but the presence of an electron-donor group favors the heterolytic ring-opening of the cyclopropane by increasing the polarisation of a C-C bond and stabilising the positive charge created by the heterolytic ring-opening. The polarisation of a C-C bond can also be increased by the presence of an electron-withdrawing group. The negative charge resulting from the ring-opening is better stabilised by the presence of the electron-withdrawing group as well.

Cyclopropanes with both electron-donor and -withdrawing groups are called "donor-acceptor cyclopropanes" (DACPs). The relative position of the groups has an influence on the reactivity (Scheme 1.2). The DACPs with both groups on the same carbon have a low reactivity towards ring-opening whereas the DACPs with the two groups on vicinal carbons have their effects working in synergy to facilitate the heterolytic ring-opening of the cyclopropane and the formation of a 1,3-dipole in which both charges created by the heterolytic ring-opening are stabilised. Cyclopropanes bearing two acceptor groups on the same carbon lead to a better stabilisation of the negative charge and an increased reactivity of the DACP. Commonly used EWG include esters, aldehydes, ketones, amides, nitriles and nitro groups. EDGs can be heteroatom based (OR, SR, NR_2) or carbonated (aryls, hetaryls).

The ring-opening of DACPs can be further facilitated by the addition of a catalyst enabling to increase the stabilisation of the negative charge; the most common activation mode of DACPs using the complexation of the EWGs by a Lewis acid.

EWG: CO_2R, COR, CHO, $CONR_2$ CN, NO_2
EDG: OR, NR_2, SR, aryls, hetaryls
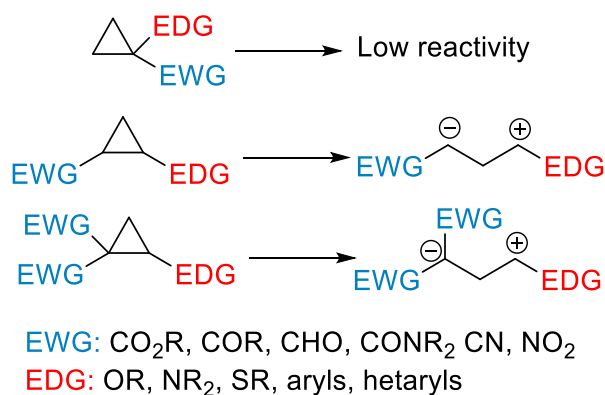
Scheme 1.2: Reactivity of geminal and vicinal donor-acceptor cyclopropanes

Nowadays, the DACPs are widely used in organic synthesis as building blocks for the construction of linear and cyclic structures. Indeed, the high polarisation of a C-C bond of the scaffold by a push-pull effect enables the formation of a 1,3-dipole which can be involved in wide variety of chemical transformations.

1.1.2. Ring-opening reactions

1.1.2.1. Ring-opening reaction by nucleophiles

The ring-opening of DACPs by nucleophiles is an access route to the formation of 1,3-functionalised compounds. The process is often described as a homologous Michael addition (Scheme 1.3).
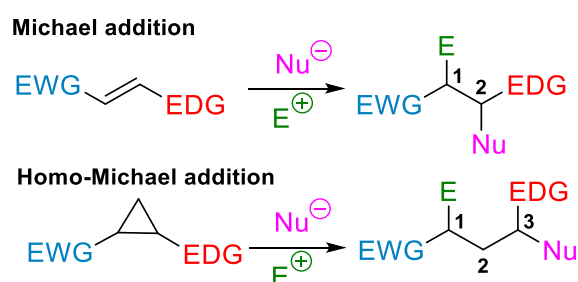
Scheme 1.3: Michael addition and the homo-Michael addition (ring-opening of DACPs by nucleophiles)

1.1.2.1.1. Carbonated nucleophiles

Carbonated nucleophiles can be used in ring-opening reaction of donor-acceptor cyclopropanes. Kerr *et al.* investigated the ring-opening of DACPs with aryl donor groups by the addition of 3-indoyls moieties, via a Friedel-Crafts alkylation catalysed by Yb(OTf)$_3$ under high pressure (13000 bars) conditions (Scheme 1.4).[4]
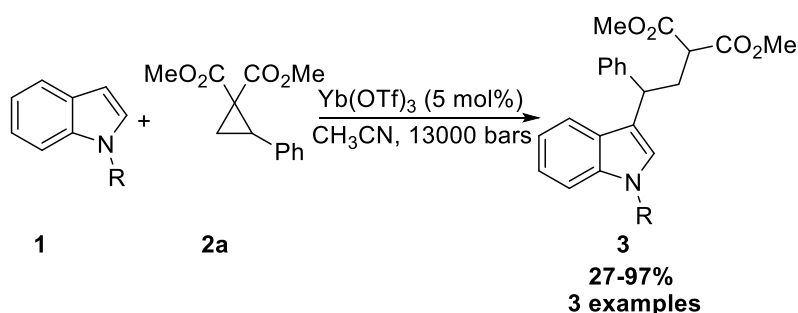
Scheme 1.4: Ring-opening of **2a** with 3-indoyls nucleophiles

Later, the group of Prof. Johnson developed an enantioselective method for creating a stereocenter in the 1,3-addition product **3** (Scheme 1.5).[5] Good to excellent *e.e.* were obtained. The stereocontrol was achieved by using MgI$_2$ as the Lewis acid with a chiral ligand, pyBOX. This catalytic system allowed the authors to avoid performing the reaction under high pressure.
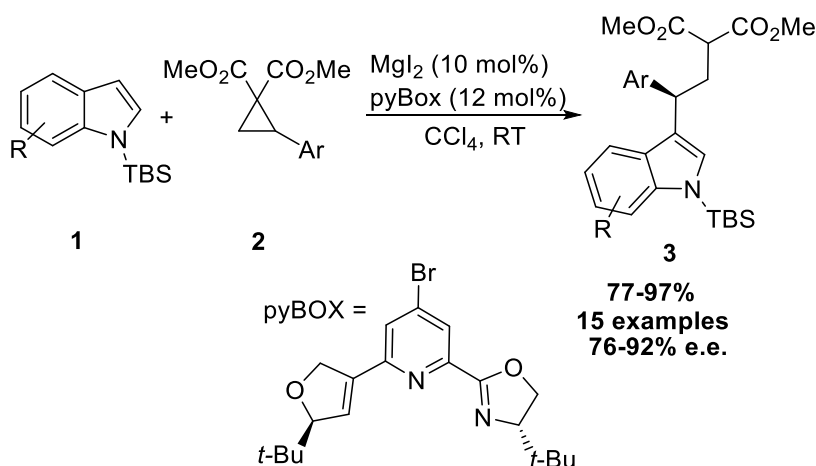
Scheme 1.5: Enantioselective ring-opening of **2** with 3-indoyl nucleophiles

1.1.2.1.2. Heteroatomic nucleophiles

Heteroatoms are also widely used as nucleophilic reagents in Homo-Michael addition reactions. The DACPs have been reported for being sensitive to ring-opening induced by the attack of N-based nucleophiles. Mattson and co-workers reported the ring-opening of 1-nitrocyclopropanes-1-carboxylate **4** with an amine in the presence of the difluoroborylphenyl urea **cat** (Scheme 1.6).[6] The catalyst activates the DACP through hydrogen bonding of the NH of the urea function with the nitro group. The presence of a B-O interaction (highlighted in red in **cat**) was found to increase the yields in the desired product.Compound **5** is obtained after the reprotonnation of the carbon bearing the two acceptor groups. 10 examples of the acyclic adduct were obtained in good yields.
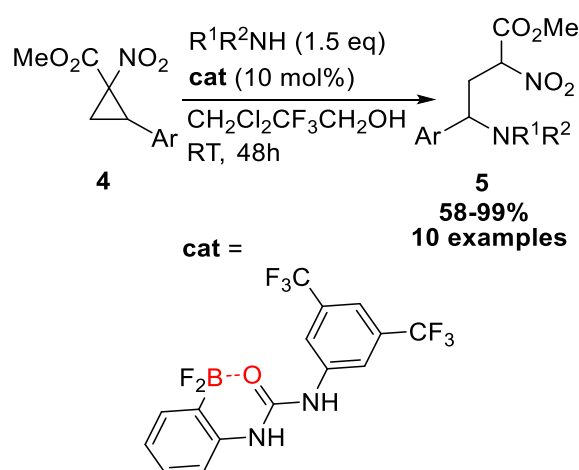
Scheme 1.6: Ring-opening of DACP **4** with amines in the presence of a urea catalyst

After developing the methodology, the authors envisaged the use of optically active substrate **(S)-4a**. The reaction proceeds with a complete inversion of the configuration of the carbon involved in the attack of the amine (Scheme 1.7). The product **(R)-5a** was then further transformed to lactam **6**, a reverse agonist of the CB-1 receptors, in multiple steps.
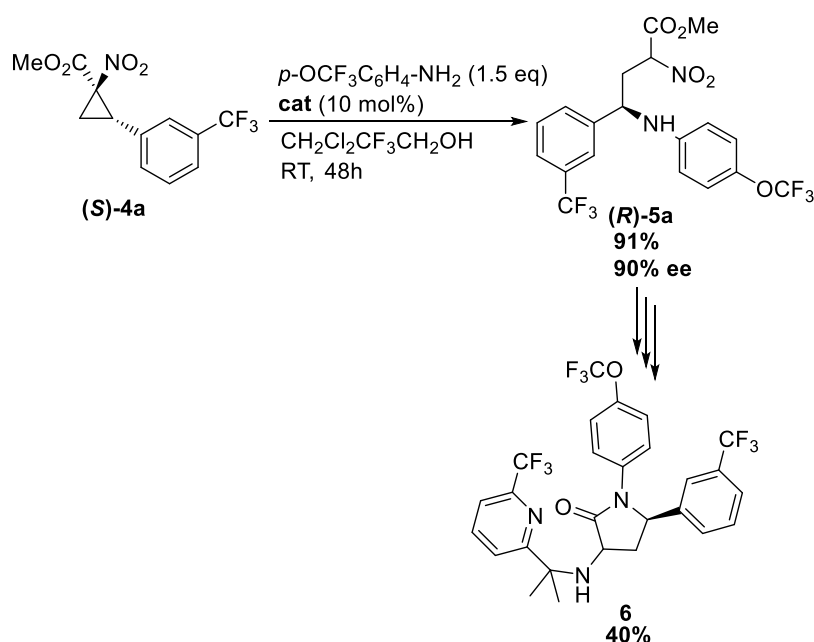
Scheme 1.7: Total synthesis of a CB-1 reverse agonist, **6**.

The ring-opening of donor-acceptor cyclopropanes can be accompanied by secondary processes leading to the formation of heterocyclic compounds. One example of such process is the cascade ring-opening/lactamisation of cyclopropanes-1,1-dicarboxylates to γ-lactams (Scheme 1.8). Chen *et al.* reported the stereoselective synthesis of γ-butyrolactams **8**.[7] The first step of this strategy is the addition of anilines acting as the nucleophilic reagent opening the cyclopropane. The so-formed intermediate **9** can undergo a rotation followed by an attack of the amine on the carbonyl of the ester, triggering the departure of a molecule of acetone. The authors reported the synthesis of 24 examples of the lactams **8** with good to excellent yields.
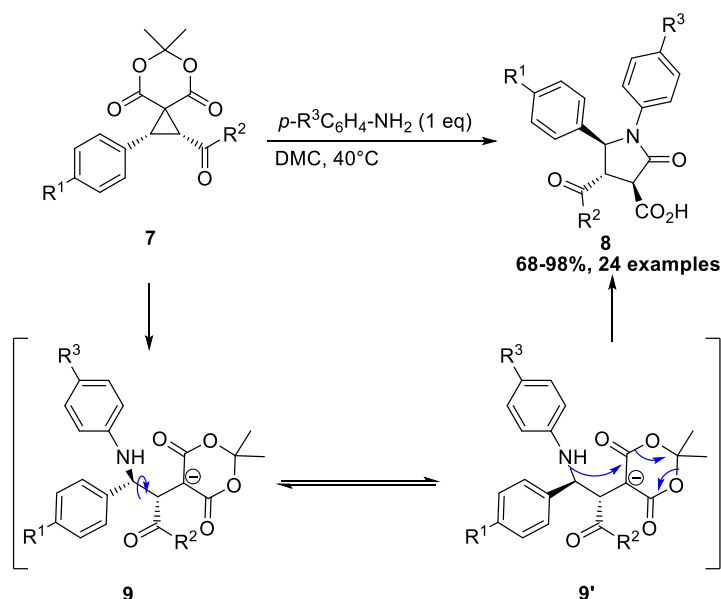
Scheme 1.8: Domino process for the formation of γ-lactams **8** from **7**

Cyclopropanes activated by a ketone group can also be involved in domino reactions with primary amines to form pyrrolidines. The group of Prof. A. Charette developed a strategy for the obtaining of cyano and nitropyrrolidines **12** by reaction of **10** (with EWG = NO$_2$ or CN) with aliphatic amines or anilines (Scheme 1.9).[8] The process involves the condensation of the ketone group with the secondary amine created by the addition of the primary amine on the cyclopropane.
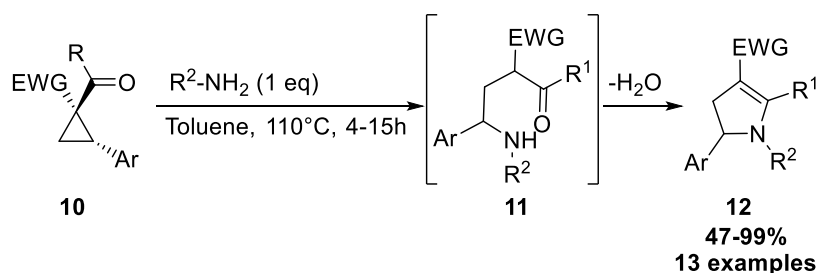
Scheme 1.9: Domino process for the formation of pyrrolidines **12** from **10**

1.1.3 Rearrangement reactions

The donor-acceptor cyclopropanes can undergo rearrangement reactions such as the formal homo-Nazarov reaction or the formation of olefins.

1.1.2.1 Formal homo-Nazarov reaction

The formal homo-Nazarov process is a synthetic strategy for the obtaining of cyclohexanones and other related polycycles. Compared to the Nazarov cyclisation, one of the unsaturations is replaced by a cyclopropane moiety.[9] It has been suggested that the cyclisation of the vinyl carbonyl ketone is a stepwise process contrary to the Nazarov cyclisation (Scheme 1.10). The presence of an electron-donor group at the R^2 position of the DACP **13** helps the ring-opening of the cyclopropane by increasing the stabilisation of the created positive charge in **14**.
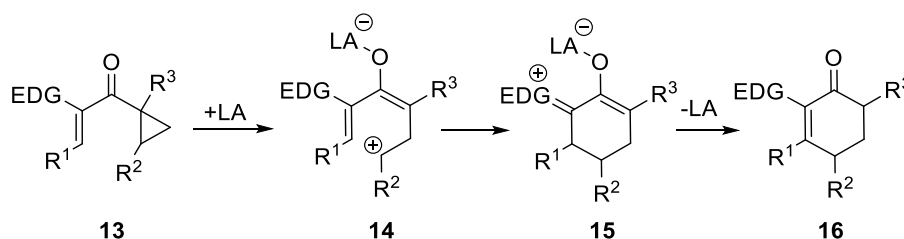
Scheme 1.10: Mechanism of the formal homo-Nazarov reaction

Two different approaches can be used to activate the DACP moiety for this formal homo-Nazarov reaction.[10] The first strategy is the addition of a second carbonyl acceptor group (ketone or ester) at the R^3 position. This leads to the further polarisation of the donor-acceptor cyclopropane and decreases the barrier of activation for its ring-opening. The addition of a heteroatom as the EDG group also activates the system. The heteroatom can increase the electron density at the terminal position of the π-system hence increasing the reactivity of this position towards intramolecular attack on the carbocation formed by the ring-opening of the cyclopropane. The unsaturation with the heteroatom can be part of heterocycles such as thiophen, furyl or indoles.

Phun *et al.* reported the use of the formal homo-Nazarov reaction to synthesise cyclohexanones 2,3-fused to furans, thiophenes, benzofuranes and indoles (**18-20**) using In(OTf)$_3$ as a catalyst (Scheme 1.11).[11] Their work uses the addition of a second electron-withdrawing group to help the heterolytic C-C cleavage of the cyclopropane.
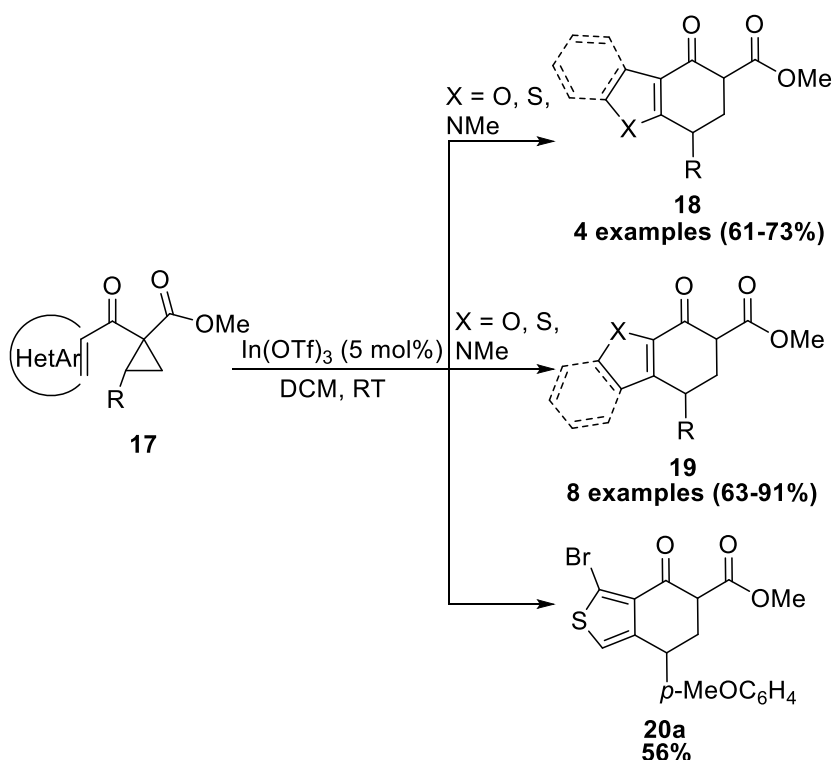
Scheme 1.11: Formation of cyclohexanones 2,3 fused furans, thiophenes, benzofuranes and indoles

The group of Prof. J. Waser also investigated the homo-Nazarov reaction of DACPs. After investigating the formation of heterocycles from DACP with only one electron-withdrawing group, they only manage to obtain cyclohexanones fused with an indole group **22**. Then, they decided to focus their efforts on the formation of polycyclic alkaloidal scaffold coming from DACPs with an amine donor group (**21**) (Scheme 1.12).[9,12]

9

21 → **22**
3 examples (70-99%)

Cu(OTf)$_2$ (10 mol%)
CH$_3$CN, RT
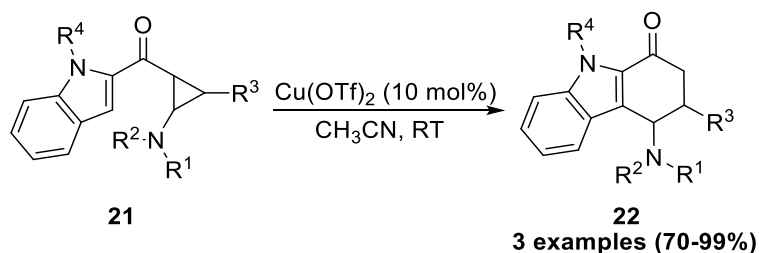
Scheme 1.12: Formal homo-Nazarov cyclisation with amine donor group

Amongst the examples reported by the group of Prof. J. Waser, the product **22a** was a protected precursor to a target intermediate for the formal total synthesis of the natural product aspidospermine **23** (Scheme 1.13).

22a → **23**
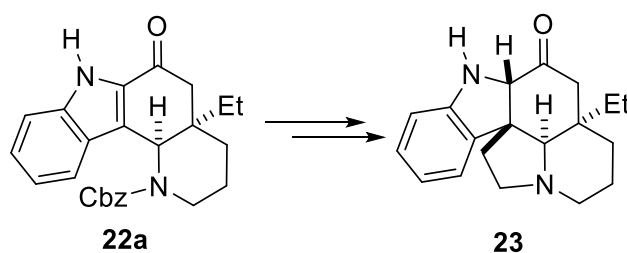
Scheme 1.13: Aspidospermine **23**

1.1.3.2 Rearrangement into olefins

The rearrangement of donor-acceptor cyclopropanes catalysed by the trifluoroacetic acid (used as the solvent) was studied by Kosaker and Jensen.[13] In one example of their studied scope, **25**, they observed the formation of two olefins, isomers to one another (**25** and **26**) (Scheme 1.14).

24 → **25, 58%**   **26, 27%**

TFA
RT
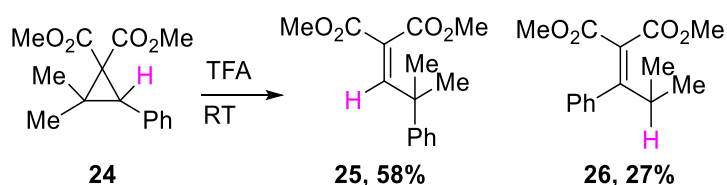
Scheme 1.14: Protolysis of **24** leading to the formation of **25** and **26**

The authors studied the mechanism explaining the formation of these two olefins by performing the reaction in TFA-d. Their NMR spectra showed no deuterium in the resulting products, indicating that the pink hydrogens in **25** and **26** comes from the DACP **24** and not by protonation by the solvent. This led Kosaker and Jensen to suggest the following mechanims (Scheme 1.15): the DACP **24** undergoes a heterolytic ring-opening catalysed by H$^+$ to form 1,3-dipole **27-H$^+$**. The negative charge triggers the 1,2-migration of either the Ph or H group to form **25** and **26**, respectively, upon deprotonation of the ester groups of the olefins.
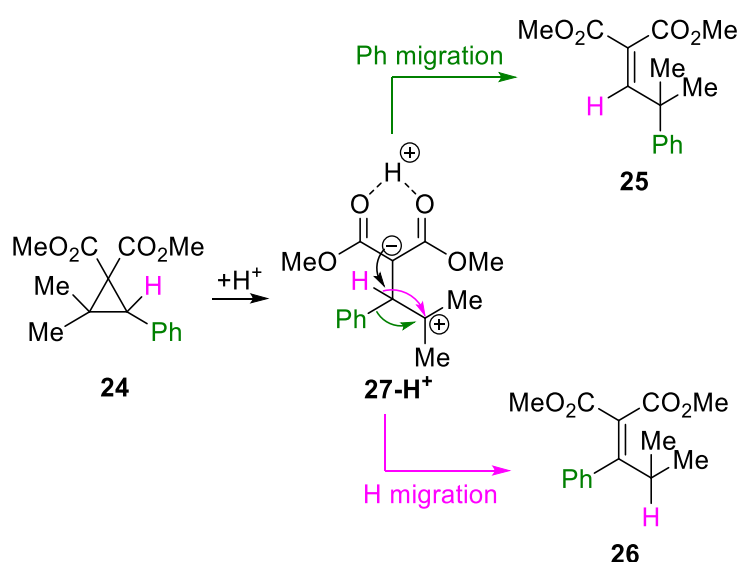
Scheme 1.15: Suggested mechanism for the formation of **25** and **26**

The other DACPs studied in this report were found to rearrange into other products such as lactones or aldehydes.

In 2016, the group of Prof. Tomilov reported the rearrangement of DACPs **2** to the olefins **28** (Scheme 1.16).[14] This time, the transformation was triggered by a Lewis acid, GaCl$_3$, and was exploited for the formation of 12 olefins **28** in good yields (72-98%). The authors investigated the nature of the aryl group and reported that mild donor aryls with alkyls at every position of the aromatic ring,

mild acceptor aryls with halogens at every position and 1- and 2-naphthyl groups were tolerated by their methodology.

MeO$_2$C CO$_2$Me   1) GaCl$_3$ (1.1 eq)   MeO$_2$C CO$_2$Me
                     DCM, 0°C, 10 min
              Ar   2) MeOH   Ar
   2   **28**
                                        12 examples (72-98%)
        Ar = Ph, mild donor aryls, mild acceptor aryls,
        1- and 2-naphthyl
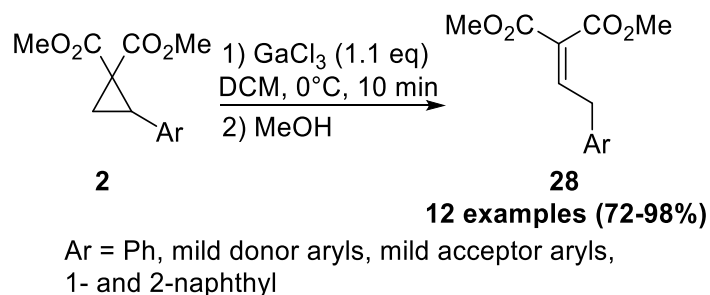
Scheme 1.16: GaCl$_3$ induced rearrangement of **2** to **28**

The mechanism postulated by Tomilov to explain the rearrangement is similar to the one suggested by Jensen and colleague (*vide supra*). It starts by the complexation of the ester groups by the Lewis acid (Scheme 1.17). A heterolytic ring-opening occurs to form the zwitterionic intermediate **29-LA**. Then, the 1,2-migration of a hydrogen produces the complexed olefin **28-LA** which is decomplexed by the addition of methanol to quench the reaction. The DACPs **2** were the only substrates to be studied by the authors and then the hydrogen substituent was the only reported migrating group in this reactivity of donor-acceptor cyclopropanes.

MeO$_2$C CO$_2$Me   LA   LA
                              O   O   O   O
          Ar   MeO   OMe   MeO   OMe
   2   H   Ar
                           Ar   **28-LA**
                     29-LA
                                            MeOH -LA
                                    MeO$_2$C CO$_2$Me
                                                 Ar
                                             28
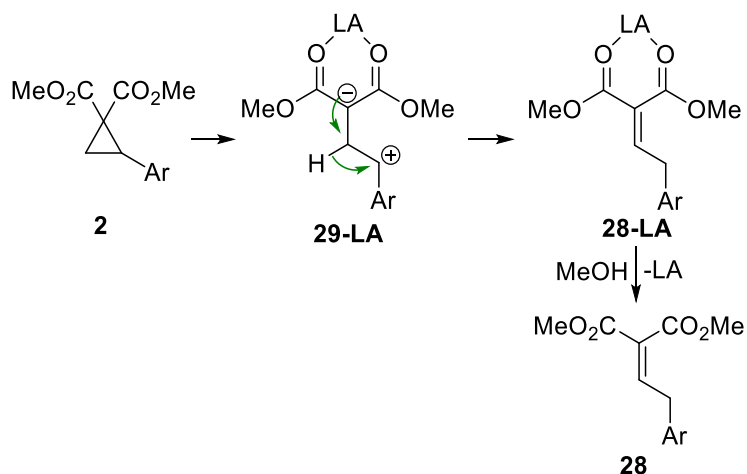
Scheme 1.17: Postulated mechanism for the formation of **28**

The DACP **2** is obtained via a Corey-Chaykovski type reaction between Knoevenagel adduct **30** and the sulfoxonium salt **31**. The strategy is a formal one-carbon homologation methodology by insertion of a methylene fragment (Scheme 1.18).
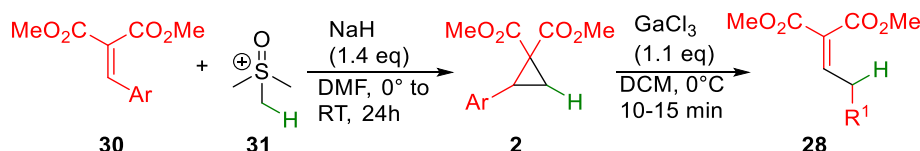
Scheme 1.18: One-carbon homologation of Knoevenagel adducts by insertion of a methylene fragment

Chagarovskiy reported the rearrangement of the same DACP to the olefin **32**, which is an isomer of the one obtained by the group of Prof. Tomilov (**28**).[15] (Scheme 1.19). Eight examples with yields ranging from 56 to 86% were described. The authors screened Lewis acids for triggering this reaction and settled on TMSOTf because with other candidates some side products (lactone, chlorinated product) were observed in significant amount or even as the main product of the reaction. The exploration of the scope of their methodology allowed the authors to report the synthesis of olefins with electron-rich and –poor aryls, indoles, thionyls, naphthyls and indole groups.
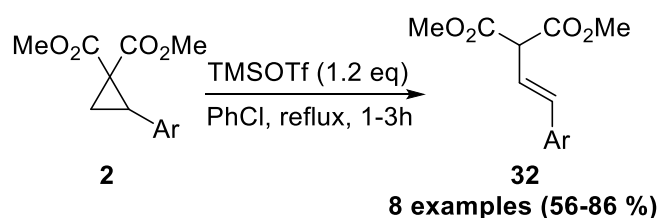
Ar = Donor aryls, acceptor aryls, indoles, thionyls, naphthyls

Scheme 1.19: TMSOTf induced rearrangement of **2** to **32**

The authors proposed the mechanism depicted in Scheme 1.15 to explain this transformation. The Lewis acid complexes one ester group and promotes the heterolytic ring-opening of the DACP **2**. The oxygen of the non-complexed ester of the zwitterion intermediate **33-LA** can act as a base and abstracts a proton on the β position to create

an unsaturation. The departure of the Lewis acid allows for the isolation of the olefin **32**.
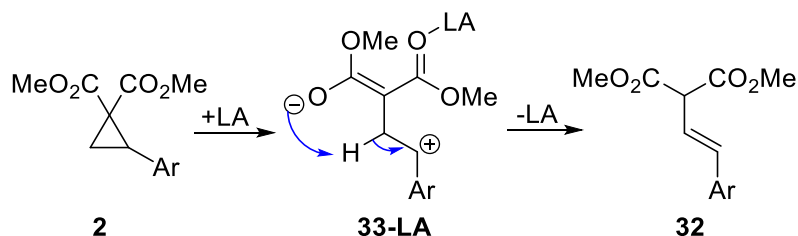
Scheme 1.20: Postulated mechanism for the formation of **32**

1.1.4. (3+n) cyclodimerisation reactions

The donor-acceptor cyclopropanes can also be involved in (3+3) and (3+2)-cyclodimerisation reactions.

1.1.4.1. (3+3) Cyclodimerisation reactions

The (3+3) cyclodimerisation requires the cyclopropane to be heterolytically opened to form 1,3-dipoles. The DACPs with aryls as the donor group can be considered as synthons of two different 1,3-dipoles, I or II (Scheme 1.21). The (3+3) cyclodimerisation can occur via the reaction of the same two types of dipole (I+I or II+II) or by a combination of two dipoles of different nature to form substituted six membered carbocycles scaffolds which can be fused with (hetero)aromatic groups to form polycyclic compounds.
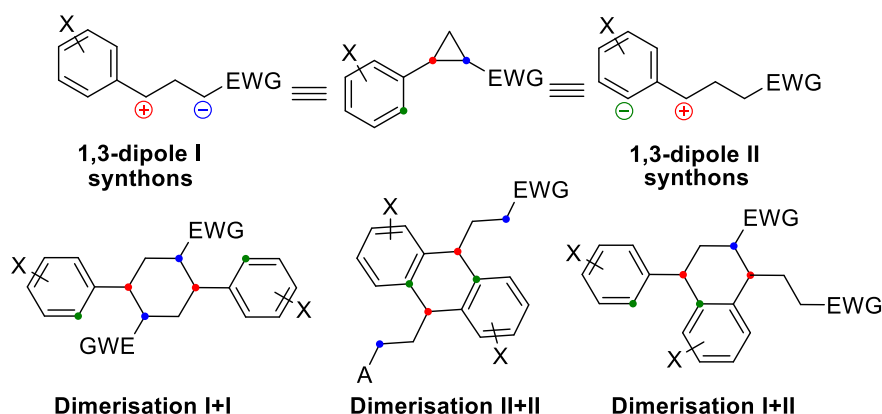
Scheme 1.21: Three pathways for the (3+3) cyclodimerisation of DACPs

The dimerisation of DACPs was first observed by Ila *et al.* and reported in 2002 (Scheme 1.22).[16] The intermediate **35** is obtained via a (3+3) dimerisation of the cyclopropane **34** (I+II type). This is one step of a domino process allowing for the formation of the polycyclic compounds **36** via the elimination of an indole moiety and dehydrogenation leading to aromatisation followed by an intramolecular aldol condensation of the side chains. Multiple examples of the domino process were reported with yields ranging from 57 to 89%.
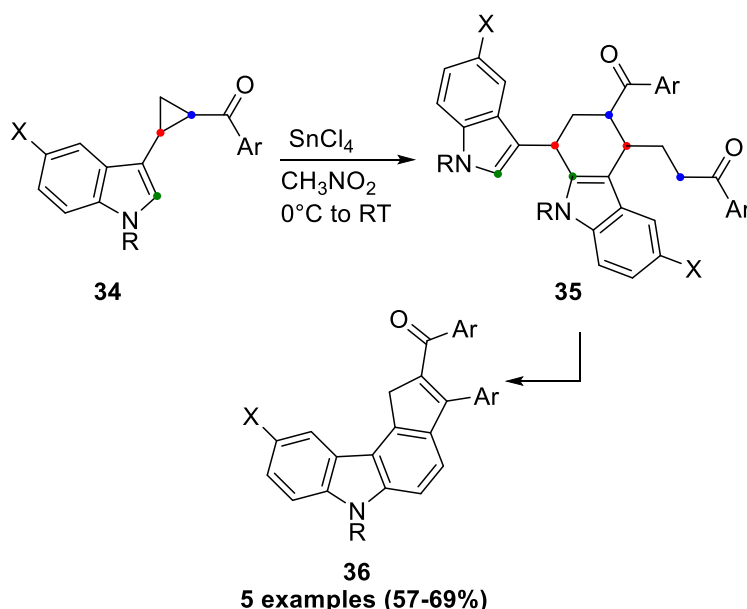
Scheme 1.22: The first reported example of (3+3) cyclodimerisation

In 2011, Ivanova and co-workers developed the divergent (3+3) cyclodimerisation leading to the three different types of dimers.[17] The outcome of the dimerisation depends on the nature of the substrate and the reaction conditions. They observed that the ring-opening of the donor-acceptor cyclopropane **2** can produce an intermediate **33-LA** acting as 1,3-dipole synthons I or II depending on the nature of the aryl group (Scheme 1.23). The presence of very electron-rich (hetero)aryls can increase the nucleophilicity of the *ortho* position of the aryls allowing them to react as 1,3-dipole II.
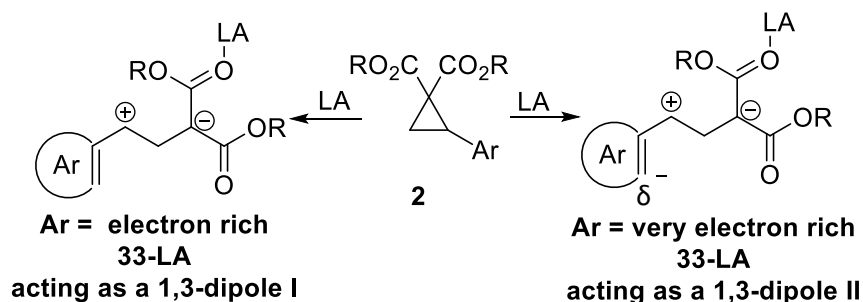
Scheme 1.23: Ring-opening of **2** with Lewis acid

The I+I dimerisation is favoured by using an aryl group able to stabilise the positive charge formed on the aromatic group in the 1,3-dipole type I and with a low nucleophilicity of the *ortho* atom (Ar = 2,4,6-MeOC$_6$H$_4$, 4-MeOC$_6$H$_4$ or 4-NR$_2$C$_6$H$_4$). Reaction conditions used SnCl$_4$ (1.2 eq) for methoxy substituted aryls and TiCl$_4$ for amine substituated aromatic rings. The nitromethane was the solvent leading to the best yields and the least amount of side products. The cyclohexanes **37** were obtained in good yields and with a full diastereoselectivity for the *cis* isomer.
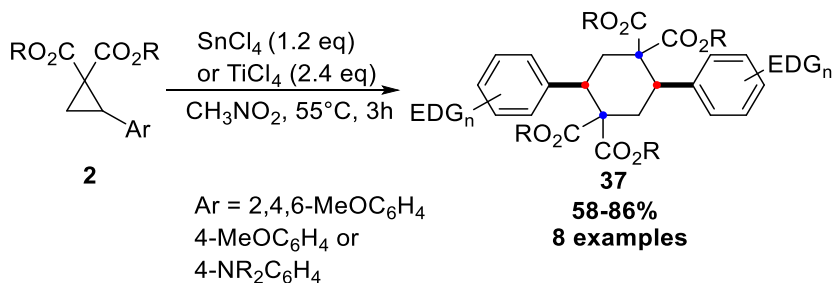
Scheme 1.24: I+I (3+3)-cyclodimerisation of **2**

In addition to the dimers **37**, the formation of 1-aryltetralines **38** and heterocyclic analogues (**39-41a**) were reported (Scheme 1.25). These dimers are obtained via a I+II dimerisation of DACPs possessing aryl groups such as 4-methoxyphenyl, 3,4-dialkoxyphenyl, thienyl, 2-benzofuryl or 3-indolyl. The d.r. (*cis/trans*) of the resulting tetralines and derivatives vary greatly. The arylteratlines **38** and derivatives **40** favour the formation of the *cis* compounds, whereas **39** and **41a** are obtain with a d.r. in favour of the *trans* isomer. The reaction conditions

16

used nitromethane as well but it was not the only solvent giving rise to the desired product. The reaction conditions were carefully chosen to optimise the yield and avoid the formation of dimers from the I+I pathway.

38, 40-90%, 4 examples, d.r.: 55/45 - 95/5

39, 50-65%, 5 examples, d.r.: 42/58 - 5/95

40, 54-78%, 2 examples, d.r.: 56/44 - 71/29

41a, 20%, d.r.>5/95
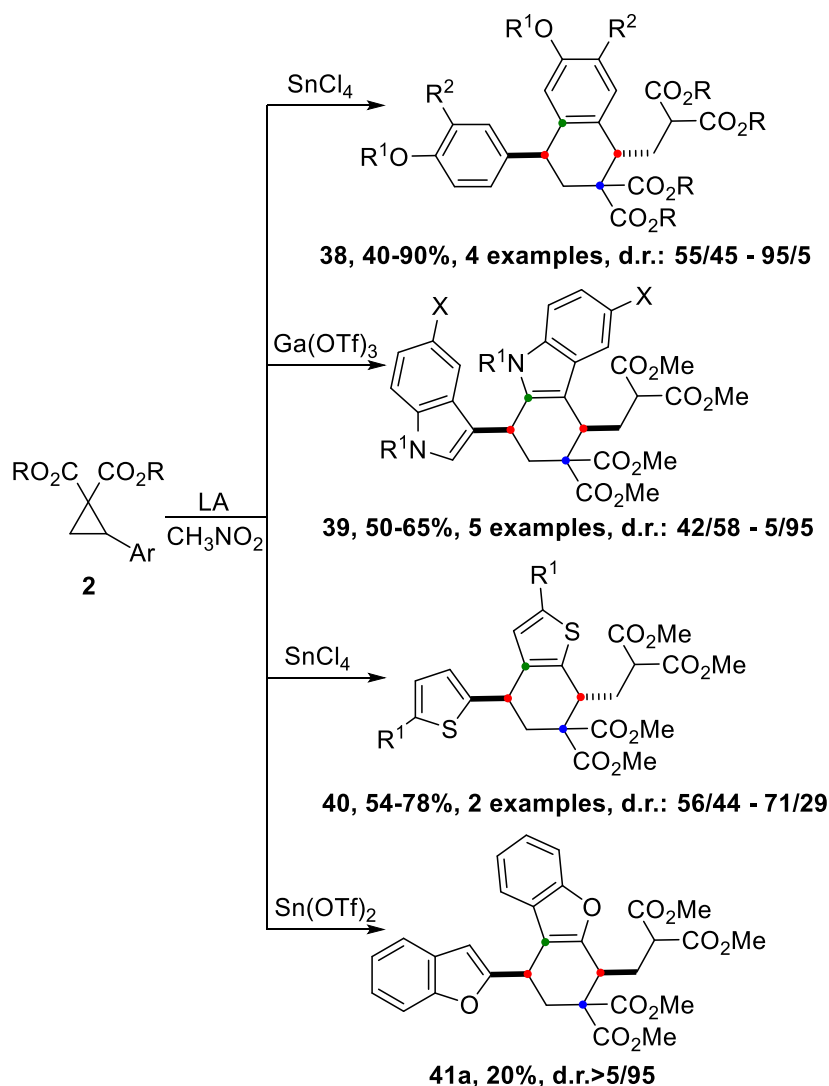
<u>Scheme 1.25</u>: I+II (3+3) cyclodimerisation of **2**

The authors also reported the formation of dihydroanthracenes **42** obtained via a (3+3) cyclodimerisation which can be classified as II+II (Scheme 1.26). This reactivity was favoured by

increasing the nucleophilicity of the *ortho* position of the aryl groups by the addition of electron-donor groups in the *meta* position. The reaction conditions used for the I+I dimerisation could be used to obtain the product **42** but the use of $Sn(OTf)_2$ allowed the authors to obtain better yields.

2

$Ar = 3,4,5\text{-MeOC}_6H_4$
$3,5\text{-MeOC}_6H_4$ or
$2,3\text{-MeOC}_6H_4$

42
61-88%
3 examples
d.r.: 63/37 - 90/10
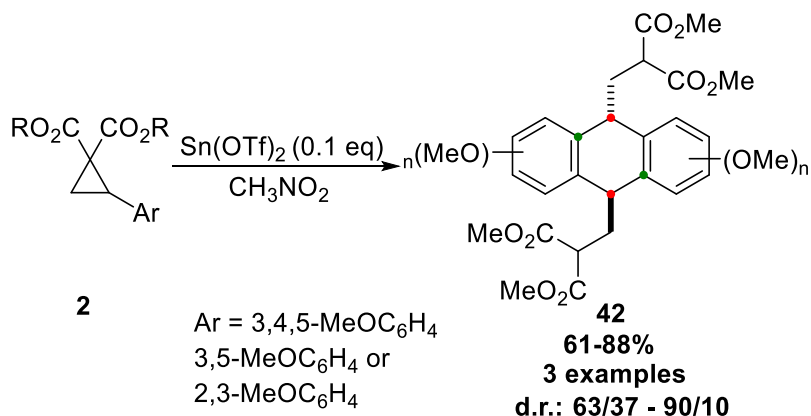
Scheme 1.26: II+II (3+3) cyclodimerisation of **2**

1.1.4.2. (3+2) cyclodimerisation reactions

The (3+2) cyclodimerisation is another dimerisation process in which the donor-acceptor cyclopropanes can be involved. The three carbons component is still the 1,3-dipole created by the heterolytic ring-opening of **2** but a two carbons component needs to be generated from the same cyclopropane. The olefin **24** is generated via isomerisation of **2** under Lewis acid catalysis by the reactivity described in section 1.1.2.

Ivanova *et al.* reported the *homo* and *cross* coupling of arylcyclopropanes **2** (Scheme 1.27).[18] The *homo* coupling strategy used reaction conditions able to promote both the rearrangement of **2** to **24** and the (3+2) cyclodimerisation. It is carried out in the presence of $Sn(OTf)_2$ in nitromethane. Optimisation of the reaction conditions showed that this solvent led to the obtaining of the best yield for this transformation. On the other hand, the *cross*-variant is described as a two-step process in which one of the DACPs is isomerised to the corresponding olefin using the same Lewis acid in chlorobenzene

before being put in reaction with the DACP intended to act as the 1,3-dipole. The conditions used for the *homo*-variant are used for the dimerisation step. In total, the authors reported 15 examples of *homo* and *cross*-coupling products **43**.
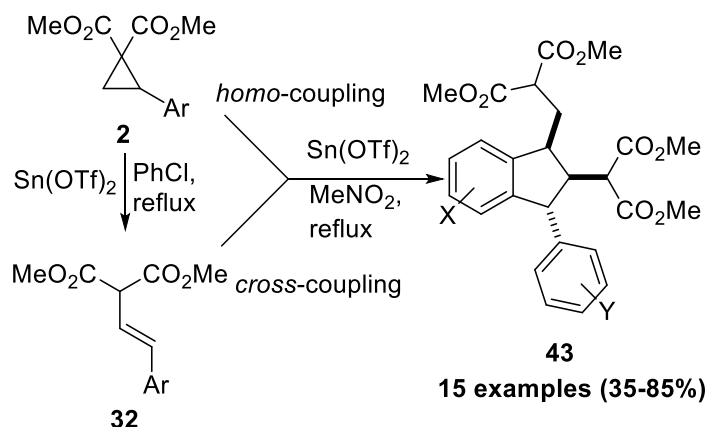
Scheme 1.27: (3+2) cyclodimerisation of **2**

1.1.5. (3+n) cycloaddition reactions

The reactivity of the DACPs via the formation of 1,3-dipoles allows them to be involved in (3+n) cycloadditions. This section presents the (3+2) and (3+4) cycloadditions of donor-acceptor cyclopropanes activated by two esters groups.

1.1.5.1 (3+2) cycloaddition reactions

The DACPs can be engaged in (3+2) cycloaddition reactions with a molecule containing a reactive double bond.

1,3-Dienes are widely used in organic chemistry as 4π-component in cycloaddition reactions such as the Diels-Alder reaction.[19] Budynina and co-workers reported the (3+2) cycloaddition of acyclic and cyclic 1,3-dienes **44** and **2** activated by TiCl$_4$ to form the necessary 1,3-zwitterion (Scheme 1.28).[20] 8 examples of cyclopentanes derivatives with a vinyl bond **45** were obtained with a good d.r.. Bicyclic compounds **46** were also isolated in similar yields but moderate d.r. when the 1,3-diene was the 1,3-cyclohexadiene.
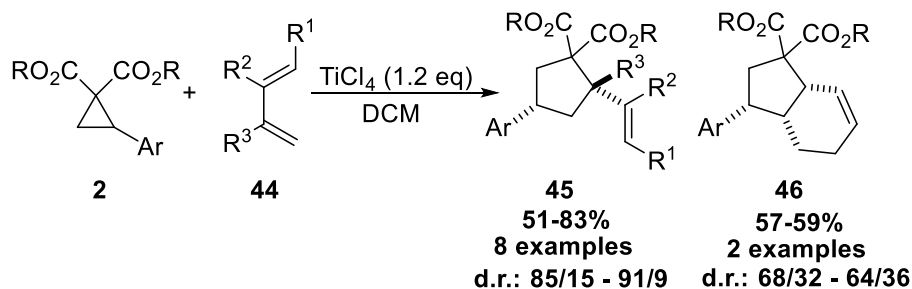
Scheme 1.28: (3+2) cycloaddition of **2** with **44**

Furans are also widely used in cycloaddition. Chagarovskyi *et al.* investigated the (3+2) cycloaddition of furans with donor-acceptor cyclopropanes.[21] The furan and methylfuran were found to be unreactive towards the desired transformation. However, the dimethylfuran **47** can successfully be engaged in the cycloaddition process to form bicyclic compound **48** (Scheme 1.29).
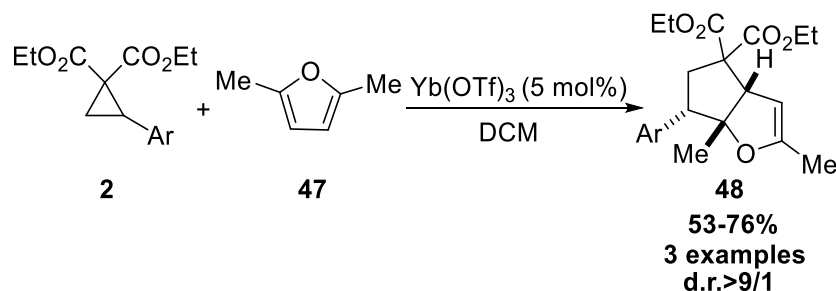
Scheme 1.29: (3+2) cycloaddition of **2** with **41**

The authors also developed a double (3+2) cycloaddition between **41** and two equivalents of the donor-acceptor cyclopropane **2** (Scheme 1.30). Two examples of tricyclic compounds **43** were reported.

2   **47**   **49**

LA = $Yb(OTf)_3$ or $SnCl_4$ **82-94%**
2 examples
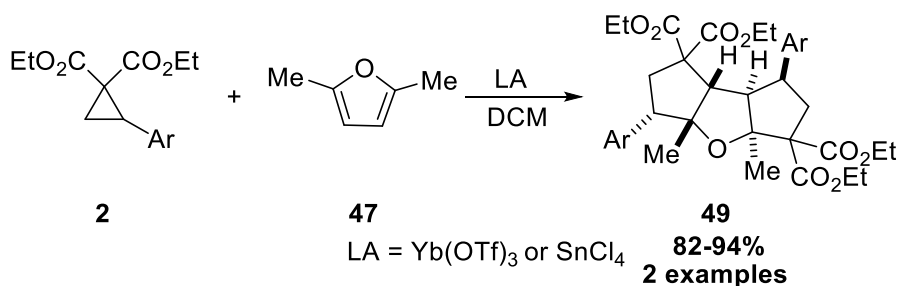
Scheme 1.30: Double (3+2) cycloaddition of **2** with **47**

1.1.5.2 (3+4) cycloaddition reactions

The 1,3-dienes can also be engaged in (3+4) cycloaddition reactions in which both unsaturations of the 1,3-diene are involved. The strategy is an interesting process for the obtaining of seven membered carbocycles in organic synthesis.[22]

Ivanova and co-workers expanded their work on the cycloaddition of donor-acceptor cyclopropane with furans (*vide supra*) and showed that isobenzofuran **50** is a suitable (3+4) cycloaddition partner for **2** (Scheme 1.31).[23] The products **51** are formed in the presence of 5 mol% of a Lewis acid, in this case $Yb(OTf)_3$. The authors reported the formation of *endo* and *exo* cycloadducts with ratios in favour of the *exo* product up to 86/14.

2   **50**   **51**
61-94%
12 examples
up to 86/14 *exo/endo*
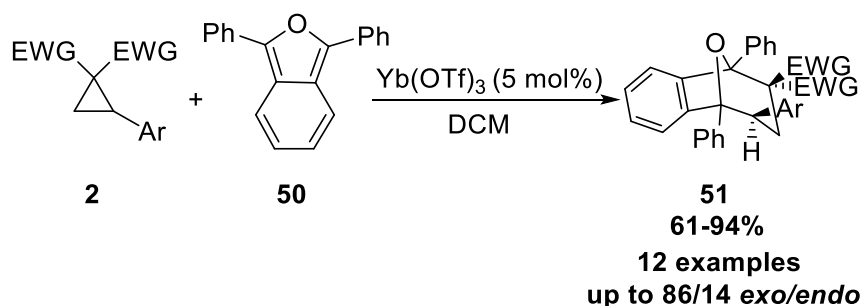
Scheme 1.31: (3+4) cycloaddition of **2** and **50**

The strategy was successfully used to obtain other (3+4) cycloaddition products using fully carbonated carbocycles as the 1,3-diene moiety such as anthracene or cyclopentadienes. However, the use of non-cyclic 1,3-dienes leads to the preferred formation of the

(3+2) cycloadduct.[20] Zhang *et al.* proposed a solution to this problem (Scheme 1.32).[24] They used an intramolecular reaction of **52** in the presence of Yb(OTf)$_3$ to generate the two (3+2) cycloaddition products **53** and **54**. The presence of the two vinyl groups in **54** allows for its rearrangement to the desired seven membered ring **55**. The rearrangement occurs through the heterolytic ring-opening of **54** by cleavage of the red bond, the resulting positive charge being stabilised by both vinyl groups. This process can be considered as a formal (3+4) cycloaddition. This reaction is however limited to intramolecular reactions.
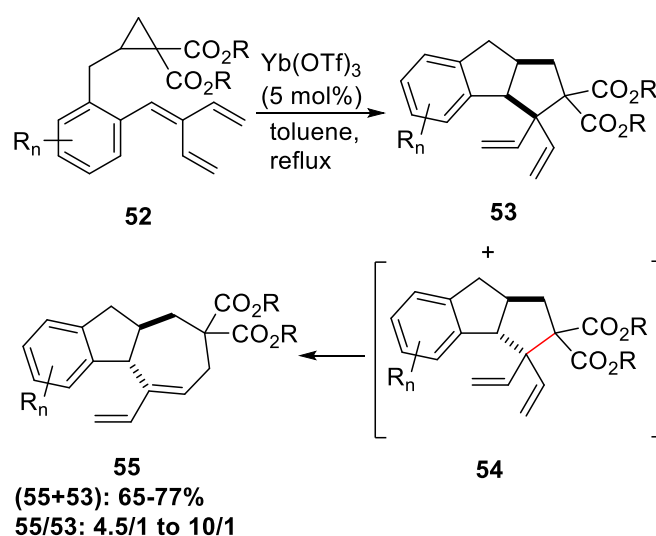
Scheme 1.32: Formal intramolecular (3+4) cycloaddition of **52**

The group of Prof. Y. Tang reported the asymmetric (3+4) cycloaddition between **2** and conjugated enol ethers **56** acting as the four carbons components (Scheme 1.33).[25] The authors first studied the BOX ligands for this transformation but observed the presence of a significant amount of the (3+2) cycloaddition product. They investigated the TOX ligands and found that the best candidate was a TOX-Cy ligand which allows for the formation of seven membered carbocyles **57** in good to excellent yields and excellent *e.e.* with a (3+4)/(3+2) selectivity >99/1. The authors postulated that the mechanism is stepwise and not concerted. The formation of the (3+2)

cycloadducts is kinetically favoured and a ring-opening/intramolecular cyclisation sequence allows for the formation of the seven membered carbocycles **57** which are thermodynamically more stable.
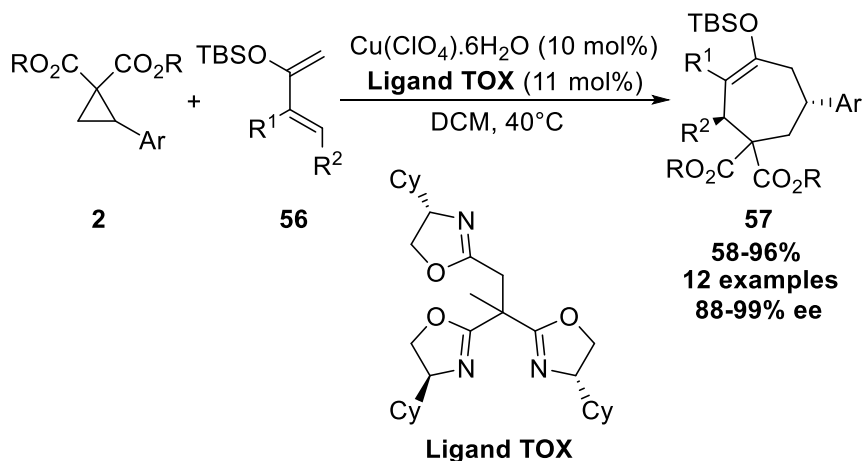
Scheme 1.33: First example of asymmetric (3+4) cycloaddition of DACPs

1.2. Vinylcyclopropanes

Vinylcyclopropanes are another types of cyclopropane rings. The addition of a vinyl group has no influence on the ring strain energy (27 kcal/mol)[3] but has an impact on the activation energy towards ring-opening. The activation energy of the homolytic ring-opening of the unsubstituted vinylcyclopropane has been determined to be around 13 kcal/mol lower than the one of the cyclopropane (see 1.1.1.). This can be accounted for by the stabilisation of the radical in a delocalised π system (12.6 kcal/mol).[3]

Vinylcyclopropanes are important intermediates in organic synthesis. They have been reported to undergo a heterolytic or homolytic ring-opening (allowing for the release of the ring-strain). The zwitterion or diradical opened intermediates can then be involved in ring-opening reactions, rearrangement reactions to cyclopentene or skipped diene, or cycloaddition reactions (Scheme 1.34).
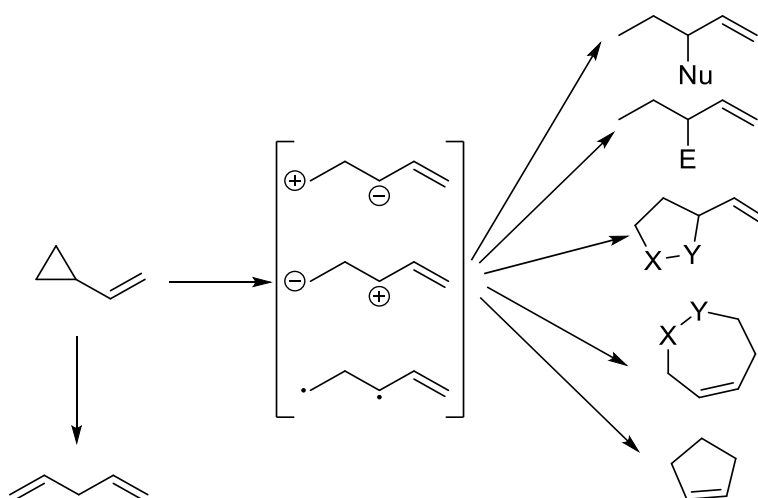
Scheme 1.34: Rearrangement or cycloaddition reactions of VCPs

When the VCP is activated by one or two electron-withdrawing groups on the vicinal carbon to the vinyl group, the VCP can be considered as a donor-acceptor vinylcyclopropane (Scheme 1.32). The reactivity of these activated VCPs shares similarities with DACPs but includes additional reactivities involving the double bond and made possible by delocalisation of the positive charge. The DA vinylcyclopropanes can be engaged in the same reactions as their DACPs counterparts.
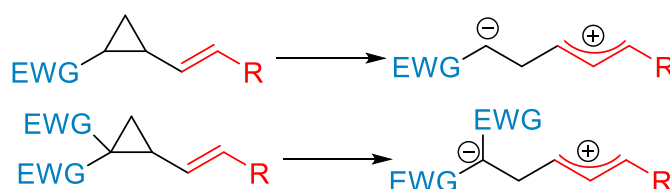
Scheme 1.35: Similarities of donor-acceptor VCPs reactivity with DACPs

1.2.1. Ring-opening reactions

The most common reactivity of VCP is the ring-opening with nucleophiles (Scheme 1.36, a). Interstignly, in addition to the ring-opening via the addition of a Lewis acid (*vide supra*), VCPs can be opened by the complexation of the double bond of **58** by a transition metal complex such as a palladium complex, which stabilises the

positive charge created by the heterolytic cleavage of a C-C bond of the VCP. The so-formed π-allyl moiety of **59** is electrophilic and can react with nucleophiles to generate adduct **60**.

The ring-opening reaction with electrophiles requires an inversion of the polarisation (umpolung) by the creation of a nucleophilic allyl metal specie in **59** which can react with electrophiles to form adducts **61** (Scheme 1.36, b).
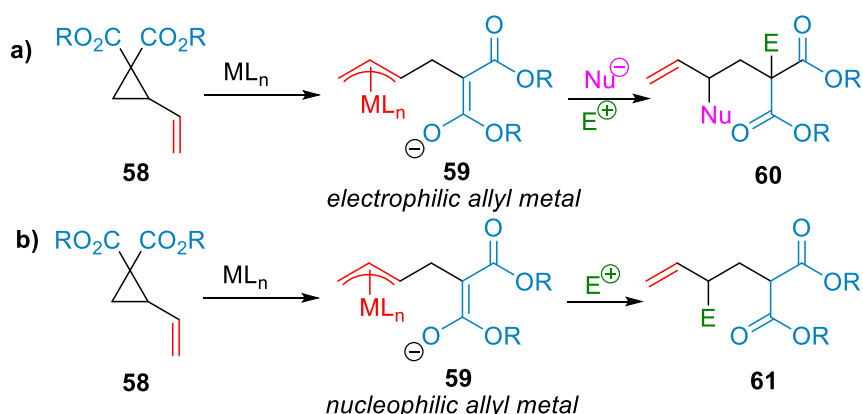
Scheme 1.36: Ring-opening reaction of VCP **52** with nucleophiles (a) and electrophiles (b)

1.2.1.1. Ring-opening reactions with nucleophiles

The most commonly studied ring-opening reactions of VCPs involves the reaction with nucleophiles. The electrophilic allyl metal specie can be generated with the use of palladium or iron catalysts.

Hyland *et al.* reported the use of palladium acetate in water for the ring-opening of VCP **58** by reaction with boronic acids (Scheme 1.37).[26] The position of the addition depends on the substitution pattern of the vinylcyclopropane and is highly regioselective. Non-substituted unsaturations (R^1 = H) led to the selective formation of the linear adducts **62**. The 13 examples of linear compounds **62** showed *E/Z* selectivity higher than 85/15. Non-terminal olefin on the vinylcylopropanes were also investigated (R^1 = Ar). In these cases, the attack of the nucleophile occurs at the other position of the π-allyl and

yields the adducts **63** with similar yields. The selectivity towards the *E* olefin is, in this case, total.
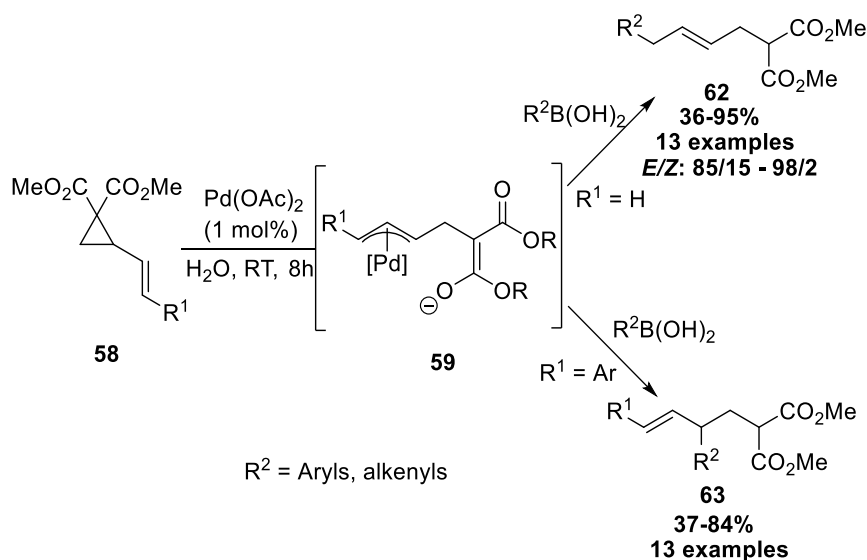
<u>Scheme 1.37</u>: Ring-opening of VCP **58** with boronic acids catalysed by [Pd]

1.2.1.2. Ring-opening reactions with electrophiles

Ring-opening reactions of VCPs with electrophiles have also been more recently reported. The polarity inversion required for this strategy can be achieved with the use of iridium complexes. The group of Prof. M. J. Krische developed a methodology using an iridium chiral complex (**S**)-**Ir** for the formation of nucleophilic allyl metal compound before its reaction with a carbonyl either formed *in situ* from the corresponding alcohol **64** or used as a starting material (**65**) (Scheme 1.38).[27] This report was the first to show the umpolung reactivity of activated VCP towards electrophiles.
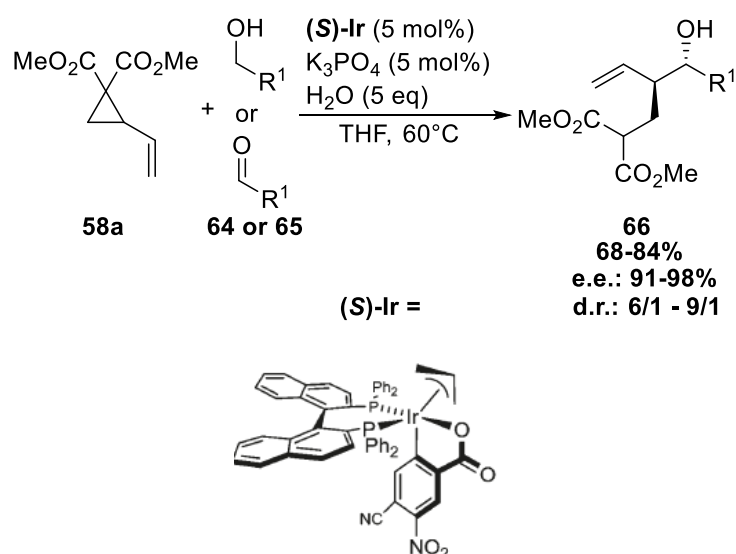
Scheme 1.38: Ring-opening of VCP **58a** with alcohols/carbonyls catalysed by **(S)-Ir**

1.2.2. Cycloaddition reactions

Cycloaddition reactions of VCPs are widely used in organic synthesis for the formation of five and seven membered (hetero)cycles via (3+2) or (5+2) of vinylcyclopropanes with a two-atom component.

1.2.2.1. (3+2) cycloaddition reactions

Similarly to the DACPs (see 1.1.5.1.), the vinylcyclopropanes can be involved in (3+2) cycloaddition reactions with aldehydes, imines or olefins. The heterolytic ring-opening of the VCP can be achieved by the formation of a π-allyl complex, similarly as the reactivity presented in 1.2.1 (Scheme 1.39). The 1,3-zwitterion formed can react with polarised double bonds (Nu=E) to form five membered cycles **67**.
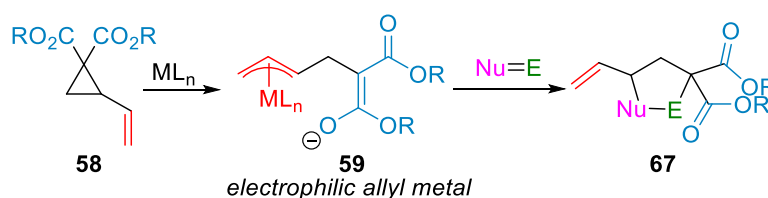
Scheme 1.39: (3+2) cycloaddition of VCPs and Nu=E in presence of a transition metal catalyst

The group of Prof. J.S. Johnson reported the diastereoselective (3+2) addition between the VCP **52a** and an aldehyde (**59**) under Pd catalysis with a phenantroline ligand **L** to lead to the formation of 15 examples of substituted tetrahydrofurans **62** in good yield and diastereoselectivity towards the *cis* isomer (Scheme 1.40).[28]

MeO$_2$C CO$_2$Me + R^1 O →(Pd$_2$(MeO-dba)$_3$, **L** (10 mol%), Toluene, RT) MeO$_2$C CO$_2$Me R^1

58a   **65**   **68**

L = (Ph ... Ph phenanthroline)

53-99%
15 examples
d.r.: 4/1 - 98/2
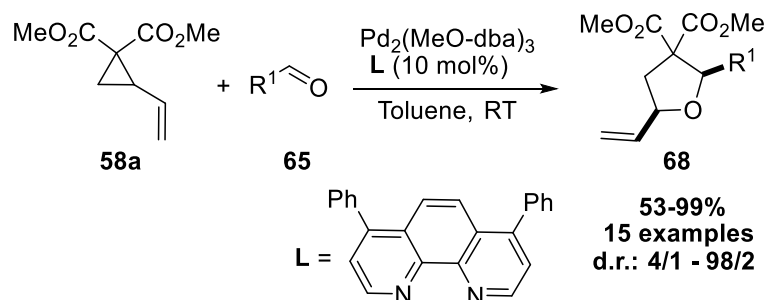
Scheme 1.40: Diasteroselective (3+2) cycloaddition of **58a** with aldehydes

It is interesting to notice that the reaction of VCPs with carbonyls leading to acyclic adducts **66** catalysed by iridium complexes was presented in the previous section (*vide supra*). The choice of the nature of the transition metal catalyst is thus crucial depending on the desired outcome of the reaction.

Tombe *et al.* reported a similar reaction using nickel catalysis to allow the obtaining of functionalised pyrrolidines from the cycloaddition of **58a** with tosylimines **69** (Scheme 1.41).[29] The diastereoselectivity obtained for the *cis* isomer of **70** by the authors is improved compared to the previous example (>11/1).

MeO$_2$C CO$_2$Me + R^1 NTs →(Ni(cod)$_2$ (5 mol%), dmpe (5 mol%), MeCN, 30°C, 5h) MeO$_2$C CO$_2$Me R^1 NTs

58a   **69**   **70**
49-99%
16 examples
dr : 11/1 - >99/1
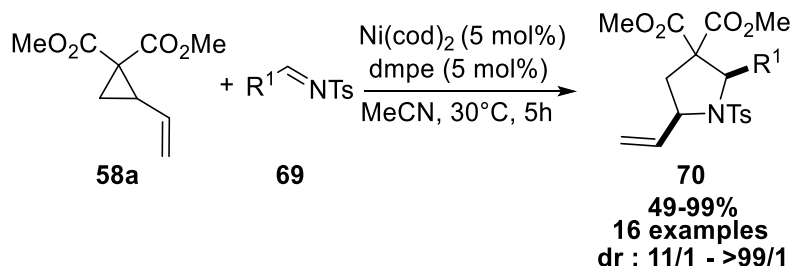
Scheme 1.41: Diasteroselective (3+2) cycloaddition of **58a** with imines

Enantioselective (3+2) cycloaddition has been developed. Liu and co-workers used palladium catalysis with the chiral ligand **L2** to catalyse the formation of the spiro compound **73** via the cycloaddition of **71** and the nitroolefin **72** (Scheme 1.42).[30] The obtained *e.e.* are excellent.
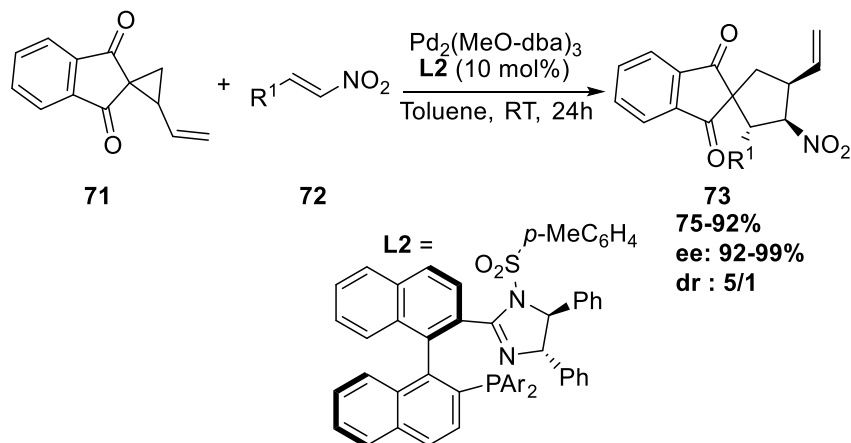
Scheme 1.42: Enantioselective (3+2) cycloaddition of **71** with nitroolefins **72**

1.2.2.2. (5+2) cycloaddition reactions

Vinylcyclopropanes have been reported to also be involved in (5+2) cycloaddition reactions with their five carbons.[31] The following methods allows for the formation of seven membered rings.

The first reported example of (5+2) cycloaddition involves an alkyne as the source of the two carbon component.[32] Since then, the scope of this transformation has been widened to alkenes[33] and allenes.[34]

Alkynes are common source of two carbons component for the (5+2) cycloaddition of VCP. Intramolecular cycloaddition reactions using rhodium catalysts allows the formation of bicycles with one of them being a cycloheptadiene. This reactivity has been applied to the synthesis of natural product of interest. Ashfeld and Martin used a (5+2) cycloaddition from the VCP **74** to form **75,** in presence of a rhodium catalyst (Scheme 1.43).[35] Seven additional steps are required

to obtain the natural product tremulenediol (**76**). The authors reported the first enantioselective synthesis of the sesquiterpene **76**.
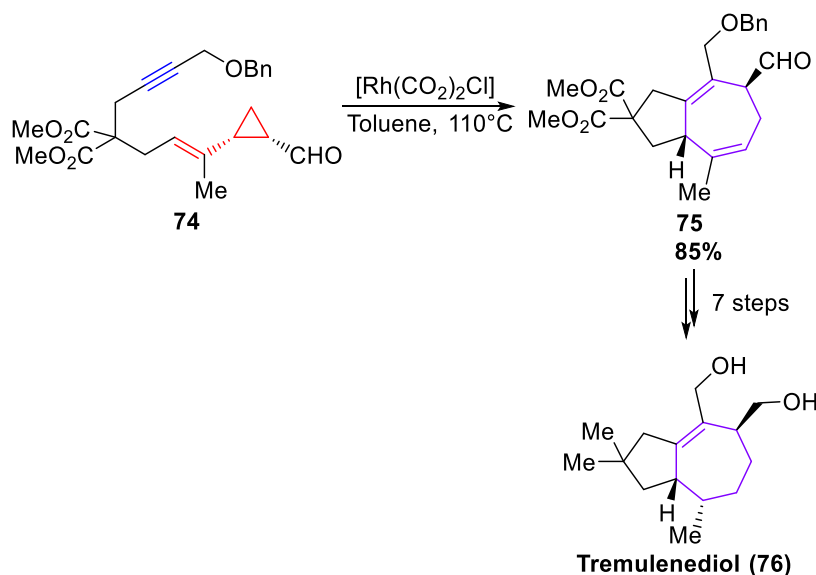
Scheme 1.43: Total synthesis of tremulenediol (**70**) involving an intramolecular (5+2) cycloaddition

Vinylcyclopropanes bearing an allene can also undergo (5+2) cycloaddition reactions. Wender and Zhang reported the cycloaddition reaction of **77** using the same reaction conditions as previously presented (Scheme 1.44).[36] The product formed in this case is a cycloheptene with an *exo* cyclic unsaturation. The obtained product **78** was further transformed into the (+)-Aphnamol **79** in an asymmetric synthesis.
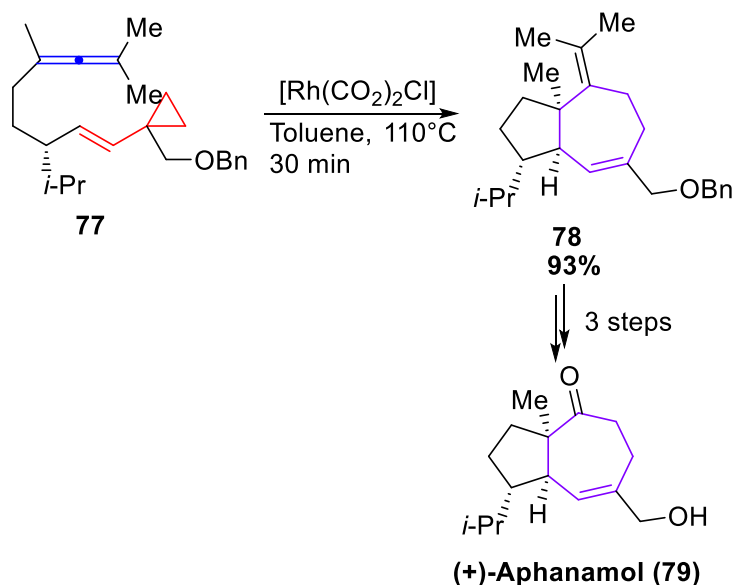
Scheme 1.44: Total synthesis of (+)-aphanamol (**79**) involving an intramolecular (5+2) cycloaddition

The first example of an asymmetric (5+2) cycloaddition reaction was reported using alkenes as the two carbons component for the reaction (Scheme 1.45).[37] Wender and co-workers used (*R*)-BINAP ligand and rhodium transition metal to form **81** from the vinylcyclopropane **80**. The e.e. was found to depend on the substrate but two examples (X = $C(CO_2Et)_2$ and NTs) led to excellent e.e., greater than 96%.
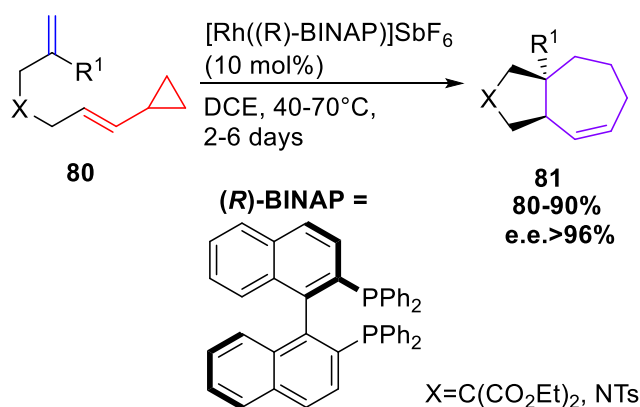
Scheme 1.45: Enantioselective intramolecular (5+2) cycloaddition

1.2.3. Rearrangement reactions

The VCPs can be involved in rearrangement reactions. This section focuses on the rearrangements to cyclopentenes and skipped dienes but the rearrangement reactions are not limited to these transformations.[38]

1.2.3.1. Rearrangement to cyclopentenes

Vinylcyclopropanes are known to undergo a rearrangement reaction leading to cyclopentenes. The first example of this transformation was reported in 1959 by Neureiter *et al.* [39] The reaction consists of the heating of the dichlorovinylcyclopropane **82** to trigger the rearrangement to the corresponding dichlorocyclopentene **83** (Scheme 1.46). **83** was not the only product of this reaction, 1,4-diene **84** and 1,3-diene **85** were also obtained.
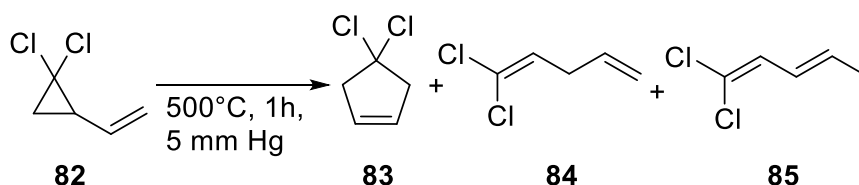
Scheme 1.46: Pyrolysis of dichlorovinylcyclopropane

A year later, Vogel reported the thermolysis of the VCP **80** and the formation of the CP **87**.[40] Frey analysed more deeply the products of the reaction.[41] The cyclopentene (**87**) was reported to be the main product of this rearrangement amid dienes molecules (**88-91**) (Scheme 1.44).
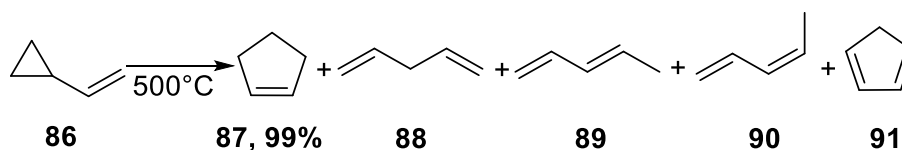
Scheme 1.47: Pyrolysis of the unsubstituted vinylcyclopropane **86**

The activation energies for the formation of the cyclopentene **87** and the skipped diene **88** have been measured to be 49.3 kcal/mol and 57.3 kcal/mol respectively.[3] This explains the selectivity towards the cycloalkene.

The mechanism explaining the rearrangement to the cyclopentene **87** has been the subject of long debates.[42] The two possible mechanisms are either a concerted mechanism (red, Scheme 1.48). The second, the biradicalar mechanism, involving the ring-opening of the VCP via the homolytic cleavage of a C-C bond (blue, Scheme 1.45). The cyclisation occurs from diradical intermediate **92**. These pathways are formal 1,3-sigmatropic shifts.
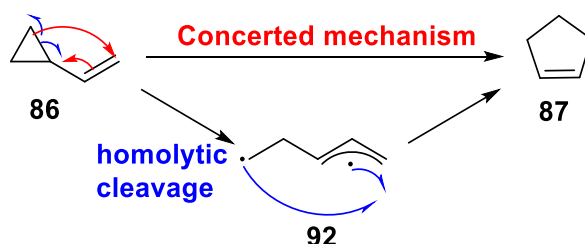
Scheme 1.48: Two possible mechanisms explaining the rearrangement of **86** into **87**

The argument in favor of the concerted mechanism is related to the retention of the configuration of optically active VCPs. Indeed, this stereospecificity is a characteristic of concerted mechanisms. On the other hand, the activation energy of the pyrolysis of VCP **86** is 13 kcal/mol lower in energy than the cyclopropane (60 kcal/mol, see 1.1.1.). This energy difference is close to the stabilisation energy of an allyl radical (12.6 kcal/mol). More recent studies support the diradicalar mechanism.[43]

Since these reports, activation of the VCP by the addition of substituents have led to a decrease of the temperature required for its opening.[44] The presence of an EWG group on the cyclopropane moiety of donor acceptor VCPs can also allow for a mechanism with a zwitterionic pathway (Scheme 1.49).[45] The negative charge created by the ring-opening is stabilised by the presence of the EWG whereas the positive one is stabilised by the formation of an allyl cation moiety.

EWG

EWG

EWG

93   **heterolytic cleavage**   **94**   **95**
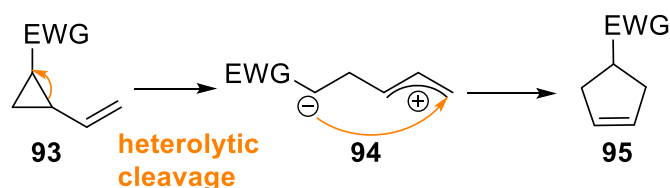
Scheme 1.49: The stepwise mechanism involving the heterolytic ring-opening of EWG substituted VCPs **93**

The nature of the substituents also influence if the reaction occurs via the zwitterionic or diradicalar pathway.[46]

Many progresses have been achieved in this field since these reports. Nowadays, this transformation can be catalysed by the use of a Lewis acid or a transition metal.

1.2.3.1.1. Lewis acid catalysis

The rearrangement of VCP to cyclopentene can be catalysed by a Lewis acid. The mechanism occurs via the zwitterionic pathway. The Lewis acid complexes the EWG of the donor-acceptor vinylcyclopropanes to facilitate their heterolytic ring-opening by further stabilising the resulting negative charge, the positive charge is stabilised by the vinyl group.

The group of Prof. Tomilov started investigating the Lewis acid activation of donor-acceptor VCP **96a**. The first attempts were carried out using the Lewis acid commonly used for the activation of DACPs (TMOTf, $Sn(OT)_2$, … see 1.1.) but the authors did not observe any reaction involving the unsaturation of the vinylcyclopropane; VCP **96a** behaving similarly to a DACPs.[47] However, when $GaCl_3$ was used as a Lewis acid, the VCP **96a** was found to rearrange into the corresponding cyclopentene **97a** (Scheme 1.50). This is one of the first reported examples of the Lewis acid catalysed VCP-cyclopentene rearrangement.
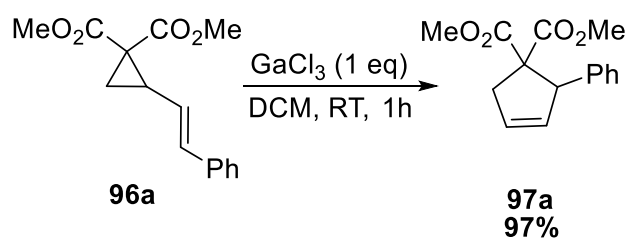
Scheme 1.50: Rearrangement of **88a** to **89a** with GaCl₃ catalysis

Later, the group of Prof. I.V. Trushkov expanded on this transformation by widening its scope (Scheme 1.51).[48] 14 examples of cyclopentenes **97** with various substitution patterns of the double bond and electron-withdrawing groups were reported. The nature of the Lewis acid used (GaCl₃, SnCl₄, Sc(OTf)₃, Ni(ClO)₄, TiCl₄) depends on the nature of the investigated substrate.

LA = GaCl₃, SnCl₄, Sc(OTf)₃, Ni(ClO)₄, TiCl₄
EWG = CO₂Me, PO(OMe)₂, CN, CONRR'
R¹ = H, alkyls
Ar = Donor aryls, weak acceptor aryls
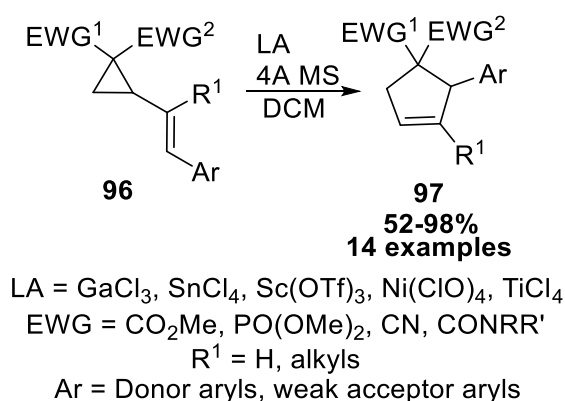
Scheme 1.51: Rearrangement of **96** to **97** with Lewis acid catalysis

A limitation found by Ivanova and colleagues was the non-compatibility of their rearrangement reaction with strong acceptor aryls (*o*-NO₂C₆H₄). When GaCl₃ is used to trigger the rearrangement of **96b**, it leads to the 1,3-diene **100b**. This latter was postulated to come from the isomerisation of the skipped diene **99b** which is would be obtained via the 1,2-migration of a hydrogen with a reactivity similar to the rearrangement of DACP into olefins (see 1.1.3.2.) (Scheme 1.52).
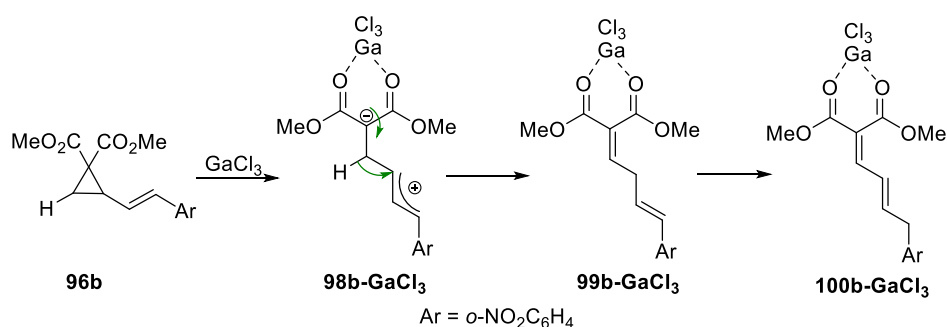
Scheme 1.52: Formation of the 1,3-diene **100b**

Recently, our group reported the enantioselective synthesis of cyclopentenes **104** from 1,3-dienes **101** and sulfur ylides (Scheme 1.53).[49] The chiral information was introduced using chiral sulfonium salts **102** developed by the group of Prof. V.K. Aggarwal.[50] The transformation goes through the formation of optically active VCPs which rearrange stereospecifically into the corresponding cyclopentenes upon MgI$_2$ catalysis leading to excellent *e.e.* across 9 examples.
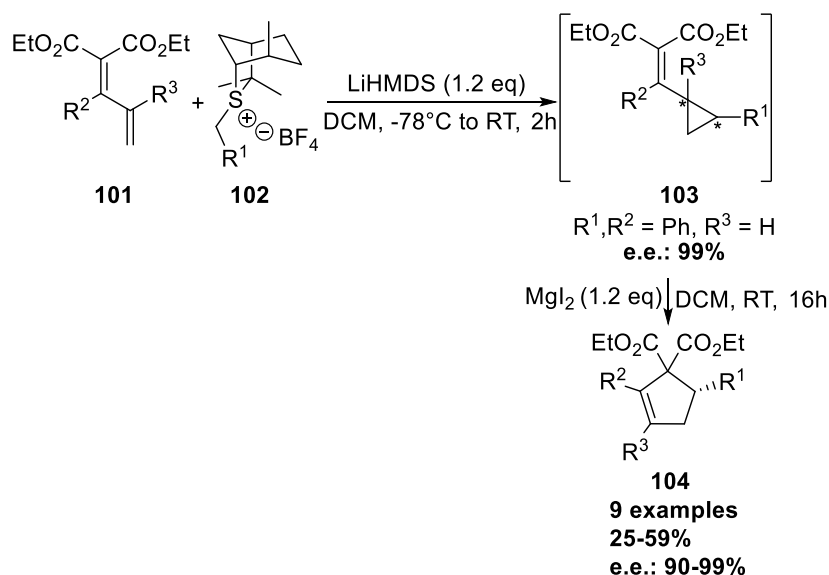
Scheme 1.53: Enantioselective synthesis of cyclopentenes from VCPs

1.2.3.1.2. Transition metal catalysis

Transition metal catalysis is also a common strategy for the rearrangement of vinylcyclopropanes into cyclopentenes. Palladium is widely used for this purpose. The mechanism of the activation of the VCP by palladium complexes is shown in Scheme 1.54.[51] the mechanism starts by the complexation of the double bond of the VCP by the palladium complex. A heterolytic ring-opening of the cyclopropane occurs to form the zwitterion **105-Pd** in which the so created positive charge is stabilised by the formation of a π-allyl palladium. Ring closing and decomplexation provides the formation of the cyclopentene **87**.
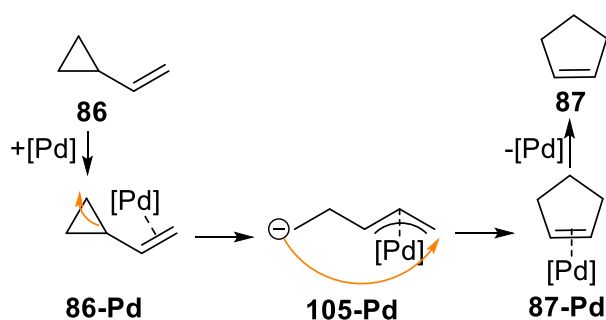
Scheme 1.54: Postulated mechanism for the Pd catalysed rearrangement of **80** to **81**

Oshima *et al.* reported the first work on the Pd(0)-catalysed rearrangement of VCPs into cyclopentenes with the synthesis of 4 cyclopentenes **107** coming from the corresponding VCPs **106** with two EWG groups and a dienyl substituent (Scheme 1.55). [52]
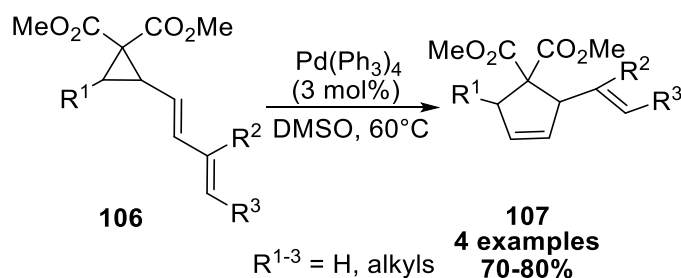
Scheme 1.55: First report involving the Pd(0)-catalysed VCPs into cyclopentenes rearrangement

Their studies showed that these groups were essential for this reaction. They thus proposed the mechanism in which the negative charge of the intermediate is stabilised by the two esters groups whereas the dienyl substituent is involved in the formation of a π complex with the palladium catalyst (Figure 1.2).

108
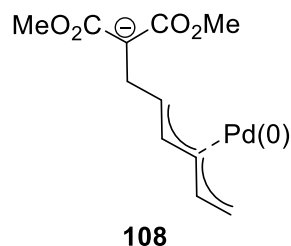
Figure 1.2: Proposed intermediate involved in the Pd(0)-catalysed rearrangement of **108**

Later, Shanmugam *et al.* reported the preparation of 3-spiro-2-oxindoles **110** using Pd(Ph$_3$)$_4$ to catalyse the vinylcyclopropane-cyclopentene rearrangement from highly substituted VCPs **109** (Scheme 1.56).[53]
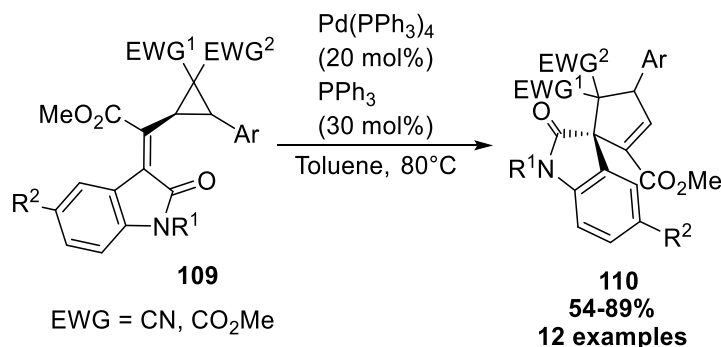
Scheme 1.56: Pd catalysed vinylcyclopropane-cyclopentene rearrangement for the preparation of 3-spiro-2-oxindoles **95**

The use of nickel catalysis has been documented as well. However, the mechanism postulated to explain the transformation differs with this transition metal (Scheme 1.57).[51] The postulated mechanism involves the oxidative addition of the metal in the cyclopropane moiety to form a 4 membered metallocycle **111** which

can isomerise into a 6 membered metallocycle **112** before the reductive elimination to form a cyclopentene.
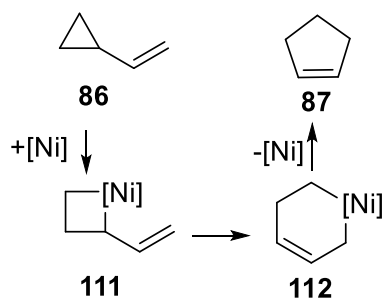
Scheme 1.57: Postulated mechanism for the Ni catalysed rearrangement of **86** to **87**

The postulated mechanism does not involve the stabilisation of a negative charge and hence this rearrangement can be applied to donor-acceptor VCPs[54] and VCPs without EWG groups. These rearrangement are sometimes plagued by the formation of mixtures of products including 1,3-dienes and skipped dienes.[55]

The rearrangement of poorly activated vinylcyclopropanes operating at room temperature or 60°C using a nickel catalyst with the NHC ligand **IPr** was reported by Zuo and Louie (Scheme 1.58).[56] This represents a significant decrease of temperature compared to the thermolysis of non-activated VCP (see 1.2.2.1.). The obtained yields are excellent.
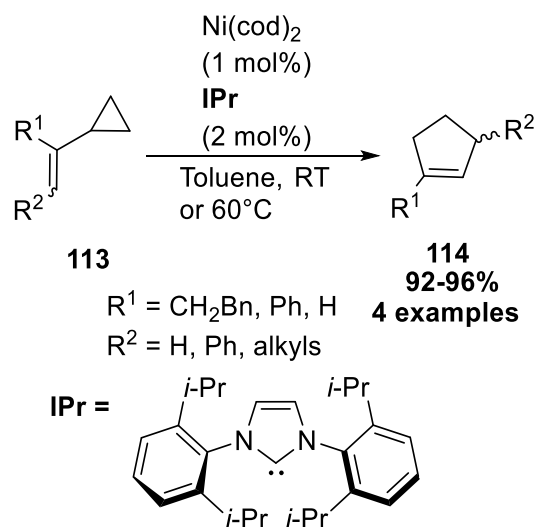
Scheme 1.58: Ni catalysed vinylcyclopropane-cyclopentene rearrangement

Later, the group of Louie investigated the mechanism of this transformation by combining experimental and computational methods.[57] Their results led them to propose the mechanism depicted in Scheme 1.51. They also investigated diradicalar and zwitterionic mechanisms but the free energy of the intermediates were higher and hence they postulated that these mechanisms were unlikely to occur.

1.2.3.2. Rearrangement to skipped dienes

As mentioned in the section regarding the rearrangement of VCPs to cyclopentenes, a skipped diene was obtained as a minor side product of the thermolysis unsubstituted VCP **80** (see 1.2.3.1.).[41]

The mechanism proposed by Frey for this transformation is the following (Scheme 1.59). It starts by the heterolytic ring-opening of VCP to form the zwitterion **86**. A 1,2-migration of a hydrogen (red arrows) occurs to form **82**.
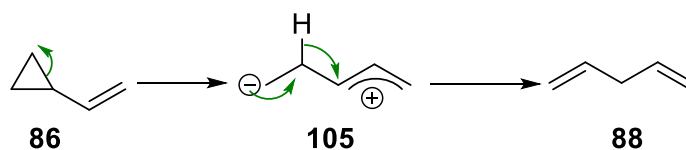
Scheme 1.59: Postulated mechanism explaining the formation of **88** from **86**

Frey and co-workers investigated the thermolysis of other small molecules and noticed that the *cis*-methylVCP **115-*cis*** led to the formation of the skipped diene **116** as the only product of the rearrangement with a quantitative yield (Scheme 1.54).[58] They postulated that this reactivity was explained by a 1,5-hydrogen shift (magenta arrows) which, for geometrical reasons, requires the two substituents of the cyclopropane to be in the *cis* configuration. The thermolysis was performed at a significantly lower temperature that the one of the non methylated VCP (500°C, see 1.2.3.1.) what can explain the fact that other products such as 1,3-dienes and cyclopentene were not observed. Indeed, the activation energy was measured to be lower for this transformation, 30-35 kcal/mol.[3]
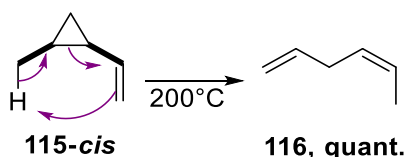
Scheme 1.60: Formation of **116** from **115-*cis*** via [1,5]-hydrogen shift

The same year, Frey and co-workers investigated the thermolysis of the *trans* isomer of the methyl-vinylcyclopropane, **115-*trans*** (Scheme 1.61).[59] They reported that the skipped diene **116** was still the main product of the reaction. Its formation is explained by the *trans-cis* isomerisation of **115-*trans*** prior to the [1,5]-hydrogen shift leading to the 1,4-diene. The isomerisation requires a higher temperature (300°C). This time, **116** was not the only product of the reaction as the cyclopentene **117** was observed.
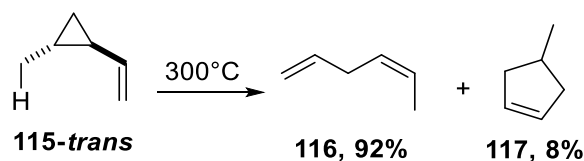
Scheme 1.61: Thermolysis of **115-*trans*** leading to **116** and **117**

Inspired by this reactivity, Macklin and co-workers designed a cross-coupling/fragmentation strategy for the preparation of skipped polyenes (dienes or trienes) **122** using Ti complexes (Scheme 1.62).[60] The titanium mediated coupling between the VCP **118** and **119** (alkene or alkyne) form the tricyclic titanacylopentane **120**. The stereospecific fragmentation of **120** leads to the formation of **121** which is then hydrolysed to form the skipped polyene **122**.
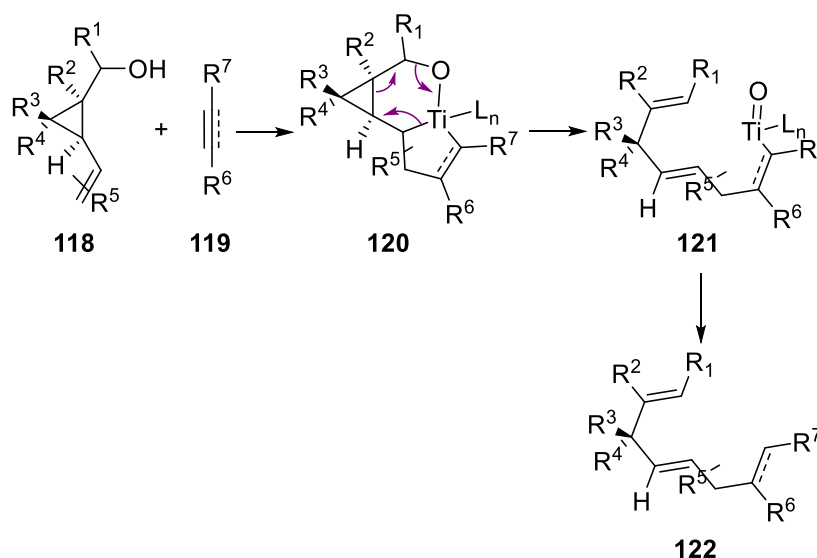
Scheme 1.62: Design of a cross-coupling/fragmentation strategy for the preparation of skipped polyenes **122**

This design was successfully applied to the synthesis of skipped dienes **123** from the VCP **118** (Scheme 1.63). The vinylcyclopropane is engaged in a coupling reaction with chlorodimethylvinylsilane. The silylated skipped diene **122** is obtained. This corresponds to the reactivity shown by Scheme 1.62. The authors then removed the silyl group via the second step of the process, a Fleming-Tamao oxidation

leading to the formation of **123** from **122**. This methodology allows the formation of skipped dienes of defined structure. The configuration of the CR^3R^4 carbon is fixed by the substrate like the CR^5 carbon when the substituent is on the sp^3 carbon. The obtained skipped dienes possess a methylene group between the two unsaturation but also a methyl group of defined stereochemistry in some examples. Terminal and non terminal dienes were obtained.
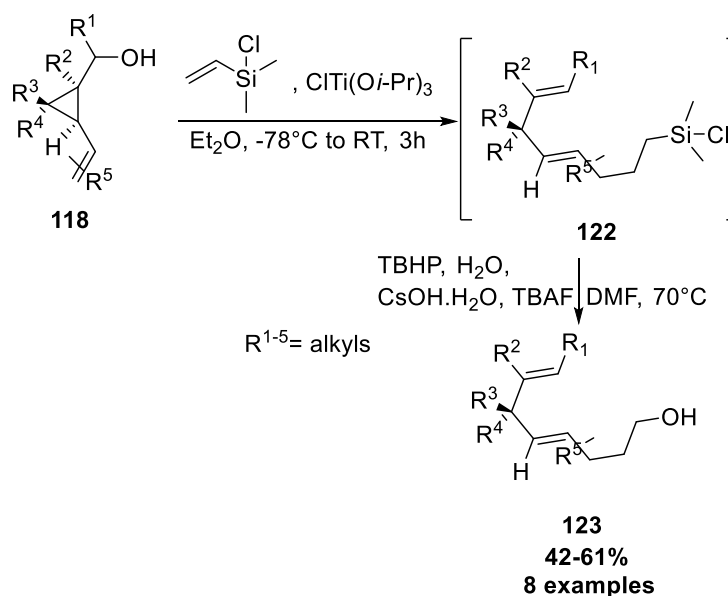
Scheme 1.63: Formation of skipped dienes by Ti mediated cross-coupling/fragmentation cascade

The authors also reported the formation of a skipped triene **124a** by titanium mediated cross-coupling of **118a** with an alkyne (Scheme 1.64). The coupling/fragmentation strategy leads to a skipped triene with a alcohol function protected by a TBS group. The skipped trienes are obtained after a deprotection in presence of TBAF, a fluoride source. The triene **124a** was obtained with fixed stereochemistry for the two stereocenters between the two *E* unsaturations
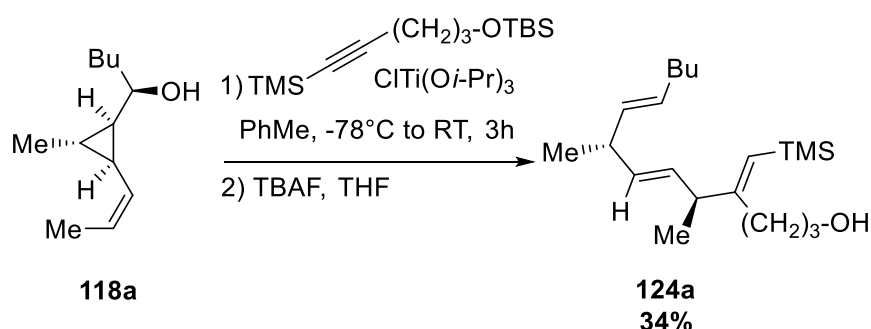
Scheme 1.64: Formation the skipped triene **124a** by Ti mediated cross-coupling/fragmentation cascade followed by deprotection

Macklin *et al.* applied the reaction between a vinylcyclopropane **118** and alkynes to the formation of polyunsaturated fatty acids **125** (Scheme 1.65). The first step of this process is the coupling reaction between the VCP and the alkyne. The resulting skipped triene is then deprotected of both its two silane groups in the second step. The resulting alcohol is oxidised in the presence of pyridinium dichromate to yield the desired polyunsaturated fatty acids in three steps with overall yields ranging from 53 to 57%.
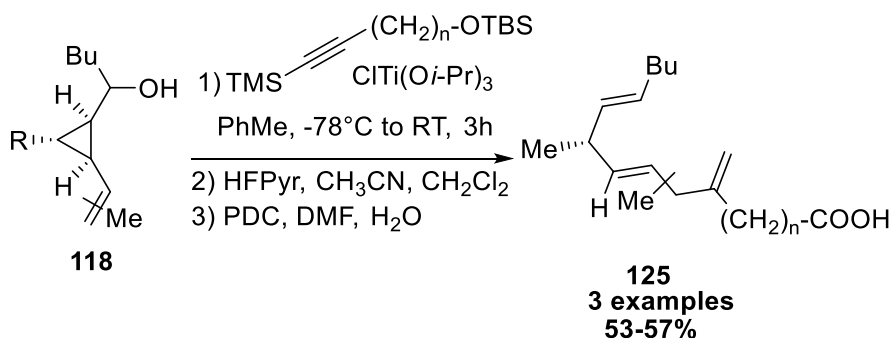
Scheme 1.65: Formation of polyunsaturated fatty acids

In 2010, the group of Prof. D. W. Stephan reported the effect of the frustrated Lewis pairs on the heterolytic ring-opening of less activated cyclopropanes which could not be activated by Lewis acid or transition metal catalysis (Scheme 1.66).[61] The authors applied their

strategy to the vinylcyclopropane **126a** which was ring-opened to form the adduct **127a**.
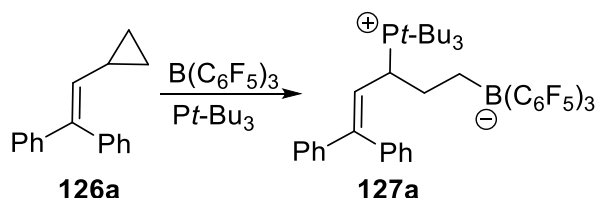
Scheme 1.66: Activation of VCP **126a** by a frustrated Lewis pair

Inspired by this work, Zhang *et al*. developed the ring-opening and rearrangement of cyclopropanes to olefins.[62] Vinylcyclopropanes were investigated during this study and were found to lead to the formation of the corresponding skipped diene **128**. The substitution of the obtained VCPs is not broad as one of the olefin is always terminal and the central sp^3 carbon does not bear substituents. The *E/Z* ratio of the obtained VCP **126** with $R^1 \neq R^2$ was found to carry over unaltered to the skipped diene (from 1/2.7 to 1/6.2 in favour of the *Z* isomer). The VCPs were synthesised via a Wittig olefination between the corresponding ketone and a phosphonium salt with a cyclopropyl subsituent.
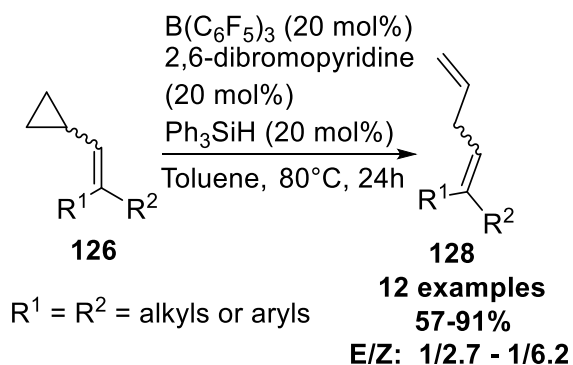
Scheme 1.67: Rearrangement of poorly activated VCPs to skipped dienes catalysed by FLPs

The authors postulated the following mechanism to explain this transformation (Scheme 1.68). The VCP is first heterolytically opened by $B(C_6F_5)_3$ to form the zwitterion intermediate **129**. The 1,2-

migration of a hydrogen occurs to form the intermediate **130** which can undergo the dissociation of B(C$_6$F$_5$)$_3$ by H-SiPh$_3$ to yield the skipped diene **128**. The zwitterion intermediate **129** is stabilised by a reversible FLP type interaction by B(C$_6$F$_5$)$_3$ and the 2,6-dibromopyridine.
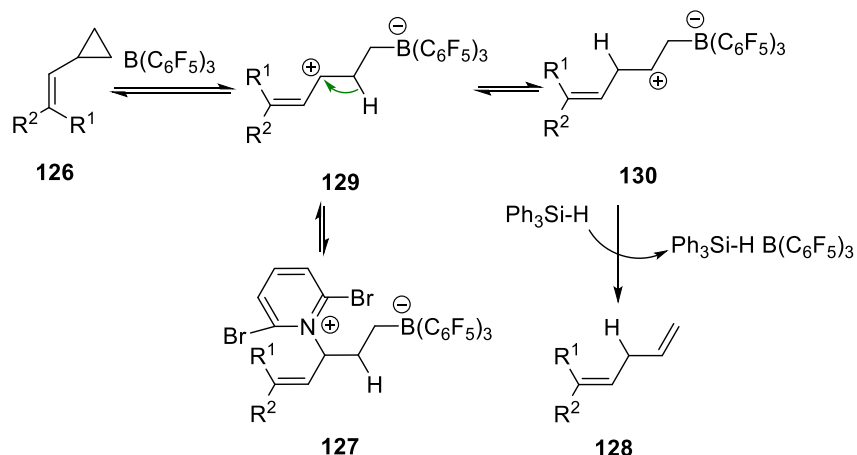
Scheme 1.67: Mechanism of the FLPs catalysed rearrangement of poorly activated VCPs

The rearrangement of VCPs into skipped dienes has been reported but the 1,4-diene is not the most common product of the rearrangement of vinylcyclopropanes, these being the cyclopentenes (see 1.2.3.1.) or the conjugated dienes. The few reported methodologies for their selective synthesis include the 1,5-hydrogen shift, the Ti-mediated coupling/fragmentation sequence and the 1,2-migration of H catalysed by frustrated Lewis pairs. Poorly activated VCPs are the substrates of these methodologies and the scope is limited to poorly substituted skipped dienes (terminal olefins, no subsittuents on the central carbon, alkyl chains).

The 1,2-migration of H from donor-acceptor vinylcyclopropanes was observed as well but the skipped diene was not isolated due to its isomerisation to the corresponding more stable conjugated 1,3-diene (1.2.3.1.).

The rearrangement of vinylcyclopropanes is not the only strategy allowing the synthesis of skipped dienes. The following

methodologies have also been reported; cross-coupling reactions,[L] hydroalkenylation of 1,3-dienes,[63] hydroallylation of alkynes[64] or olefination reactions.[65] However, these methodologies also possess drawbacks. The obtained skipped dienes are mainly non-substituted on the central carbon of the 1,4-diene moiety and one of the two unsaturation is terminal. These methodologies involve expensive metals and ligand tedious to synthesise.

In conclusions, despite their presence in numerous biologically active and flavourful compounds, the synthesis of skipped dienes remains a challenge in organic synthesis.

1.3. Rearrangements of divinylcyclopropanes

This section deals with a new type of cyclopropanes, the 1,2-divinylcyclopropanes (1,1-divinylcyclopropanes rearrangements have also been studied but will not be discussed here).[66] The 1,2-divinylcyclopropanes can undergo a Cope rearrangement releasing the ring strain of the cyclopropane moiety.

1.3.1. Cope rearrangement of divinylcyclopropanes

The Cope rearrangement of 1,5-dienes, which was first reported in 1940 by Cope *et al.*,[67] is a [3,3]-sigmatropic rearrangement leading to a 1,5-diene isomer to the starting material (Scheme 1.68). The position of the equilibrium depends on the relative stability of the two products **131** and **132**.
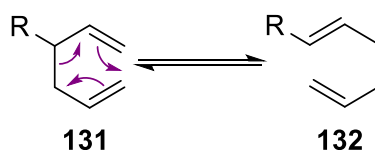
Scheme 1.68: Cope rearrangement of 1,5-dienes

The Cope rearrangement of divinylcyclopropanes was first observed in 1960 by Vogel *et al.* (Scheme 1.69).[40] In this work, the *cis* divinylcyclopropane **134-*cis*** was not observed after its intended synthesis from **133** as it was spontaneously isomerised into the corresponding cycloheptadiene **135**. In this case, the 1,5-diene

47

substrate is a divinylcyclopropane and the [3,3]-sigmatropic rearrangement to cycloheptadiene is favoured by the release of the cyclopropane's ring-strain.
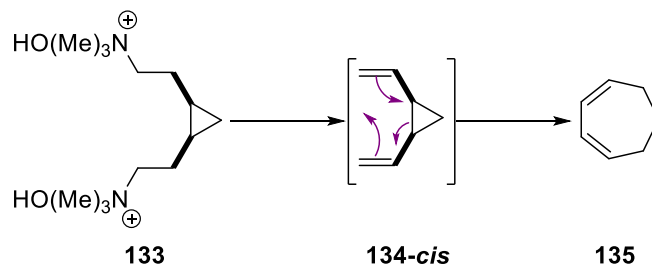
Scheme 1.69: First report of the diVCP-cycloheptadiene rearrangement

Conversely, the *trans* divinylcyclopropane was isolated, characterised and was found to undergo the Cope rearrangement into **135** but at 200°C by Vogel and co-workers. Indeed, the higher temperature was required to promote the *trans* to *cis* isomerisation of the diVCP needed for the rearrangement to occur.

Ten years later, Brown *et al.* were the first to isolate **134-*cis*** to perform its characterisation (Scheme 1.70).[68] They used a short time Wittig reaction (1 min) between the *cis* vinylcarbaldehyde **136** and the methylenetriphenylphoshorane performed in DMSO/isopentane at 5°C. The ^{1}H NMR analysis was carried out at -20°C. The half time of **134-*cis*** at 20.4°C was determined to be 449s.
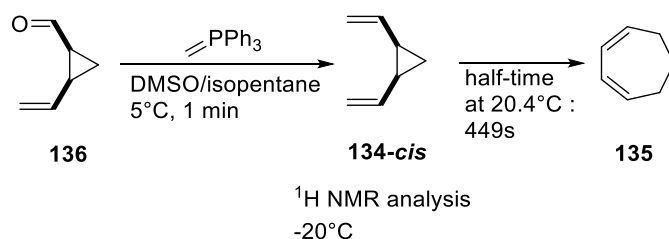
Scheme 1.70: Brown's isolation and characterisation of **134-*cis***

1.3.1.2. Applications

Since the first reports and investigations, the Cope rearrangement of divinylcyclopropanes became an interesting tool in

organic synthesis for the formation of seven membered ring structures.

For instance, the group of Prof. R.J.K. Taylor worked on the Cope rearrangement of divinylcyclopropanes **137** to cycloheptadienes **138**.[69] The influence of the temperature and the diastereoselectivity of the starting diVCP on the conversion was studied (Table 1.1). The solvent (xylene mix) and time (17h) were kept constant during the analysis.

Table 1.1: Optimisation of the Cope rearrangement of **137** to **138**
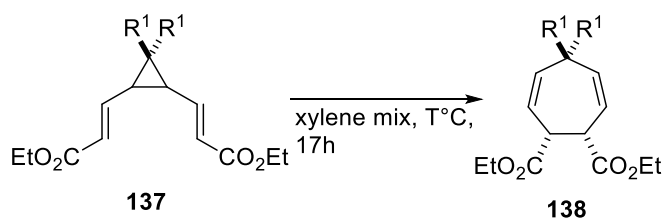
Entry	R^1	d.r. (*cis/trans*)	Conversion[a]			
			T°C = RT	T°C = 70°C	T°C = 100°C	T°C = 130°C
1	H	1/0	100	n.d.	n.d.	n.d.
2	H	0/1	0	0	20	100
3	Me	1/0	0	90	100[b]	100
4	Me	0/1	0	0	0	0

[a] Measured on the ^{1}H NMR of the crude mixture. [b] Optimised reaction conditions, the product was isolated in 78% yield.

The authors started by investigating the Cope rearrangement of the substrate with R^1 = H in its *cis* (entry 1) and *trans* configuration (entry 2). Both isomers of this diVCP led to the same **119**. They observed that the sigmatropic rearrangement of the *cis* diVCP was spontaneous at room temperature as they never isolated the divinylcyclopropane after its synthesis. The *trans* isomer, on the other hand, requires a heating to the solvent's boiling point (130°C) to afford full conversion of the diVCP into the cycloheptadiene. This is explained by the need of isomerising the *trans* diVCP to its *cis* counterpart prior

to the rearrangement. After the isomerisation, its rearrangement is spontaneous (see entry 1).

The Cope rearrangement of the diVCP **137b** with the addition of methyl groups on the cyclopropane ring (R^1) required the heating of the *cis* diVCP to afford full conversion (entry 3), the rearrangement is no longer spontaneous at room temperature. This is due to the increase of the steric hindrance by the two methyl groups. The corresponding *trans* diVCP did not lead to any conversion, even at 130°C. Instead, degradation was observed. This suggests that the temperature was not enough to pass the barrier for the *trans* to *cis* isomerisation.

The optimised reaction conditions for the obtaining of the cycloheptadiene of interest, **138b,** were selected to be heating at 100°C (entry 3). The isolated yield was 78%.

The group of Prof. R.J.K. Taylor later carried on this research by using the cycloheptadiene **138b** (entry 3 of Table 1.1) obtained to produce interesting structures (Scheme 1.71).[70]
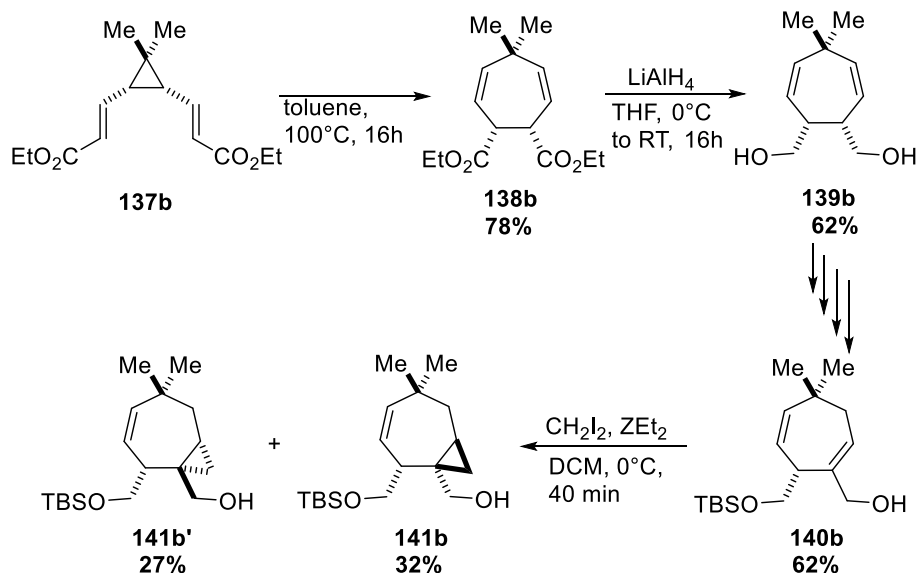
Scheme 1.71: Synthetic path for the access to **141b** and **141b'**

The first transformation performed on the cycloheptadiene **138b** is a reduction of the two ester groups into alcohols to form **139b**. Then a four reactions sequence consisting of the protection of one alcohol, the DMP oxidation of the second alcohol, the isomerisation of the obtained β,γ-unstatured aldehyde to α,β-unsaturated aldehyde and finally its reduction to allylic alcohol to form **140b**. The latter is then transformed to the two isomers **141b** and **141b'** by the Simmons-Smith cyclopropanation. The structure **141b** was targeted as an intermediate for the formation of africanane sesquiterpenes (Figure 1.3). These structures possess a decahydro-1*H*-cyclopropan[42]azulene core. Pyxidatol C was isolated from *Clavicorona pyxidata* mushroom which is used in traditional Chinese medicine for the treatment of gastric pain.[71]

pyxidatol C   omphadiol

africanol   africanene
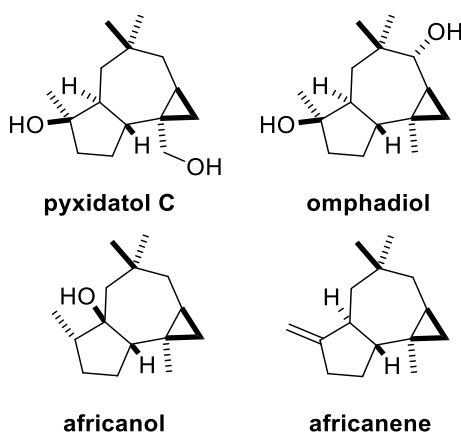
Figure 1.3: Examples of africanane sesquiterpenes

The divinylcyclopropane rearrangement (diVCPR) is the central step of the total synthesis of the tremulenolide (**151**) and tremulenediol (**152**) reported by Davies and co-workers (Scheme 1.72).[72] The sigmatropic rearrangement is used to create the seven membered carbocycle present in these natural products isolated from fungus. The synthesis starts by a Horner-Wittig-Emmons reaction between **142** and **143** to form **144** as a mixture of *E/Z* products. The deconjugation of **144** to **145** is achieved by a deprotonation/reprotonation sequence using LiTMP and TFA. A diazo group is then introduced to form **146** which reacts with **147** in

presence of a rhodium catalyst to form **148**, containing a *cis*-divinylcyclopropane moiety, highlighted in blue. The diVCP underwent the Cope rearrangement to form the bicycle **149** during the Kugelrohr distillation. The less hindered unsaturations of the cyclohepadiene was selectively reduced by hydrogenation in presence of Wilkinson's catalyst to give **150**, an intermediate which can produce **151,** by a deprotection/lactonisation sequence, or **152** by reduction of the ester group and deprotection.
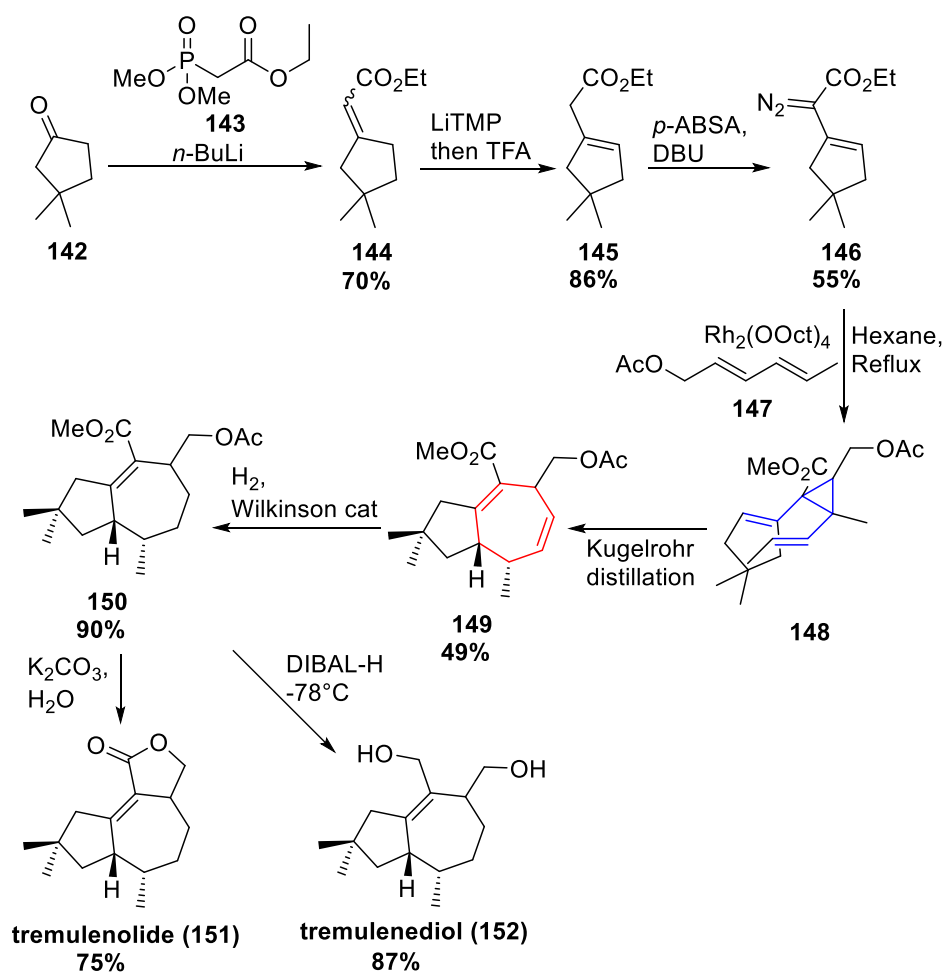
Scheme 1.72: Davies total syntheses of **151** and **152** including a diVCPR step

1.3.1.3. Heteroatom variants

Heteroatom variants of the Cope rearrangement have been developed. The oxygen variant is the most studied of these variants. Two positions are possible for the oxygen atom, either in the three membered ring, making the substrate a divinylepoxide **153** or on the vinyl moiety making the substrate a vinylcarbaldehyde **136** (Scheme 1.73). The products of these rearrangements are seven membered heterocycles differing by the position of the oxygen atom in the scaffold **154** and **155**.
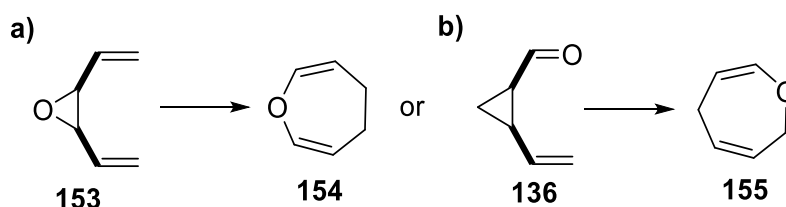
Scheme 1.73: Oxygen variants of the diVCP-cycloheptadiene rearrangement. a) Rearrangement of divinylepoxides **153** b) Rearrangement of vinylcarbaldehydes **136**

The group of Prof. de Meijere investigated the divinylepoxide rearrangement (Scheme 1.74).[73] The authors started from the triene **137** which was selectively epoxidised to the corresponding divinylepoxide **138**. The latter was heated at 60°C in dioxane to produce the desired bicyclic product **139** in a good yield.
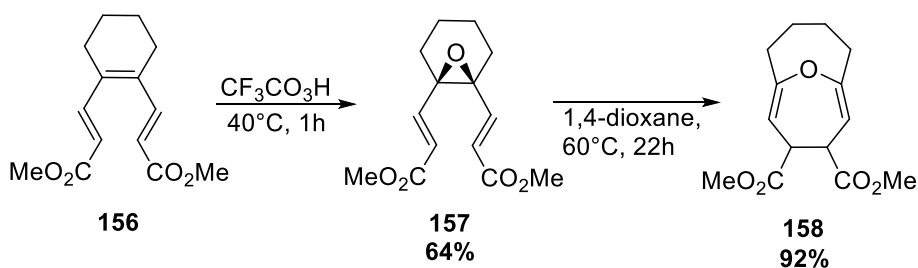
Scheme 1.74: Rearrangement of the divinylepoxide **157** to **158**

Lee *et al.* obtained the dihydrooxepine **161** via the rearrangement of a vinylcarbaldehyde (Scheme 1.75).[74] The latter was obtained by the reaction of rhodium carbenoid compound,

formed *in situ* from diazo compound **159** and the rhodium catalyst, with butadiene **160** but is not observed as the rearrangement product was recovered after 3 hours of reaction. The major competitive reaction in this process was found to be the vinylcylopropane-cyclopentene rearrangement (see 1.2.3.2.).
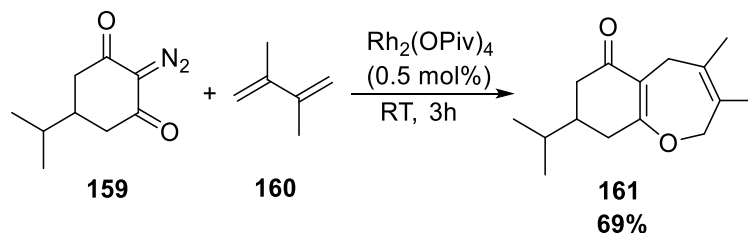
Scheme 1.75: Synthesis of the dihydrooxepine **161**

Nitrogen can also be integrated into the divinylcyclopropane substrate to produce seven membered heterocycles containing a nitrogen. Similarly to the rearrangement of divinylepoxides (*vide sufra*), the Cope rearrangement of divinylaziridines has been reported. Doyle and co-workers used rhodium catalysis to form the divinylaziridine **145** from divinyldiazo compound **162** and imine **163** (Scheme 1.76).[75] The [3,3]-sigmatropic rearrangement of **164** led to the formation of dihydroazepine **165**.
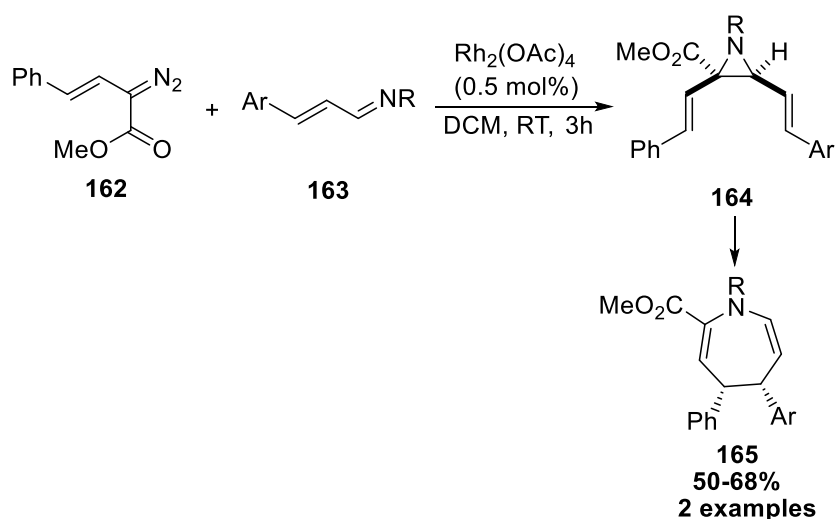
Scheme 1.76: [3,3]-Sigmatropic rearrangement of **145** to **146**

1.3.2. Buchner ring expansion

The Buchner rearrangement is another important strategy for the formation of seven membered rings. Buchner worked on the thermolysis of ethyldiazo acetate **166** in benzene and reported that the norcadiene **167** was the product of the reaction (Scheme 1.77).[76] The emergence of modern NMR techniques allowed Doering and co-workers to analyse more deeply the products of this reaction. It was found to be a mixture of the esters **169-171**.[77] These esters are formed via a [1,5]-hydrogen shift from the cycloheptatriene **168** which is obtained from the product proposed by Buchner via a reversible 6π disrotatory electrocyclisation reaction.
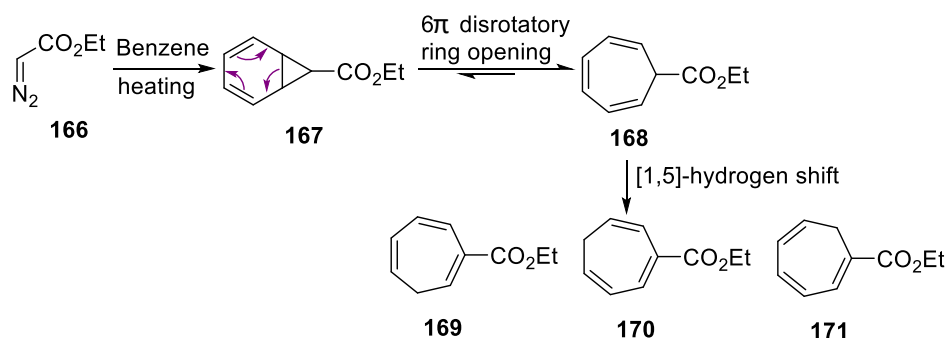
Scheme 1.77: Buchner's thermolysis of **166** in benzene

This transformation was not a great tool for the formation of carbocyles. Indeed, the low yields obtained combined with the formations of 3 isomers that were difficult to separate greatly limited its usefulness in organic synthesis.

The resurgence of the Buchner ring expansion arrived with the use of transition metal to catalyse the reaction. Noels and co-workers showed that the cycloheptatriene **168** could be obtained from benzene and the diazo compound **166** at room temperature without any signs of further [1,5]-hydrogen shift (Scheme 1.78).[78]
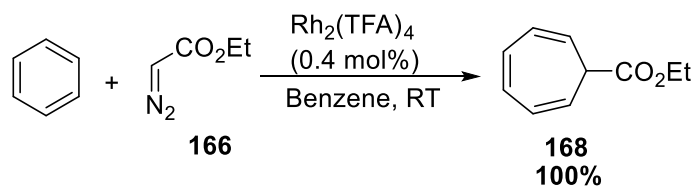
Scheme 1.78: Rhodium catalysed Buchner ring expansion

Since the initial reports of rhodium and copper catalysis, numerous research groups used the Buchner ring expansion reaction for the preparation of polycyclic compounds composed of a seven membered cycle.

For instance, the group of Prof. Kennedy used a rhodium catalyst with a diazo compound **172** which underwent an intramolecular cyclopropanation reaction to yield the nocaradiene **173** (Scheme 1.79).[79] ^{1}H NMR analysis showed that an equilibrium mixture of **173** and **174** was obtained. The reduction of **174** to the corresponding cycloheptatriene **175** proceeded with a good yield. Additional steps were required to synthesise (±)-confertin A (**176**).
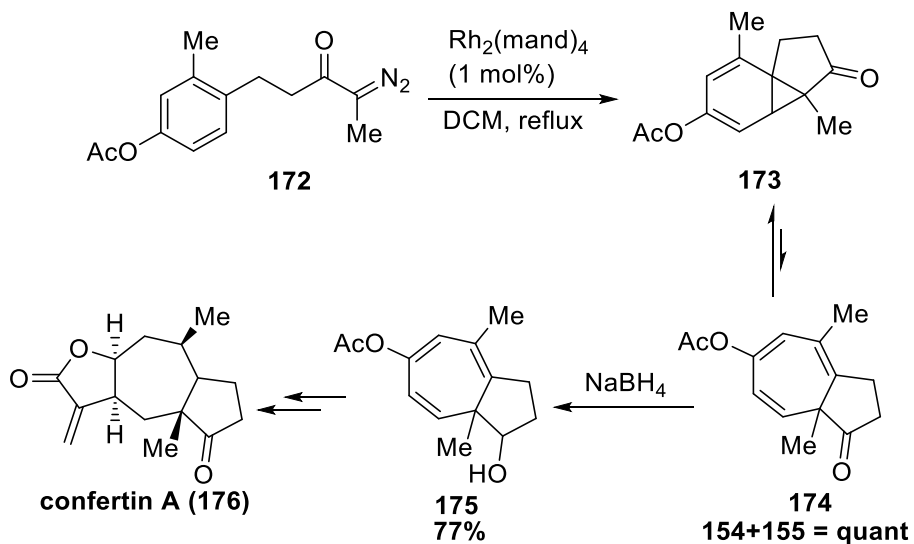
Scheme 1.79: Total synthesis of (±)-confertin A involving a Buchner ring expansion step

Chapter 2: Preliminary results of the laboratory

This chapter details the research carried out by Prof. Robiette's group leading to this PhD thesis. The results presented in this section were obtained by Dr. Maximilien Richald during his PhD thesis (2015-2019)[80] and myself during my Master's thesis (2017-2018).[81]

Our group has been investigating annulation strategies towards carbonated five-membered rings for years.[49] In this context, the laboratory developed a new formal two-step (3+2) annulation methodology (Scheme 2.1). The first one is a cyclopropanation reaction between an activated olefin **177aa** and an allylic sulfonium ylide obtained by the deprotonation of the corresponding salt **178aa** by a base (NaH). In the second step, the obtained vinylcyclopropane **179aa** is rearranged into the *cis* cyclopentene **180aa-*cis*** in the presence of a Lewis acid, TiCl$_4$, for 24 hours (Scheme 2.1).
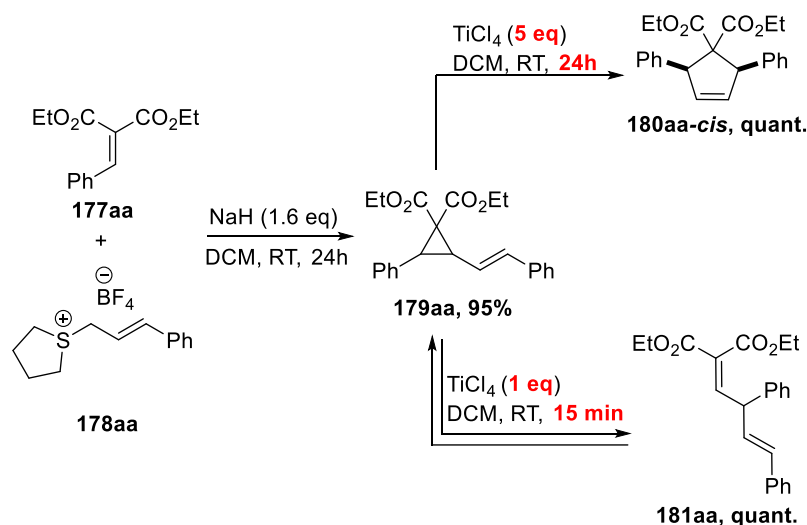
Scheme 2.1: Divergent rearrangement of **179aa** into **180aa** and **181aa**

Interestingly, Dr. Maximilien Richald showed that if the rearrangement reaction was stopped after 15 minutes – and not 24 hours – it was possible to quantitatively isolate the skipped diene **181aa**. He highlighted the fact that the diene is selectively obtained

after a short reaction time whereas the cyclopentene is isolated after 24 hours of reaction. This led our group to postulate that skipped diene **181aa** is the kinetic product of the system whereas cyclopentene **180aa** is the thermodynamic product. This hypothesis is supported by the fact that **181aa** affords **180aa** after 24 hours of reaction in the presence of $TiCl_4$. The rearrangement of VCPs to cyclopentenes and skipped dienes had already been reported in the literature (see 1.2.3.) but these results were the first to show that a single VCP could be selectively rearranged to either a cyclopentene or a skipped diene depending on the reaction conditions.

The mechanism explaining the formation of the skipped diene **181aa** was experimentally investigated by Dr. Maximilien Richald using a deuterium labelling experiment. Indeed, two paths can be postulated for the formation of the **181aa**. They both start by a heterolytic cleavage of a C-C bond, A or B, resulting in zwitterrionic intermediates in which the positive charge is stabilised either by a phenyl (**183aa**) or a styryl group (**182aa**) (Scheme 2.2). A 1,2-migration of the phenyl (Path A) or the styryl group (Path B), according to the nature of the intermediate, can then take place to afford the same skipped diene. However, if the VCP bears a deuterium atom, the two paths produce skipped dienes differing by the position of the deuterium atom **181aa-D** and **181aa-D'** respectively (Scheme 2.2); thus enabling to differentiate the two mechanisms (A or B).
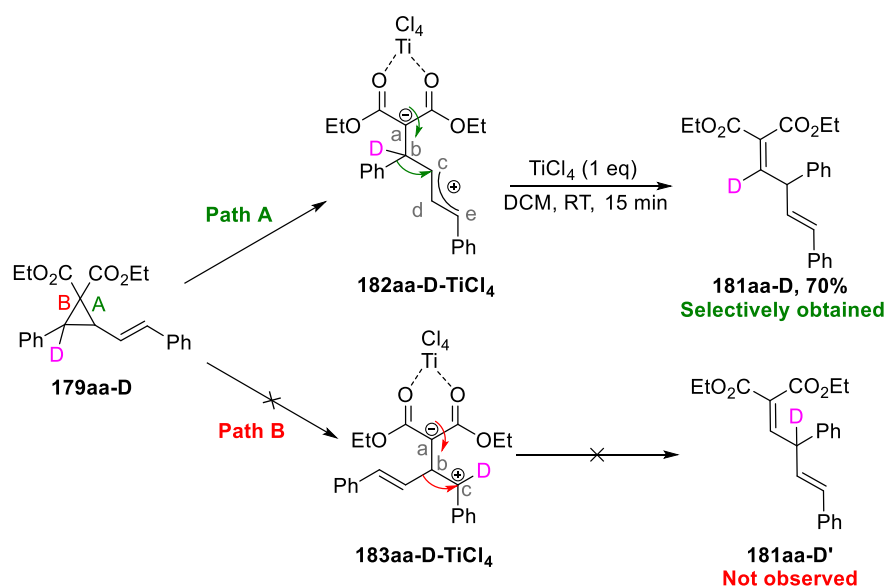
Scheme 2.2: Deuteriation experiment

Deuteriated VCP **179aa-D** was obtained and rearranged in the presence of TiCl$_4$ for 15 minutes at room temperature. The analysis of the ^{1}H NMR spectrum of the crude mixture showed that diene **181aa-D** was the exclusive product, meaning that the rearrangement operates exclusively via path A. It suggests that the stabilisation of the positive charge created by the heterolytic ring-opening of the cyclopropane moiety is the determinant factor for explaining the selectivity for path A.

Considering the novelty of the observed VCP-skipped diene rearrangement and the challenge that is the preparation of skipped dienes in organic synthesis (see 1.2.3.2.), our group decided to capitalise on this rearrangement. Accordingly, Maximilien's explored the scope of his divergent and selective rearrangements of vinylcyclopropanes into skipped dienes and cyclopentenes. In the meantime, our group started to work on an alternative strategy to obtain the vinylcyclopropanes **179** from 1,3-dienes **184** and benzylic sulfonium salts **185** (Scheme 2.3). The regioselectivity for the 1,4-addition of the ylide on the diene was found to be total.[81] It was the objective of our Master's thesis project (2017-2018). Our work,

however, only aimed at obtaining skipped dienes and not cyclopentenes.
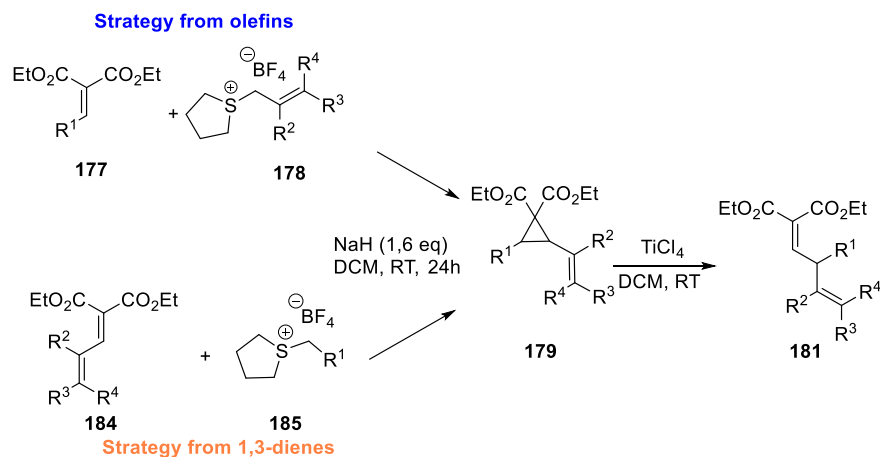
Scheme 2.3: Two complementary strategies for obtaining **179**

The cyclopropanation reaction of 1,3-dienes **184** and benzylic sulfonium ylides operates in the same reaction conditions as those developed by Maximilien for the strategy using activated olefins **177** and allylic sulfonium salts **178**. A one-pot version of our one-carbon homologation of 1,3-dienes into skipped dienes methodology by insertion of a CHR^1 fragment was successfully developed during our Master's thesis work (Scheme 2.4).
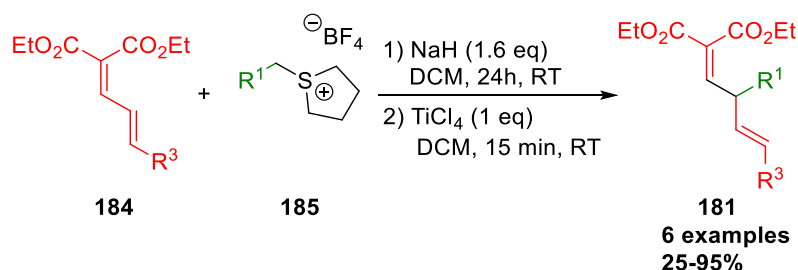
Scheme 2.4: One pot version of the homologation of 1,3-dienes to skipped dienes

These two complementary strategies allowed us to obtain a large library of vinylcyclopropanes **179** to explore the scope of their rearrangement into skipped dienes **181**. These investigations shed

light on some limitations. Indeed, in some cases the cyclopentene was obtained even after 15 minutes of rearrangement. The following table shows the impact of the substitution (R^1 and R^3) on the outcome of the reaction (Table 2.1).

Table 2.1: Scope and limitations of the rearrangement reaction

R^1		R^3	
Skipped diene	**Cyclopentene**	**Skipped diene**	**Cyclopentene**
Ph	p-CO$_2$MeC$_6$H$_4$	Ph	p-MeOC$_6$H$_4$
p-MeOC$_6$H$_4$	i-Pr	p-MeC$_6$H$_4$	
p-MeC$_6$H$_4$	i-Bu	p-ClC$_6$H$_4$	
p-FC$_6$H$_4$	H	p-BrC$_6$H$_4$	
p-ClC$_6$H$_4$		p-CO$_2$MeC$_6$H$_4$	
p-BrC$_6$H$_4$		H	
2-furyl			

The nature of the migrating group (R^1) has an impact on the selectivity of the rearrangement. Many groups have been found to be compatible with the formation of the skipped diene **181** such as a phenyl group, a halogen-, EDG-substituted aryl groups or an electron-rich heteroaryl (2-furyl). However, when R^1 is a poor migrating group such as an alkyl (*i*-Pr or *i*-Bu), a H or p-CO$_2$MeC$_6$H$_4$, the skipped diene is not observed and the cyclopentene is obtained even after short reaction times (15 min). In these cases, the carbocyle is postulated to be the kinetic and the thermodynamic product of the system; **181** being therefore not observed. The rearrangement allows for the synthesis of skipped dienes substituted by an aryl group on the central carbon atom.

The R^3 group has also an influence on the selectivity of the rearrangement. Aryls substituted by a weak electron-donor or an

electron-withdrawing group led to the desired skipped diene **181**. However, when R³ is an aryl substituted by a strong electron-donor group in the *para* position, the cyclopentene is exclusively obtained.

Our group also highlighted that the presence of two acceptor groups (in this case esters groups) is mandatory for observing any rearrangement product when the VCP is exposed to a Lewis acid. Skipped dienes with EWG of different nature (EWG = CN) were briefly investigated but not yet observed.

We further explored the mechanisms explaining the formation of the skipped diene **181aa** and the cyclopentenes **180aa** from the VCP **179aa** by means of computational methods (DFT) during our Master's thesis. This allowed us to gain a better understanding of the mechanism of the transformation and some factors controlling the reactivity were identified (Scheme 2.5). Our calculations predict that both mechanisms occur via a zwitterionic pathway and not through a diradical. The first step is the heterolytic ring-opening of the *trans* or *cis* vinylcyclopropane **179aa** to form 1,3-dipole **182aa** which can be rearranged into skipped diene **181aa** via the 1,2-migration of a phenyl group or cyclise to form **180aa**. The stereospecificity of the rearrangement into skipped dienes was predicted to be excellent.The model developed at the B3LYP-D3/6-311+G**(CH$_2$Cl$_2$)//B3LYP-D3/6-31+G*(CH$_2$Cl$_2$) level was found to underestimate the free energy of the transition states **TS$_{cycl}$aa-co-*trans-Z*** and **TS$_{cycl}$aa-co-*cis-Z***. Indeed, the obtained values would predict that the cyclisation reaction occurs faster than the migration reaction (occurring via **TS$_{mig}$aa-co**), which does not correlate with our experimental data (*vide supra*). Due to a lack of time during our Master's thesis, the model could not be developed further.
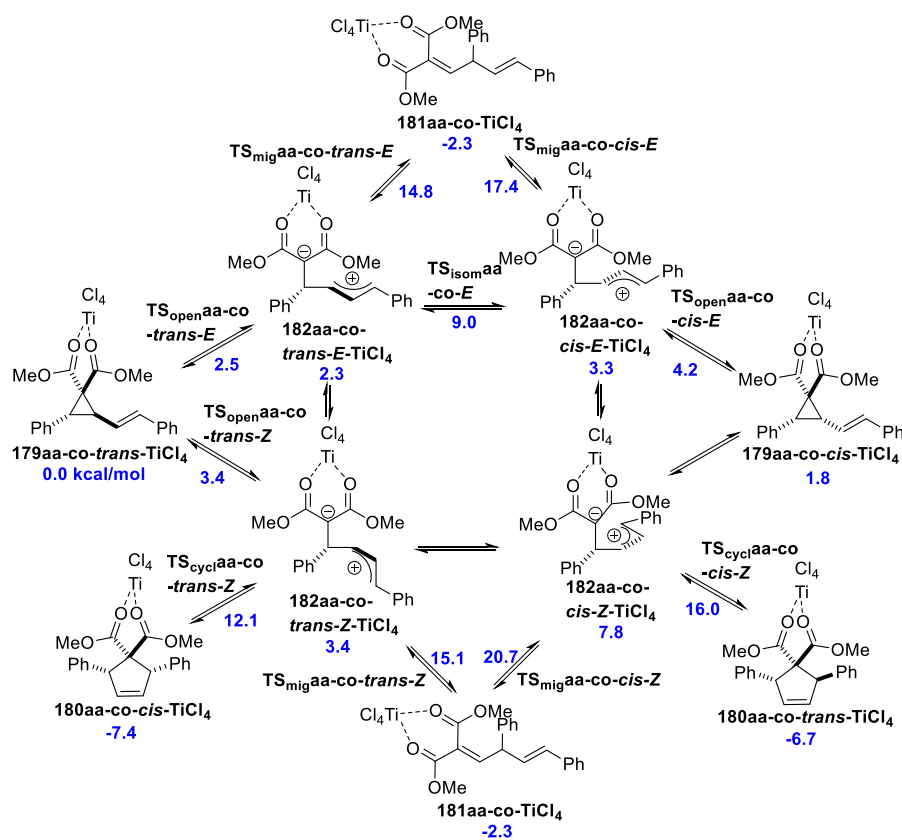
Scheme 2.5: Model established at the B3LYP-D3/6-311+G**(CH₂Cl₂)//B3LYP-D3/6-31+G*(CH₂Cl₂) level. Values are free energies relative to **179aa-co-*trans*-TiCl₄** and given in kcal/mol

Chapter 3: Objectives and strategies

We set ourselves four objectives for our PhD thesis.

1) First, we plan to explore the limitations of the VCP/skipped diene rearrangement and develop an enantioselective version of this methodology.

   We also aim to develop a series of related strategies by capitalising on our understanding of the VCP/skipped diene rearrangement.

2) Development of a one-carbon homologation of α,β-unsaturated aldehydes strategy.
3) Investigation of the one-carbon homologation of activated olefins.
4) Exploring the rearrangement of divinylcyclopropanes for the development of a (4+3) annulation strategy.

3.1. Rearrangement of vinylcyclopropanes

In the first part of this PhD thesis, we will investigate further the rearrangement of vinylcyclopropanes. We set ourselves three tasks for this part.

3.1.1. Exploration of the scope

First, we plan to further experimentally explore the scope of the Lewis acid triggered vinylcyclopropane **179** to skipped diene **181** rearrangement our group unexpectedly discovered (Scheme 3.1). This will expand our understanding of the effect of the substitution on the skipped diene/cyclopentene selectivity.

Scheme 3.1: Exploration of the scope of the **179** to **181** rearrangement

The targeted products bear alkyl groups at every position on the second unsaturation of the skipped dienes (R$^{2-4}$). The migration of poor migrating group such as H, alkyls or *p*-CO$_2$MeC$_6$H$_4$ is a target for our investigations. For these R^1 groups, the undesired side product, the cyclopentene, was always observed. We then aim to develop and use strategies to slow down this competitive reaction to allow the isolation of the diene **181** coming from the migration of these poor migrating groups. Varying the nature of the electron-withdrawing group to obtain skipped dienes with ketones or cyano groups will also be investigated.

3.1.2. DFT studies

We also aim to further investigate the rearrangement into skipped dienes and cyclopentenes by using DFT means. First, we will search for a new level of theory to perform our calculations. As mentioned in Chapter 2, the method used during our previous work was not suitable to describe our system.

After finding a theory level consistent with our experimental data, it will be used to further investigate the mechanism of the vinylcyclopropane rearrangement by answering new questions. We will investigate the addition of TiCl$_4$ on the vinylcyclopropane by

studying the complexation reaction and the non-catalysed rearrangement of **179** to **181**. The model will also be used to investigate the selectivity for the mechanism involving the opening of the VCP on the styryl side and migration of the phenyl group. The selectivity for the migration of the phenyl over the one of the hydrogen on the same carbon will be explored to understand why it was never observed.

Studying the effect of the substituents on the system to help us understand the observations made during the exploration of the scope of the rearrangement is also an aim of this work.

3.1.3. Enantioselective version

The last task related to the rearrangement of vinylcyclopropanes is the development of an enantioselective version of the methodology allowing for the synthesis of enantioenriched skipped dienes **181** (Scheme 3.2). We aim to use chiral sulfonium salts **102**[50] to introduce a chiral information during the cyclopropanation step. The key for this strategy to work is the stereospecificity of the rearrangement step. Calculations previously carried out predict the 1,2-migration reaction triggered by Lewis acids to be stereospecific.
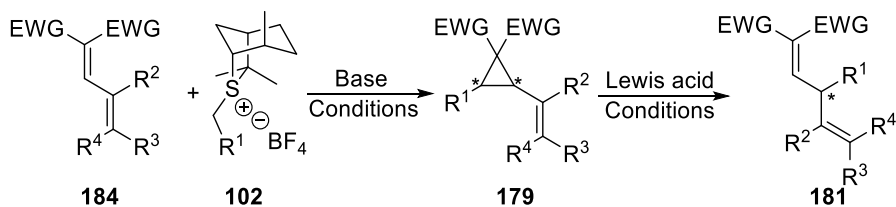
Scheme 3.2: Strategy for the synthesis of enantioenriched skipped dienes **181**

3.2. Homologation of α,β-unsaturated aldehydes

The second objective of this thesis concerns the development of a new methodology: the one-carbon homologation of α,β-unsaturated aldehydes (Scheme 3.3). Compared to our previous work, the 1,3-diene moiety is replaced by its synthetic precursor, the α,β-unsaturated aldehyde **186**. The structures obtained after the Corey-Chaykovky type reaction are vinylepoxides **187** which will be

rearranged into β,γ-unsaturated aldehydes in the presence of a Lewis acid. This methodology is a formal one-carbon homologation of the aldehydes **186** by the insertion of a CHR^1 fragment. The synthesis of the targeted structure of this methodology, the β,γ-unsaturated aldehydes, remains a challenge in organic chemistry, especially the enolisable β,γ-unsaturated aldehydes which are known to isomerise easily in presence of traces of acids or bases.
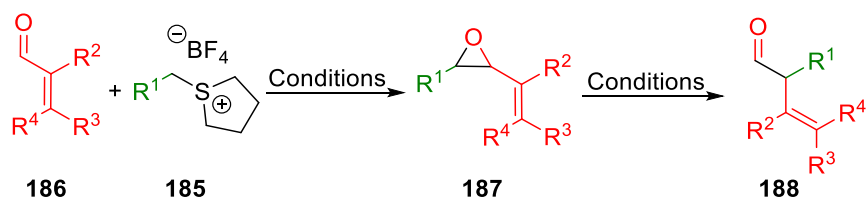
Scheme 3.3: One-carbon homologation of **186** to **188** methodology

3.2.1. Development of the methodology

We first aim to develop the methodology by finding sets of suitable mild conditions for the two reactions (epoxidation and Meinwald rearrangement) in order to allow for the selective synthesis of **188**, despite its propensity to isomerise. These reaction onditions will then be used to explore the scope of the methodology and find potential limitations.

3.2.2. Derivatisation

After their obtaining, the aldehydes will be involved in derivatisation reactions in order to demonstrate the interest of our methodology. We plan to investigate the following reactions: olefination reactions and addition of an organometallic reagent on the carbonyl function. The reduction of the aldehydes to the corresponding homoallylic alcohols **192**, or the controlled isomerisation into α-aryl α,β-unsaturated aldehydes **191** would allow us to develop new methodologies for the obtaining of other structures remaining a challenge in organic synthesis (Scheme 3.4).
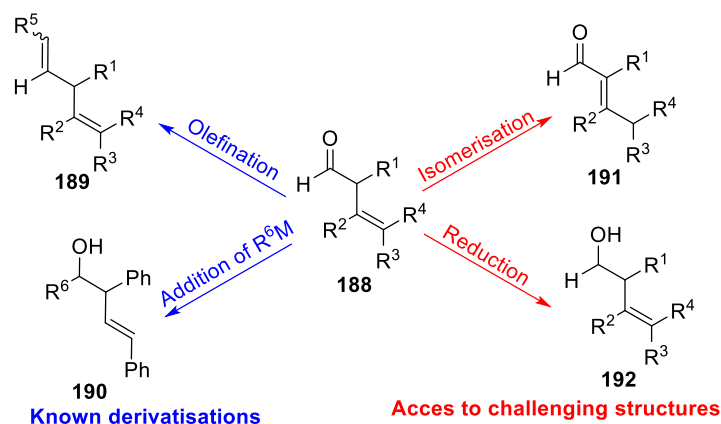
Scheme 3.4: Envisioned derivatisation reactions of **188**

3.2.3. Enantioselective version

Eventually, we will develop an enantioselective version of the methodology using chiral sulfonium salts **102** (Scheme 3.5).
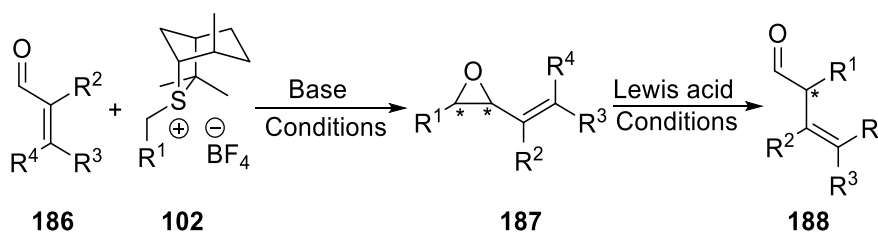
Scheme 3.5 Strategy for the synthesis of enantioenriched β,γ-unsaturated aldehydes **188**

3.3. Homologation of activated olefins

The third objective of this work is the development of another related methodology, the one-carbon homologation of activated olefins by insertion of a CHR^2 fragment (Scheme 3.6). This time, the 1,3-dienes are replaced by activated olefins **177**. The donor-acceptor cyclopropanes **193** are obtained after the first step and are rearranged to the olefins **194** by a 1,2-migration reaction triggered by a Lewis acid. This reactivity was discussed in the introduction but was limited to the migration of hydrogens (see 1.1.3.2.). This methodology is a new example of one-carbon homologation of olefins by insertion of CHR

fragment; these homologation methodologies being usually restricted to the insertion of methylene groups.
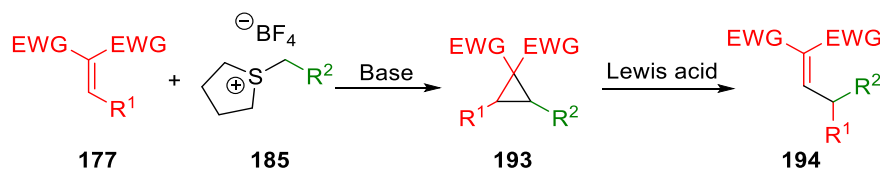
Scheme 3.6: One-carbon homologation of **177** to **194** methodology

3.3.1. Development of the methodology

First, we will experimentally develop the methodology by optimising the two steps. The exploration of the scope will be the next step in our experimental investigations.

3.3.2. Mechanistic studies

The second task related to this objective is a combined experimental and computational mechanistic study of the second step to further understand the factors governing the reactivity and selectivity in the process.

3.3.3. Enantioselective version of the methodology

Similarly, to our two previous methodologies, the development of the enantioselective version using chiral sulfonium salts **102** will be envisaged.
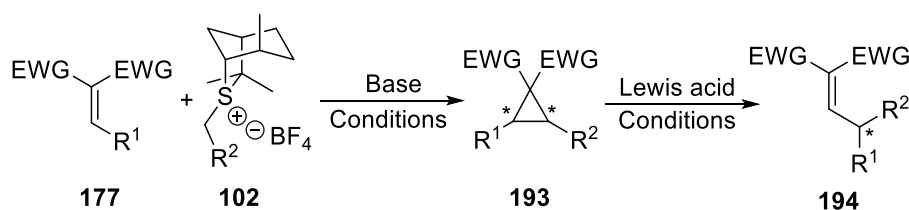
Scheme 3.7: Strategy for the synthesis of enantioenriched homologated olefin **194**

3.4. Divergent rearrangements of divinylcyclopropanes

The last objective of this work will focus on divinylcyclopropanes **195**. We plan to develop the divergent rearrangements of these diVCPs to 1,4,4'-trienes **196** under Lewis acid catalysis and to the cycloheptadienes **197** by a thermally induced Cope rearrangement (Scheme 3.8). Despite the presence of seven membered carbocycles in a number of natural products, few (4+3) annulation methodologies have been reported in the literature thus far. Our work will represent a new addition to this low number of strategies.
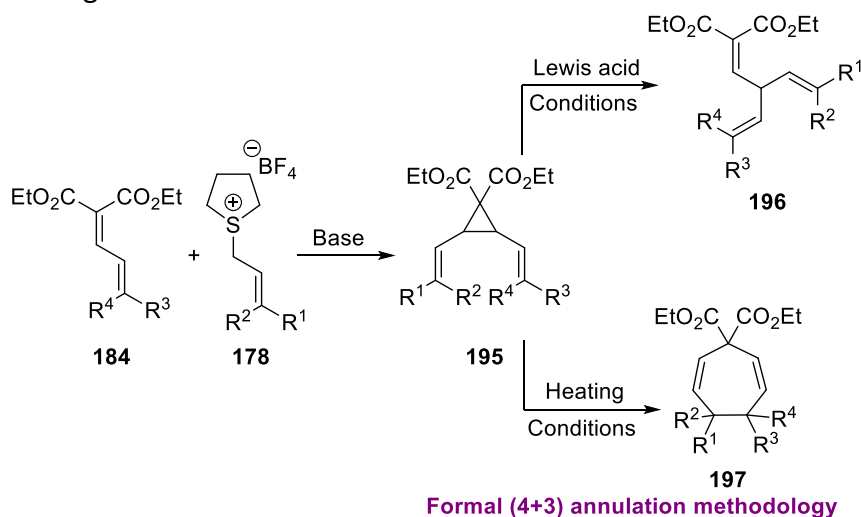
Scheme 3.8: Divergent rearrangements of **195** to **196** and **197**

Chapter 4: Synthesis and rearrangements of vinylcyclopropanes

The first objective of our PhD thesis work is the further study of the rearrangement of the vinylcyclopropanes **179** into skipped dienes **181** by exploring the effect of new substituents (R^{1-4}) and EWG on the system (Scheme 4.1). For the synthesis of the VCPs, the strategy starting from 1,3-dienes will be used in priority but the one starting from olefins will also be applied for VCPs bearing R^1 = alkyl groups.
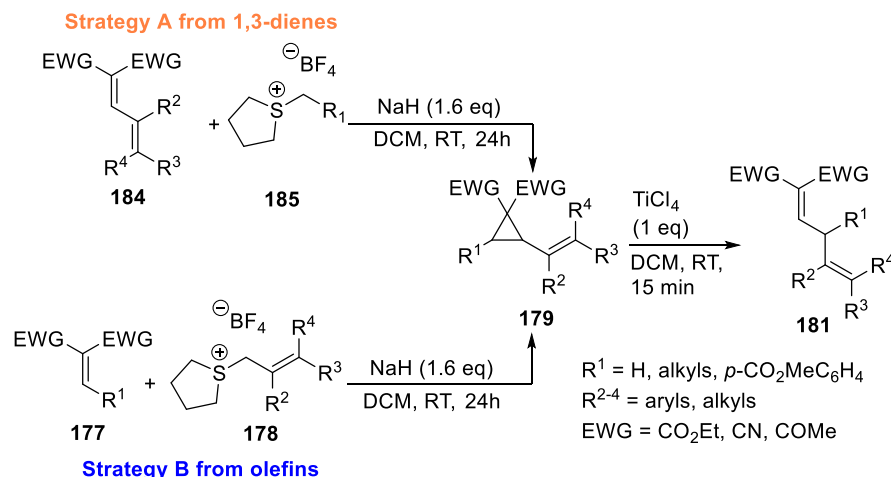
Scheme 4.1: Two complementary strategies for obtaining VCPs **179** and their rearrangement into skipped dienes **181**

These researches will be accompanied by DFT studies in order to better understand the experimentally observed effects of the substituents on the system and the origin of some limitations. The development of an enantioselective version of the methodology using chiral sulfonium salts will also be investigated.

4.1. Synthesis of vinylcyclopropanes

The ylide-mediated cyclopropanation reaction was used to synthesise new vinylcyclopropanes in the aim of exploring their rearrangement (see 4.2.). This section is divided into in three subsections, related to three different electron-withdrawing groups

on the cyclopropanes. The synthesis of the substrates used in the vinylcyclopropanation reactions and for our other methodologies is an important part of this work. Their synthesis are detailed in section 9.2 The numbering logic used for the molecules in this manuscript is detailed in section 9.1.

4.1.1. EWG = CO$_2$Et

The reaction conditions for the cyclopropanation using NaH as the base to deprotonate the sulfonium salts **185** or **178** were found not to be suitable for the obtaining of vinylcyclopropanes having alkyl groups on the 1,3-diene (R$^{2-4}$) or the activated olefin (R^1) substrates. The hypothesis formulated to explain this observation is that the alkyl groups possess acidic protons that can be deprotonated in the presence of the base leading to the formation of a negative charge delocalised up to the ester groups through the conjugated system (Figure 4.1).
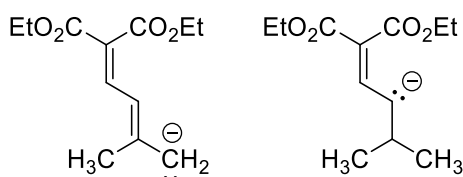
Figure 4.1: Deprotonated 1,3-diene and olefin

This problem has already been encountered by our group in the context of the development of the (4+1) annulation reaction. We decided to use the conditions developed by Dr. Olivier Rousseau[82], *i.e.* the use of LiHMDS to deprotonate the sulfonium salt at -78°C prior to the addition of the **177** or **184** with a 15-minute delay between the two additions to ensure complete deprotonation of the salt. These conditions showed to be compatible with akyl-substituted substrates and were used to obtain 22 vinylcyclopropanes from 1,3-dienes (Table 4.1). The strategy using allylic sulfonium salts was used to synthesise VCPs bearing alkyl groups at the R^1 position. This choice was made due to the easier handling and synthesis of activated olefins with R^1 = alkyl groups as opposed to non-stabilised sulfonium ylides. The VCPs

obtained with the second strategy were obtained in collaboration with Julien Janssens during his Master's thesis.[83]

Table 4.1: Synthesis of vinylcyclopropanes
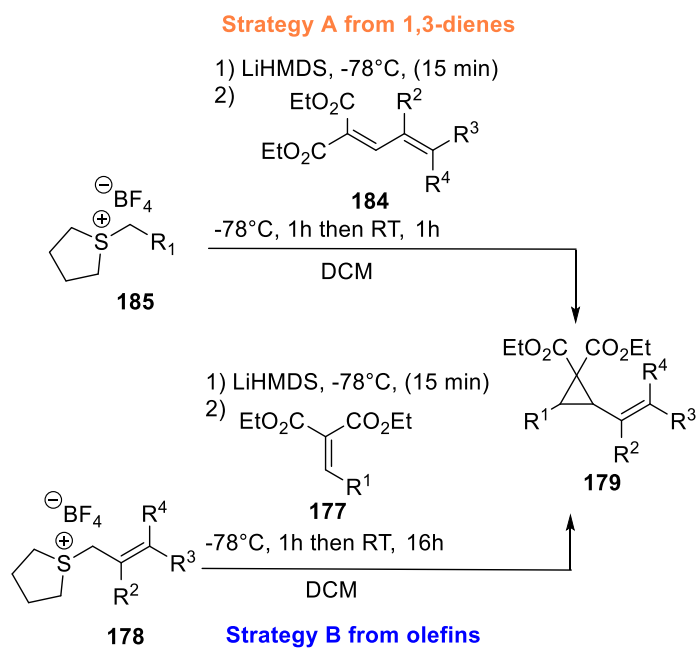
Entry	R^1	R^2	R^3	R^4	A or B	Yield (%)[a]	d.r. (cis/trans)[b]
1	Ph	H	Me	Me	A	44[c]	50/50
2	Ph	H	i-Pr	H	A	33[c]	50/50
3	Ph	Me	Ph	H	A	45[c]	40/60
5	Ph	H	p-BrC$_6$H$_4$	H	A	82	40/60
6	Ph	H	Ph	Ph	A	69	40/60
7	Ph	H	2-furyl	H	A	13	0/100
8	o-MeC$_6$H$_4$	H	Ph	H	A	70	40/60
9	m-MeOC$_6$H$_4$	H	Ph	H	A	37	40/60
10	t-Bu	H	Ph	H	B	quant	0/100
11	Cyclopropyl	H	Ph	H	B	78[c]	30/70
12	p-CO$_2$MeC$_6$H$_4$	H	Me	Me	A	54[c]	33/66
13	p-CO$_2$MeC$_6$H$_4$	H	i-Pr	H	A	44[c]	30/70
14	p-CO$_2$MeC$_6$H$_4$	H	Ph	Ph	A	70	40/60
15	i-Pr	H	i-Pr	H	B	90[c]	40/60
16	Me	H	i-Pr	H	B	91[c]	40/60
17	t-Bu	H	i-Pr	H	B	76	0/100
18	Cyclopropyl	H	i-Pr	H	B	41[c]	50/50
19	i-Bu	H	i-Pr	H	B	35[c]	40/60
20	i-Pr	H	p-CO$_2$MeC$_6$H$_4$	H	B	48[c]	45/55
21	t-Bu	H	p-CO$_2$MeC$_6$H$_4$	H	B	76	0/100
22	H	H	Ph	Ph	A	48[d]	-

[a] Yield in pure isolated compound. [b] Measured on the ^{1}H NMR spectrum of the crude mixture [c] A 15-minute delay was applied between the addition of the base and the addition of the 1,3-diene or the activated olefin. [d] A special procedure was used (*vide infra*).

The library of obtained vinylcyclopropanes with ester groups as the EWG contains 22 molecules obtained in yields varying from 33% to quantitative. The diastereoisomeric ratio (*cis/trans*) of the products ranges from 50/50 to 0/100.

Some of these VCPs will enable the exploration of the effect of substitution of the double bond (R^{2-4}, entries 1-7) and of aryls with groups in the *ortho* and *meta* positions (entries 8-9). Other vinylcyclopropanes will be involved in Lewis acid promoted

rearrangement to investigate the migration of poor migrating groups (R^1 = H, alkyls, p-CO$_2$MeC$_6$H$_4$) by changing the nature of R^{3-4} for disfavouring the competitive cyclisation reaction (see 4.2.2.2.) (entries 10-22).

The migration of R^1 = H group was also among the targets of the exploration of the scope. Since our LiHMDS protocol never afforded us the corresponding VCP **179jf**, this latter was obtained using trimethylsulfonium iodide following a reported procedure (Scheme 4.2.).[26]
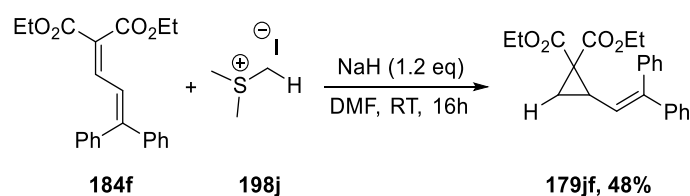
Scheme 4.2: Special procedure for the formation of **179jf**

4.1.2. EWG = CN

The synthesis of skipped dienes bearing electron-withdrawing groups other than esters was a point of interest of this work. We chose to investigate cyano groups first, starting from a 1,3-diene. Accordingly, we attempted to synthesise **184a-CN** (Scheme 4.3).
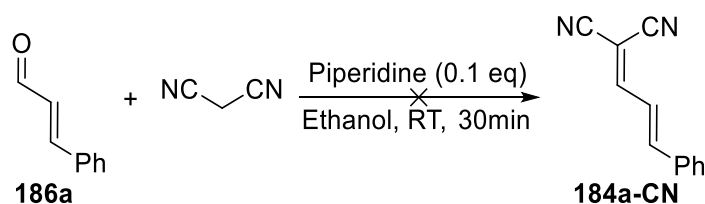
Scheme 4.3: Failed attempt at synthesising **184a-CN**

The purification of this compound was however tricky. We thus decided to use the second strategy in which the electron-withdrawing groups are brought by an activated olefin. Indeed, **177a-CN** was available in sufficient amount in our lab. In this case, the methodology using NaH as a base was used and the VCP was obtained in a good yield.
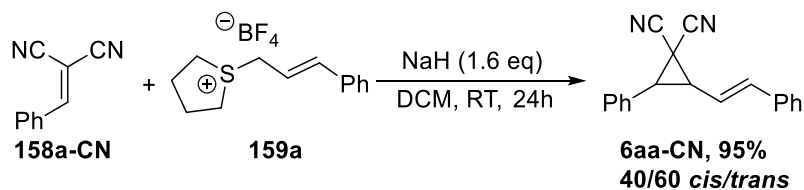
Scheme 4.4: Synthesis of **179aa-CN**

4.1.3. EWG = COMe

The next EWG investigated was a ketone group. We tried to
obtain **179aa-COMe** via both strategies (A and B, Scheme 4.5).
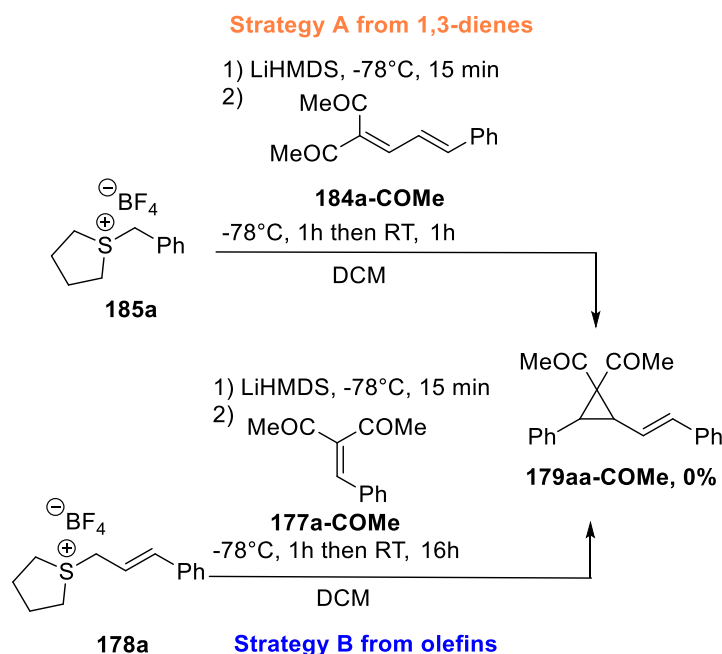
Scheme 5.5 Failed attempt for the synthesis of **179aa-COMe**

The desired VCP, **179aa-COMe**, could not be obtained as both
reactions led to the formation of very complex mixtures, even when
we applied the 15-minute delay between the addition of LiHMDS and
the electrophile (**184a-COMe** or **177a-COMe**) because of the acidity of
the protons of the ketone groups. We decided to stop our
investigation on this electron-withdrawing group at this stage.

4.2. Rearrangement reactions

This section details the rearrangement reactions of the previously obtained vinylcyclopropanes.

4.2.1. Aromatic migrating groups

Our work on the rearrangement reaction started by the rearrangement of 9 vinylcyclopropanes with aromatic migrating groups, phenyl or weakly electron-donor and -acceptor aryls using the reaction conditions previously developed by our laboratory (see Chapter 2) (Table 4.2).

<u>Table 4.2</u>: Rearrangement of VCPs to skipped dienes using the typical reaction conditions
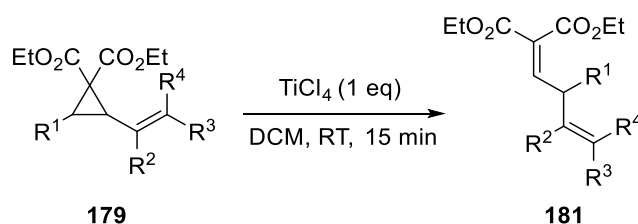
Entry	1,4-diene	R^1	R^2	R^3	R^4	Yield (%)[a]
1	**181aa**	Ph	H	Ph	H	95
2	**181ab**	Ph	H	Me	Me	25
3	**181ac**	Ph	H	i-Pr	H	33
4	**181ad**	Ph	Me	Ph	H	54
5	**181ae**	Ph	H	p-BrC$_6$H$_4$	H	82
6	**181af**	Ph	H	Ph	Ph	81
7	**181ag**	Ph	H	2-furyl	H	0[b]
8	**181ba**	o-MeC$_6$H$_4$	H	Ph	H	25(37[c])
9	**181ca**	m-MeOC$_6$H$_4$	H	Ph	H	28(39[c])

[a] Yield in pure isolated compound. [b] Corresponding cyclopentene was obtained (86% isolated yield). [c] Measured by ^{1}H NMR using dimethylterephtalate (DMT) as an internal standard on the crude mixture.

New dienes **181** bearing alkyl groups at R^2, R^3 and R^4 positions were obtained (entries 2-4). The lower yields obtained for entries 1 and 2 can be explained by the presence of side products which were

not the corresponding cyclopentene. We were also able to isolate the diene **181af** with 2 phenyl groups on the terminal position of the second unsaturation and **181ae** (R^3 = p-BrC$_6$H$_4$) in good yields (entries 5-6). Unfortunately, the skipped diene **181ag** bearing a 2-furyl group at the R^3 position could not be obtained (entry 7). Instead, the cyclopentene **180ag** was obtained in 86% yield (Scheme 4.6).
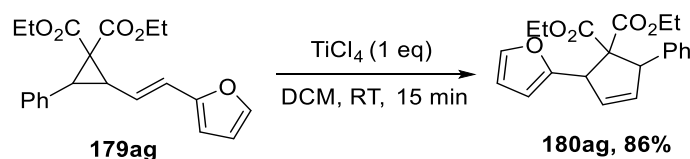
Scheme 4.6: Rearrangement of **179ag** to the corresponding CP **180ag**

Further experiments with a lower TiCl$_4$ loading showed that **180ag** was in fact the first product to be formed during the rearrangement of **179ag**, indicating that the cyclopentene is both the thermodynamic and the kinetic product of the reaction. This reactivity was already observed with R^3 = p-MeOC$_6$H$_4$, an electron-rich aryl.[81] This will be further investigated in our computational studies in section 4.3.3.2.1.

Ortho and *meta* substituted aryls were also found to be migrating to afford dienes **181ba** and **181ca** (entries 7-8). The desired products were obtained in complex mixture of products, explaining the lower yields for these examples.

Interestingly, we noticed that putting skipped dienes **181ac** and **181ae** back in the presence of TiCl$_4$ did not afford the corresponding cyclopentene **180** after 24 hours of reaction. It was also the case when R^3 = p-CO$_2$MeC$_6$H$_4$, as discussed by Dr. Maximilien Richald in his PhD thesis.[80] Indeed, the presence of an alkyl group or electron-poor aryls at this position is disfavouring the formation of the cyclopentene (*vide infra*).

4.2.2. Migration of poor migrating groups

Our attention then shifted to the migration of poor migrating groups such as H, alkyls and p-CO$_2$MeC$_6$H$_4$ (see 4.3.3.1.1. for a scale of migratory aptitudes). During his thesis, Dr. Richald found that one

limitation of the VCP/skipped diene rearrangement is that the migration of electron-poor aryls is not observed when the vinyl part of the VCP is a styryl group (Scheme 5.7).[80] This was also the case for the hydrogen, isopropyl and isobutyl groups. In these cases, the cyclopentene **180** is the first product to be formed, indicating that its formation is faster than the one of the desired skipped dienes, possibly due to the slow migration rate of these substituents. Exploring longer reaction times did not lead to the formation of any other rearrangement product. Maximilien did not investigate the influence of the substitution of the vinyl group of the VCP in these cases.
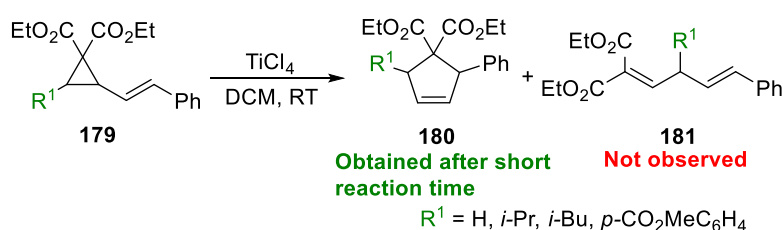
Scheme 4.7: Outcome of the rearrangement of poor migrating groups

The investigation will be started by exploring the 1,2-migration of new alkyl groups (*t*-Bu and cyclopropyl) and keeping the vinyl group as a styryl. After these studies, we will use strategies to slow down the cyclisation reaction (by varying the nature of the R^3 group) and hence favour the migration of previously not compatible groups (R^1 = H, *i*-Pr, *i*-Bu, *p*-CO$_2$MeC$_6$H$_4$) and new groups (Me, *t*-Bu and cyclopropyl). This will allow us to gain a better understanding of the skipped diene/CP selectivity in the rearrangement of vinylcyclopropanes.

4.2.2.1. Migration of t-Bu and cyclopropyl

The work on the migration of poor migrating groups started by exploring new alkyl groups while keeping the vinyl group of the VCP as a styryl. The goal was to see if the *t*-Bu and cyclopropyl groups were capable of making the migration reaction leading to **181** faster than the cyclisation reaction and thus avoiding the formation of the undesired cyclopentene **180**.

In the context of Julien Janssens' Master's thesis, we studied the migration of the *t*-Bu group, a better migrating group than *i*-Pr and

i-Bu, to investigate if its higher migrating ability is sufficient to make the formation of the skipped diene win the competition against the cyclisation reaction (Table 4.3).

<u>Table 4.3</u>: Optimisation process for the selective synthesis of **181da**

Entry	Eq TiCl$_4$	Time	181da/180da[a]	Yield 180da (%)[b]	Yield 181da (%)[b]
1	1	15 min	traces/1	93	0
2	3	20h	1/2	n.d.	n.d.
3	5	24h	1/traces	0	quant.

[a] Measured on the ^{1}H NMR spectrum of the crude mixture. [b] Yield in pure isolated compound.

Unfortunately, our standard reaction conditions led, as for other alkyl groups, to the formation of the cyclopentene with an excellent yield (entry 1). Interestingly, it was however noticed that increased reaction times along with a greater amount of the Lewis acid allow the formation of the desired diene, **181da** (see entry 2). This indicates that the formation of the cyclopentene is, in this case, reversible and that the latter is the kinetic product of the system whereas the skipped diene **181da** is the thermodynamic product. The *tert*-butyl group was the first substituent to show this behaviour. Entry 3 presents the optimised reaction conditions for obtaining the desired skipped diene in a quantitative yield. **181da** was the first skipped diene with an alkyl group at the central sp^3 carbon of the 1,4-diene moiety isolated by our group. The competition between the formation of **181da** and **180da** will be investigated by computational methods later in this manuscript (see 4.3.3.1.3.).

CHAPTER 4: SYNTHESIS AND REARRANGEMENTS OF VINYLCYCLOPROPANES

After successfully obtaining of a skipped diene coming from the migration of an alkyl group, Julien investigated the rearrangement of **179ea** with a cyclopropyl group (Table 4.4).

Table 4.4: Optimisation process for the selective synthesis of **181ea**
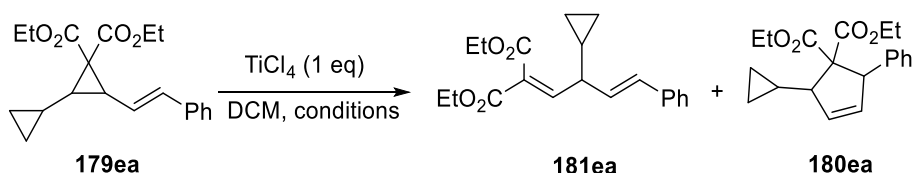
Entry	Conditions	181ea/180ea[a]	Yield 181ea (%)[b]
1	RT, 15 min	4/1	n.d.
2	-78°C, 1h then RT, 1h	16/1	50

[a] Measured on the ^{1}H NMR spectrum of the crude mixture. [b] Yield in pure isolated compound.

The classic rearrangement conditions led to the formation of a 4/1 mixture of the desired diene **181ea** and the cyclopentene **180ea** (entry 1). Contrary to other secondary alkyl group such as *i*-Pr, this time the formation of the desired product is observed. We then tried to influence the selectivity in favour of the desired skipped diene by lowering the temperature. The second conditions used consisted in 1 hour of stirring at -78°C and another hour at room temperature. We were able to successfully increase the selectivity **181ea/180ea** up to 16/1, to obtain **181ea** in 50% isolated yield.

Our hypothesis to explain the formation of the skipped diene **181ea** is a mechanism involving the ring-opening of the cyclopropane moiety on the cyclopropyl side to form a zwitterionic intermediate **183ea-TiCl₄** in which the positive charge is stabilised by the presence of the cyclopropyl group furnishing a non-classical character to the carbocation (Scheme 4.8).[84]
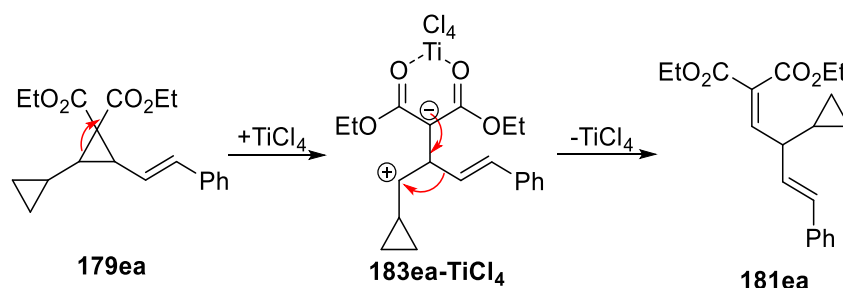
<u>Scheme 4.8</u>: Postulated mechanism for the formation of **181ea** via a
non-classic carbocation **183ea-TiCl₄**

The 1,2-migration of the styryl group following the red arrows
leads to the formation of **181ea** upon the decomplexation of TiCl₄. The
opening on this side is in competition with the heterolytic cleavage on
the styryl side, necessary to explain the formation of the cyclopentene.
This hypothesis will be investigated in the computational part of this
manuscript (see section 4.3.3.1.1.).

The Lewis acid triggered rearrangement of biscyclopropanes
was already reported.[84d] Denisov *et al.* demonstrated that the ring-
opening on the cyclopropyl side via the obtaining of products formed
via a double ring-opening involving both cyclopropanes (cyclohexanes,
skipped dienes). In our case, no products formed via a double ring-
opening were observed which can be explained by the lack of an
electron-donor group on the cyclopropyl substituent as compared to
the publication by Denisov and colleagues.

The data presented in this section complete the one obtained
by Dr. Maximilien Richald during his PhD thesis on the migration of
poor migrating groups when the vinyl group of the VCP is a styryl (see
4.2.2.). The skipped dienes **181da** and **181ea** are the first dienes with
an alkyl group on the central sp^3 carbon of the skipped diene moiety
isolated by our group. The cyclisation was however still present during
our investigations.

In order to further favour the 1,2-migration over the cyclisation
and enable the obtaining of skipped dienes with other alkyl groups, we

searched for strategies with the aim of slowing down the cyclisation step.

4.2.2.2. Strategies for disfavouring the cyclisation reaction

After obtaining skipped dienes **181** with t-Bu and cyclopropyl groups on the central sp^3 carbon of the moiety, we became interested in disfavouring the competitive cyclisation reaction by modifying the substitution on the vinyl side of the VCP (R^{3-4}). Doing so, we hoped to isolate skipped dienes **181** with $R^1 = p\text{-CO}_2\text{MeC}_6\text{H}_4$, i-Pr, i-Bu that could not be obtained previously (see 5.3.2.) as well as to increase the selectivity towards skipped dienes **181** over cyclopentene **180** in the cases of $R^1 = t$-Bu and cyclopropyl. The two strategies envisaged are detailed in Scheme 4.9.
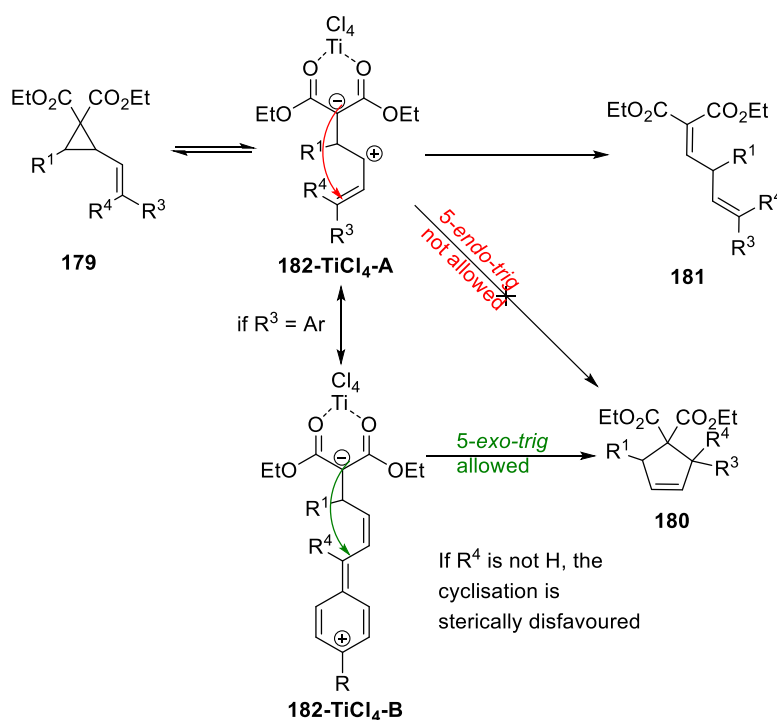
Scheme 4.9: Strategies to disfavour the cyclisation reaction

We previously determined that the cyclisation reaction was occurring via a heterolytic mechanism by DFT methods (see Chapter 2). As shown in Scheme 4.9, the positive charge resulting from the

heterolytic cleavage of a C-C bound in **179** can be stabilised by conjugation with the allylic cation motif but also with the aryl group when R^3 = aryl. Two mesomeric forms of the zwitterionic intermediate are drawn, **182-TiCl₄-A** and **182-TiCl₄-B**. The cyclisation reaction from **182-TiCl₄-A** is a 5-*endo-trig* process, which is not allowed by Baldwin's rules.[85] However, the cyclisation experimentally takes place. This can be accounted for by the fact the charge can be delocalised into the aryl group, one of the mesomeric form being **182-TiCl₄-B**. The cyclisation reaction starting from **182-TiCl₄-B** is a 5-*exo-trig* process, allowed by Baldwin's rules.

Accordingly, our first strategy to disfavour the cyclisation involves the use of derivatives with R^3 = alkyl groups to prevent the possibility of mesomeric forms such as **182-TiCl₄-B** which allow the reaction to occur. The second strategy consists of sterically hindering the position by using VCPs in which $R^4 \neq H$.

4.2.2.3. Slowing down the cyclisation reaction with R^3 = i-Pr or p-CO₂MeC₆H₄

We first tried to disfavour the cyclisation towards the cyclopentenes by disfavouring or preventing the delocalisation of the positive charge using p-CO₂MeC₆H₄ or i-Pr derivatives, respectively.

4.2.2.3.1. TiCl₄ promoted rearrangement

Our investigations started by using our standard rearrangement conditions with TiCl₄ to promote the desired transformation (Table 4.5). The investigated poor-migrating group were also R^1 = i-Pr and p-CO₂MeC₆H₄.

Table 4.5 Rearrangement of VCPs to skipped dienes using the typical
reaction conditions
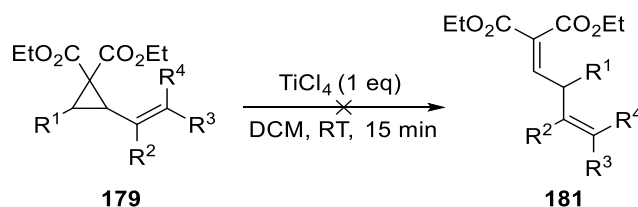
Entry	1,4-diene	R^1	R^2	R^3	R^4	Yield (%)
1	**181fb**	p-CO$_2$MeC$_6$H$_4$	H	Me	Me	0
2	**181gh**	i-Pr	H	p-CO$_2$MeC$_6$H$_4$	H	0
3	**181gc**	i-Pr	H	i-Pr	H	0

We found that our strategy successfully disfavours the cyclisation towards the cyclopentene but that it does not lead to the desired skipped diene either. Indeed, the formation of a series of side products was observed (Figure 4.2): A 1,3-diene (**199fb**), a lactone (**200gh**) and a chlorinated product (**201gc**).

Ar = p-CO$_2$MeC$_6$H$_4$
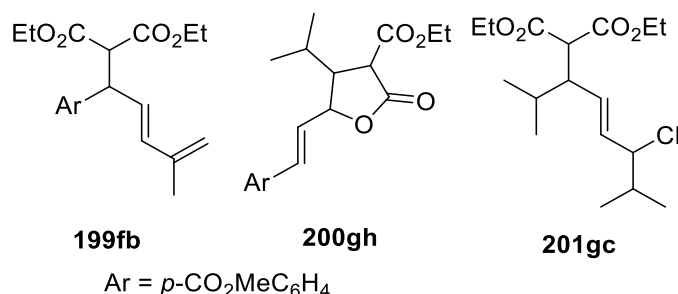
Figure 4.2: Three different side products observed

The postulated mechanism to explain the formation of the 1,3-diene **199fb** is depicted in Scheme 4.10. The negative charge resulting from the heterolytic cleavage of the cyclopropane can act as a base to abstract, intra- or inter-molecularly, one of the protons in β position to the carbocation, creating a 1,3-diene moiety.

179fb   **182fb-TiCl$_4$**   **199fb**

Ar = p-CO$_2$MeC$_6$H$_4$
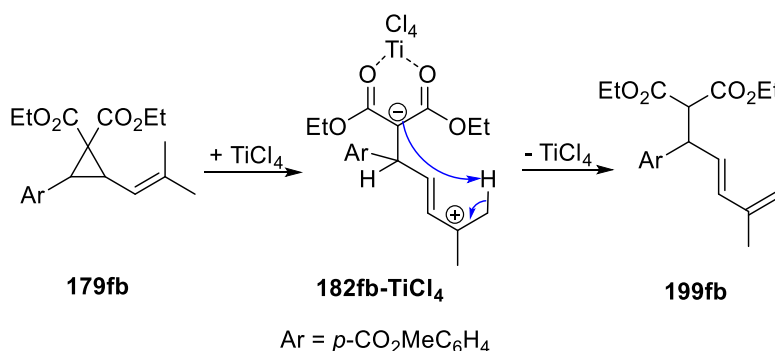
Scheme 4.10: Postulated mechanism explaining the formation of **199fb**

     Scheme 4.11 details the postulated mechanism for the formation of the lactone **200gh** from **179gh**. The first step is the ring-opening of **179gh** to give **202gh**, which has only one of its carbonyl group complexed by TiCl$_4$. The free carbonyl group can add onto the allylic cation moiety to form **203gh**. A nucleophile, probably a chloride, can attack the ethyl group, forcing its departure, and the formation of lactone **200gh**.

179gh   **202gh**   **203gh**

Ar = p-CO$_2$MeC$_6$H$_4$
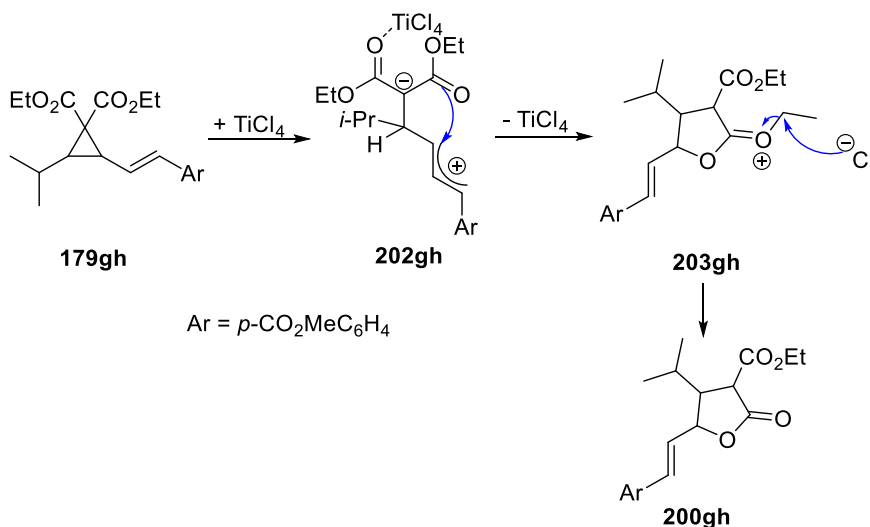
200gh

Scheme 4.11: Postulated mechanism explaining the formation of **200gh**

The formation of the chlorinated side product **189gc** can be explained by the following suggested mechanism (Scheme 4.12). An attack of a chloride ion on the allylic cation moiety can occur. Upon protonation of the negative charge during the work-up and decomplexation of the Lewis acid, **189gc** is obtained.
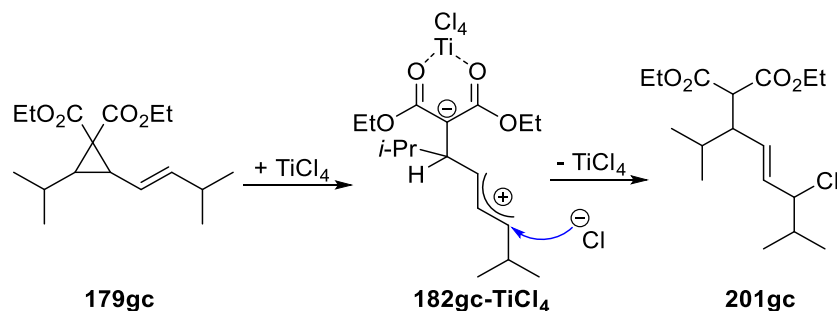
Scheme 4.12: Postulated mechanism explaining the formation of **189gc**

The use of titanium chloride (IV) leading to the formation of three different side products, we decided to investigate the use of another Lewis acid to trigger the desired rearrangement.

4.2.2.3.2. FeCl₃ promoted rearrangements

After our unsuccessful attempts to obtain the skipped dienes **181fb**, **181gh** and **181gc** with TiCl₄, the nature of the Lewis acid was switched to FeCl₃. Available in our lab, FeCl₃ was indeed found to promote our rearrangement during previous studies carried out by our group.[86] Julien Janssens determined that the optimal conditions for the FeCl₃-promoted rearrangement are 1 equivalent of the Lewis acid for 2h30 of reaction time at room temperature in dichloromethane.[83] The optimised reaction conditions were used to rearrange 9 vinylcyclopropanes (Table 4.6).

Table 4.6: FeCl$_3$ promoted rearrangement of VCPs
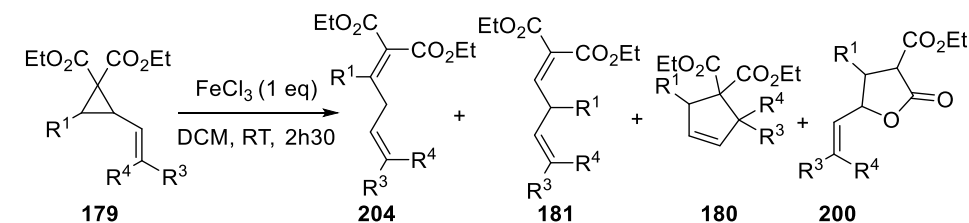
Entry	VCP	R^1	R^3	R^4	Yield (%)[a]			
					204	181	180	200
1	**179gc**	*i*-Pr	*i*-Pr	H	26	0	0	0
2	**179ic**	*i*-Bu	*i*-Pr	H	49	0	0	0
3	**179hc**	Me	*i*-Pr	H	39	0	0	0
4	**179dc**	*t*-Bu	*i*-Pr	H	0	57	0	0
5	**179ec**	Cyclopropyl	*i*-Pr	H	0	54	0	0
6	**179fb**	*p*-CO$_2$MeC$_6$H$_4$	*i*-Pr	H	5	12	0	0
7	**179fc**	*p*-CO$_2$MeC$_6$H$_4$	Me	Me	6	30	0	0
8	**179gh**	*i*-Pr	*p*-CO$_2$MeC$_6$H$_4$	H	23	0	0	24
9	**179dh**	*t*-Bu	*p*-CO$_2$MeC$_6$H$_4$	H	0	33	7	20

[a] Measured on the ^{1}H NMR spectrum of the crude mixture using DMT as an internal standard.

The formation of the desired skipped diene **181gc** was not observed (entry 1). No trace of cyclopentene **180gc** was however observed in this rearrangement, proving the efficiency of our strategy. Interestingly, the skipped diene **204gc** with no substituent on the central sp^3 carbon was obtained instead, in a moderate yield of 26%. Formation of this skipped diene can be accounted for by the ring-opening of the cyclopropane followed by the migration of a hydrogen atom, instead of the isopropyl group (Scheme 4.13).
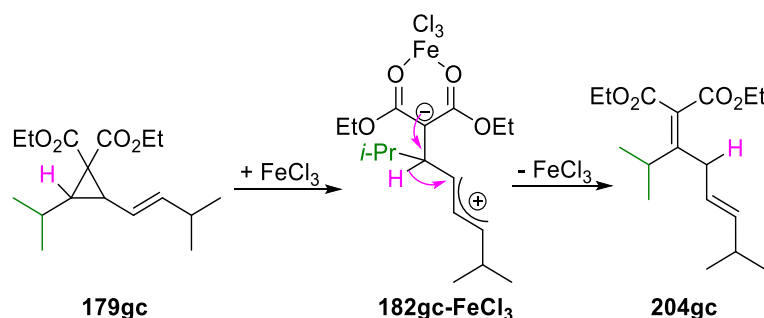
Scheme 4.13: Postulated mechanism explaining the formation of **204gc**

The first group we sought to vary was R^1 and keeping $R^3 = i$-Pr to block the cyclisation reaction. The previously developed conditions allowed us to obtain other skipped dienes coming from the migration of a hydrogen, **204,** when $R^1 = $ Me and i-Bu (entries 2 and 3). We then investigated the rearrangement of VCPs bearing better migrating alkyl groups such as t-Bu and cyclopropyl. Satisfyingly, it led to skipped dienes having the alkyl group on its central carbon, **181** (entries 4 and 5).

Next, we considered the migration of an electron-poor aryl group, p-CO$_2$MeC$_6$H$_4$. In this case, the difference of migratory aptitude is not significant with H as a mixture of diene **181** and **204** is obtained with **181** being the main product in both cases (entries 6 and 7).

We then investigated another type of R^3 substituent to slow down the competitive cyclisation reaction, $R^3 = p$-CO$_2$MeC$_6$H$_4$ (entries 8-9). Again, the nature of the R^1 group influenced the nature of the diene obtained (**181** or **204**). In these cases, the lactone **200** obtained with TiCl$_4$ cannot be avoided and was present in a significant amount. Entry 9 shows that a small amount of the corresponding cyclopentene **180** was formed, meaning that this strategy did not allow complete prevention of the cyclisation of the zwitterionic intermediate, conversely to when R^3 was an alkyl group.

4.2.2.4. Slowing down the cyclisation by steric hindrance

We also explored the possibility of slowing down the cyclisation reaction by increasing the steric hindrance on the attack position of the negative charge by adding a second phenyl group.

The first investigated VCP was **179fe**, its rearrangement was studied using various reaction conditions (Table 4.7).

Table 4.7: Optimisation of the rearrangement of **179fe** to **181fe**
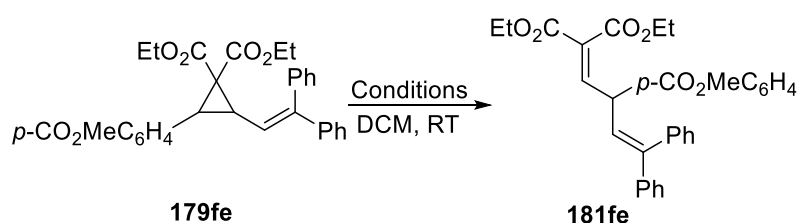
Entry	Conditions	Yield (%)
1	$TiCl_4$, 30 min	traces
2	$TiCl_4$, 45 min	traces
3	$TiCl_4$, 1h30	traces
4	$FeCl_3$, 2h30	0

The reaction conditions used in entry 1 only led to a partial conversion of **179fe**. However, the desired skipped diene **181fe** was only observed as traces on the ^1H NMR spectrum of the crude mixture; the main products being unidentified side products. The reaction time was then increased to 45 minutes and full conversion of **179fe** was then observed (entry 2). The proportion of **181fe** in the crude mixture was slightly increased but the main products were still unidentified side products. The rearrangement time was further increased to 1h30 and the desired diene was found to be present, albeit in traces amount more similar to entry 1.

The nature of the Lewis acid was changed to $FeCl_3$. This Lewis acid led to the formation of the same side products as $TiCl_4$ but without traces of **181fe**.

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After this unsuccessful investigation of the migration of *p*-$CO_2MeC_6H_4$, we decided to carry on with our studies on the steric hindrance of the zwitterionic intermediate to disfavour the cyclisation by studying R^1 = H. The vinylcyclopropane **179jf** was rearranged in the aim of isolating the skipped diene **181jf** with two hydrogen atoms on the central sp^3 carbon of the moiety and a hydrogen on the olefin function (Table 4.8).

Table 4.8: Optimisation of the rearrangement of **179jf** to **181jf**
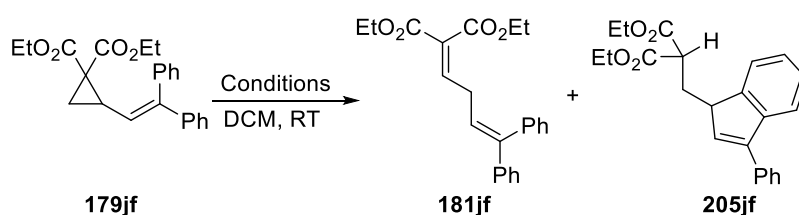
Entry	Conditions	Observations
1	TiCl$_4$, 15 min	Formation of **205jf**[a]
2	TiCl$_4$, 1h15	Formation of **205jf**
3	FeCl$_3$, 30 min	Formation of **205jf**
4	FeCl$_3$, 1h	Formation of **205jf**
5	FeCl$_3$, 1h30	Formation of **205jf**

[a] Conversion of **179jf** to **205jf** was not complete.

The standard reaction conditions led to the partial conversion of **179jf** to an undesired side product **205jf** (entry 1). The reaction time was then increased to 1h15, which allowed us to isolate the side product and determine its structure as an indene.

The proposed mechanism explaining the formation of the indene **205jf** is depicted in Scheme 4.14. The first step of this suggested mechanism is the heterolytic cleavage of a C-C bond on the vinyl side of the VCP. Then, the phenyl group in *cis* position can add onto the carbocation formed by the cleavage. The negative charge stabilised by the two complexed ester group can then act as a base and abstract a proton to restore the aromaticity.

93
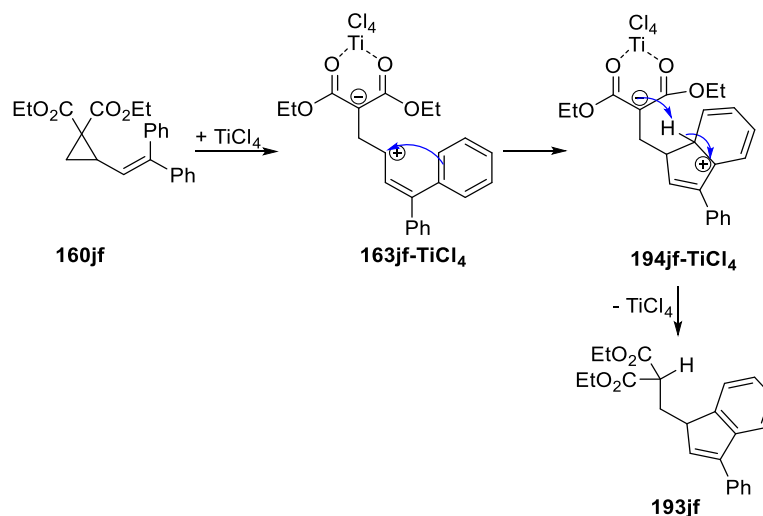
Scheme 4.14: Postulated mechanism for the formation of **205jf**

The synthesis of indenes substituted by a –CH_2-$(CO_2R)_2$ group has already been reported in the literature starting from a donor-acceptor cyclopropane and an alkyne.[87] Our reaction is an intramolecular rearrangement leading to this structure but we decided not to investigate this rearrangement further due to the previous report detailing its obtaining.

Switching the Lewis acid used to promote the rearrangement to iron chloride (III) also led to the formation of the indene **205jf** as the main product. Considering this result and the difficulty of obtaining other VCPs with R^1 = H, this part of the exploration of the scope of the vinylcyclopropane to skipped diene rearrangement was stopped.

4.2.2.5. Conclusions on the strategies

We succeeded in disfavouring the competitive cyclisation reaction to observe the migration of poor migrating groups such as electron poor aryls, alkyls and hydrogen.

The strategy consisting of using R^3 = *i*-Pr or *p*-$CO_2MeC_6H_4$ was a success but required to change the nature of the Lewis acid used, from $TiCl_4$ to $FeCl_3$. The alkyl group showed better results, the undesired cyclopentene was never observed during our investigations. Disfavouring the cyclisation by using R^3 = *p*-$CO_2MeC_6H_4$ proved to be

less efficient as the cyclopentene was detected in one example as a
minor product of the rearrangement.

Increasing the steric hindrance to slow down the competitive
cyclisation did not allow for the isolation of any skipped diene. The
problem was the formation of a lot of side products. Among them, one
was identified to be an indane. The postulated mechanism explaining
its formation involves the reaction of the phenyl group that was added
to disfavour the cyclisation. This strategy could be further explored by
adding an alkyl group on this position, instead of an aryl.

4.2.3. EWG = CN

The rearrangement of VCP with cyano groups as EWG was also
studied. Unfortunately, the reaction in the presence of two
equivalents of TiCl$_4$ led exclusively to the formation of the
corresponding cyclopentene **180aa-CN** in a good yield and a
diastereoisomeric ratio of 2/1 in favour of the *cis* isomer (Scheme
4.15).
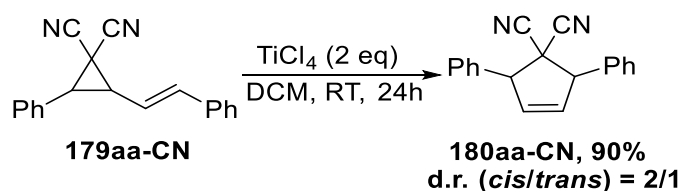
Scheme 4.15: Synthesis of **180aa-CN**

The rearrangement reaction of **179aa-CN** carried out with 2
equivalents of FeCl$_3$ for the same reaction led to the same result, the
desired skipped diene was not obtained. A kinetic study of the
rearrangement, with TiCl$_4$ as the Lewis acid, showed that the
cyclopentene is the first product formed. This will be studied in the
computational section of this work (see 4.3.2.2.3.).

The rearrangement of a VCP with cyano group and a better
migrating group (R^1 = *p*-MeOC$_6$H$_4$) was attempted but did not lead to
the formation of the desired skipped diene. Since cyano-bearing
cyclopentenes were already reported by Ivanova *et al.* (see 1.2.3.1.1.),
we decided to shift our attention on the development of new synthetic

methodologies and not to investigate the strategies for slowing down the cyclisation reaction (see 4.2.2.2.) or the use of different Lewis acids.

4.2.4. Conclusions on the exploration of the scope

We developed a two-step strategy towards skipped dienes using LiHMDS as a base to deprotonate the sulfonium salt **185**. During our investigations, we sought to obtain vinylcyclopropanes with R^1 = alkyl groups, those were formed using activated olefins **177** and allylic sulfonium salts **178**. These VCPs could be rearranged to dienes **181** or **204** depending on the nature of the R^1 group (Scheme 4.16).
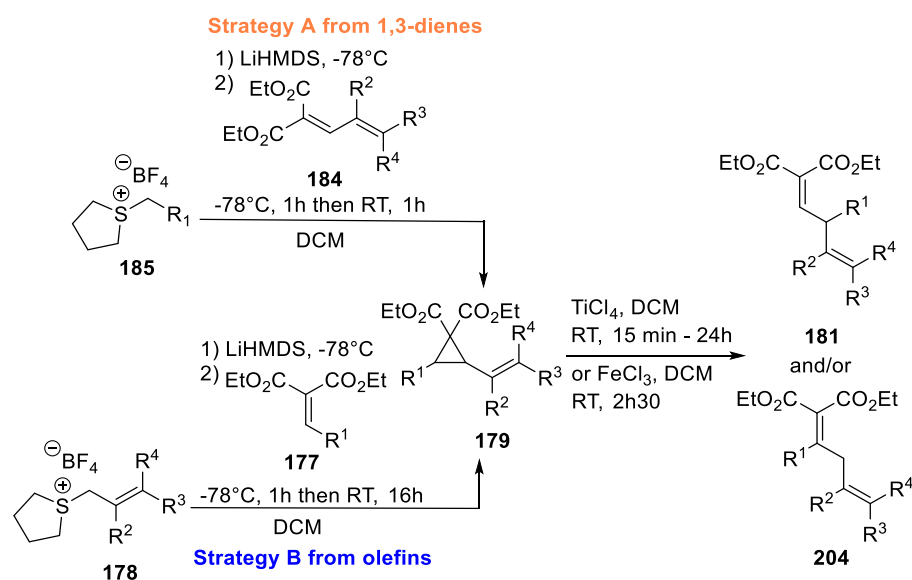
Scheme 4.16: Exploration of the scope of the rearrangement

The investigation of the scope carried out during this work allowed us to gain a better understanding of the factors controlling the competition between the skipped dienes and cyclopentenes formation and how to influence the outcome of the Lewis acid triggered rearrangement of our vinylcyclopropanes.

Prior to this PhD work, the migration of poor migrating groups such as H, p-CO$_2$MeC$_6$H$_4$ and alkyls groups was never observed, instead the corresponding cyclopentenes were obtained as the selective

products of the rearrangements, even after short reaction times. We elaborated and successfully used strategies to slow down the competitive cyclisation reaction and thus enabling the observation of the migration of these groups. This allowed us to note that the hydrogen migrates preferentially as compared to Me, *i*-Bu and *i*-Pr whereas *t*-Bu migrates faster than H. For the rearrangement of these VCPs, $FeCl_3$ was used over $TiCl_4$ because the latter was found to lead to the formation of different side products (chlorinated product, lactone).

Unfortunately, we were not able to obtain skipped dienes with other EWGs than CO_2Et. Vinylcyclopropane **179aa-COMe**, with two ketone groups, was not obtained and its cyano-bearing counterpart was selectively rearranged into the corresponding cyclopentene in the presence of a Lewis acid, $TiCl_4$ or $FeCl_3$.

4.3. DFT calculations

This section is devoted to the computational studies carried out using DFT methods. The aim of these investigations is to improve our understanding of the mechanism and identify factors determining reactivity and selectivity in the rearrangements of vinylcyclopropanes.

A new method for carrying out these calculations needs to be found first. As mentioned in Chapter 2, the method used during our previous work was not suitable to describe our system. After finding a level of theory consistent with our experimental data, it will be used to further investigate the mechanism of the vinylcyclopropane rearrangement by answering new questions. We will investigate the addition of $TiCl_4$ on the vinylcyclopropane by studying the complexation reaction and the non-catalysed rearrangement of **179** to **181**. The mechanisms explaining the formation of other products than cyclopentene and skipped diene will be investigated. The selectivity for the migration of the phenyl over the one of the hydrogen on the same carbon will also be explored to understand why it was never observed. After the formation of the isomer skipped diene, the mechanism of obtaining an isomer of the cyclopentene will be studied as well.

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The effect of the substituents (R^1 and R^3) on the system will also be studied by DFT to help us understanding the observations made during the exploration of the scope of the rearrangement.

4.3.1. Method

In the computational part of this thesis, the ethyl esters used experimentally have been replaced with methyl esters to make the calculations faster. Figure 4.3 shows an example of the nomenclature used in this part of the work. The structures which have been optimised by the means of computational methods retain the name they were given during the experimental part with the addition of **-co** in the name. For the structures complexed by $TiCl_4$ **-TiCl₄** is added to the name of the structure.

181aa-co   **181aa-co-TiCl₄**
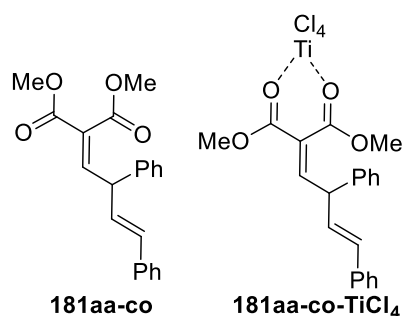
Figure 4.3: Computed molecules **181aa-co** and **181aa-co-TiCl₄**

During our Master's thesis the calculations were carried out at the B3LYP-D3/6-311+G**(CH_2Cl_2)//B3LYP-D3/6-31+G*(CH_2Cl_2) theory level with an implicit description of the solvent (CH_2Cl_2). However, as mentioned in the preliminary work of our lab (see Chapter 2), the free energy barriers predicted for the formation of **181aa-co-TiCl₄** and **180aa-co-*cis*-TiCl₄** were not consistent with our experimental observations. Thus, we performed benchmark calculations to find a more suitable method (see 10.2. for details) and the obtained results led us to choose the following method: M06-2X/6-311+G**(CH_2Cl_2)//M06-2X/6-31+G*(CH_2Cl_2).

4.3.2. Mechanism of the rearrangement of **179aa**

4.3.2.1. Reoptimised system

All the structures involved in the formation of the skipped diene **181aa** and cyclopentenes (**180aa-*cis*** and **180aa-*trans***) were reoptimised and the energy was recalculated using our new method. Corresponding data are shown in Scheme 4.17. Full details of computational methods are described in section 10.1.
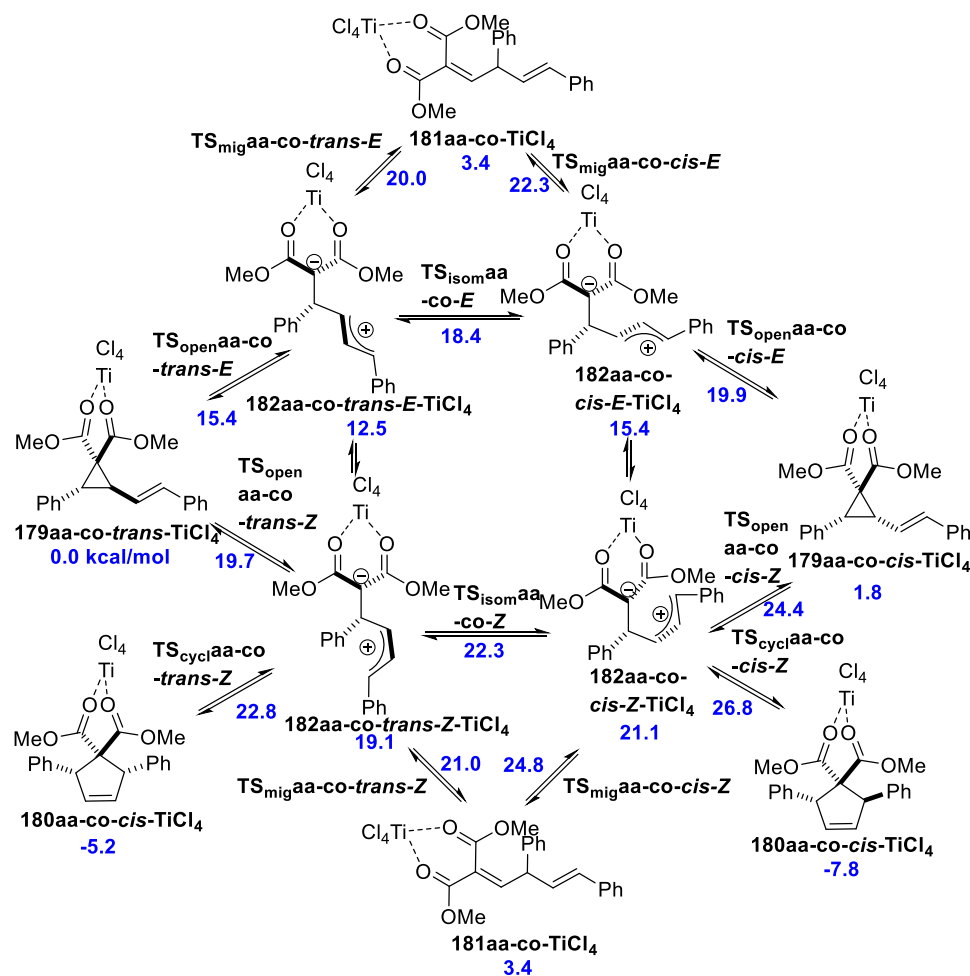
Scheme 4.17: Reoptimised system at the M06-2X/6-311+G**(CH$_2$Cl$_2$)//M06-2X/6-31+G*(CH$_2$Cl$_2$) (free energy in kcal/mol relative to **179aa-co-*trans*-TiCl$_4$**)

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The model predicts that the lower barrier corresponds to the *cis-trans* isomerisation barrier, via **TS$_{isom}$aa-co-*E***, which correlates with the experimental data. Indeed, the *cis-trans* isomerisation of the VCP has been shown to happen before any rearrangement reactions. This isomerisation leads to **179aa-co-*trans*-TiCl$_4$** since its higher thermodynamic stability over **179aa-co-*cis*-TiCl$_4$** (4.1 kcal/mol in favour of the *trans* isomer).

This new model predicts that the migration reaction, via **TS$_{mig}$aa-co-*trans*-E** and **TS$_{mig}$aa-co-*trans*-Z**, is faster than the cyclisation reaction leading to **180aa-co-*cis*-TiCl$_4$**. The computed free energy difference of the migration and cyclisation transition states is greater than 2.5 kcal/mol, predicting a kinetic selectivity higher than 99/1 at room temperature. This is in good agreement with our experimental data showing that **181aa-co-TiCl$_4$** is the kinetic product of our system. However, this model seems to slightly overestimate the free energy of the skipped diene **181aa-co-TiCl$_4$**.

The use of this level of theory did not alter the conclusions on the stereospecificty that were drawn with the previous model.[81] The analysis for this parameter involves **TS$_{mig}$aa-co-*trans*-E** and **TS$_{mig}$aa-co-*cis*-E**, the difference of relative free energy of the two transition states leading to two different enantiomers of **181aa-co-TiCl$_4$** (Scheme 4.18). Again, our results predict the selective formation of the skipped diene via **TS$_{mig}$aa-co-*trans*-E**. This is illustrated with a *trans* vinylcylopropane of fixed stereochemistry.
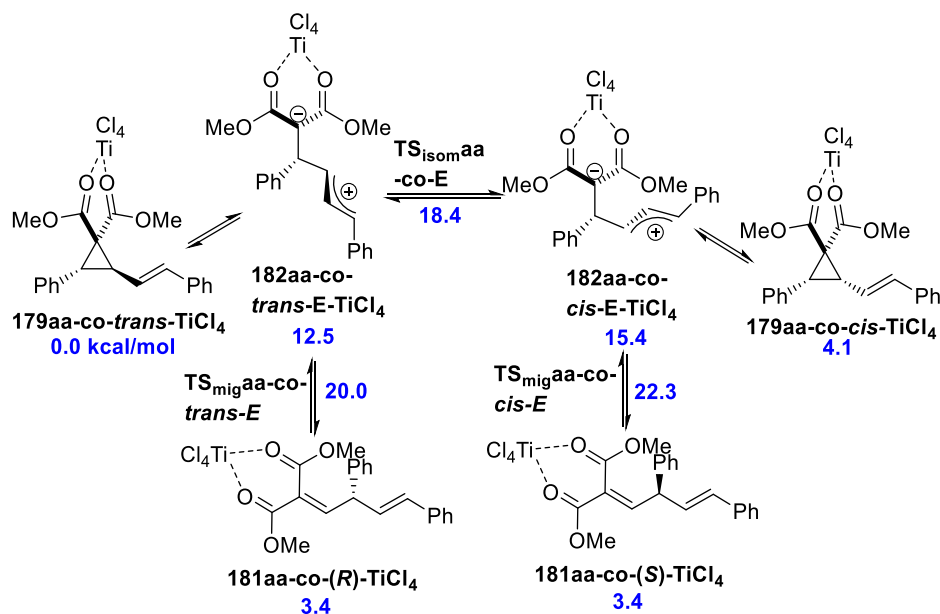
Scheme 4.18: Study of the stereospecificity of VCPs of fixed stereochemistry (free energy in kcal/mol relative to **179aa-co-trans-TiCl₄**)

During his research focussing on the formation of cyclopentenes, Dr. Maximilien Richald obtained the cyclopentene **180aa** with a d.r. *cis/trans* of 100/0. Our computational results are in good agreement with these experimental data as they predict a kinetic selectivity in favour of the *cis* isomer (**TS_cyclaa-co-trans-Z-TiCl₄** lies 4.0 kcal/mol lower than **TS_cyclaa-co-cis-Z-TiCl₄**; see Scheme 5.17). The increase in steric hindrance in both the zwitterion **182aa-co-cis-Z-TiCl₄** and the transition state **TS_cyclaa-co-cis-Z-TiCl₄** explains why the global cyclisation barrier to **180aa-co-trans-TiCl₄** is greater than the one involved in the formation of **180aa-co-cis-TiCl₄**. The formation of the *cis* cyclopentene is not reversible and **180aa-trans** is never observed despite being a more stable rearrangement product.

4.3.2.2. Role of the TiCl₄

It has been experimentally observed that a Lewis acid is mandatory to trigger either the rearrangement of the vinylcyclopropanes or the *cis-trans* isomerisation. VCPs are stable

when they are in solution in dichloromethane. We thus decided to study the non-catalysed pathways leading to the formation of **180aa-co-*cis*** and **181aa-co** for the non-complexed VCP **179aa-*trans***.

In good agreement with our experimental observations, our calculations indicate that the non-catalysed processes involve free energy barriers too high to allow any conversion at room temperature (41.4 and 39.8 kcal/mol for the migration and the cyclisation, respectively; Scheme 4.19). We also found that the most stable form of the VCP-TiCl$_4$ complex involves the complexation of the two ester groups by one TiCl$_4$, with a free energy of complexation of 17.5 kcal/mol. However, the stabilisation of the zwitterionic intermediates and transition states by complexation is even higher, thus decreasing the free energy barrier towards migration and cyclisation; the overall free energy barrier towards TiCl$_4$-catalysed migration and cyclisation being 20.0 and 22.8 kcal/mol, respectively.
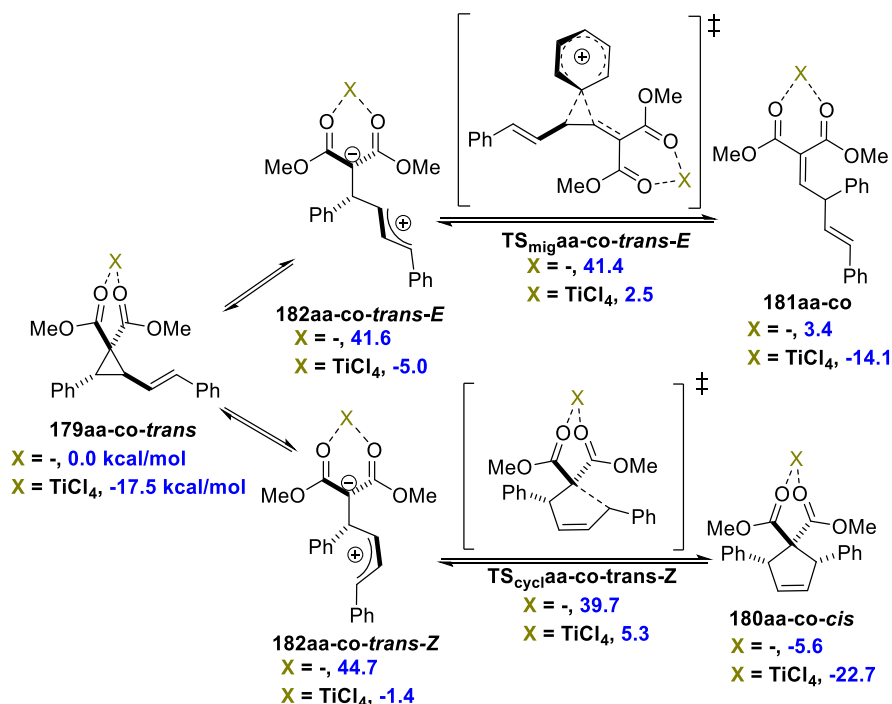
Scheme 4.19: Catalysed and non-catalysed rearrangement of the VCP **179aa-co *trans*** (free energy in kcal/mol relative to **179aa-co-*trans***)

4.3.2.3. Mechanism involving the ring-opening on the phenyl side of 179aa

The mechanism involved in the formation of the skipped diene **181aa** was investigated by a deuteriation experiment by Dr. Maximilien Richald (see Chapter 2). The result showed a selectivity for the path involving the opening on the vinyl side and the migration of the phenyl group. Our computational results are in good agreement with this observation (Scheme 4.20). Indeed, they show that neither the formation of the skipped diene (via **TS$_{migStyryl}$aa-co-*trans***) nor the *cis-trans* isomerisation (via **TS$_{isomPh}$aa-co**) are predicted to be competitive in the case of the ring-opening on the vinyl side (**TS$_{mig}$aa-co-*trans*-*E***: 20.0 kcal/mol ; **TS$_{isom}$aa-co-*E***: 18.4 kcal/mol). This can be explained by the lower stabilisation of the positive charge created by the heterolytic cleavage of the C-C bond of the VCP by the phenyl group, as compared to the styryl substituent.
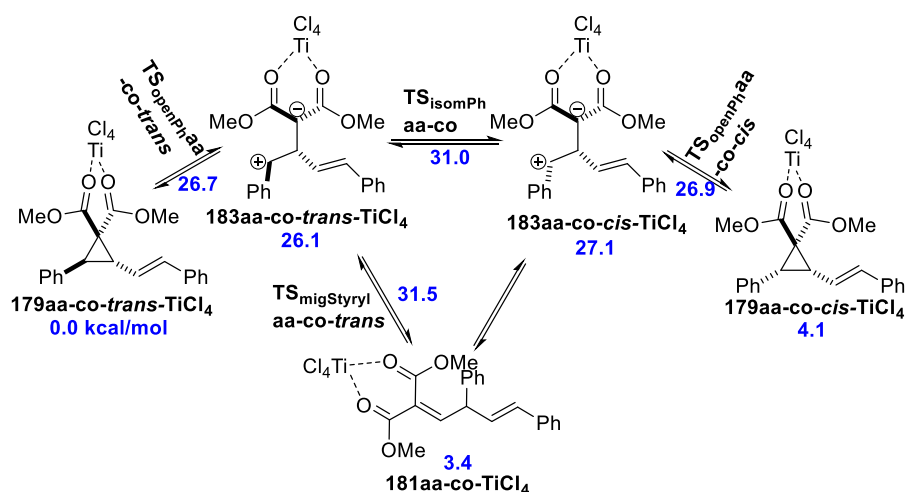
Scheme 4.20: Mechanism of rearrangement and *cis-trans* isomerisation occurring via the ring-opening on the phenyl side of the VCP (free energy in kcal/mol relative to **179aa-co-*trans*-TiCl$_4$**)

5.3.2.4. Formation of new rearrangement products

After the change of level of theory and the updating of the computational methods, we decided to investigate the formation of the other potential products of rearrangements of the vinylcyclopropane **179aa**.

4.3.2.4.1. Formation of the regioisomer of the skipped diene

The first product we considered is the regioisomer skipped diene **204aa**, issued from the migration of a hydrogen atom. This latter was never observed during the rearrangement of **179aa** (Figure 5.4) but their analogues were observed in the case of poor migrating groups such as Me, *i*-Pr, *i*-Bu and as a minor product alongside the diene **181** coming from the migration of *p*-CO$_2$MeC$_6$H$_4$. The goal of this part is to gain a better understanding of the experimentally observed selectivity towards the migration of the phenyl group, over the hydrogen atom.

EtO$_2$C   CO$_2$Et

Ph

H

Ph
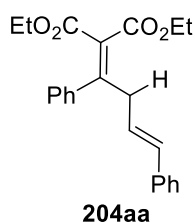
204aa

Figure 4.4: Regioisomer skipped diene **204aa**

We thus studied the competition between the migration of these substituents during our mechanistic studies. The relative migratory aptitude of these two groups is determined by conformational and electronic factors. Indeed, in order for the substituent to be involved in a 1,2-migration reaction, it has to be properly positioned in relation to the orbital of the allylic cation moiety. Our calculations show that the most stable conformer of **182aa-co-*trans-E*-TiCl$_4$** is the one presenting the hydrogen atom in the optimal position for the migration; the one presenting the phenyl group in that position being 3.6 kcal/mol higher in energy (Scheme 4.21). The conformational factors are thus in favour of the migration of the hydrogen atom.

The free energy difference between the transition states and the conformers with the substituent properly positioned (**182aa-co-*trans-E'*-TiCl$_4$** for the Ph group and **182aa-co-*trans-E*-TiCl$_4$** for the H) enables estimating the electronic contribution to the migration barrier. Our results predict that the intrinsic migration aptitude of the

phenyl group (3.9 kcal/mol) is better than the one of a hydrogen (13.4 kcal/mol). This is thus the determinant factor for explaining the experimentally observed selectivity for migration of the phenyl group; the conformational factors not being sufficient to compensate the difference in intrinsic migratory aptitudes. The selectivity has to be of kinetic origin, since the diene coming from the migration of a hydrogen group (**204aa-co-TiCl₄**) is predicted to be more stable than **181aa-co-TiCl₄**.
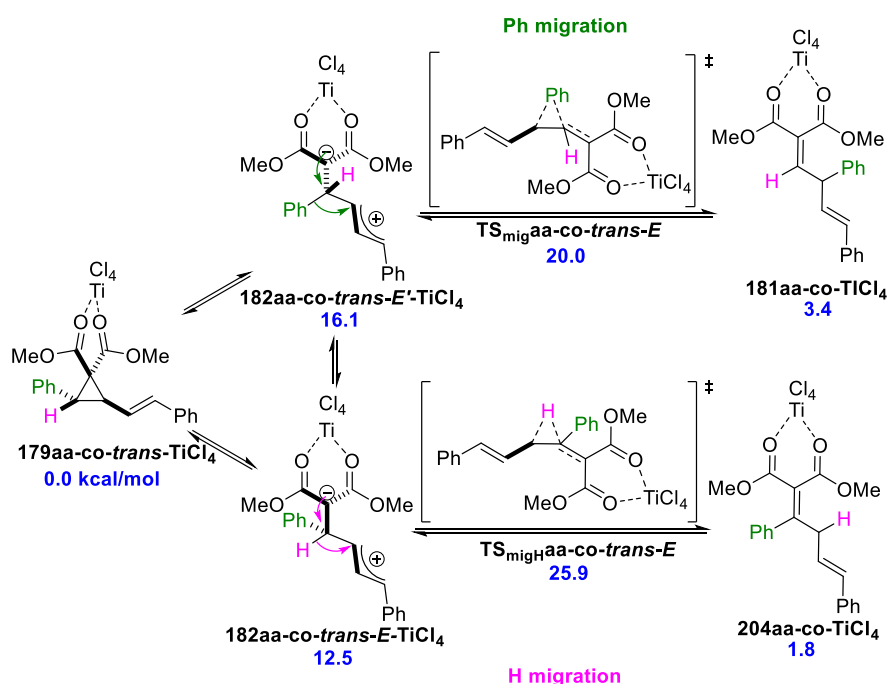
Scheme 4.21: Competition between the migration of Ph and H (free energy in kcal/mol relative to **179aa-co-*trans*-TiCl₄**)

4.3.2.4.2. Formation of a cyclopentene isomer

During his PhD work, Dr. Maximilien Richald systematically observed, alongside the formation of the *cis*-cyclopentene **180aa**, the formation of a regioisomer of this latter (**206aa**, Figure 4.5).[80]
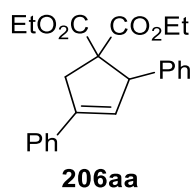
206aa

Figure 4.5: Regioisomer cyclopentene **206aa**

The suggested mechanism explaining the formation of **206aa**
was computationally studied (Scheme 5.22). The first step is the
formation of the skipped diene **181aa**, which was previously discussed
and hence omitted in Scheme 5.22 to ensure better clarity.
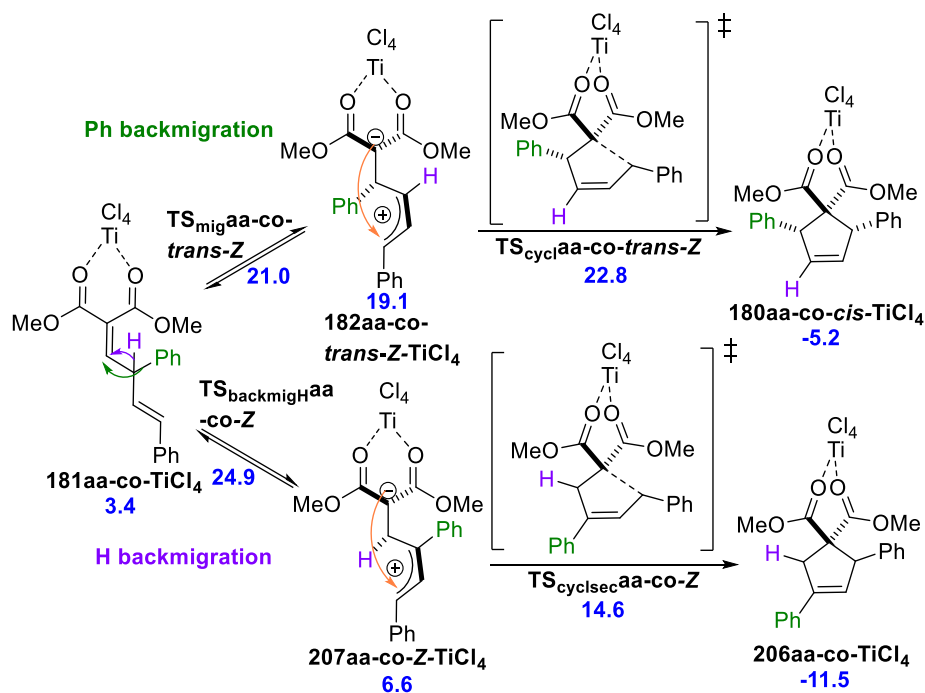
Scheme 4.22: Study of the postulated mechanism for the formation
of **206aa-TiCl₄** (free energy in kcal/mol relative to **179aa-co-trans-
TiCl₄** which is omitted for better clarity)

The formation of the skipped diene has been experimentally
observed to be reversible. Indeed, our calculations show that the TiCl₄
complexed 1,4-diene can undergo migration of the phenyl group to
give back **182aa-co-trans-Z-TiCl₄** (see green arrows). This zwitterionic

intermediate can then cyclise via **TS$_{cycl}$aa-co-*trans-Z*** to form the cyclopentene **180aa-co-*cis*-TiCl$_4$**. However, the hydrogen on the same carbon as the green Ph group can also migrate on the same position, even if the free energy barrier is slightly higher. The so-obtained zwitterionic intermediate **207aa-co-*Z*-TiCl$_4$** can then cyclise via **TS$_{cyclsec}$aa-co-*Z*** to form **206aa-co-TiCl$_4$**. The predicted global free energy barriers for these two competitive processes are 22.8 kcal/mol and 24.9 kcal/mol, for the formation of **180aa-co-*cis*-TiCl$_4$** and **206aa-co-TiCl$_4$** respectively. Interestingly, the highest transition state in the two paths does not correspond to the same step of the process. The cyclisation transition state **TS$_{cycl}$-co-*trans-Z*** is the highest point in the path leading to the formation of **180aa-co-*cis*-TiCl$_4$** while that is **TS$_{backmigH}$aa-co-*Z*** in the path leading to the formation of the isomer cyclopentene **206aa-co-TiCl$_4$**. Experiment suggests that none of these cyclopentene formations are reversible, as the ratio of the two products does not change over time.

4.3.3. Substituent effects

It was experimentally observed that the nature of the substituents has an impact on the outcome of the rearrangement reactions. In some cases, the desired skipped diene could not be observed and another isomer of the skipped diene with 2 hydrogen atoms on the central carbon is formed. The competitive cyclisation reaction can also be impacted by the substituents. Accordingly, we have studied the influence of the nature of the migrating group (R^1) and of the vinyl substitution (R^3) on the different rearrangements and their relative rates.

4.3.3.1. Effect of R^1

The influence of the nature of the R^1 group on both the migration and cyclisation reactions was investigated.

4.3.3.1.1. Skipped diene formation

The first point of interest of this study was the influence of the migrating group on the ring-opening and migration reactions (Table 4.9).

Table 4.9: Influence of R^1 on the migration reaction (free energy in kcal/mol relative to the corresponding VCP **179-co-*trans*-TiCl₄**)
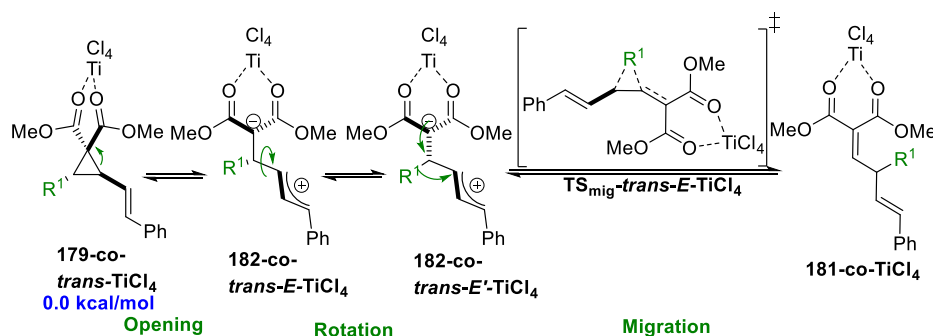
Entry	R^1	182-co-*trans-E*-TiCl₄	182-co-*trans-E'*-TiCl₄	TS$_{mig}$-co-*trans-E*	ΔG_{rot}[a]	$\Delta G^{\ddagger}_{mig}$[b]
1	p-MeOC₆H₄	9.3	13.4	12.7	4.1	-0.7
2	Styryl	12.9	13.5	15.9	0.6	2.4
3	p-MeC₆H₄	12.5	13.9	16.4	1.4	2.5
4	Ph	12.5	16.1	19.9	3.6	3.8
5	p-ClC₆H₄	10.9	15.0	20.4	4.1	5.4
6	Cyclopropyl	9.8	12.9	21.2	3.1	8.3
7	t-Bu	8.9	12.0	23.3	3.1	11.3
8	p-CO₂MeC₆H₄	12.4	16.7	23.4	4.3	6.7
9	H	8.4	8.6	24.6	0.2	16.0
10	Me	9.3	12.4	25.3	3.1	12.9

[a] ΔG_{rot} corresponds to the free energy difference between **182-co-*trans-E'*-TiCl₄** and **182-co-*trans-E*-TiCl₄**, the conformational contribution to the global free energy for the migration. [b] $\Delta G^{\ddagger}_{mig}$ corresponds to the free energy difference between **TS$_{mig}$-co-*trans-E*** and **182-co-*trans-E'*-TiCl₄** and represents the contribution of the intrinsic migration ability of the substituent to the global migration barrier.

The migration order based on the global migration barrier (given in Table 5.9 by the **TS$_{mig}$-co-*trans-E*** column giving the relative free energy of the transition state relative to the *trans* VCP) is the following:

p-MeOC₆H₄ > Styryl > p-MeC₆H₄ > Ph > p-ClC₆H₄ > Cyclopropyl > t-Bu > p-CO₂MeC₆H₄ > H > Me
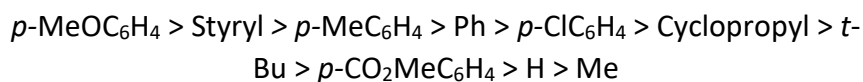
These results are consistent with our experimental observations.

In order to understand the factors responsible for this order of migration, the migration reaction has been split into three steps. The first one is the heterolytic cleavage of **179-co-*trans*-TiCl₄** resulting in the formation of **182-co-*trans*-E-TiCl₄**. A rotation is then necessary to bring the migrating group (R^1) perpendicular to the allylic cation moiety (**182-co-*trans*-E'-TiCl₄**), the free energy required for this rotation is given by ΔG_{rot} in Table 5.9. The migration of R^1 (see green arrows) then leads to the formation of **181-co-TiCl₄**. The **ΔG‡mig** column of the table represents the intrinsic migration ability of the given substituent and is calculated by subtracting the free energy of the zwitterion **182-co-*trans*-E'-TiCl₄** from the free energy of the transition state **TSmig-*trans*-E-TiCl₄**. The energy difference between **TSmig-*trans*-E-TiCl₄** and **179-co-*trans*-TiCl₄** is the global migration barrier taking every contributions into account.

Our computational results predict that the ring-opening reaction is not greatly impacted by the presence of a group in the *para* position of the R^1 aryl group, except for R^1 = p-MeOC₆H₄. Zwitterions intermediates **182-co-*trans*-E-TiCl₄** are also more stable when R^1 = H, t-Bu, Me. This is due to steric effects.

The nature of R^1 has also a low influence on the conformational equilibrium. Indeed, the energy difference between **182-co-*trans*-E'-TiCl₄** and **182-co-*trans*-E-TiCl₄** is in the same range for all the investigated aryl and alkyl groups (except for entries 2, 3 and 9).

In terms of intrinsic migratory aptitude of the studied substituents the computed order is

p-MeOC₆H₄ > Styryl > p-MeC₆H₄ > Ph > p-ClC₆H₄ > p-CO₂MeC₆H₄ > Cyclopropyl > t-Bu > Me > H
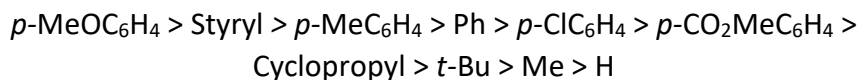
The similitude of this order with the one above suggests that the intrinsic migratory aptitude is the main factor influencing the relative global migration free energy barrier. This is however not the only one.

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Indeed, the increase in stability of the zwitterion intermediates **182-co-*trans-E*-TiCl₄** in the case of alkyl groups explains the position of the p-$CO_2MeC_6H_4$ group on the global migration barrier scale when it is predicted to have a better migratory aptitude than the cyclopropyl and *tert*-butyl groups.

The intrinsic migratory aptitude order determined by our model predicts that the H is the poorer migrating group among those investigated. However, it was not predicted to be the last on the global migration free energy barrier order. The zwitterion when R^1 = H is indeed slightly more stable than with R^1 = Me (H: 8.4 kcal/mol, Me: 9.3 kcal/mol) and the rotation necessary to align R^1 with the p orbital of the allylic cation moiety requires more energy for the methyl group (3.1 kcal/mol) than for the hydrogen (0.2 kcal/mol). These two effects lower the global migration barrier for the hydrogen despite the prediction that it is intrinsically the worst migrating group.

During our experimental research, the alkyl migrating groups were investigated. The cyclopropyl and t-Bu were compatible with the obtaining of skipped **181,** whereas the Me, i-Bu and i-Pr groups were not. The migration of these groups was explored further to improve our understanding of the rearrangement of vinylcyclopropanes bearing these substituents.

We hypothesised that the diene **181ea** could be formed via a mechanism involving the formation of a non-classical carbocation (**183ea-*trans-E*-TiCl₄**, Scheme 4.23) (see 4.2.2.1.). This hypothesis was explored during our DFT studies.
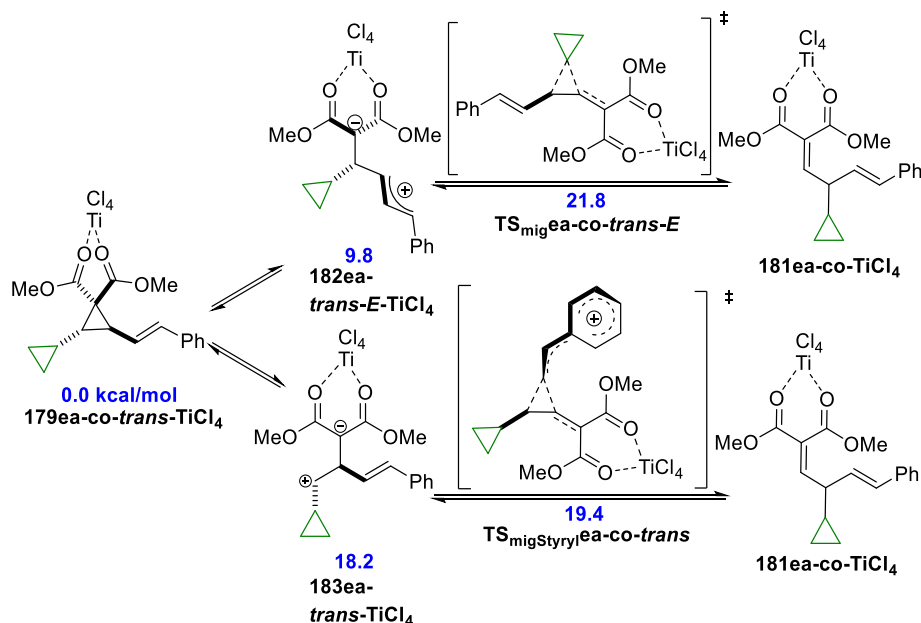
Scheme 4.23: Study of the operating mechanism for the formation of **181ea-co-TiCl₄** (free energy in kcal/mol relative to the corresponding VCP **179ea-co-trans-TiCl₄**)

Our model backs this hypothesis and predicts that the formation of **181ea** occurs exclusively via the transition state **TS_migStyryl ea-co-trans**. Despite the better stabilisation of the positive charge by the styryl group as compared to the cyclopropyl substituent, the pathway involving the non-classical carbocation is preferred. Indeed, the better intrinsic migratory aptitude of the styryl group over the cyclopropyl more than compensates the difference in carbocation stabilisation.

During our experimental investigations, a regioisomer of the expected skipped diene **181** was sometimes formed (see **204** in Table 4.6). This behaviour was observed for R^1 = Me, *i*-Bu, *i*-Pr but not for the *t*-Bu group which selectively led to **181**. We thus decided to study the competition between the migration of alkyl groups and the H for the Me and *t*-Bu substituents (Scheme 4.24). The first step of both competitive migration reactions is the heterolytic ring-opening of **179-co-trans-TiCl₄** leading to zwitterions **182-co-trans-E'-TiCl₄** and **182-co-**

***trans*-*E*-TiCl₄**. The most stable conformer of the intermediate is **182-co-*trans*-*E*-TiCl₄** with the H in the proper position for its migration. A rotation equilibrium exists between the most stable zwitterion and **182-co-*trans*-*E'*-TiCl₄**, the zwitterion with the R^1 group positioned for its migration.
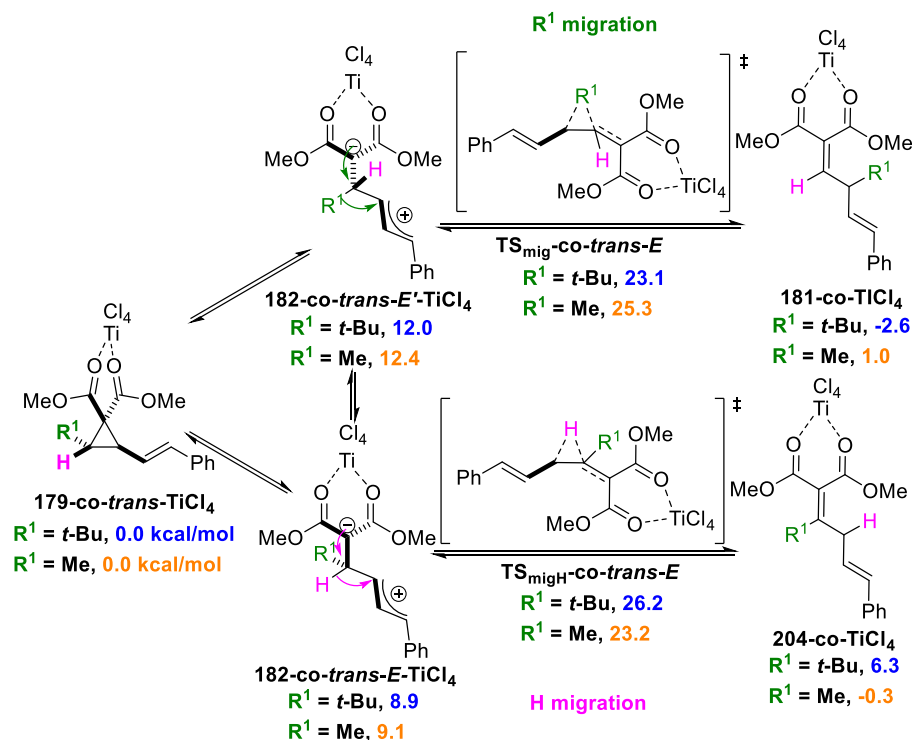
Scheme 4.24: Competition between the migration of R^1 = *t*-Bu or Me and H (free energy in kcal/mol relative to the corresponding VCP **179-co-*trans*-TiCl₄**)

The obtained results are in agreement with our experimental observations. Indeed, the formation of **181** is predicted to be favoured over **204** for R^1 = *t*-Bu whereas the migration of the H leading to **204** is faster when R^1 = Me.

Our calculations indicate that the preferential migration of the *t*-Bu group can be explained by its better intrinsic migratory aptitude, as compared to H, which surpasses conformational factors favouring the conformer presenting the H aligned for the 1,2-migration reaction

(**182-co-*trans-E*-TiCl₄**). The regioisomer **204** is also predicted to be less stable than **181** when R^1 = *t*-Bu. This can be explained by the fact that the bulky *t*-Bu group is close to the ester groups in this structure inducing a destabilisation by steric hindrance.

The situation is different for the methyl group (values presented in orange). **182-co-*trans-E*** is also the more stable zwitterion intermediate and the methyl is also predicted to be a better migrating group than H. However, in this case, the difference in intrinsic migratory aptitude (1.2 kcal/mol) is not sufficient to compensate the difference in relative free energy of the two conformers of the zwitterion (3.3 kcal/mol) resulting in a selectivity for the migration of H, the group with the worst migrating aptitude in our rearrangement (*vide supra*).

4.3.3.1.2. Cyclisation reaction

The nature of the R^1 group was found to have a significant influence on the skipped diene/cyclopentene selectivity. The impact of the group on the competitive cyclisation reaction was thus also studied by DFT methods (Table 4.10).

Table 4.10: Influence of R^1 on the cyclisation reaction (free energy in kcal/mol relative to the corresponding VCP **179-co-*trans*-TiCl₄**)
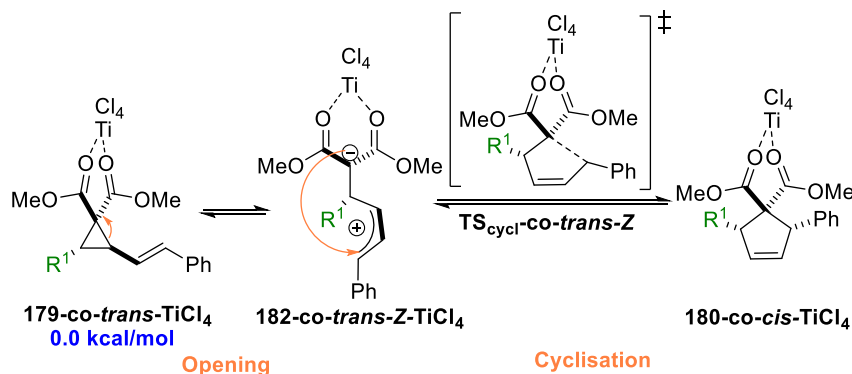
Entry	R^1	**182-co-*trans*-Z-TiCl₄**	**TS$_{cycl}$-co-*trans*-Z**	$\Delta G^{\ddagger}_{cycl}{}^a$
1	Ph	19.1	22.9	3.8
2	*p*-CO₂MeC₆H₄	19.4	22.5	3.1
3	H	14.9	19.3	4.4
4	*t*-Bu	12.7	18.4	5.7

ᵃ Calculated as the free energy difference between **TS$_{cycl}$-co-*trans*-Z** and **182-co-*trans*-Z-TiCl₄** to estimate the contribution of the cyclisation step to the global barrier**.**

Entry 2 shows that adding a group in the *para* position of the aryl has no impact on the heterolytic cleavage (**182-co-*trans*-Z-TiCl₄**) and the subsequent cyclisation reaction (**TS$_{cycl}$-co-*trans*-Z**). As previously discussed in section 4.3.3.1.1., the zwitterionic intermediate is more stable when R^1 is an alkyl or a H. This results in a lowering of the global cyclisation barrier **TS$_{cycl}$-co-*trans*-Z** (entries 3 and 4).

4.3.3.1.3. Migration of R^1 vs cyclisation

After investigating the influence of the R^1 group on the migration and the cyclisation reactions, we decided to combine these data and study the competition between these two reactions for a select number of R^1 groups.

During our experimental research, we observed that VCPs bearing some R^1 groups (R^1 = H, *i*-Bu, *i*-Pr, *t*-Bu, *p*-CO₂MeC₆H₄) led to

the fast formation of the cyclopentene **180** (see 4.2.2.). The formation of **180** was found not to be reversible and thus the end point of the rearrangement.

The influence of these groups on the competition between the migration and the cyclisation reactions was thus investigated (Table 5.11).

Table 4.11: Influence of R^1 on the competition between the migration and cyclisation reactions (free energy in kcal/mol relative to the corresponding VCP **179-co-*trans*-TiCl₄**)
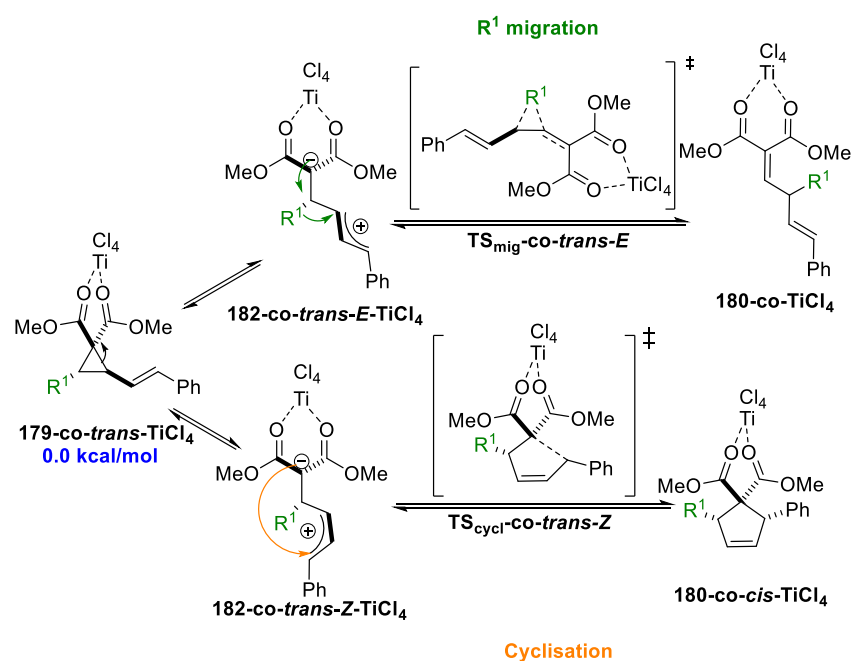
| Entry | R^1 | **R¹ migration** | | | **Cyclisation** | | |
		182-co-*trans*-E-TiCl₄	TS$_{mig}$-co-*trans*-E	181-co-TiCl₄	182-co-*trans*-Z-TiCl₄	TS$_{cycl}$-co-*trans*-Z	180-co-*cis*-TiCl₄
1	Ph	12.5	20.0	3.4	19.1	22.9	-5.2
2	p-CO₂MeC₆H₄	12.4	23.4	3.6	19.4	22.5	-6.1
3	H	8.4	24.6	2.1	14.9	19.3	-9.5
4	t-Bu	8.9	23.1	-2.6	12.7	18.4	-3.9

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Entry 2 shows that the substitution of the aryl by a *p*-CO$_2$Me group has no significant impact on the global free energy barrier to cyclisation or on the relative stability of the two products. On the contrary, it has a significant impact on the migration reaction due to the decrease of intrinsic migration ability provoked by the electron-withdrawing group (see 4.3.3.1.1.). Accordingly, the migration becomes slower than the cyclisation reaction. This explains why experimentally the skipped diene is not observed with this substituent.

The poor migration ability of the H is also responsible for an increase of the global migration barrier for this substituent. The cyclisation barrier is significantly decreased when R^1 = H as compared to Ph. The combination of these two effects lead to the observed selectivity for the formation of the cyclopentene which is still predicted to be significantly more stable than the diene with less bulky group (H) as compared to aryls (entries 1 and 2)

The rearrangement of the vinylcyclopropane bearing a *tert*-butyl group as R^1 group is interesting. Our model indeed predicts that the global cyclisation barrier is lower in energy (18.4 kcal/mol) as compared to the competitive migration barrier (23.1 kcal/mol). This is consistent with the experimental data, as the cyclopentene is the first product to be formed. Even though our model predicts that the cyclopentene is more stable than the skipped diene, the model seems to overestimate the free energy of the 1,4-diene, **181** (see 4.3.2.). Comparing entries 1 and 4, one can see that the skipped diene is 6.0 kcal/mol more stable (relative to the vinylcyclopropane) when R^1 = *t*-Bu as compared to the phenyl group. Which could be explained by the decrease of the steric clash between the alkyl group and the esters when the VCP is transformed into the skipped diene. The steric hindrance of the *tert*-butyl group can also explain the fact that the cyclopentene is predicted to be 1.3 kcal/mol less stable with this R^1 group (entry 4) as compared to the phenyl group (entry 1). The skipped diene is, in this case, the thermodynamic product of the system.

4.3.3.2. Effect of R^3

Our experimental investigations showed that the substitution of the vinyl side of the VCPs has also an impact on outcome of the rearrangement. The influence of the nature of the R^3 group on the rate of formation of the cyclopentene was studied and compared to the migration reaction.

4.3.3.2.1. Cyclisation reaction

The substitution of the vinyl side of the vinylcyclopropanes has been shown to have an impact on the cyclisation reaction (see 4.2.1.). Accordingly, we investigated computationally the influence of the nature of the R^3 group on the cyclisation reaction (Table 5.12).

Table 4.12: Influence of R^3 on the cyclisation reaction (free energy in kcal/mol relative to the corresponding VCP **179-co-*trans*-TiCl₄**)

Entry	R^1	182-co-*trans*-Z-TiCl₄	TS$_{cycl}$-co-*trans*-Z	ΔG$^{\ddagger}_{cycl}$ [a]
1	Ph	19.1	22.9	3.8
2	p-MeOC₆H₄	16.4	19.6	3.2
3	p-CO₂MeC₆H₄	22.2	24.2	2.0
4	i-Pr	21.6	30.2	8.6
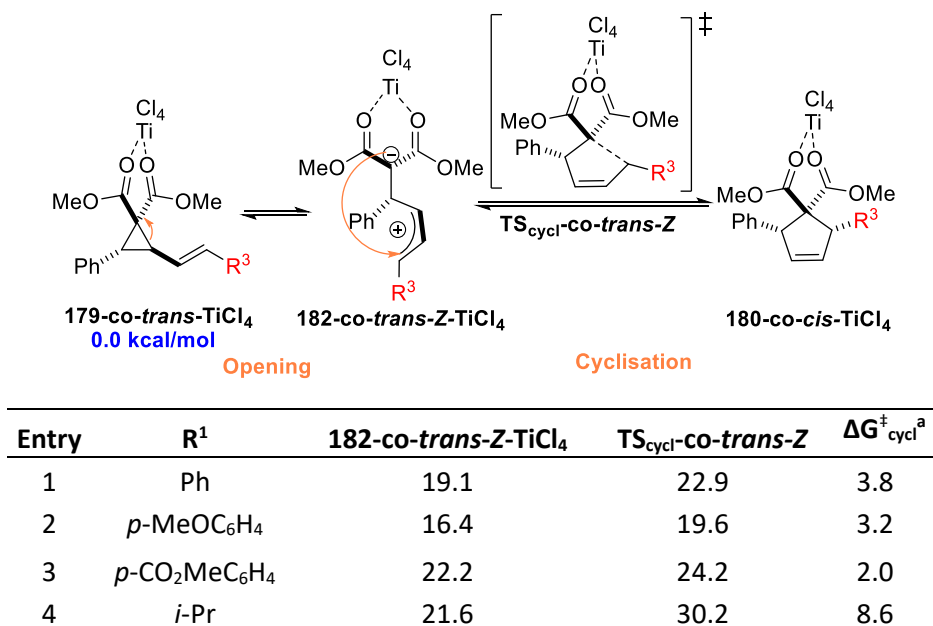
[a] Calculated as the free energy difference between **TS$_{cycl}$-co-*trans*-Z** and **182-co-*trans*-Z-TiCl₄** to estimate the contribution of the cyclisation step to the global barrier.

Our results showed that the reactivity order based on the global free energy to cyclisation is as follows:

p-MeOC₆H₄ > Ph > p-CO₂MeC₆H₄ >> i-Pr
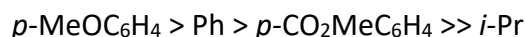
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The cyclisation reaction can be decomposed in two steps, the ring-opening of the vinylcyclopropane and the cyclisation step. Our calculations indicate that the increased reactivity with substitution of the styryl moiety by electron-donor groups is mainly due to the stabilisation of the zwitterionic intermediate **182-co-*trans-Z*-TiCl$_4$**, the cyclisation step being poorly impacted by the substitution of the aryl group. Conversely, when electron-withdrawing groups destabilise the positive charged created by ring-opening, the overall reactivity is decreased. The isopropyl group is predicted to have a strong influence on the cyclisation component of the global barrier, which is consistent with our design of strategies for disfavouring the cyclisation (see 4.2.2.2.) and the experimentally observed fact that this strategy is more efficient for preventing the cyclisation than using VCPs with the R^3 = *p*-CO$_2$MeC$_6$H$_4$ group (see 4.2.2.3.2.)

4.3.2.2.2. Migration vs cyclisation

The experimental exploration of the influence of the R^3 group on the outcome of the rearrangement showed that R^3 = *p*-MeOC$_6$H$_4$, a strong electron-donor aryl, led to the fast formation of the cyclopentene.[81] On the other hand, R^3 = *p*-CO$_2$MeC$_6$H$_4$ and *i*-Pr groups allowed us to isolate the desired skipped dienes but the reaction was found not to be reversible and the cyclopentene was never observed (see 4.2.1.). To fully understand the effect of R^3 on the outcome of the rearrangement, we have studied its influence on the migration/cyclisation competition (Table 4.13).

Table 4.13: Influence of R^3 on the competition between the migration and cyclisation reactions (free energy in kcal/mol relative to the corresponding VCP **179-co-*trans*-TiCl₄**)
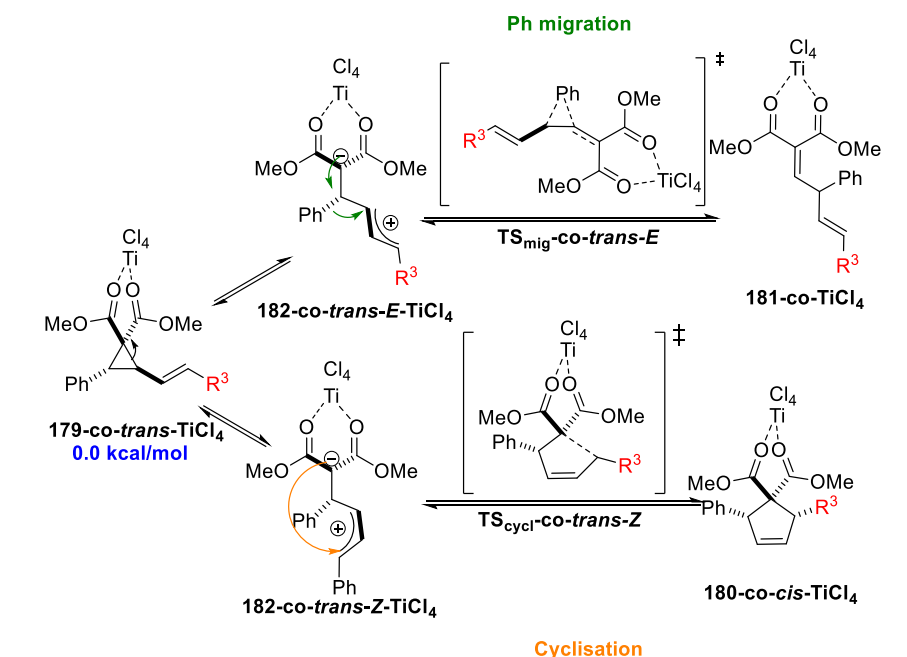
Entry	R^3	Ph migration			Cyclisation		
		182co-*trans*-E-TiCl₄	TS_mig-*co*-*trans*-E	181-co-TiCl₄	182-co-*trans*-Z-TiCl₄	TS_cycl-*co*-*trans*-Z	180-co-*cis*-TiCl₄
1	Ph	12.5	20.0	3.4	19.1	22.9	-5.2
2	*p*-MeOC₆H₄	9.6	19.8	3.0	16.4	19.6	-4.9
3	*p*-CO₂MeC₆H₄	17.6	20.9	4.7	22.2	24.2	-5.8
4	*i*-Pr	18.7	19.2	4.2	21.6	30.2	-5.9

The relative free energy of the zwitterion intermediate **182-co-*trans*-E-TiCl₄** depends on the stabilisation of the positive charge formed by the ring-opening of the cyclopropane moiety which is increased by the electron-donor character of R^3 (*p*-MeOC₆H₄ > Ph > *p*-CO₂MeC₆H₄ > *i*-Pr). On the contrary, the migration involves a lower barrier when R^3 is destabilising the positive charge in the zwitterion.

The two effects are thus compensating each other and it results that the global free energy barrier to migration (see column **TS$_{mig}$-*co-trans-E*-TiCl$_4$)** is not significantly impacted by the nature of the R^3 group.

The influence of the R^3 group on the cyclopentene/skipped diene selectivity has its roots in its impact on the kinetic of the cyclisation reaction (*vide supra*). When R^3 = *p*-MeOC$_6$H$_4$, the cyclisation becomes faster than the migration reaction and since it leads to the formation of a more stable product, the skipped diene is never observed.

Since the presence of *p*-CO$_2$MeC$_6$H$_4$ or *i*-Pr group on the double bond has no impact on the migration reaction and slows the cyclisation reaction down (*vide supra*), it results in the fast formation of the skipped diene, the less stable of the two possible products. In these cases, the migration reaction was found not to be reversible, as the cyclopentene has not been experimentally observed (see section 4.2.2).

4.3.2.2.3. Effect of the electron withdrawing groups

During our exploration of the scope (see 4.3.3.), we shed light on the impossibility of obtaining the skipped diene **181aa-CN**. The cyclopentene was the first product to be formed during the rearrangement of **179aa-CN**. Accordingly, the competition between the migration and cyclisation reactions was studied (Scheme 4.25).
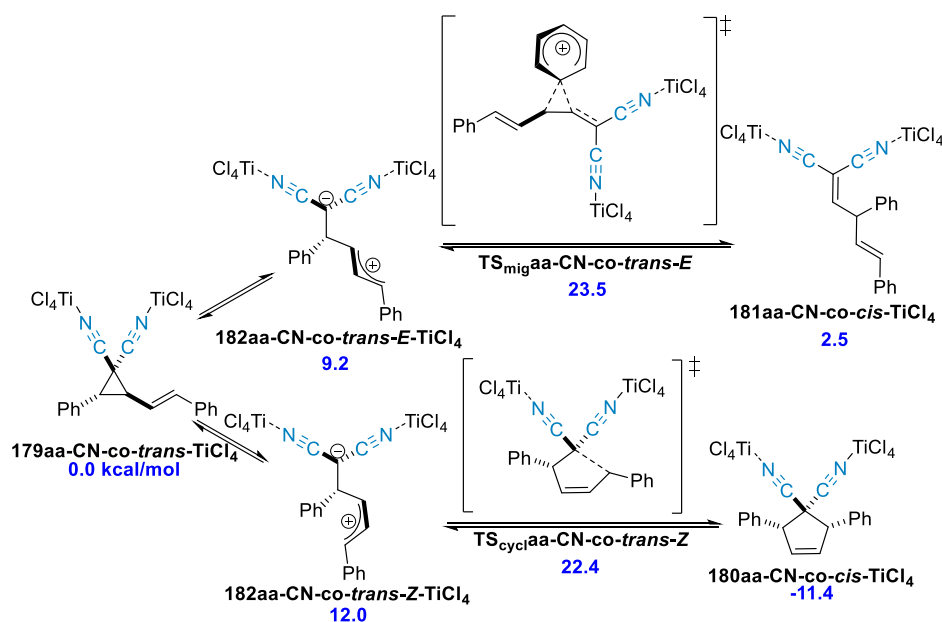
Scheme 4.25: Competition between the migration and cyclisation reactions with EWG = CN (free energy in kcal/mol relative to the corresponding VCP **179aa-CN-co-trans-TiCl₄**)

Our calculations indicate that migration involves a higher global free energy barrier in the case of cyano-activated cyclopropanes than with our reference model in which the electron withdrawing groups are esters (**TS_mig aa-CN-co-trans-E**: 23.5 kcal/mol; **TS_mig aa-co-trans-E**: 20.0 kcal/mol). This can probably be explained by the better stabilisation of the negative charge by the cyano groups in the zwitterion (**182aa-CN-co-trans-E-TiCl₄**: 9.2 kcal/mol; **182aa-co-trans-E-TiCl₄**: 12.5 kcal/mol). The increased stabilisation of the negative charge leads to a lower nucleophilicity of the latter which translates into an increase of the relative free energy of the transition state **TS_mig aa-CN-co-trans-E** for the 1,2-migration reaction.

On the contrary, the kinetic of the cyclisation reaction is not significantly influenced by the change of electron-withdrawing groups (**TS_cycl aa-CN-co-trans-Z-TiCl₄**: 22.4 kcal/mol; **TS_cycl aa-co-trans-Z-TiCl₄**: 22.8 kcal/mol). The zwitterionic intermediate **182aa-CN-co-trans-Z-TiCl₄** (12.5 kcal/mol) is predicted to be more stable than its

counterpart with the ester groups (**182aa-co-*trans*-Z-TiCl₄**, 16.1 kcal/mol). We formulate the hypothesis that the lower steric hindrance of the cyano groups as compared to the ester groups could compensate the increased cyclisation barrier due to the lower availability of the negative charge for the cyclisation reaction. This accounts for the fact that, in the case of the cyano-activated vinylcyclopropane **179aa-CN-TiCl₄**, the cyclopentene is not only the thermodynamic but also the kinetic product, in good agreement with our experimental observations (see section 4.2.3.).

4.3.2.3. Conclusions on the effects of the substituents

The computational part of this work enabled us to get a better understanding of the origin of the substituent effects that were observed during our experimental work. We started by investigating the impact of the nature of the migrating group, R^1 on the system (Scheme 4.26).
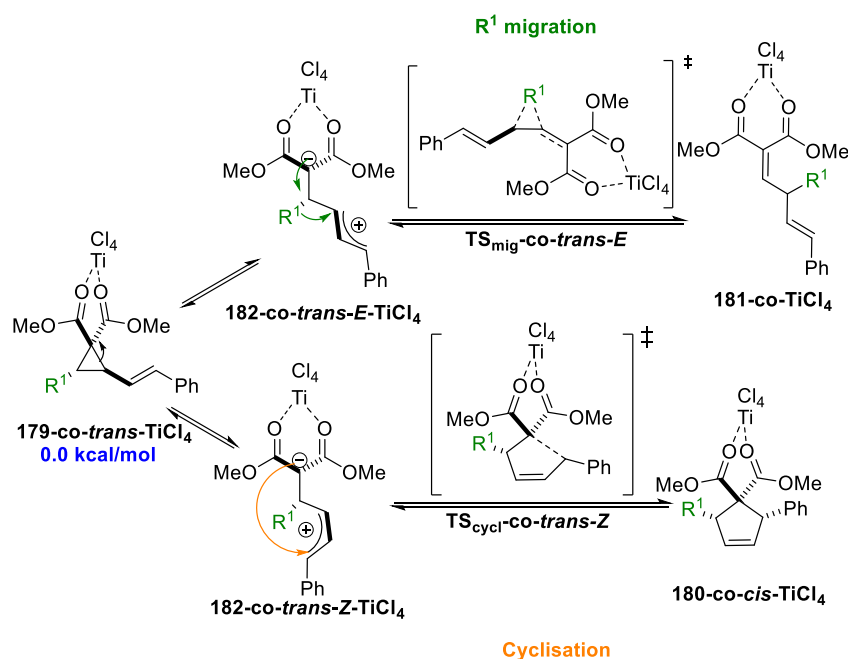
Scheme 4.26: Influence of R^1 on the competition between the migration and cyclisation reactions

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The computed global migration order is :

p-MeOC$_6$H$_4$ > Styryl > p-MeC$_6$H$_4$ > Ph > p-ClC$_6$H$_4$ > Cyclopropyl > t-Bu > p-CO$_2$MeC$_6$H$_4$ > H > Me
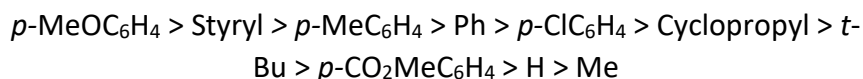
The intrinsic migration ability of the migrating group is found to be the primary factor explaining the reactivity order but the stability of the zwitterion intermediates also plays a role.

A decrease in the relative free energy of the intermediate **182-co-*trans-Z*-TiCl₄** leads to a decrease in the global barrier, as the cyclisation step in not significantly influenced by the nature of the R^1 group. This was observed for the alkyls groups and the H and combined with the poor migrating ability of these groups, explain the selectivity in favour of the formation of the cyclopentene.

The cyclisation reaction was predicted to be influenced by the nature of the R^3 group (Scheme 4.27).
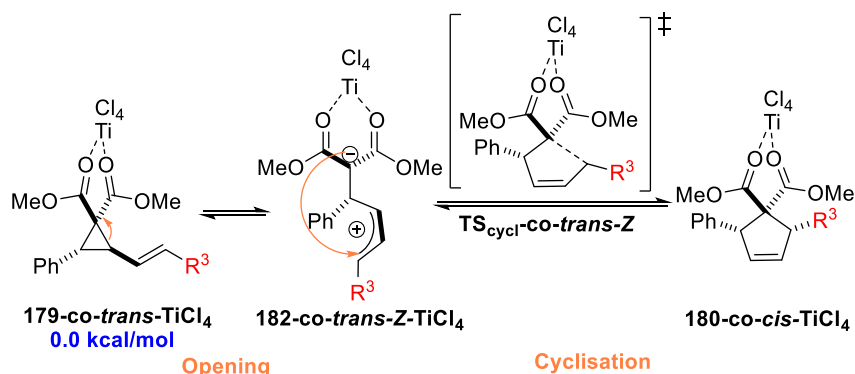
Scheme 4.27: Influence of R^3 on the cyclisation reaction

The latter has an impact on the stabilisation of the positive charge created by the heterolytic cleavage of the C-C bond of the VCP. The better the group stabilises the positive charge, the faster is the formation of the cyclopentene, as the global barrier is decreased by the ring-opening step. It allowed us to explain the experimentally observed impact of the R^3 on the cyclisation.

4.4. Development of an enantioselective version of the methodology

We envisaged the development of an enantioselective version of our methodology in order to access optically active skipped dienes.

4.4.1. Strategy

As discussed in section 4.3.2.1., our computational study predicts a high stereospecificity for the VCP/skipped diene rearrangement. We will then focus our efforts on the cyclopropanation reaction by investigating the introduction of a chiral information during this step. The proposed strategy to obtain enantioenriched skipped dienes involved the use of sulfonium salts **91** (Figure 4.6).

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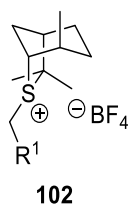
Figure 4.6: Chiral sulfonium salts developed by Prof. Aggarwal's group

The synthesis of these salts has been reported by the group of Prof. V. K. Aggarwal and they have been successfully used by our laboratory for the development of the enantioselective version of the (4+1) annulation reaction (Scheme 4.28).[49,50] An e.e. of 99% was measured on the VCP **103** for one example ($R^1 = R^2 = Ph$, $R^3 = H$), indicating an excellent induction of a chiral information. The rearrangement into cyclopentene **104** was found to be stereospecific. Dr. Sébastien Clergue obtained 9 examples of his targeted cyclopentenes with a yield varying between 25 and 59% and e.e. ranging from 90 to 99%.

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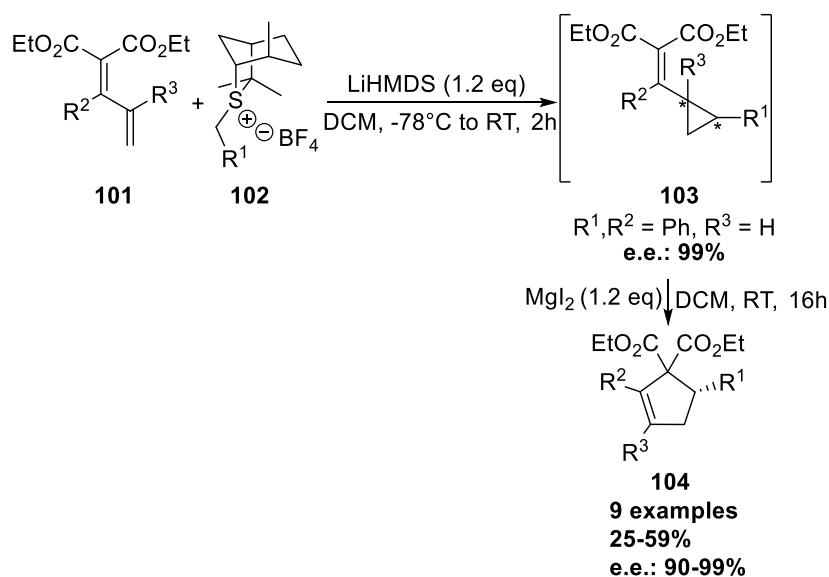
Scheme 4.28: Enantioselective synthesis of cyclopentenes using chiral sulfonium salt **102**

Our planned strategy also used 1,3-dienes and chiral benzylic sulfonium salts but the substitution pattern of the electron-poor 1,3-dienes allows for the cyclopropanation reaction to occur at a different position and lead to the VCPs **179** instead of **103** (Scheme 4.29).
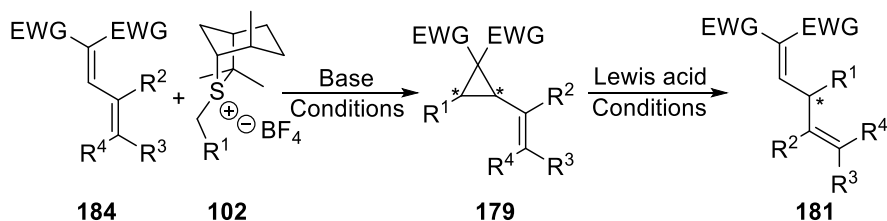
Scheme 4.29: Envisioned strategy for the synthesis of enantioenriched skipped dienes

During the development of the racemic version of our methodology, two bases were used (NaH during our Master's thesis and LiHMDS during this work). Both protocols were envisaged to obtain the desired vinylcyclopropanes before their rearrangements which could be triggered by either $TiCl_4$ or $FeCl_3$.

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The cyclopropanation step is where the chiral information is introduced in the system. The model developed by Aggarwal's group enables predicting the stereoselectivity of the reaction of ylides **208**. The deprotonation of the chiral sulfonium salt leads to the formation of the corresponding sulfonium ylide that shows two possible conformers (Scheme 4.30).
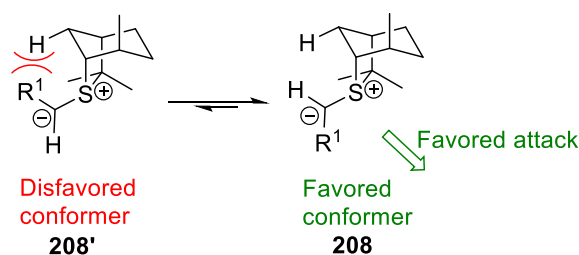
Scheme 4.30: Conformational equilibrium for **208**

The conformational equilibrium is displaced towards the conformer on the right side of the scheme, due to steric factors. Indeed, as shown on the scheme, the disfavoured conformer involves a steric clash between the R^1 group and a hydrogen from the chiral auxiliary. Accordingly, the reaction takes place exclusively from the conformer on the right side, and the latter will add onto electrophiles via its *Re* face since the *Si* face is hindered by a methyl group.

The mechanism of the cyclopropanation reaction is depicted in Scheme 4.31. Depending on the orientation of the 1,3-diene **184**, two diastereomeric betaines can be formed, **209-*trans*** and **209-*cis***, provided that the ylide reacts exclusively on its *Re* face. A rotation of a C-C bond in these two betaine intermediates is required to set the leaving group in the proper position for the attack of the negative charge. The two diastereoisomers of the vinylcyclopropane, being differentiated by the stereochemistry of the allylic stereocenter, are then formed; the stereochemistry of the carbon brought by the sulfonium ylide being controlled.
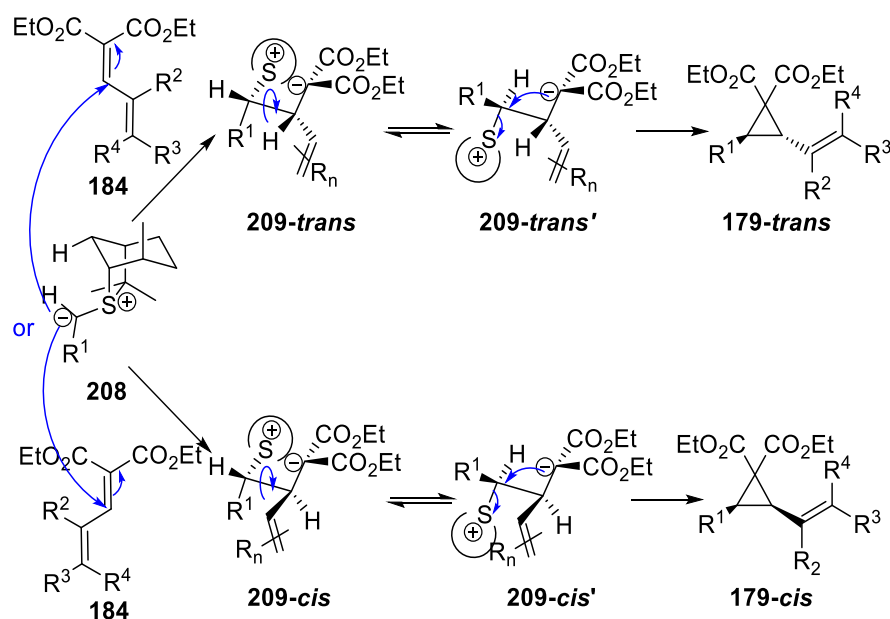
Scheme 4.31: Mechanism of the cyclopropanation reaction using
chiral sulfoniums ylide **208**

It is important to remind that a fast isomerisation of the *cis* diastereomer into its *trans* isomer takes place before any rearrangement reaction. However, given the fact that this isomerisation occurs via the ring-opening of the cyclopropane on the allylic side (see 5.3.2.), it should lead to the formation of a single isomer of the vinylcyclopropane and hence have no impact on the stereospecificity of the process.

4.4.2. Preliminary results

Dr. Maximilien Richald started to work on an enantioselective synthesis of skipped dienes during his PhD thesis.[80] He planned to determine the enantiomeric excess using chiral HPLC. Unfortunately, Maximilien and the HPLC specialist, Laurent Collard, were confronted by the fact that it was difficult to find a substitution pattern for which the enantiomers of both the VCP and the skipped diene were separable by chiral HPLC method. The only system found during their investigation was the one depicted in Scheme 4.32 (skipped diene **181na**).
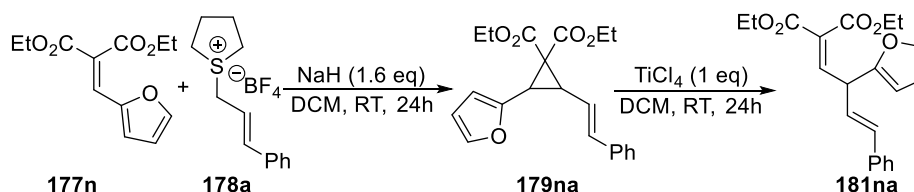
Scheme 4.32: Racemic synthesis of skipped diene **181na**

The sample was obtained using the strategy involving an activated olefin and a chiral allylic sulfonium salt. This is a potential problem since, in this case, the stereocenter which is controlled during the cyclopropanation is the allylic one (Scheme 4.33).
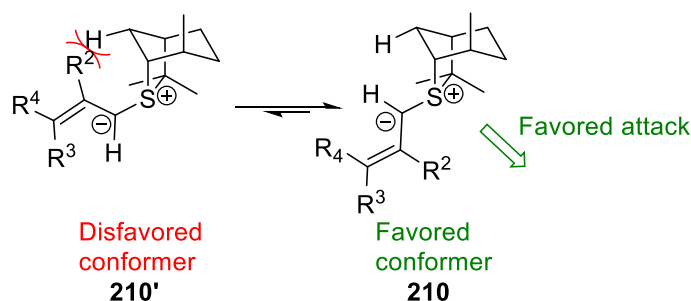
Scheme 4.33: Conformational equilibrium for **210**

As previously discussed, the isomerisation of the *cis* VCP occurs via the opening on the styryl side. It means that the isomerisation of the obtained **179-cis** would lead to the other enantiomer of the *trans* VCP and so in a mixture of the two enantiomers of **179-trans** in a ratio determined by the d.r. of the vinylcyclopropane. This would eventually lead to a mixture of the two enantiomers of the desired skipped diene as both enantiomers of the *trans* VCP are rearranged into different enantiomers of the skipped diene.
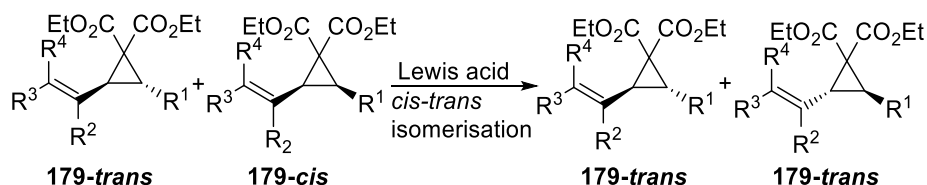
Scheme 4.34: *Cis-trans* isomerisation of a sample of diastereoisomers with a fixed vinylic stereocenter

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4.4.3. Enantioselective version

Accordingly, we decided to attempt the synthesis of the vinylcyclopropane **179na** through our strategy involving a 1,3-diene and a chiral sulfonium salt with R^1 = 2-furyl (**91n**, Scheme 4.35).
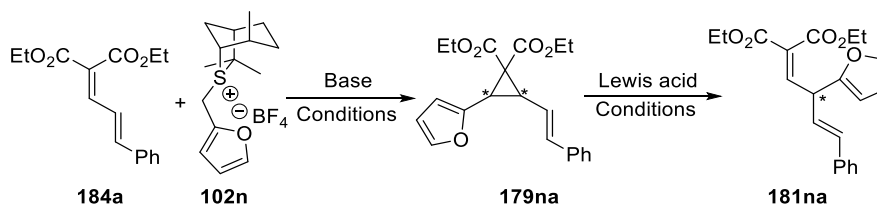
Scheme 4.35: Envisaged synthesis of enantioenriched skipped diene
181na

The electron-poor diene **184a** was already available in our laboratory but the chiral sulfonium salt needed to be synthesised. We first envisaged obtaining it starting from furfuryl alcohol **64n** in the presence of $HBF_4.Et_2O$ (Table 5.14).

Table 4.14: Synthesis of the chiral sulfonium salt with a BF_4^- counter-ion
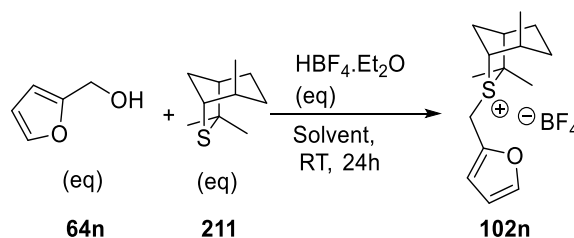
Entry	eq 64n	eq 211	eq HBF₄.Et₂O	Solvent	Result
1	2	1	2	1,4-dioxane	Non soluble Black solid
2	3	1	3	Et₂O	Non soluble Black solid
3	1	2	1	1,4-dioxane	Non soluble Black solid

The investigated reaction conditions were inspired by previous results of our lab (entries 1 and 3)[49] or from the group of Prof. V. K.

Aggarwal (entry 2).[50] All our attempts led to the formation of a black solid which was not soluble in organic solvents, even in DMSO after ultrasound irradiation. One hypothesis explaining this result could be the polymerisation of the methylfuryl cation formed by the departure of the alcohol moiety from **64n**.

We then decided to stop investigating those protocols and switched our target to the sulfonium salt with a OTf⁻ counter-ion (**213n**), which has already been reported to be a suitable counter-ion for sulfonium salts (Scheme 4.36).[50]
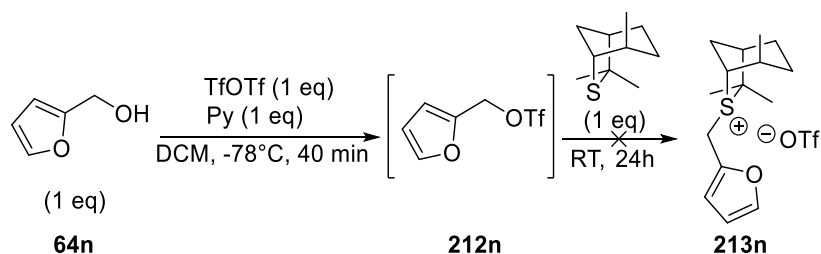
Scheme 4.36 Synthesis of the chiral sulfonium salt with a OTf⁻ counter-ion

The desired salt was still not obtained and the outcome of the reaction is again a black non-soluble solid.

This prompted us to turn our attention towards brominated compound **179n**, obtained by a bromination reaction starting from furfuryl alcholol **64n** (Scheme 4.37)

Scheme 4.37: Bromination of furfuryl alcohol

The product was formed but could not be properly isolated. It was found to be too volatile to be isolated by concentration under reduced pressure. **214n** was recovered in the cold trap of the Schlenk line which proved its formation. We then tried to isolate it by other means. Removing the solvent via distillation at controlled temperature

and pressure did not succeed either. We thus resigned ourselves not to isolate **214n** and try adding immediately the chiral auxiliary on the brominated compound (Scheme 4.38).
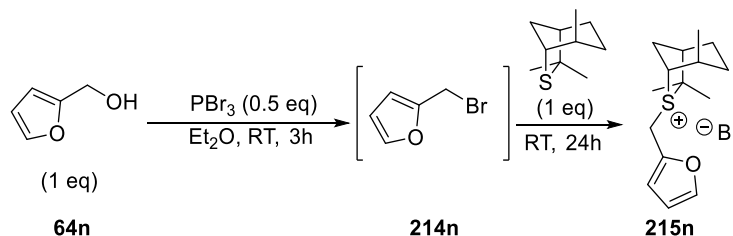
Scheme 4.38: Synthesis of the chiral sulfonium salt with a Br⁻ counter-ion

Unfortunately, the desired product was not observed either. It was then decided to stop working on the chiral sulfonium salts with the 2-furyl group.

We decide to try a new substituent, 2-napthyl, which is known to help the separation of the enantiomers in chiral HPLC analysis.[88] We decided to use the 2-napthyl group as R^1, the migrating group coming from the sulfonium salt (Scheme 5.39).
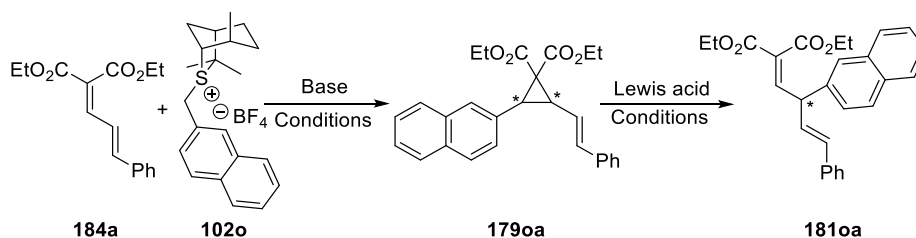
Scheme 4.39: Envisaged synthesis of enantioenriched skipped diene
181oa

This substitution pattern was not investigated during the exploration of the scope (see Chapter 2 and section 4.2.), so we attempted to synthesise the chiral sulfonium salt **102o** before obtaining the racemic VCP and skipped diene needed for the development of a chiral HPLC method capable of separating all the isomers of **179oa** and **181oa** (Scheme 4.40).
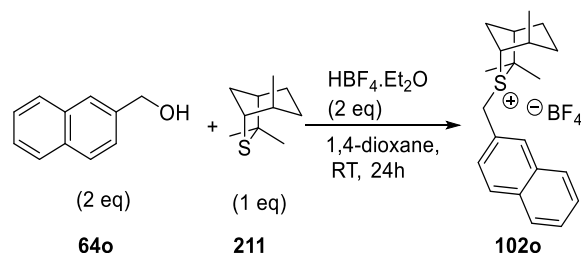
<u>Scheme 4.40</u>: Synthesis of the chiral sulfonium salt with a BF_4^- counter-ion

The desired sulfonium salt was obtained but could not be purified by the different precipitation methods that we tried. For this substituent, we did not investigate other counter-ions. The exploration of this substitution pattern was then stopped and the chiral HPLC methods were not developed.

With the difficulty of identifying suitable substrates for the development of a chiral HPLC method and the difficulty of obtaining the chiral sulfonium salts **102**, we decided to stop our work on the enantioselective version of the methodology in favour of other investigations.

4.5. Conclusions

4.5.1. Exploration of the scope

This work started by the exploration of the scope and limitations of the rearrangement of vinylcyclopropanes into skipped dienes discovered by our laboratory. Two strategies were successfully used for the formation of the VCPs **179** depending on the nature of the targeted substrates (Scheme 4.41). In total, 14 skipped dienes **181** were obtained.
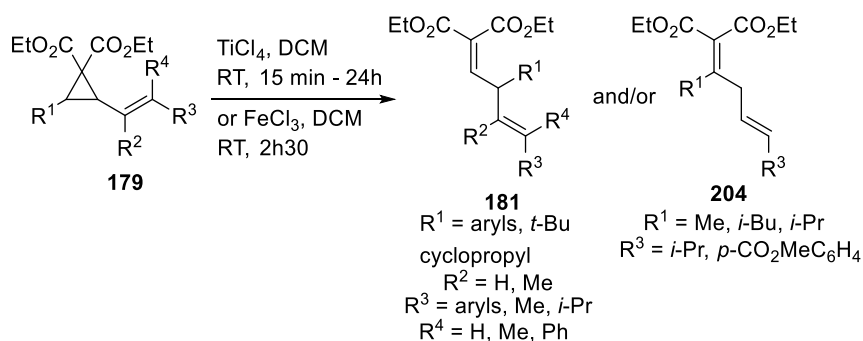
Scheme 4.41: Exploration of the scope of the rearrangement to skipped dienes **181** and **204**

A new product of the rearrangement of vinylcyclopropanes was identified, the skipped diene **204** with the R^1 group on the olefin moiety and a CH_2 between the two unsaturations. Its selective formation was observed 4 times, when R^1 was a methyl, *iso*-butyl or *iso*-propyl group. Indeed, these poor migrating group lose the 1,2-migration competition with the H on the same carbon. These observations were made possible by the successful design of strategies for slowing down the competitive cyclisation reaction allowing us to investigate the migration of poor migrating groups such as H, alkyls or p-$CO_2MeC_6H_4$. Our studies allowed us to gain a better understanding of the substituents effect on the nature of the obtained product (skipped diene or cyclopentene). Unfortunately, we were not able to obtain skipped dienes bearing other EWG groups than CO_2Et.

4.5.2. DFT studies

The mechanistic studies on the rearrangement of vinylcyclopropanes using DFT methods were carried on. We started by performing a benchmark study to find a new level of theory able to correlate to our experimental data. The following method was selected: M06-2X/6-311+G**(CH_2Cl_2)//M06-2X/6-31+G*(CH_2Cl_2). The new model is consistent with the experimental data by predicting the skipped diene to be the kinetic product whereas the cyclopentene is computed to be the thermodynamic product.

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The model was used to investigate the effect of the migrating group (R^1) and the group stabilising the positive charge created by the cleavage of the C-C bond of the VCP (R^3) on the skipped diene/CP selectivity. The nature of the R^1 group was found to greatly influence the migration reaction but had little to no influence on the CP formation. The opposite can be said for R^3, the group has no significant impact on the migration but has an influence on the cyclisation. The results were found to be in good agreement with the experimental data and allowed us to gain a better understanding of the origin of the observed effects.

4.5.3. Enantioselective version

The development of an enantioselective version of our methodology towards skipped dienes was another objective of this work. The main challenge in this regard turned out to be the search for a system for which the 4 isomers of the vinylcyclopropane and the 2 enantiomers of the skipped diene could be separated by chiral HPLC in order to enable the determination of the ratios of isomers. Eventually, such system could be identified: R^1 = 2-furyl, $R^{2,4}$ = H, R^3 = Ph. Our approach was based on the use of chiral sulfonium salts. Scheme 4.42 depicts the synthetic strategy envisaged to obtain the enantioenriched 1,4-diene.
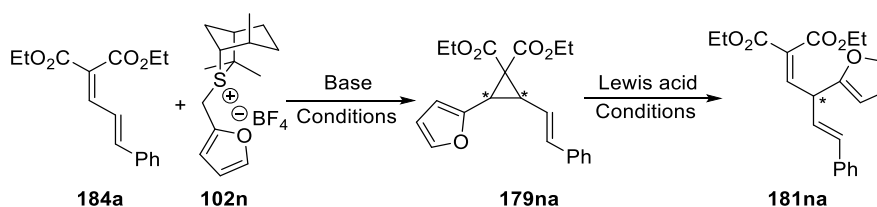
Scheme 4.42: Envisaged synthesis of enantioenriched skipped diene **181na**

The chiral sulfonium salt with the furyl group needed to be synthesised. Despite our best efforts and multiples strategies, **102n** was never obtained. The development of this enantioselective version was stopped to prioritise the work on enantioselective versions of the other methodologies (see Chapter 5 and 6).

Chapter 5: Homologation of α,β-unsaturated aldehydes

5.1. Introduction

β,γ-Unsaturated aldehydes are versatile intermediates in organic chemistry[89,65b] which can serve as substrates for the synthesis of secondary homoallylic alcohols[89] or skipped dienes by olefination reactions.[65b] However, the preparation of these aldehydes is still a challenge in organic synthesis, especially the preparation of enolisable β,γ-unsaturated aldehydes which can easily isomerise into the corresponding conjugated α,β-unsaturated aldehydes in presence of traces of an acid or a base.[90] One of the strategy for their preparations consists of the oxidation of the corresponding primary homoallylic alcohols.[89,90] This strategy is however limited because the preparation of these alcohols is also a challenge in organic synthesis.[91] Other strategies include the Meinwald rearrangement of vinylepoxides and the hydroformylation of 1,3-dienes.

5.1.1. Hydroformylation of 1,3-dienes

In 2018, Watson and Clark reported the enantioselective hydroformylation of 1,3-dienes (**216**) using a rhodium catalyst and a chiral ligand allowing the preparation of enolisable β,γ-unsaturated aldehydes (Scheme 5.1).[92] The drawback of this strategy is that it necessitates high pressure of syngas (≥ 10 atm). This methodology has been applied to the synthesis of natural products of interest.[65b]
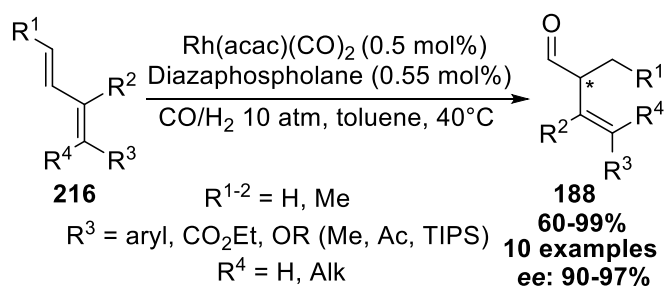
Scheme 5.1: Synthesis of β,γ-unsaturated aldehydes via hydroformylation of 1,3-dienes

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5.1.2. Rearrangement of vinylepoxides

The Meinwald rearrangement of epoxides into carbonyl compounds is a useful tool in organic chemistry which has been used to synthesise natural and/or biologically active compounds.[93] Interestingly, it was showed that in the case of vinylepoxides it can lead to β,γ-unsaturated aldehydes.[93e]

Pace and co-workers reported the formation of enolisable β,γ-unsaturated aldehydes **188** (Scheme 5.2).[94] These latter were however not isolated but in situ engaged in a subsequent reaction (alkylation of isomerisation). The first step is an epoxidation reaction providing the vinylepoxides **217** which undergoes a Meinwald rearrangement to lead to a Lewis acid complexed β,γ-unsaturated aldehydes (**188-LA**). This latter is then, *in situ*, trapped by the addition of an electrophile R^2-Br to form the non-enolisable aldehyde **218**. The methodology has a broad scope with 54 isolated aldehydes. The authors attempted the formation of enolisable aldehydes **188** by not adding the electrophile during the acidic quench. However, the migration of the double bond was observed, providing the corresponding α,β-unsaturated aldehydes **191**.
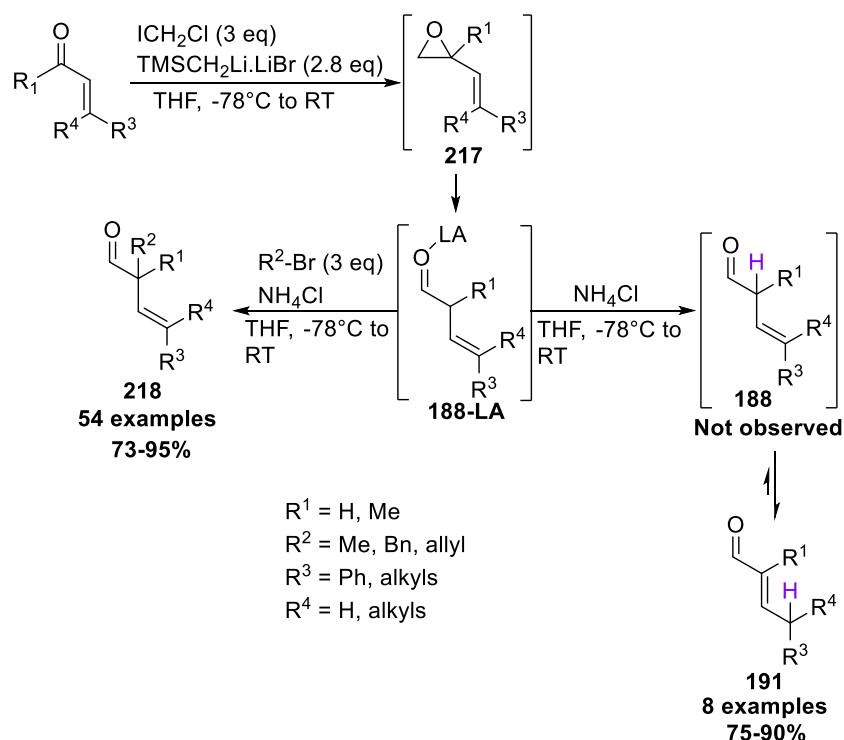
Scheme 5.2: Synthesis of non-enolisable β,γ-unsaturated aldehydes **218** via the Meinwald rearrangement of vinylepoxides

Deng *et al.* reported the Ga(OTf)$_3$-catalysed Meinwald rearrangement of vinylepoxides leading to enolisable β,γ-unsaturated aldehydes **188** (Scheme 5.3).[95] The methodology starts by the epoxidation reaction between an aldehyde **58** and an allylic sulfonium ylide formed *in situ* by the reaction of the allyl bromide **219** and tetrahydrothiophene. The epoxide is rearranged into aldehyde **188** via the 1,2-migration of aryl groups (R^1). The scope of this transformation is limited to derivatives with a TMS group at the R^3 position (only four examples). Indeed, when R^3 = H, the isomerisation into the corresponding α,β-unsaturated aldehydes **191** is observed.
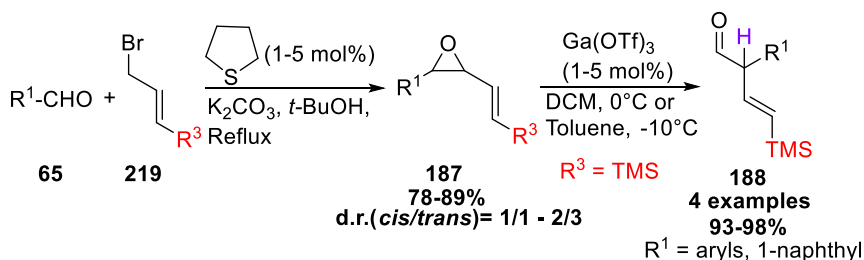
<u>Scheme 5.3:</u> Synthesis of enolisable β,γ-unsaturated aldehydes **188** via the Meinwald rearrangement of vinylepoxides

5.1.3. One-carbon homologation of **α,β**-unsaturated aldehydes (This work)

We decided to investigate a new methodology allowing the preparation of enolisable β,γ-unsaturated aldehydes. Indeed, we reasoned that the application of the methodology we developed for the synthesis of skipped dienes from 1,3-dienes to α,β-unsaturated aldehydes could enable a short and efficient access to enolisable β,γ-unsaturated aldehydes (Figure 5.1). The 1,3-dienes would just be replaced by their synthetic precursors, the α,β-unsaturated aldehydes **186**.
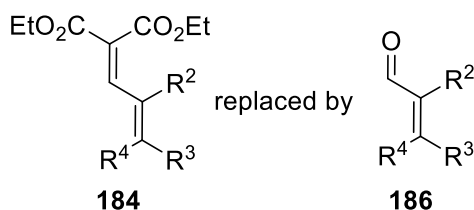
<u>Figure 5.1</u>: 1,3-Dienes are replaced by α,β-unsaturated aldehydes

The envisioned two-step strategy is illustrated in Scheme 6.1. The first reaction is the sulfur ylide mediated epoxidation of α,β-unsaturated aldehyde **186** to provide a vinylepoxides **187**. This latter will then be rearranged into β,γ-unsaturated aldehydes **188** via a Meinwald rearrangement in the presence of a Lewis acid. Overall, the process is a formal one-carbon homologation of α,β-unsaturated aldehydes into β,γ-unsaturated aldehydes by the insertion of a CHR[1] fragment. This methodology would allow for a broader scope

regarding the substitution of the unsaturation (R$^{2-4}$) of the α-aryl β,γ-unsaturated aldehydes (see 5.1.2.). We are aiming at developing reaction conditions which are milder than the one used in the hydroformylation of 1,3-dienes strategy (see 5.1.1).
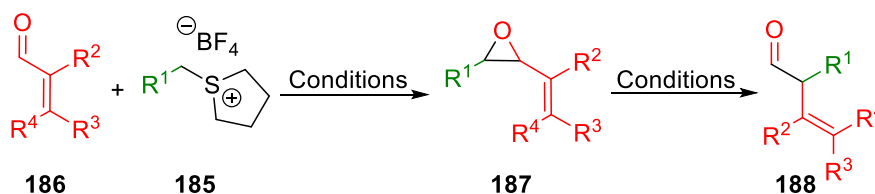
Scheme 5.4: Formal one-carbon homologation of α,β-unsaturated aldehydes into β,γ-unsaturated aldehydes

5.2. Optimisation

We started the development of this new methodology by optimising the two reactions separately. We chose as reference substrates for this part those with R^1 = R^3 = Ph and R^2 = R^4 = H (Scheme 5.5).
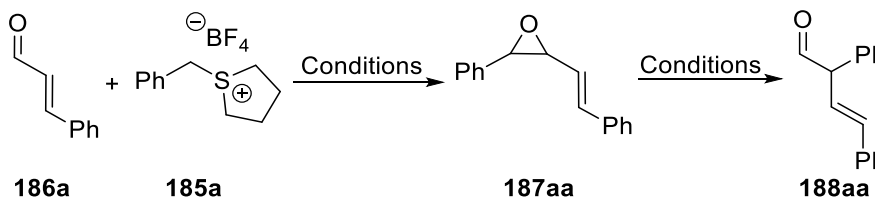
Scheme 5.5: System chosen for the optimisation process

After finding the best reaction conditions for the obtaining of the desired **188aa**, the development of a one-pot version of the methodology will be investigated. This optimisation process was carried out by Boris Takam during his Master's thesis.[96]

5.2.1. Epoxidation reaction

The epoxidation reaction was the first to be investigated. The nature of the base, the solvent, as well as the reaction time were the factors which were varied (Table 5.1).

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Table 5.1: Optimisation of the epoxidation reaction
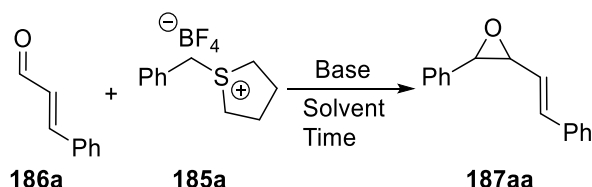
Entry	eq 185a	Conditions	Conversion[a]	Yield (%)[b]	d.r. (*cis/trans*)[a]
1	1.0	KOH (1.0 eq), MeCN/H$_2$O (9/1), 0°C to RT, 16h	66	n.d.	20/80
2	1.2	KOH (1.2 eq), MeCN/H$_2$O (9/1), 0°C to RT, 24h	93	n.d.	20/80
3	1.4	KOH (1.4 eq), MeCN/H$_2$O (9/1), 0°C to RT, 24h	98	88	20/80
4	1.2	LiHMDS (1.2 eq), DCM, -78°C to RT, 6h	79	n.d.	30/70
5	1.5	LiHMDS (1.5 eq), DCM, -78°C to RT, 6h	-	0[c]	-
6	1.2	LiHMDS (1.2 eq), DCM, -78°C to RT, 16h	98	89	30/70
7	1.5	NaH (1.6 eq), DCM, RT, 24h	72	n.d.	10/90
8	1.5	NaH (3.0 eq), DCM, RT, 24h	95	89	10/90

[a] Determined on the crude mixture by ^{1}H NMR spectrum. [b] Yield in pure isolated compound. The yield was not determined when a satisfactory conversion was not observed. [c] Degradation.

The use of KOH in a MeCN/H$_2$O mixture has been reported by the group of Prof. V. K. Aggarwal for the formation of epoxides and aziridines using sulfonium salt as ylide precursors.[50] We thus started our investigations by using the conditions reported by this group (see entry 1; Table 5.1). In our case, these conditions were not sufficient to give a full conversion of the starting aldehyde **186a**. We then rose the amount of base and sulfonium salt **185a** to 1.2 eq and the reaction time to 24 hours (see entry 2). The impact on the conversion was significant but the amount of base and salt were further increased up to 1.4 (entry 3). A conversion of 98% was then reached and the yield of the reaction was calculated to be 88%. The diastereoisomeric ratio of the epoxide is 8/2 in favour of the *trans* isomer. The purity of the

obtained epoxide is excellent and no extra purification step after the work-up is required.

The base used to form our vinylcyclopropanes in the context of this PhD thesis, LiHMDS, was also tested for obtaining the vinylepoxide **187aa** (entries 4-6). Similarly to our vinylcyclopropanes synthesis protocol, dichloromethane was used as solvent and the reaction was started at -78°C and allowed to warm up to room temperature overtime. We first tried to utilise 1.2 equivalents of sulfonium salt and LiHMDS with a reaction time of 6h (entry 1). The desired product was observed but the conversion calculated on the ^{1}H NMR spectrum was not complete (79%). In order to improve the conversion, we increased the amount of salt and base keeping the reaction time unchanged (entry 2). These reaction conditions led to the degradation of the starting material without traces of the desired epoxide **187aa** in the reaction mixture. We then decided to revert back to using 1.2 equivalents but, this time, with a longer reaction time, 24 hours (entry 3). The desired product was obtain in a good yield and a 3/7 d.r. (*cis/trans*). This shows that the d.r. depends on the nature of the base used. Unfortunately, the purity of the obtain product was not excellent and would require to perform flash chromatography to isolate **187aa**, making these conditions less practical than the one using KOH as the base.

We then decided to change the nature of the base by investigating NaH, which was used by our lab for the obtaining of vinylcyclopropanes (entries 7-8).[86] The base was dissolved in mineral oil and washed by two portions of *n*-hexane to remove the oil. Entry 7 shows the exact conditions we used during our previous work on the synthesis of vinylcyclopropanes. The conditions were found to lead to only 72% of conversion. We then increased the amount of NaH used up to 3.0. The results were satisfactory with a similar yield as for LiHMDS and KOH (*vide supra*). The *cis/trans* diastereoisomeric ratio of the obtained epoxide is 1/9. The purity of the obtained epoxide was excellent and no additional purification step after the work-up was required, what was an improvement over the use of LiHMDS as a base.

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The reaction conditions using KOH were selected as our best conditions for the development of a two-step process. Indeed, this protocol affords the desired epoxide with a high degree of purity and is easy to use, not requiring the washing of the base or anhydrous conditions. However, the other investigated reaction conditions could be used during the development of a one-pot version of our methodology. Indeed, these reaction conditions led to the formation of the desired epoxide and have the advantage of involving an anhydrous medium which is more compatible with the use of a Lewis acid.

Having two complementary strategies leading to the formation of the vinylcyclopropanes was an important factor which enabled us to study in depth the scope of the rearrangement reaction to skipped dienes (see 4.3). After finding that the conditions with KOH were the best for the epoxidation leading to the formation of **187aa**, we tried to obtain this latter from benzaldehyde **65a** and allylic sulfonium salt **178a** using the same protocol (Scheme 5.6).
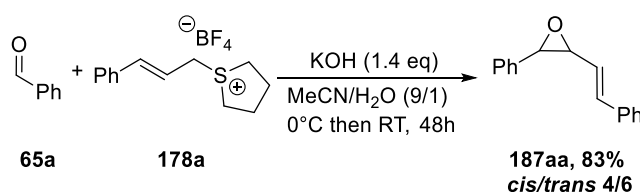
Scheme 5.6: Synthesis of **187aa** from benzaldehyde and allylic sulfonium salt **178a**

187aa was obtained with an excellent yield and a different d.r. still in favour of the *trans* epoxide. It shows that one can use these two strategies to obtain a large library of vinylepoxides to study their rearrangement, including with non-aryl migrating groups.

5.2.2. Rearrangement reaction

After finding the best reaction conditions for obtaining vinylepoxides, our focus shifted to their Lewis acid promoted rearrangement into β,γ-unsaturated aldehydes. During this

optimisation process carried out by Boris Takam during his Master's thesis, the nature of the Lewis acid was investigated.

5.2.2.1. Mechanisms

Scheme 5.7 shows all the hypothetical products that can be formed during the Meinwald rearrangement of the vinylepoxide **187aa** triggered by a Lewis acid (LA). Since β,γ-unsaturated aldehydes without a quaternary center on the α position are known to easily isomerise into their corresponding α,β-unsaturated aldehyde **191aa**, this isomerisation is also represented.
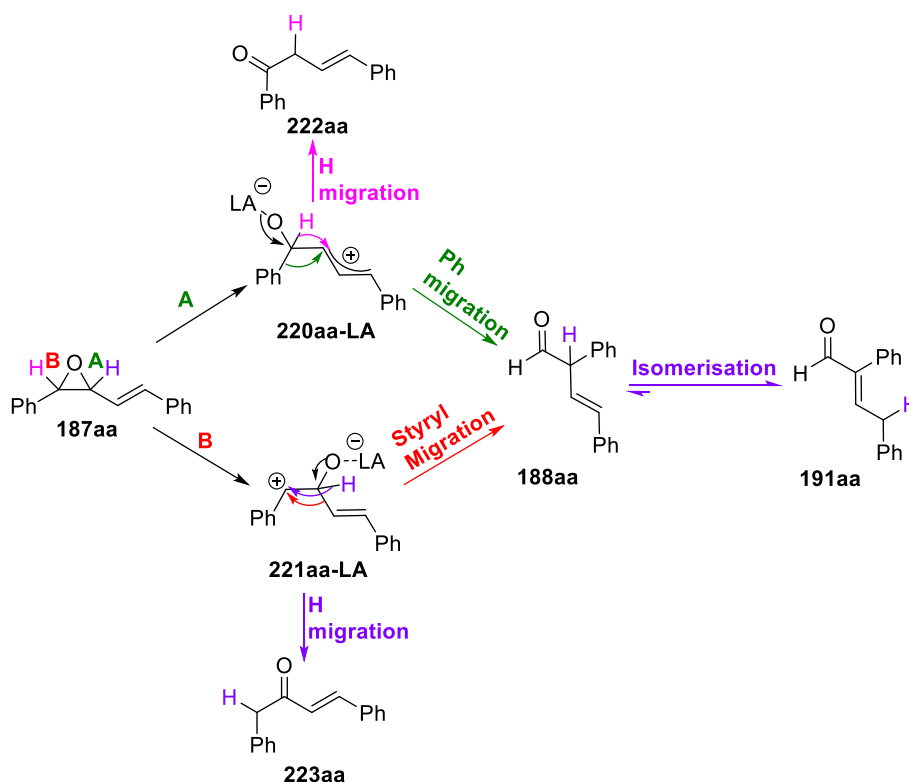
<u>Scheme 5.7</u>: Postulated mechanisms and hypothetical products of the Meinwald rearrangement of **187aa**

Two mechanisms are possible to explain the formation of the desired aldehyde, **188aa**. Both pathways start by a heterolytic cleavage of a C-O bond, A or B, to form intermediates **220aa** and **221aa**, respectively. A 1,2-migration of a phenyl group from **220aa**

(Path A) and/or a styryl group from **221aa** (Path B) affords **188aa**. It is important to note that there is also the possibility for a hydrogen atom to migrate. If a H migrates instead of the phenyl group in Path A, the β,γ-unsaturated ketone **222aa** is formed. The migration of a H from **221aa** affords the α,β-unsatured ketone **223aa**.

The objective of the optimisation process was to find reaction conditions leading to the desired aldehyde **188aa** without the formation of ketones **222aa** or **223aa**, nor the occurrence of the isomerisation into the α,β-unsaturated aldehyde **191aa**.

5.2.2.2. Finding the best Lewis acid

We first considered the Lewis acids that were our catalysts of choice for the rearrangement of our vinylcyclopropanes (Table 5.2).

Table 5.2: first investigations of the nature of the Lewis acid
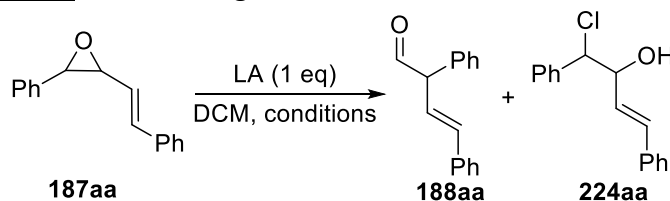
Entry	Conditions	Outcome
1	$TiCl_4$, RT, 15 min	**224aa**
2	$FeCl_3$, RT, 2h30	Degradation
3	Ti(Oi-Pr)$_4$, RT, 4h	**187aa**
4	Fe(OTf)$_3$, RT, 16h	Degradation

Unfortunately, none of these conditions led to the formation of the desired aldehyde (**188aa**). The reaction with $TiCl_4$ afforded a chlorinated product whereas the use of $FeCl_3$ led to the degradation of the starting epoxide. We also tried to keep the same metals with other ligands: Ti(OiPr)$_4$ led to no conversion of the starting material and Fe(OTf)$_3$ led to the degradation of **187aa** as for iron chloride(III).

Accordingly, we turned our attention towards other Lewis acid candidates. The first Lewis acid that gave interesting results was

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Sc(OTf)$_3$, which is also capable of promoting our VCP/skipped diene rearrangement (Table 5.3).[97]

Table 5.3: Investigation of Sc(OTf)$_3$ to promote the formation of **188aa**
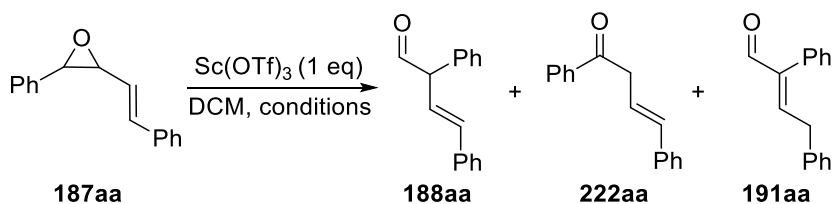
Entry	Conditions	Yield (%)[a]		
		185aa	222aa	191aa
1	-78°C 3h, RT 16h	4	29	21
2	-78°C 3h, RT 3h	19	27	7
3	-78°C 3h, RT 1h30	24	26	3
4	-78°C 3h	28	25	0
5	-78°C 30min	29	25	0

[a] Measured on the ^{1}H NMR spectrum of the crude mixture using DMT as an internal standard.

We started by using the reaction conditions that were developed for the rearrangement of vinylcyclopropanes (entry 1).[97] These conditions afforded a mixture of three products presented in Scheme 5.7: the desired aldehyde **188aa**, the corresponding ketone coming from the migration of a H (**222aa**) and the α,β-unsaturated aldehyde **191aa** coming from the isomerisation of **188aa**. If the yield for these aldehydes is summed up (**188aa** + **191aa**), it indicates a 56/44 selectivity was favour of the migration of the H over the one of the phenyl group. We then decreased the reaction time at room temperature from 16 to 3 hours, which significantly lowers the yield of the isomerised aldehyde **191aa** (entry 2). The ketone/aldehyde selectivity was still not in favour of the aldehyde and was not significantly affected by the change of reaction conditions. Entry 3 shows that 1h30 of stirring at room temperature further decreased the isomerisation but did not completely prevent it. If the reaction was stopped after 3 hours at -78°C, no isomerisation was detected and the

selectivity was slightly in favour of the desired aldehyde. The same result was obtained if the reaction was stopped after 30 minutes (entry 5). It shows that the isomerisation of the aldehyde only occurs at room temperature and that the time of reaction did not significantly impact the observed aldehyde/ketone selectivity.

It is interesting to note that the β,γ-unsaturated ketone **222aa** never showed any sign of isomerisation into its α,β-unsaturated counterpart even in the conditions where the aldehyde **188aa** is nearly completely isomerised into **191aa**. The β,γ-unsaturated aldehyde shows a higher propensity to isomerisation than the ketone, which is probably due to the presence of a phenyl group on the α position.

In view of these results, we decided to screen for other potential Lewis acids to obtain our desired aldehyde **188aa** without ketone and α,β-unsaturated aldehyde (Table 5.4).

Table 5.4: Investigation of new candidates to promote the rearrangement of **187aa** to **188aa**
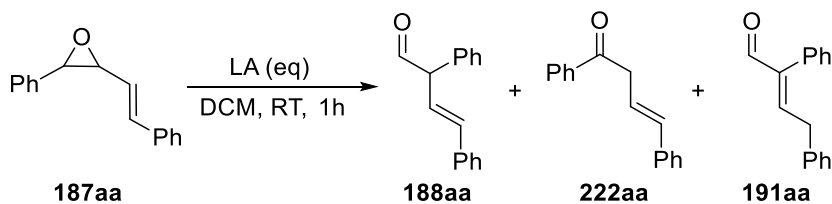
Entry	LA (eq)	Yield (%)[a]		
		188aa	222aa	191aa
1	ZnCl$_2$ (1 eq)	34	47	0
2	Yb(OTf)$_3$ (0.1 eq)	68	5	6
3	Cu(OTf)$_2$ (1 eq)	0	8	74
4	Cu(BF$_4$)$_2$ (1 eq)	78	6	2

[a] Measured on the ^{1}H NMR spectrum of the crude mixture using DMT as an internal standard.

The use of ZnCl$_2$ turned out to be more selective towards the ketone than scandium triflate(III) and was then discarded as a potential Lewis acid for our Meinwald rearrangement reaction. The

first Lewis acid showing a high selectivity for the desired aldehyde was Yb(OTf)$_3$ with a NMR calculated yield of 68%, still with small amounts of the ketone (5%) and the isomerised aldehyde (6%). The use of copper triflate(II) (entry 3) afforded the α,β-unsaturated aldehyde **191aa** as the major product (74%) with traces of the ketone as well (8%). Another interesting result is shown by entry 4. One equivalent of copper tetrafluoroborate(II) produced the highest yield in aldehyde **188aa** with less isomerisation than for entry 3.

Thus, two Lewis acids used in stoechiometric amounts caught our attention: copper tetrafluoroborate(II) and copper triflate(II). Inspired by the substoechiometric amount used in the reaction conditions with Yb(OTf)$_3$, we investigated the effect of the amount of these catalysts on the outcome of the reaction (Table 5.5).

Table 5.5: Reducing the loading of Lewis acid Cu(BF$_4$)$_2$ and Cu(OTf)$_2$
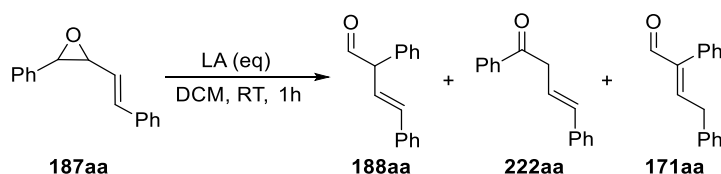
Entry	LA (eq)	Yield (%)[a]		
		188aa	222aa	191aa
1	Cu(BF$_4$)$_2$ (1 eq)	78	6	2
2	Cu(BF$_4$)$_2$ (0.5 eq)	77	5	0
3	Cu(BF$_4$)$_2$ (0.25 eq)	72	4	0
4	Cu(BF$_4$)$_2$ (0.1 eq)	77	5	0
5	Cu(BF$_4$)$_2$ (0.05 eq)	82	4	0
6	Cu(BF$_4$)$_2$ (0.01 eq)	48	2	0
7	Cu(OTf)$_2$ (1 eq)	0	8	74
8	Cu(OTf)$_2$ (0.1 eq)	38	6	40
9	Cu(OTf)$_2$ (0.05 eq)	61	6	3
10	Cu(OTf)$_2$ (0.01 eq)	73	4	1

[a] Measured on the ^{1}H NMR spectrum of the crude mixture using DMT as an internal standard.

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We found out that decreasing the loading of $Cu(BF_4)_2$ to 5 mol% could be done without decreasing the yield. The isomerisation was completely prevented and the ketone yield was still low. A 1 mol% loading of the Lewis acid was found to be difficult to handle due to the small amount of catalyst that had to be weighted at the scale of our tests and afforded a lower yield (entry 6).

The reduction of the copper triflate(II) loading started at 10 mol% as it was shown by the process carried out on $Cu(BF_4)_2$ that a copper based Lewis acid could be used at 1 mol%. Entry 7 shows that isomerisation of the aldehyde still happened and that **191aa** was still the main product of this reaction. The loading was further decreased down to 1 mol% which gives a yield comparable to copper tetrafluoroborate(II) with traces of the two undesired side products **222aa** and **191aa**.

5.2.2.3. Influence of the diastereoisomeric ratio of the epoxide on the rearrangement

The influence of the diasteroselectivity of the starting epoxide on the outcome of the Meinwald rearrangement reaction was investigated. To do so, we carried out the rearrangement step starting from a pure sample of **187aa-*trans*** (Scheme 5.8).
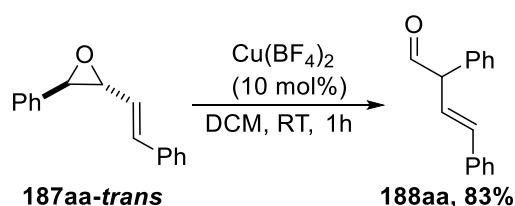
Scheme 5.8: Investigation of the rearrangement of **187aa-*trans***

The obtained result was identical to the rearrangement reaction carried out on a *cis/trans* mixture of **187aa**. This suggests that the diastereoisomeric ratio of the epoxide **187aa** has no impact on the Lewis acid promoted Meinwald rearrangement reaction into **188aa**.

5.2.2.4. Conclusions on the Meinwald rearrangement optimisation

After screening multiples Lewis acid to promote the desired transformation, we found that the three best candidates were Cu(BF$_4$)$_2$, Cu(OTf)$_2$ and Yb(OTf$_3$). We then decided to prioritise the use of copper based compound over ytterbium triflate for a question of availability and price. Copper tetrafluoroborate(II) was chosen due to the lower tendency to isomerisation as compared to the copper triflate(II)-catalysed reaction and the good yields that were obtained by using it.

5.2.2.5. Stability of the β,γ-unsaturated aldehydes

The β,γ-unsaturated aldehydes are known to be poorly bench-stable at room temperature. We investigated this by letting a sample of **188aa** at room temperature for a week-end. The NMR spectrum recorded on the Monday showed degradation of the aldehyde. Some isomerisation into the α,β-unsaturated aldehyde **191aa** was observed as well. Therefore, our samples were stored at -18°C in the freezer.

We also investigated the stability of **188aa** on flash silica by performing a silica plug with a 7/3 mixture of hexane/AcOEt as eluent. The ^{1}H NMR spectrum of the resulting sample also showed some degradation of **188aa** and isomerisation to **191aa**, which would make the purification of our aldehydes tricky.

5.2.3 One pot version of the methodology

After finding suitable reaction conditions for the two-step homologation of α,β-unsaturated aldehydes into β,γ-unsaturated aldehydes, we investigated the possibility of developing a one-pot version of our methodology combining the two steps. The nature of the base, the nature and equivalence of the catalyst were varied during this investigation (Table 5.6).

Table 5.6: Investigation of a one-pot version of the methodology

O
‖
+ Ph
186a
185a

Ph—S⊕ (five-membered ring), ⊖BF₄

Conditions 1
DCM

[Ph epoxide 187aa, Ph]

LA (eq)
DCM, RT, 1h

O Ph
188aa
Ph

186a   185a   187aa   188aa
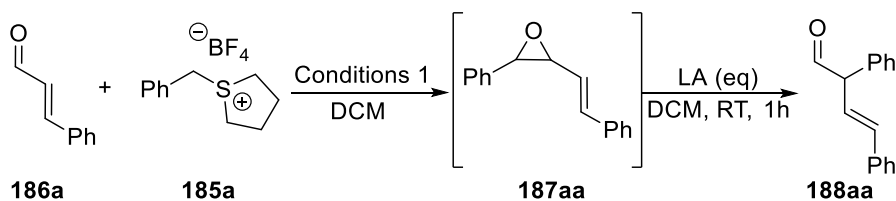
Entry	Conditions 1	LA (eq)	Outcome
1	LiHMDS (1.2 eq), -78°C to RT, 16h	Cu(BF₄)₂ (0.05 eq)	**187aa**
2	LiHMDS (1.2 eq), -78°C to RT, 16h	Cu(BF₄)₂ (0.5 eq)	**187aa**
3	LiHMDS (1.2 eq), -78°C to RT, 16h	Cu(OTf)₂ (0.5 eq)	Degradation
4	LiHMDS (1.2 eq), -78°C to RT, 16h	Yb(OTf)₃ (0.2 eq)	**187aa**
5	LiTMP (1.2 eq), -78°C to RT, 16h	Cu(BF₄)₂ (0.25 eq)	**187aa**
6	NaH (3 eq), RT, 24h	Cu(BF₄)₂ (0.5 eq)	**187aa**
7	NaH (3 eq), RT, 24h	Cu(OTf)₂ (0.25 eq)	**187aa**
8	NaH (3 eq), RT, 24h	Yb(OTf)₃ (0.2 eq)	**187aa**

The first conditions investigated used LiHMDS as a base and 5 mol% of Cu(BF₄)₂. The epoxide **187aa** was recovered without any trace of the desired aldehyde (entry 1). Increasing the amount of Lewis acid or change its nature did not enable observing the rearrangement of **187aa** (entries 2-4). The hypothesis that was suggested to explain these results is that the presence of HMDS, the conjugated acid of LiHMDS, released after the formation of the ylide was acting as a poison for the Lewis acid. An hypothesis that was also formulated to explain the non-compatibility of our LiHMDS protocol with the one-pot version of our strategy leading to the formation of skipped dienes (see 5.1). We tested this hypothesis by performing the rearrangement step on pure epoxide **187aa** in the presence of 1 equivalent of HMDS. The desired aldehyde was not obtained, the NMR spectrum of the crude mixture shows only the epoxide **187aa** (Scheme 5.9).
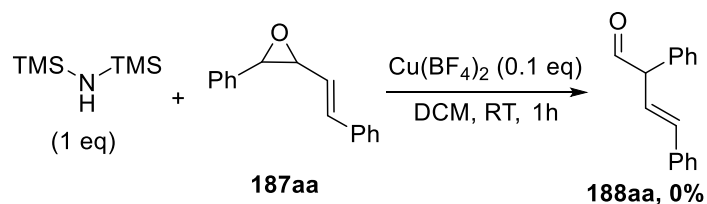
Scheme 5.9: Rearrangement of **187aa** in presence of 1 eq of HMDS

Accordingly, we replaced LiHMDS by a bulkier amide base, LiTMP hoping that the conjugated acid, TMP, would not poison the Lewis acid (entry 5). The replacement did not change the outcome of the reaction, **187aa** is the only product obtained. We then decided to change the base to NaH, which was compatible with a one-pot version of our 1,3-dienes to skipped dienes methodology (entries 6-7). Unfortunately, the aldehyde **188aa** was never observed with our three best Lewis acids. We formulated another hypothesis, that the sulfur auxiliary released during the epoxidation reaction could poison the Lewis acid. It was tested by performing the rearrangement reaction in the presence of 1 equivalent of THT. Again, only the epoxide was isolated confirming the poisoning of the catalyst by THT (Scheme 5.10).
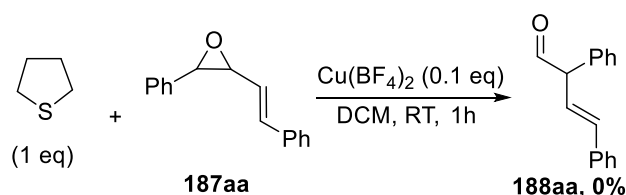
Scheme 5.10: Rearrangement of **187aa** in presence of 1 eq of THT

Accordingly, we decided to use an epoxidation protocol from the literature which uses THT in a substoechiometric amount (0.2 eq).[98] The sulfonium salt is formed *in situ* by the reaction of its synthetic precursors, benzyl bromide **214a** and THT. The reaction required the addition of TBAI and was performed in dry acetonitrile in presence of Cs_2CO_3 as the base to generate the ylide. The sulfur auxiliary is then regenerated by the epoxidation reaction. The Lewis acid was added after 16 hours in an amount more than twice of THT's equivalence (Scheme 5.11).
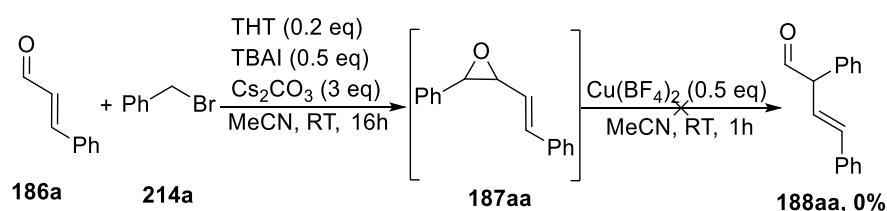
Scheme 5.11: One-pot procedure starting from benzyl bromide

The desired aldehyde was still not obtained as the epoxide **187aa** was once again the obtained product. We decided to stop our investigation at this point and use a two-step protocol for the exploration of the scope of the methodology.

5.3. Exploration of the scope

We then started to explore the scope of our methodology using our optimised reaction conditions.

5.3.1. Synthesis of vinylepoxides

5.3.1.1. From α,β-unsaturated aldehydes

WIth the help of Boris Takam (Master's thesis)[96], we synthesised a large library of variously substituted vinylepoxides **187** in order to subsequently study their Lewis acid promoted Meinwald rearrangement into β,γ-unsaturated aldehydes (Table 5.7).

Table 5.7: Synthesis of vinylepoxides **187**
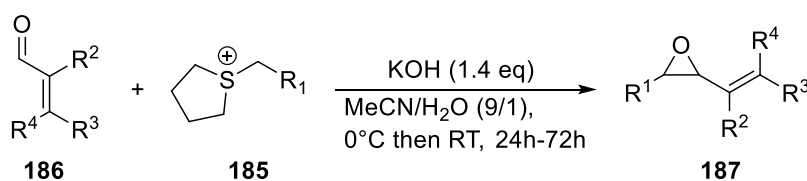
Entry	R^1	R^2	R^3	R^4	Yield (%)[a]	d.r. (*cis/trans*)[b]
1	p-MeOC$_6$H$_4$	H	Ph	H	81	37/63
2	p-MeC$_6$H$_4$	H	Ph	H	82	32/68
3	o-MeC$_6$H$_4$	H	Ph	H	78	14/86
4	m-MeOC$_6$H$_4$	H	Ph	H	75	11/89
5	p-FC$_6$H$_4$	H	Ph	H	87	24/76
6	p-BrC$_6$H$_4$	H	Ph	H	90	9/91
7	p-CO$_2$MeC$_6$H$_4$	H	Ph	H	69	0/100
8	m-CO$_2$MeC$_6$H$_4$	H	Ph	H	89	0/100
9	m-ClC$_6$H$_4$	H	Ph	H	90	0/100
10	o-FC$_6$H$_4$	H	Ph	H	91	0/100
11	Styryl	H	Ph	H	90	46/54
12	Ph	H	CH=CHMe	H	90	15/85
13	Ph	H	Me	Me	79	22/78
14	Ph	H	i-Pr	H	77	21/79
15	Ph	Cyclohexyl		H	70	7/93
16	Ph	H	Ph	Ph	65	24/76
17	Ph	Me	Ph	H	80	17/83
18	Ph	H	p-CO$_2$MeC$_6$H$_4$	H	21	0/100
19	Ph	H	p-BrC$_6$H$_4$	H	84	20/80
20	Ph	H	p-FC$_6$H$_4$	H	85	4/96
21	Ph	H	p-MeC$_6$H$_4$	H	95	17/83
22	Ph	H	p-MeOC$_6$H$_4$	H	82	0/100
23	p-MeC$_6$H$_4$	H	p-MeOC$_6$H$_4$	H	98	30/70
24	p-MeOC$_6$H$_4$	H	p-MeOC$_6$H$_4$	H	82	0/100
25	Ph	CO$_2$Me	Ph	H	45	40/60

[a] Yield in pure isolated compound. [b] Determined by ^{1}H NMR on the crude mixture.

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All the epoxides were obtained in good purities and yields without the need of an additional purification step after the work-up. The d.r. of the obtained substrates is systematically in favour of the *trans* isomer.

The formation of epoxide **187ja** with R^1 = H was carried out using a special procedure found in the literature using the sulfonium salt **198j** (Scheme 5.12).[99]

| 186a | 198j | | 187ja, quant |
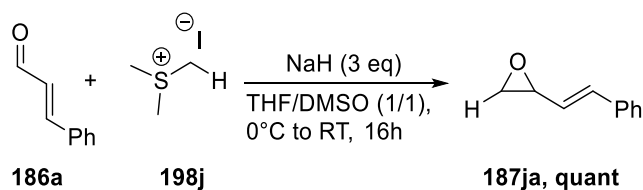
Scheme 5.12: Synthesis of **187ja**

5.3.1.2. Complementary strategy using allylic sulfonium salt

In addition to the work initiated by Boris Takam during his Master's thesis regarding the homologation of α,β-unsaturated aldehydes, the complementary strategy using allylic sulfonium ylides was used to obtain epoxides with R^1 = alkyls, heteroaryl or a naphtyl groups (Table 5.8).

Table 5.8: Synthesis of vinylepoxides from allylic sulfonium salt **178a**
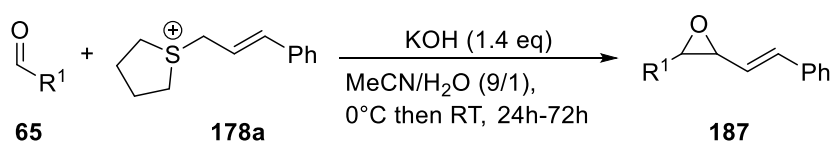
Entry	Epoxide	R^1	Yield (%)^a	d.r. (*cis/trans*)^b
1	**187oa**	2-naphtyl	quant	40/60
2	**187va**	2-Py	quant	47/53
3	**187na**	2-furyl	quant	47/53
4	**187ha**	Me	quant	60/40
5	**187ga**	*i*-Pr	quant	60/40
6	**187da**	*t*-Bu	73	60/40
7	**187ea**	cyclopropyl	quant	40/60

^{a} Yield in pure isolated compound. ^{b} Determined by ^{1}H NMR on the crude mixture.

Obtained yields are excellent and the *cis/trans* diastereoisomeric ratios were slightly in favour of the *trans* isomer in four cases (entries 1, 2, 3, 7). The epoxide with R^1 = *t*-Bu, Me and *i*-Pr showed a d.r. slightly in favour of the *cis* diastereosiomer (entry 4-6).

The aldehydes that would be obtained by the rearrangement of these epoxides could not be considered to be obtained by a homologation of α,β-unsaturated aldehydes methodology but the study of the impact of these R^1 on the Meinwald rearrangement reaction is still interesting.

5.3.2. Meinwald rearrangements

In order to investigate the influence of the different substituents on the Meinwald rearrangement of vinylepoxides **187**, we separated them into two classes.

5.3.2.1. Influence of the R^1 group

We started our investigation by varying the nature of the migrating group (R^1) and keeping the other substituent as an unsubstituted styryl group, *i.e.* R^3 = Ph, R^2 = R^4 = H) (Table 6.9).

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Table 6.9: Study of the influence of the R^1 group on the rearrangement
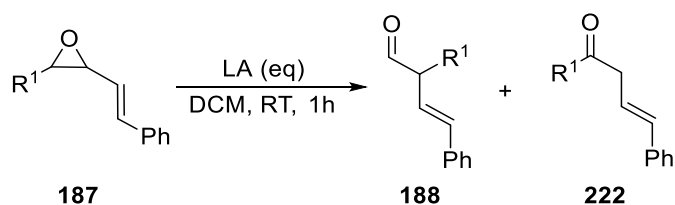
Entry	Aldehyde	R^1	LA (eq)	Time	Yield (%)[a] 188	Yield (%)[a] 222
1	**188ka**	p-MeOC$_6$H$_4$	Cu(BF$_4$)$_2$ (0.05 eq)	1h	97	0
2	**188la**	p-MeC$_6$H$_4$	Cu(BF$_4$)$_2$ (0.05 eq)	1h	84	0
3	**188ba**	o-MeC$_6$H$_4$	Cu(BF$_4$)$_2$ (0.05 eq)	1h	78	0
4	**188ca**	m-MeOC$_6$H$_4$	Cu(BF$_4$)$_2$ (0.05 eq)	1h	14[b]	0
5	**188pa**	p-FC$_6$H$_4$	Cu(BF$_4$)$_2$ (0.05 eq)	1h	82	0
6	**188qa**	p-BrC$_6$H$_4$	Cu(BF$_4$)$_2$ (0.05 eq)	1h	24[b]	11[b]
7	**188fa**	p-CO$_2$MeC$_6$H$_4$	Cu(BF$_4$)$_2$ (0.05 eq)	1h	traces	n.d.
8	**188ra**	m-CO$_2$MeC$_6$H$_4$	Cu(BF$_4$)$_2$ (0.05 eq)	1h	0	n.d.
9	**188sa**	m-ClC$_6$H$_4$	Cu(BF$_4$)$_2$ (0.05 eq)	1h	0	n.d.
10	**188ta**	o-FC$_6$H$_4$	Cu(BF$_4$)$_2$ (0.05 eq)	1h	0	0
11	**188ua**	Styryl	Cu(OTf)$_2$ (0.05 eq)	1h	18[b, c]	0
12	**188ja**	H	Yb(OTf)$_3$ (0.05 eq)	1h	77	0
13	**188oa**	2-naphtyl	Cu(BF$_4$)$_2$ (0.05 eq)	1h	83	0
14	**188va**	2-Py	Cu(BF$_4$)$_2$ (0.05 eq)	16h	2[c]	0
15	**188na**	2-furyl	Cu(BF$_4$)$_2$ (0.05 eq)	1h	2[c]	0
16	**188ha**	Me	Cu(BF$_4$)$_2$ (0.15 eq)	5h	0	51
17	**188ga**	i-Pr	Cu(BF$_4$)$_2$ (0.25 eq)	16h	0	42
18	**188da**	t-Bu	Cu(BF$_4$)$_2$ (0.15 eq)	5h	0	72
19	**188ea**	Cyclopropyl	Cu(BF$_4$)$_2$ (0.25 eq)	16h	5[b]	18[b]

[a] Yield in pure isolated compound. [b] Yield determined on the crude mixture by ^{1}H NMR by using an internal standard (DMT). [c] The use of other reactions conditions (time, temperature, nature of the Lewis acid) did not lead to a better result.

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This exploration allowed us to obtain new β,γ-unsaturated aldehydes bearing an aryl group on the R^1 position. Entries 1-3 show that a donor group at the *ortho* or *para* position led to the selective formation of the desired product, obtained in a good yield. The *para* substitution of the aryl group by an halogen was also investigated. As shown by entry 5 the *p*-FC$_6$H$_4$ group yield the desired aldehyde **188pa** in a good isolated yield whereas its brominated counterpart leads to the formation of an 2/1 ratio of the β,γ-unsaturated aldehyde **188** and the ketone side product **222** in low yields. The addition of a substituent destabilising a positive charge makes the aryl loose the migration competition with the H, the ketone **222** become the product of the rearrangement (see entries 7-9). The reaction mixture for these rearrangements was not clean enough to determine isolated yields, further purification or internal standard determination of the yields were not performed because the desired products were not observed. The rearrangement of the epoxide with R^1 = *o*-FPh led to the formation of a complex mixture of non-identified products. The reaction of the epoxide with R^1 = styryl led to the formation of a complex mixture containing the desired product **188ua**, in low yield, with Cu(OTf)$_2$. Other reaction conditions with different reaction time, temperature, Lewis acid did not lead to a better result. The α,β-unsaturated aldehyde coming from the isomerisation of **188ua** was also observed. The β,γ-unsaturated aldehyde without substituent on its central carbon (**188ja**) was isolated in a good yield after switching to Yb(OTf)$_3$ to catalyse the reaction (entry 12).

Entries 13-19 of the table concern the rearrangement of the epoxides that were obtained via the alternative strategy using allylic sulfonium salt (see section 5.3.1.2) so the following results cannot be considered to be obtained via a homologation of α,β-unsaturated aldehydes methodology. The only β,γ-unsaturated aldehyde which could be obtained in a good yield during this investigation is the one with R^1 = 2-napthyl. Indeed, despite many attempts (variation of reaction time and temperature), the aldehydes with heteroaryl R^1 groups (2-furyl or 2-Py) were never selectively obtained during our studies and were only observed in very low NMR calculated yield in

complex mixtures (entries 14-15). In the case of alkyl groups (entries 16-19), the formation of the β,γ-unsaturated ketone **222** was observed instead of the desired β,γ-unsaturated aldehyde. Indeed, in these cases, the poor migratory aptitude of the alkyl groups led to the preferential migration of the hydrogen. The desired aldehyde was only observed in one case, with R^1 = cyclopropyl but as a minor product. It indicates that the migration order of this rearrangement is not exactly the same as the one of the vinylcyclopropanes rearrangement since, in this latter case, the *t*-Bu and cyclopropyl groups migrated over the hydrogen (see 5.3).

5.3.2.2. Impact of R^2, R^3 and R^4

The last part of this exploration was dedicated to the study of the impact of the substitution of the double bond of the vinylepoxides on the Meinwald rearrangement step of our two-step homologation process (Table 5.10).

Table 5.10: Study of the influence of the R^{2-4} groups on the rearrangement
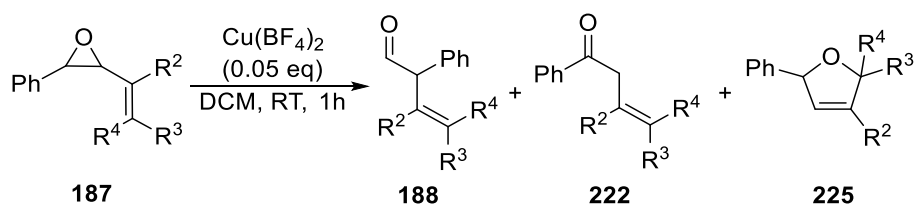
Entry	Ald.	R^1	R^2	R^3	R^4	Yield (%)[a]		
						188	222	225
1	**188aj**	Ph	H	CH=CHMe	H	0^b	0	0
2	**188ab**	Ph	H	Me	Me	78	0	0
3	**188ac**	Ph	H	i-Pr	H	80^c	0	0
4	**188ak**	Ph	Cyclohexyl		H	92^d	0	0
5	**188af**	Ph	H	Ph	Ph	80	0	0
6	**188ad**	Ph	Me	Ph	H	85	0	0
7	**188ah**	Ph	H	p-CO$_2$MeC$_6$H$_4$	H	11^e	0	0
8	**188ae**	Ph	H	p-BrC$_6$H$_4$	H	90	0	0
9	**188al**	Ph	H	p-FC$_6$H$_4$	H	2^e	17^e	0
10	**188am**	Ph	H	p-MeC$_6$H$_4$	H	$6^{e,c}$	$13^{e,c}$	0
11	**188ai**	Ph	H	p-MeOC$_6$H$_4$	H	0	0	n.d.
12	**188li**	p-MeC$_6$H$_4$	H	p-MeOC$_6$H$_4$	H	14^e	0	13^e
13	**188ki**	p-MeOC$_6$H$_4$	H	p-MeOC$_6$H$_4$	H	77	0	0
14	**188an**	Ph	CO$_2$Me	Ph	H	$0^{f,c}$	0	0

[a] Yield in pure isolated product. [b] Degradation. [c] Yb(OTf)$_3$ was used as the Lewis acid instead of Cu(BF$_4$)$_2$. [d] Reaction time = 3h instead of 1h [e] Yield determined by ^{1}H NMR by using an internal standard (DMT). [f] Unidentified side product obtained.

Different substitution patterns of the double bond were found to lead to the formation of the desired product. The presence of alkyl groups (see entries 2-4) or p-BrC$_6$H$_4$ (see entry 8) as the R^3 group is tolerated. Aldehydes with a second substituent at the R^2 or R^4 position were also obtained in good yields (R^2 = Me, entry 6 and R^4 = Ph, entry 5). Some of the *para*-substituted aryls did not lead to the selective

formation of the desired product, such as R^3 = p-FC_6H_4 (entry 9) and p-MeC_6H_4 (entry 10). In these cases, the ketone **222** was found to be the main product in complex mixtures also containing the aldehyde **188**. Despite our best efforts with the two different Lewis acids, the aldehydes with R^3 = p-$CO_2MeC_6H_4$ (**188ah** was present in low yield in a complex mixture of products) and R^3 = CH=CHMe (degradation) could not be isolated either.

Entry 11 is interesting. Indeed, the desired aldehyde was not observed but the molecule obtained was a dihydrofuran (**225ai**). This product can be considered as the equivalent of the cyclopentene obtained during the rearrangement of vinylcyclopropanes. The reaction mixture was not clean enough to indicate an isolated yield, the obtained product was not isolated prior to the structural determination. The mechanism postulated to explain the formation of **225** is depicted in Scheme 6.10. It starts by the heterolytic ring-opening of the epoxide induced by its complexation by the Lewis acid to form the zwitterion intermediate **220-Z-LA**; this step being shared with the Meinwald rearrangement mechanism. Then a cyclisation occurs to form the dihydrofuran **225**.
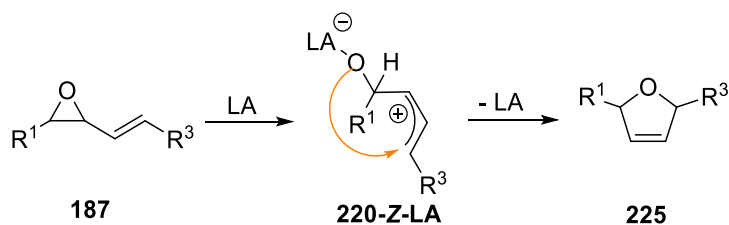
Scheme 5.13: Postulated mechanism for the formation of **225**

Its formation is favoured by the presence of a strong electron-donor group on the aryl at the R^3 position which stabilises the intermediate **220-Z-LA**. This is a reactivity that was also observed during the exploration of the scope of the vinylcyclopropane-skipped diene rearrangement (see section 4.3.2.3.).

In order to favour the migration and compete with this cyclisation, we tried to use derivatives with a better migrating group, *i.e.* electron-rich aryl groups (entries 12 and 13). It turned out that *p*-

MeC_6H_4 is not a sufficiently strong migrating group to allow for the selective formation of **188li**; the obtained reaction mixture containing both the aldehyde and the side product **225li** in similar yields. The *p*-$MeOC_6H_4$ group enables, however, the isolation of the β,γ-unsaturated aldehyde **188ki** in a good yield and without any trace of the undesired dihydrofuran (entry 13).

The epoxide with an electron-withdrawing group at the R^2 position, CO_2Me, was rearranged but did not lead to the formation of the desired aldehyde **188**. The conversion was complete but an unidentified product was isolated. It is however clear that an aldehyde group is present in the molecule as shown by the ^1H NMR spectrum and it contains only one carbonyl as observed on the ^{13}C NMR spectrum, meaning that the ester at the R^2 position is involved in a side reaction.

5.3.3. Conclusions on the exploration of the scope

We successfully used our optimised homologation of α,β-unsaturated aldehydes methodology to obtain 13 examples of β,γ-unsaturated aldehydes in overall yields varying between 52 and 79% (Scheme 5.14).
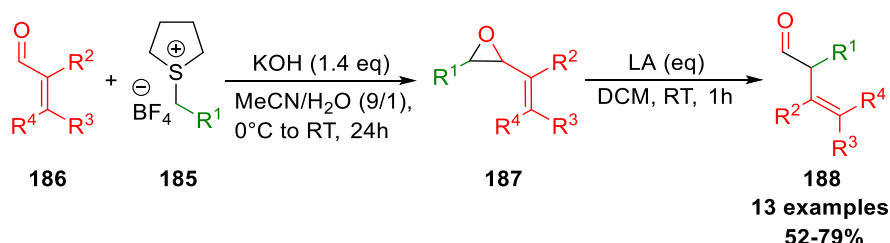
Scheme 5.14: Developed one-carbon homologation of α,β-unsaturated aldehydes methodology

The exploration of the scope of the methodology allowed us to shed light on the effect of the substituents on the Meinwald rearrangement reaction. Other undesired products such as the β,γ-unsaturated ketone **222** and the dihydrofuran **225** were obtained in some cases (Figure 5.2).

222 **225**
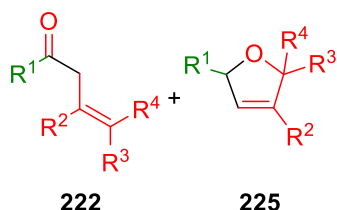
Figure 5.2: Other rearrangement products obtained

In a few examples, the desired aldehyde was observed but in low amount in complex mixtures. The difficulty of purifying the β,γ-unsaturated aldehydes due to their sensitivity (see section 5.2.2.5.) did not allow us to perform more than an aqueous work-up on the products of these reactions.

The alternate strategy for obtaining the epoxides **187**, starting from the aldehydes **65** and allylic sulfonium salt **178a** was also used to investigate the formation of more aldehydes **188** (Scheme 6.12).
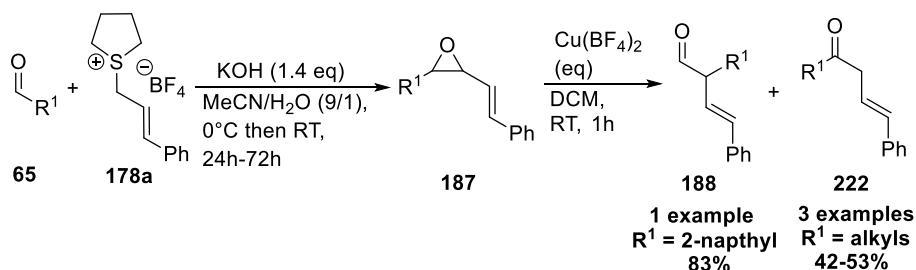
Scheme 5.15: Exploration of non-mono aryl R^1 groups

Unfortunately, only one of the example led to the selective formation of the desired product, with R^1 = 2-napthyl, which was obtained with a good overall yield on two steps of 83%. The Lewis acid promoted Meinwald rearrangement of epoxides with R^1 = alkyl groups all led to the selective formation of the ketone **222** with overall yield ranging from 42 to 53%.

5.4. Derivatisation of the β,γ-unsaturated aldehydes

In order to demonstrate the interest of our methodology, we decided to investigate the derivatisation of the β,γ-unsaturated aldehydes.

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5.4.1. Isomerisation into α-aryl α,β-unsaturated aldehydes

As previously discussed in this manuscript (see 5.1), enolisable β,γ-unsaturated aldehydes can be isomerised into their more stable conjugated α,β-unsaturated aldehydes counterparts in the presence of an acid or a base via the migration of the double bond. We decided to take advantage of this and investigate the controlled isomerisation of **188aa** into **191aa** because few methodologies are reported for the preparation of α-aryl α,β-unsaturated aldehydes.[100] Obtained results are reported in Table 5.11.

Table 5.11: Optimisation of the isomerisation of **188aa** into the corresponding α-aryl α,β-unsaturated aldehyde **191aa**
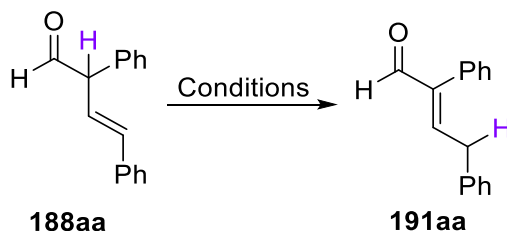
Entry	Conditions	Yield (%)
1	PTSA (0.5 eq), DCM, RT, 16h	68
2	PPh₃ (0.5 eq), DCM, RT, 16h	70
3	Filtration on silica gel washed with NEt₃	66

The first two entries show that the use of common organic acid and base for a reaction running overnight led to a complete isomerisation of the sample to form **191aa** in good yield.

However, the most interesting strategy for the obtaining of the desired product is shown by entry 3. During our investigation of a purification method for our aldehyde **188aa** on silica, we tried to treat the silica gel with 100 ml of a 8/2 *n*-hexane/AcOEt eluent with the addition of 0.5 ml of triethylamine to neutralise the acidity of the silica gel. Five washes with the eluent without the amine to remove it completely from the silica were performed before adding the aldehydes **188aa** on the silica. This process led to the isolation of the

aldehyde **191aa** with the best purity of all three conditions, good yield and a simple protocol.

It is interesting to remind that, as discussed in section 5.2.2.5., on non-treated silica gel partial isomerisation and the degradation of the product are observed.

5.4.2. Reduction into primary homoallylic alcohols

Considering the few number of synthesis of primary homoallylic alcohols[91], we became interested in investigating the reduction of our β,γ-unsaturated aldehydes. We tested classic reduction conditions that we previously used in our laboratory on the aldehyde **188aa** and then Pierre-Louis Lefebvre obtained more alcohols during his internship (Table 5.12).[101]

Table 5.12: Synthesis of primary homoallylic alcohols **192** by reduction

Entry	Alcohol	R^1	R^2	R^3	R^4	Yield (%)^a
1	**192aa**	Ph	H	Ph	H	54
2	**192la**	p-MeC$_6$H$_4$	H	Ph	H	75
3	**192pa**	p-FC$_6$H$_4$	H	Ph	H	72
4	**192ab**	Ph	H	Me	Me	12
5	**192ac**	Ph	H	i-Pr	H	16
6	**192af**	Ph	H	Ph	Ph	30
7	**192ad**	Ph	Me	Ph	H	62
8	**192ae**	Ph	H	p-BrC$_6$H$_4$	H	63

^{a} Yield in pure isolated compound.

The obtained yields varied from 12 to 75% and were found to be much lower with the examples with alkyls substituents on the

double bonds (entries 4 and 5). This can be explained by the low purity of the crude mixture which required a flash chromatography to isolate the primary homoallylic alcohol **192**.

5.4.3. Olefination reactions into skipped dienes

Olefination reactions are widely used in organic synthesis as a way to produce a carbon-carbon double bond in numerous synthetic routes leading to product of interest.[65b,102]

β,γ-unsaturated aldehydes can potentially lead to the formation of skipped dienes with different substituents than the two ester groups. This inability to synthesise 1,4-dienes without esters was one of the drawback of our previously developed methodology (see Chapter 5).

5.4.3.1. Wittig olefination

The first envisaged olefination strategy was the Wittig olefination of **188aa** with both stabilised and non-stabilised phosphonium ylides.

5.4.3.1.1. Stabilised phosphonium ylide

The investigation was started by using the commercially available stabilised phosphonium ylide **226a**. Different conditions for the formation of the skipped diene **189aaa** bearing only one ester group were tried (Table 5.13).

Table 5.13: Wittig olefination reactions with stabilised phosphonium ylide **226a**
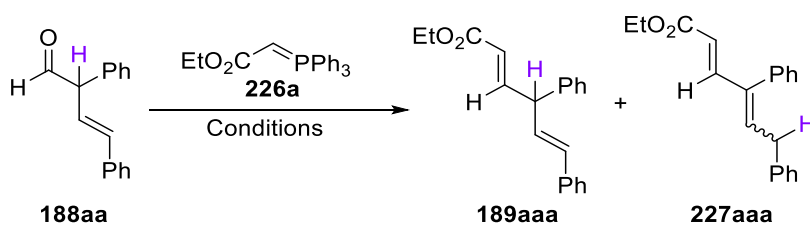
Entry	Base	Observations
1	DCM, RT, 16h	Three isomers of **227aaa**
2	THF, -78°C to RT, 16h	Three isomers of **227aaa**

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Unfortunately, the desired product, **189aaa**, was never observed. Instead, a mixture of three isomers was obtained. After analysis, the compounds have been identified as isomers of **227aaa**. The NMR spectrum of these three molecules are only differing by the chemical shifts of the signals and we could not attribute a molecule to a signal and hence determine the proportion of these isomers in the recovered mixture.

These 1,3-dienes are hypothesised to come from the isomerisation of the aldehyde **188aa** to its α,β-unsaturated aldehyde counterpart, **191aa**, before the olefination reaction. We hypothesised that this could be due to the basicity of the phosphonium ylide and the acidity of the H in α position of the aldehyde (purple; Scheme 5.16). Indeed, we showed that β,γ-unsaturated aldehyde **188aa** could be isomerised in the presence of a base (see 5.4.1.). This was tested by performing a reaction with 0.1 eq of the phosphonium ylide **226a** to see if any isomerised aldehyde was observed. The reaction led to a complex mixture of product with **191aa** among them which backed our hypothesis.
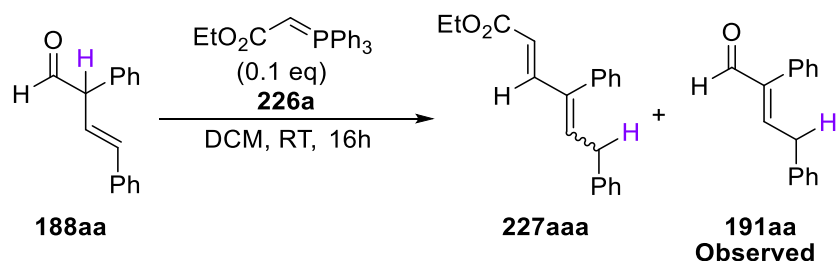
Scheme 5.16: Control experiment with 0.1 eq of **226a**

5.4.3.1.2. Non-stabilised phosphonium ylide

Contrary to their stabilised analogues, the non-stabilised ylides are not commercial nor bench-stable. We then started by preparing the phosphonium salt **228b**, precursor of the desired ylide via a simple S_N2 reaction involving propyl bromide and triphenylphosphine (Scheme 5.17).

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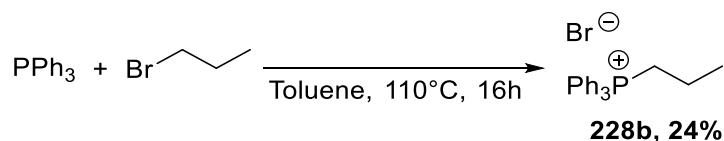
Scheme 5.17: Synthesis of the phosphonium salt **228b**

The salt **228b** could then be used in a Wittig olefination protocol starting by its deprotonation by a base to *in situ* generate the phosphonium ylide **226b**, followed by the addition of **188aa** (Table 6.14)

Table 5.14: Wittig olefination reactions with non-stabilised phosphonium ylide **226b**
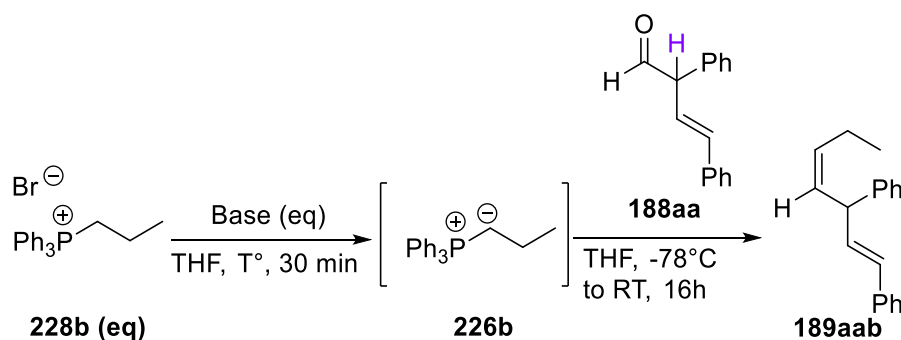
Entry	eq 228b	Base	T°	^{1}H NMR observations
1	1.05	LiHMDS (1.05 eq)	0°C	Complex mixture containing **191aa**
2	1.1	*t*-BuOK (1.1 eq)	RT	Mixture containing **191aa**

The desired skipped diene was not observed in a complex mixture containing the α-aryl α,β-unsaturated aldehyde **191aa** coming from the isomerisation of **188aa** (entry 1). This could also be due to the basicity of the ylide or because of the presence of traces of LiHMDS or by the presence of the conjugated acid of LiHMDS. Different conditions were investigated using *t*-BuOK as base (entry 2). It led to a cleaner crude mixture but still containing the isomerised aldehyde **191aa** and no trace of the desired product, **189aab**.

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The difference between our substrate and procedures from the literature involving the Wittig olefination of β,γ-unsaturated aldehydes is the nature of the substitution of the central sp^3 carbon. Indeed, all the examples we found in the literature showed no substitution in α position of the aldehyde.[90] The fact that isomerisation is observed in our case can probably be accounted for by the increased acidity of the proton in α position by the presence of the phenyl group.

We decided to stop our investigations of the Wittig olefination at this stage to explore other olefination protocols.

5.4.3.2. Takai olefination

After the failure of the Wittig olefination, our attention turned to the Takai olefination.[65b] This reaction produces an iodo alkene which can subsequently serve in a cross-coupling reaction.[65b] This strategy has been used in total syntheses of natural products containing the skipped diene moiety.[65b]

The reaction conditions used are shown in Scheme 6.15.
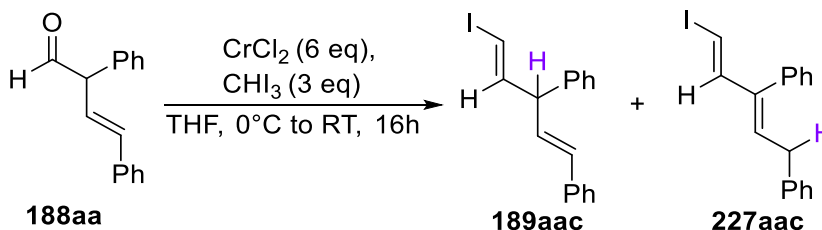
Scheme 5.18: Takai olefination of **188aa**

After a purification of the crude mixture by a silica gel plug, it was possible to analyse the composition of the mixture obtained. The major product of the reaction is the iodo 1,3-diene **227aac**, coming from the isomerisation of the aldehyde followed by the Takai olefination. The desired product, the iodo skipped diene **189aac**, is formed but in a 1/3 ratio as compared to **227aac**. The products were not isolated.

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The difference between the examples from the literature and our case is the nature of the substituent on the central sp^3 carbon of the β,γ-unsaturated aldehyde. Indeed, the reports we found used aldehydes with a methyl group on the central carbon,[76b] which led to the formation of the iodo skipped diene as the major product of the reaction with the iodo 1,3-diene as the minor product of the reaction. Thus, again, the presence of the phenyl group seems to favour the isomerisation of the β,γ-unsaturated aldehyde prior to the olefination reaction.

5.4.3.3. Petasis olefination

The last olefination method that was attempted was the Petasis olefination (Scheme 5.19). The active olefination specie is generated by the loss of a methane molecule from **229** by heating. The interest of this olefination methodology is that the active species is less basic than phosphonium ylides. We thus hoped to avoid any isomerisation of **188aa** prior to the olefination reaction. The obtained terminal olefin could be an access route to terminal skipped dienes with an aryl group on the central carbon with interesting biologic activity.[63b,103] The terminal olefin could also be involved in crossed metathesis to produce non terminal olefins.[104]
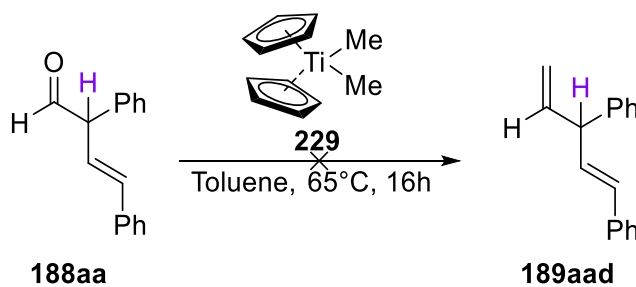
Scheme 5.19: Petasis olefination of **188aa**

The reaction was carried out in the presence of the freshly synthesised Petasis reagent **229**. Unfortunately, the desired skipped diene was not observed. Our hypothesis was that **188aa** could be unstable at the temperature required to produce the active specie for the olefination reaction from the Petasis reagent.

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This investigation was the last olefination protocol attempted for the derivatisation of the β,γ-unsaturated aldehydes into skipped dienes. We shifted our focus toward the synthesis of secondary homoallylic alcohols.

5.4.4. Nucleophilic additions

We investigated the obtaining of secondary homoallylic alcohols by addition of organometallic reagents or by allylation using potassium allyltrifluoroborate.

5.4.4.1. Addition of an organometallic reagent

The addition of an organometallic nucleophile on the electrophilic center of a carbonyl group is a well-known technique for C-C bond formation in organic synthesis. Accordingly, we decided to investigate the addition of different types of organometallic reagents on our β,γ-unsaturated aldehyde **188aa**.

5.4.4.1.1. Grignard reagents

The first type of addition that we attempted involved the use of three different commercially available Grignard reagents in solution in THF (R^6 = Ph, *i*-Pr or vinyl) (Table 5.15).

Table 5.15: Addition of Grignard reagents on the aldehyde **188aa**
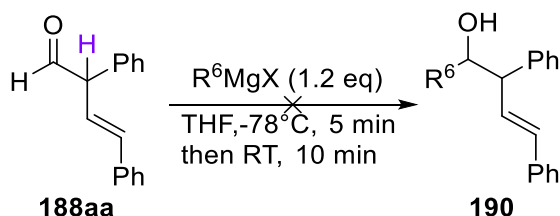
Entry	Alcohol	R^6MgX	^{1}H NMR observations
1	**190aaa**	PhMgBr	Degradation
2	**190aab**	*i*-PrMgCl	Degradation
3	**190aac**	VinylMgCl	Degradation

These three reactions led to the same outcome: the desired product was not observed, the ^{1}H NMR spectrum of the crude mixture only showed degradation. We hypothesised that it could be accounted

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for by the low stability of the aldehyde **188aa**, which is known to degrade easily, in the presence of a basic Grignard reagent. Once again, the acidity of the purple proton could explain these observations. The addition of a Grignard reagent on a β,γ-unsaturated aldehyde has been reported but on aldehydes without a phenyl group in the α position, which increases the acidity of the purple proton.[105]

5.4.4.1.2. Organocuprate reagents

We then decided to investigate the addition of an organocuprate, which is less basic than its Grignard counterpart. The organometallic reagent **230c** was synthesised *in situ* by reaction between the vinylmagnesium chloride and CuI prior to the addition of the β,γ-unsaturated aldehyde **188aa**. (Scheme 6.17)
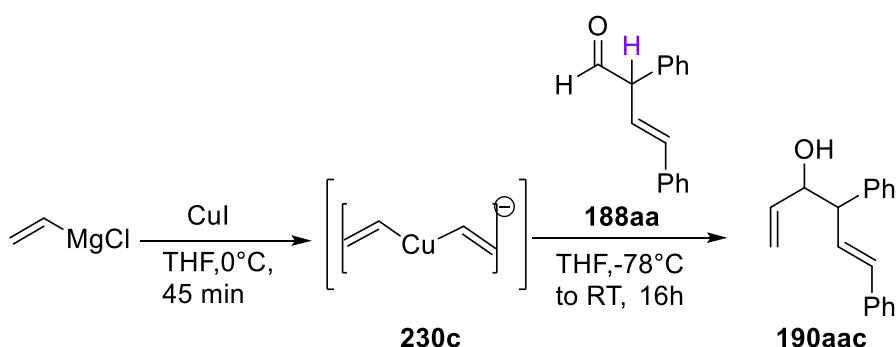
Scheme 5.20: Addition of an organocuprate reagent on **188aa**

The desired product was still not observed in the presence of a less basic organometallic compound. The analysis of the crude mixture revealed a complex mixture, similar to the use of Grignard reagents.

5.4.4.1.3. Organozinc reagents

We then shifted our focus on the use of organozinc nucleophilic compounds to achieve the addition of a nucleophilic carbon on the carbonyl group of the β,γ-unsaturated aldehyde. The following protocol was inspired by the work of the group of Prof. P. Knoechel with the use of a Turbo Grignard to form the Grignard reagent from the vinylbromide prior to its transmetallation in the presence of $ZnCl_2$ (Scheme 5.21).

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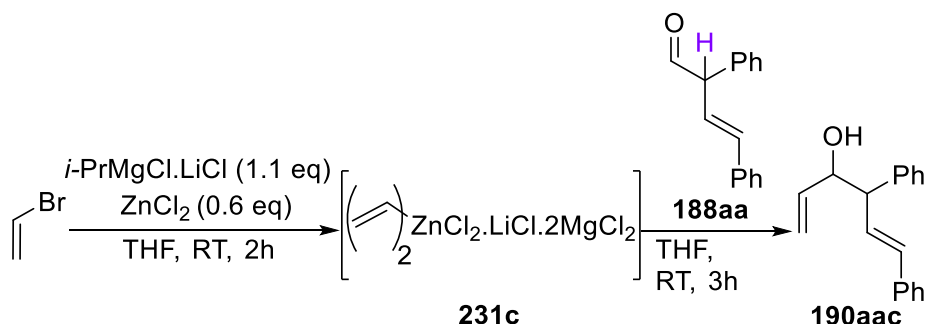
Scheme 5.21: Addition of an organozinc reagent on **188aa**

This protocol also failed to produce any addition product **190aac**. A complex mixture of products containing the α,β-unsaturated aldehyde **191aa** was obtained. We decided to stop our investigations at this point to focus on other work (see 6.4).

5.4.4.2. Allylation using potassium allyltrifluoroborate

After our unsuccessful attempts at obtaining secondary homoallylic alcohols by addition of an organometallic reagent, our attention shifted towards allylation reaction using the potassium allyltrifluoroborate (Scheme 5.22). The allylation of aldehydes using potassium allyltrifluoroborate and a Lewis acid has already been reported [106] and has the advantage of using non basic reagents. The Lewis acid has been shown to isomerise **188aa** but we hoped that the lower temperature and short reaction time could prevent it from happening alongside the desired transformation.
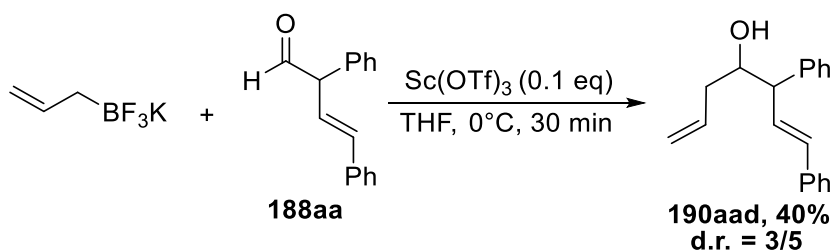
Scheme 5.22: Allylation of **188aa** using potassium allyltrifluoroborate

The desired alcohol **190aad** was isolated with a 40% yield without any sign of isomerisation of the starting aldehyde.

5.4.5. Conclusions on the derivatisation reactions

Considering their fast degradation, the derivatisation of the obtained β,γ-unsaturated aldehydes was investigated.   We developed methodologies for the synthesis of two scaffolds remaining a challenge in organic synthesis, the α-aryl α,β-unsaturated aldehydes **191** and primary homoallylic alcohols **192**.

During this work, we developed a new methodology allowing the isolation of α-aryl α,β-unsaturated aldehydes involving the controlled isomerisation of the non-isolated **188aa** by a filtration on a previously treated by NEt₃ silica gel (Scheme 5.23). The global yield over 3 steps is 49%.
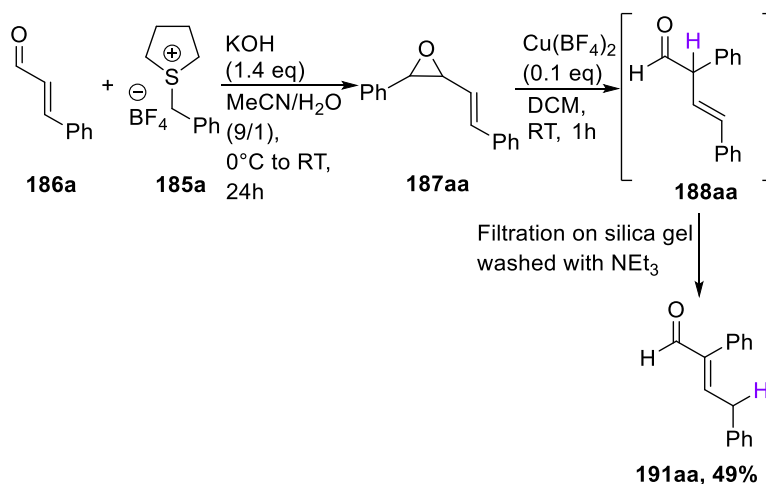
Scheme 5.23: Strategy for the synthesis of α,β-unsaturated aldehyde **191aa** from **188aa**

We also investigated the reduction of the aldehyde function to synthesise primary homoallylic alcohols. This strategy represents an easy three steps strategy access route for their synthesis (Scheme 5.24). The methodology uses cheap reagents and simples protocols but has the drawback of having the limitation of the Meinwald rearrangements step. Indeed, alkyls, electron-poor aryls were found not to migrate to form **188**. Heteroaryls led to the degradation of the vinylepoxides **187**.
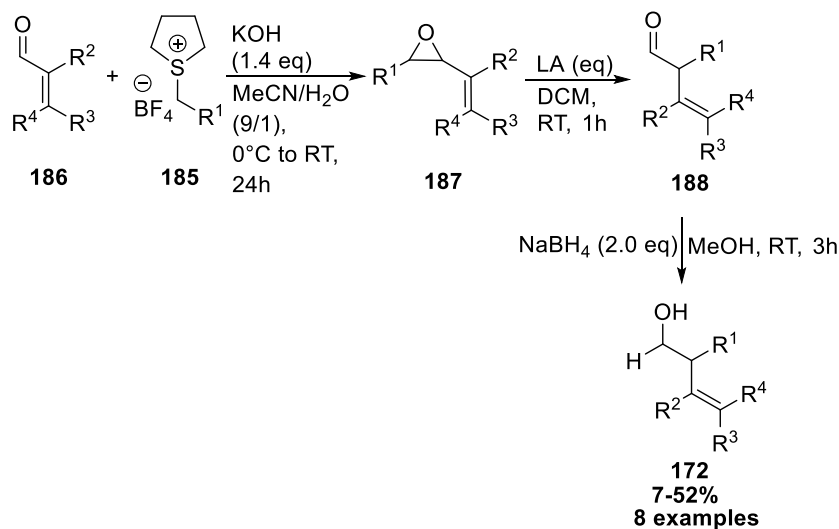
Scheme 5.24: Three steps strategy for the obtaining of primary homoallylic alcohols **192**

The derivatisation of our aldehydes **188** by olefination reaction to form skipped dienes or by addition of an organometallic regeant to form secondary homoallylic alcohols was studied as well.

The skipped dienes **189aaa-aac** were never selectively obtained during our investigations on olefination reactions. The main issue that we encountered is the isomerisation of the starting material **188aa** into **191aa** under the olefination reaction conditions prior to the desired reaction (Scheme 5.25). This led to the formation of **227** as the major product and/or the presence of **191aa** in the reaction mixture. The desired skipped diene **189** was observed during our investigations of the Takai olefination but as a minor product.
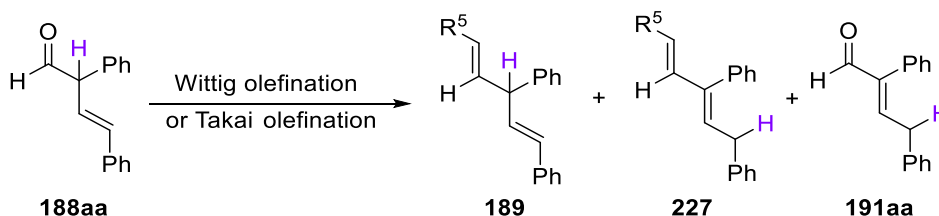
Scheme 5.25: Failed attempts at selectively obtaining skipped dienes from **188aa**

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The Petasis olefination conditions led to some degradation, presumably of the starting material.

Despite our best efforts, we failed to obtain any secondary homoallylic alcohol **190** by the addition of a nucleophilic organometallic reagent (Grignard, organocuprate or organozinc) on the β,γ-unsaturated aldehyde **188aa** (Scheme 6.21), which is possibly degraded by the organometallic compound before it can undergo the desired reaction.
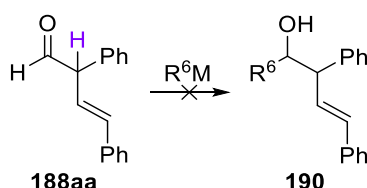
Scheme 5.26: Failed attempts at additionning an organometallic reagent on **188aa**

The acidity of the H in the α position was found to be a problem for both olefination reactions and the addition of organometallic compounds, as the reagents involved in these transformations are basic. An analysis of the existing literature for these reactions indicated that the presence of the phenyl group was detrimental to the obtaining of the desired product, as the reactions were already reported for R^1 = H and Me. Secondary homoallylic alcohol **190aad** could, nonetheless, be obtained using an allylation reaction.

5.5. Enantioselective version

5.5.1. Strategy

The development of an enantioselective version of our homologation of α,β-unsaturated aldehydes methodology was a logical continuation of this work. As for our strategy towards enantioenriched skipped dienes (see 4.4.), we envisaged the use of chiral sulfonium salts developed by the group of Prof. V.K. Aggarwal to induce enantioinduction (Scheme 5.27).

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186   **102**   **187**   **188**
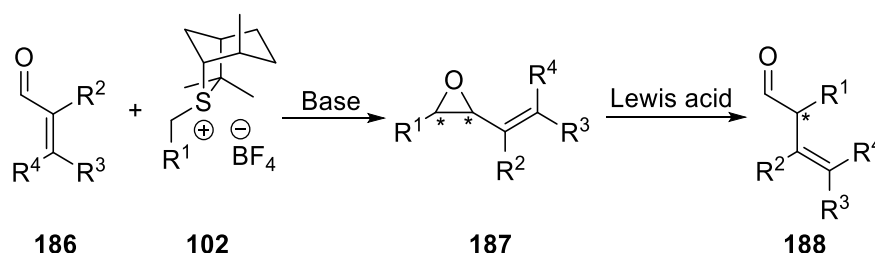
<u>Scheme 5.27</u>: Envisaged strategy for the enantioselective synthesis of β,γ-unsaturated aldehydes

      The strategy requires the Meinwald rearrangement of the epoxides to be stereospecific for the chiral information of the epoxides to be carried over to the desired β,γ-unsaturated aldehydes. Multiple parameters are of interest for the stereospecificity of the Meinwald rearrangement step.

      First, the rearrangement needs to occur through only one pathway. Indeed, two mechanisms are possible to explain the formation of **188aa** from **187aa** (see 5.2.2.1.). The rearrangement of an enantiomer of the epoxide via the two different pathways (Path A or B) lead to the formation of the two different enantiomers of the desired product **188aa** (Scheme 5.28).
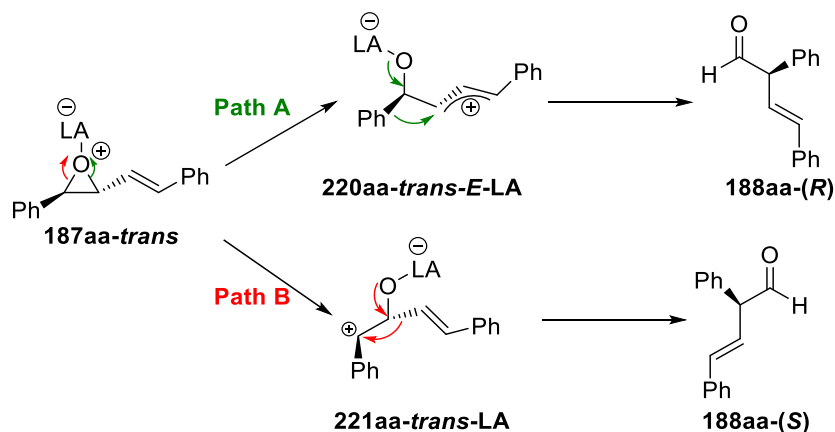
<u>Scheme 5.28:</u> Two competitive mechanisms for the formation of **188aa** and impact on the stereochemistry of the product

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It is also crucial that the Meinwald rearrangement occurs from only one of the diastereoisomers of the zwitterion intermediate **220aa-LA** (Scheme 5.29).
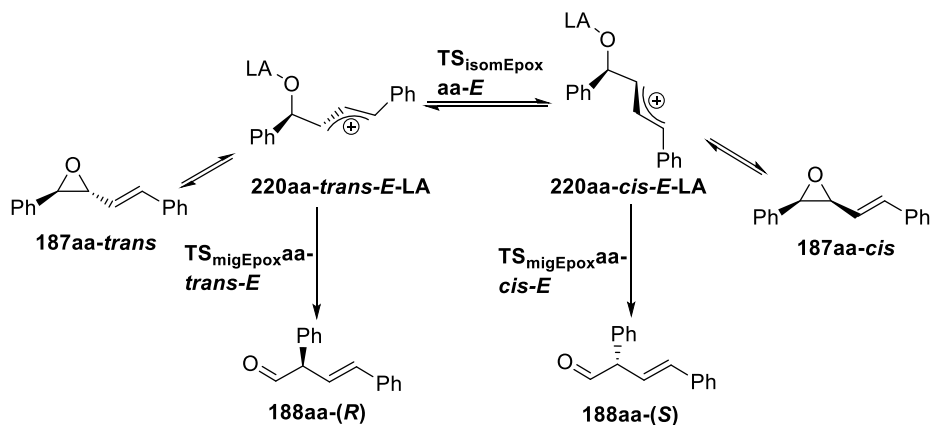
Scheme 5.29: Rearrangement of a **187aa-trans** of fixed stereochemistry

However, no evidence of *cis-trans* isomerisation of the epoxide (through **TS_isomEpox aa-E**) before the 1,2-migration has been observed. This means that the d.r. of the obtained epoxide could potentially be an issue. However, the group of Prof. V.K. Aggarwal reported excellent d.r. (>95/5) for the epoxidation reaction leading to **187aa-trans** using the same kind of sulfonium salt under similar reaction conditions (Scheme 5.30).[50] This is thus encouraging for our investigations.
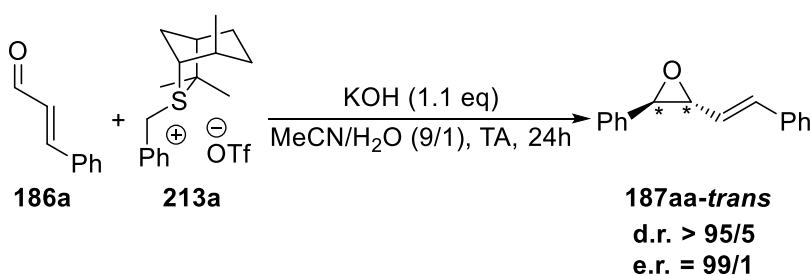
Scheme 5.30: Synthesis and determination of the e.r. of vinylepoxide **187aa-trans** by the group of Prof. V.K. Aggarwal

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5.5.2. Results

5.5.2.1. Synthesis

We started our investigations using our reference substrates, *i.e.* $R^1 = R^3 = Ph$ and $R^2 = R^4 = H$ (Scheme 5.31).

186a   **102a**   **187a-*trans*, 49%**   **188aa, 83%**
d.r. >99/1
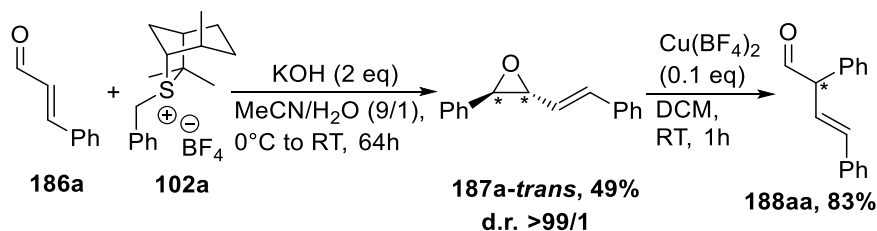
Scheme 5.31: Synthesis and rearrangement of **187aa-*trans***

The reaction conditions used for the racemic version led to the partial conversion of the cinnamaldehyde **186a**. The amount of sulfonium salt and KOH were thus increased from 1.4 eq to 2.0 eq, which led to full conversion. The epoxide was recovered in a lower yield than in the racemic version (88%, see 6.1.1.) because of the necessity to perform a flash chromatography to remove the sulfur auxiliary released during the Corey-Chaykovsky type epoxidation reaction (which was not required to remove tetrahydrothiophene due to its volatility). The epoxide was found to degrade on the silica gel, which explains the lower yield obtained. The isolation of **187aa** from the degradation products was found to be easy and the development of alternative purification technique was not carried out. The diastereoselectivity measured on the crude mixture was 98/2 in favour of the *trans* isomer but the sample recovered after the purification had a d.r. of >99/1. The Meinwald rearrangement of **187aa** was carried out using the reaction conditions previously developed for the racemic version of the methodology (see 5.2.2.). Similar yield in isolated compound was obtained (83%).

The depicted stereochemistry of the two stereocenters of **187aa-*trans*** has been predicted using the model developed by the group of Prof. V. K. Aggarwal[50] that we already used in the chapter regarding the investigations on the enantioselective synthesis of skipped dienes (see 4.4.1.).

5.5.2.2. Analysis

Having the epoxide **187aa-*trans*** and the aldehyde **188aa** in hand, the samples were analysed by chiral HPLC by Laurent Collard. The *trans* epoxide was found to have an enantiomeric ratio of 98/2. Unfortunately, our aldehyde sample was not pure enough for the determination of the e.r. of the β,γ-unsaturated aldehyde **188aa**. This could be due to the degradation of the sample at room temperature between the deposit of the sample to Laurent or on the column itself. To solve to this problem, we decided to use our previously developed reduction conditions to form the primary homoallylic alcohol **192aa** (Scheme 5.32). We hypothesised that the reduction reaction should not influence the configuration of the stereogenic center obtained after the Meinwald rearrangement. Satisfyingly, the homoallylic alcohol **192aa** was indeed found to be easy to purify, bench- and column-stable. **192aa** was then used to develop the analytical method and to measure the e.r. obtained for the Meinwald rearrangement step.
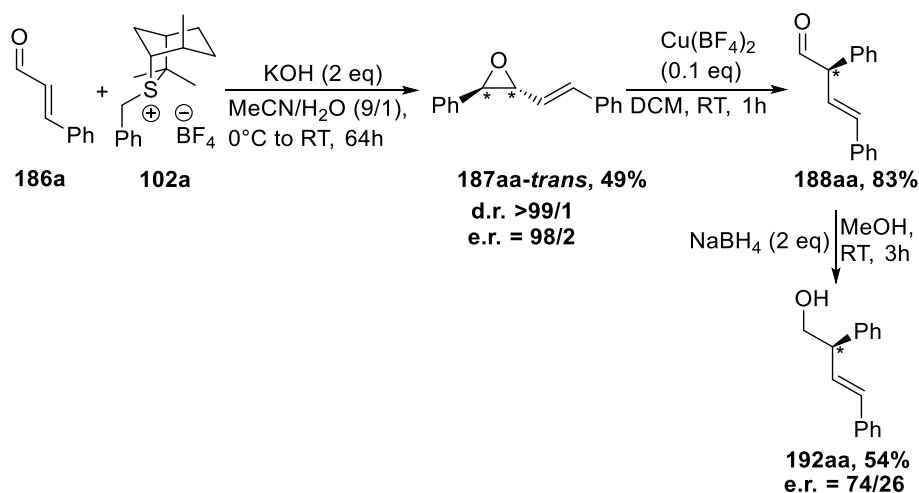
Scheme 5.32: First determination of an e.r. of the primary homoallylic alcohol **192aa**

The sequence was then started again and the aldehyde **188aa** was directly derivatised to the corresponding alcohol to prevent any degradation to occur. The alcohol **192aa** was then isolated and

analysed by chiral HPLC and the measured enantiomeric ratio was found to be 74/26, indicating a partial stereospecificity of the rearrangement step.

Accordingly, we investigated the origin of this partial stereospecificity (Table 5.16). One hypothesis to explain this result is the epimerisation of the aldehyde formed by the Lewis acid. This was investigated by studying the impact of the time of the reaction on the measured e.r.. We also tested our hypothesis that the reduction reaction was not influencing the e.r. of the obtained alcohol.

Table 5.16: Influence of the reaction conditions for the Meinwald rearrangement and reduction steps on the e.r. of the alcohol **192aa**
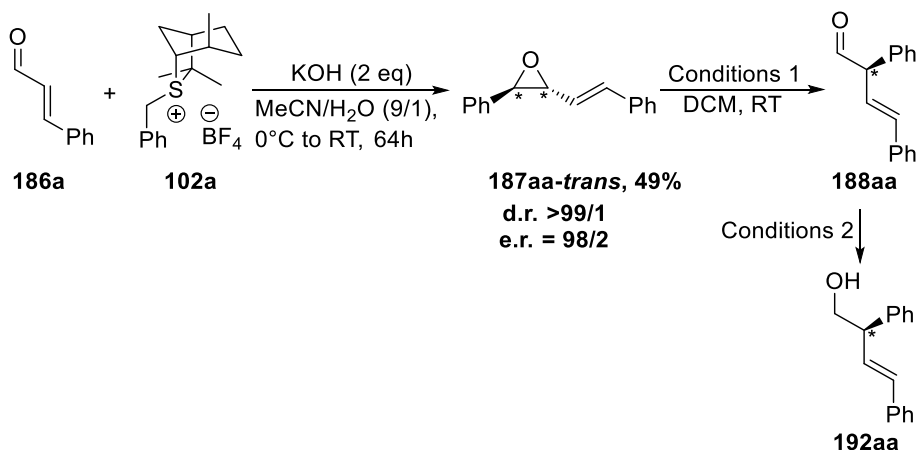
Entry	Conditions 1	Conditions 2	e.r.[a]
1	Cu(BF$_4$)$_2$ (0.1 eq), 1h	NaBH$_4$ (2 eq), MeOH, RT, 3h	74/26
2	Cu(BF$_4$)$_2$ (0.05 eq), 1h	NaBH$_4$ (2 eq), MeOH, RT, 3h	74/26
3	Cu(BF$_4$)$_2$ (0.1 eq), 30 min[b]	NaBH$_4$ (2 eq), MeOH, RT, 3h	73/27
4	Cu(BF$_4$)$_2$ (0.1 eq), 4h	NaBH$_4$ (2 eq), MeOH, RT, 3h	73/27
5	Cu(BF$_4$)$_2$ (0.1 eq), 1h	LiAlH$_4$ (1.1 eq), Et$_2$O, -78°C 1h, RT 1h	75/25

[a] Determined by chiral HPLC. [b] These conditions led to only a partial conversion of **187aa-trans**. The reduction was pursued on this mixture and the epoxide was removed by flash chromatography after the reduction step.

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It was observed that the reaction time and the amount of Lewis acid used did not have a significant impact on the enantioselectivity (entries 1-4). This indicates that there is no epimerisation occurring during the Meinwald rearrangement under tested reaction conditions.

The solvent used for our reduction reaction is protic, so we decided to investigate the possibility of the epimerisation of the aldehyde triggered by the protons of the solvent prior to its reduction by $NaBH_4$ by performing the reduction using an aprotic solvent, the diethylether (entry 5). For this protocol, the reducing agent is $LiAlH_4$. The enantiomeric ratio of **192aa** was found to be identical when the reduction reaction is performed in dry aprotic solvent. This means that the origin of the partial lost of enantioselectivity during the Meinwald rearrangement lies in the rearrangement step itself.

5.5.2.3. Other example

During his internship, Pierre-Louis Lefebvre investigated the enantioselective synthesis of the alcohol **192af**.[101] To do so, he started the synthesis using the β-phenyl cinnamaldehyde **186f** instead of the cinnamaldehyde (Scheme 6.28). The aim of his work was studying the effect of the substitution pattern of the epoxide on the e.r. of the analysed alcohol.

Scheme 5.33: Synthesis of the enantioenriched alcohol **192af** with the determined e.r.
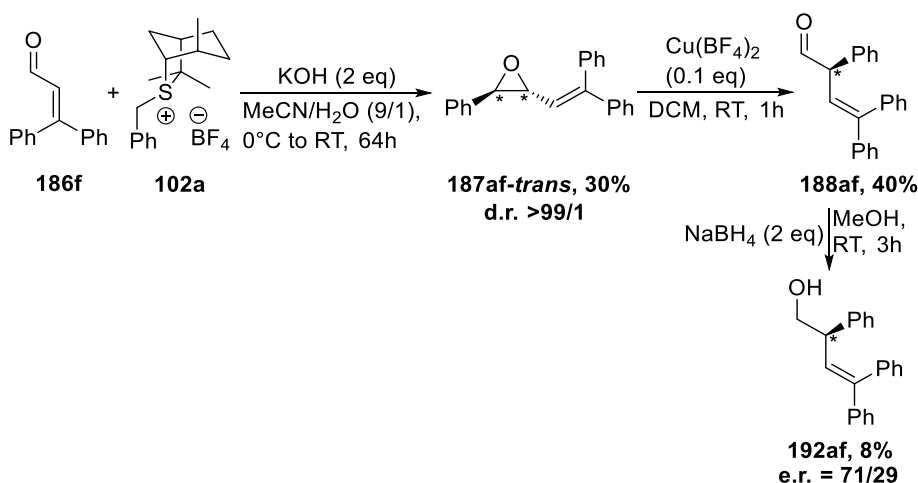
CHAPTER 5: HOMOLOGATION OF α,β-UNSATURATED ALDEHYDES

The epoxidation reaction also led exclusively to the *trans* isomer of the epoxide. Again, the yield is low due to the partial degradation of the epoxide on the silica during the purification by flash chromatography. Moreover, the products of the degradation were not as easily separable as previously and some rearrangement products such as **188af** and the corresponding ketone were already present in the sample prior to the Meinwald rearrangement reaction. Nevertheless, Pierre-Louis performed the rearrangement on the mixture. Every side products were removed by flash chromatography during the purification of the primary homoallylic alcohol **192af** which was then obtained in a very low yield.

The Meinwald rearrangement and reduction steps were performed using our first investigated reaction conditions (see entry 1, Table 6.16) and the e.r. determined by chiral HPLC was 71/29; identical to the one obtained for **192aa** (see Table 5.16). The e.r. of the epoxide was not determined by chiral HPLC for this example but we hypothesised that it is still excellent and that the origin of the poor e.r. of the analysed alcohol is also the partial stereospecificity of the Meinwald rearrangement step.

5.5.3. Conclusions

We investigated the possibility of developing an enantioselective version of our α,β-unsaturated aldehydes methodology using chiral sufonium salts. The enantiomeric ratios were measured on the primary homoallylic alcohol **192aa** due to the high degradability of the aldehyde **188aa** (Scheme 5.34).
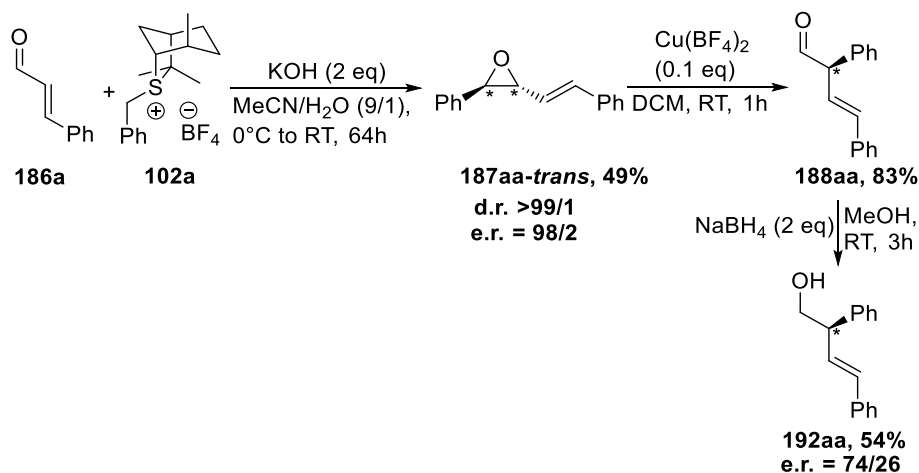
Scheme 5.34: Enantioselective synthesis of alcohol **192aa**

Unfortunately, the required high stereospecificity of the rearrangement turned out to be lacking; only a low stereospecificity was observed. Indeed, the e.r. of the alcohol **192aa** (74/26) is significantly lower than one of the epoxide **187aa-*trans*** (98/2) obtained with the chiral sulfonium salt **102a** developed by the group of Prof. V. K. Aggarwal.

We showed that the reaction parameters of the Meinwald rearrangement conditions such as the catalyst loading and the time has no impact on the e.r. of the final product. The use of a protic solvent didn't lead to any change in the stereospecificity of the second step either. An interesting parameter to explore in a further study would be the nature of the Lewis acid used to trigger the rearrangement reaction.

Two hypotheses remain to explain the low stereospecificity of the Cu(BF$_4$)$_2$-catalysed Meinwald rearrangement of vinylepoxides:

1. The reaction occurs via two competitive pathways
2. The reaction occurs via one mechanism but via two diastereoisomers of the zwiterionic intermediate **220aa-LA**

These hypotheses will be investigated later during this work.

The presence of a second phenyl group on the epoxide **187-trans** was found to have no influence the e.r. of the primary homoallylic alcohol. The obtained e.r. for **192af** is 71/29, which is similar to our previously studied example.

5.6. Mechanistic investigations

One of our hypothesis to explain the partial stereospecificity of the 1,2-migration step of our homologation strategy is that the desired product is formed by two competitive mechanisms. Similarly to our studies on the rearrangement of vinylcyclopropanes (see Chapter 2), we decided to investigate the operating mechanism of the Meinwald rearrangement of the vinylepoxide **187aa** by the means of a deuteriation experiment.

To study its rearrangement, we had to synthesise the deuteriated epoxide **187aa-D** from d^1-benzaldehyde (Scheme 5.35). The desired epoxide was obtained in good yield using our typical reaction conditions.

65a-D   **178a**   **187aa, 83%**
                                                d.r. (*cis/trans*) 4/6
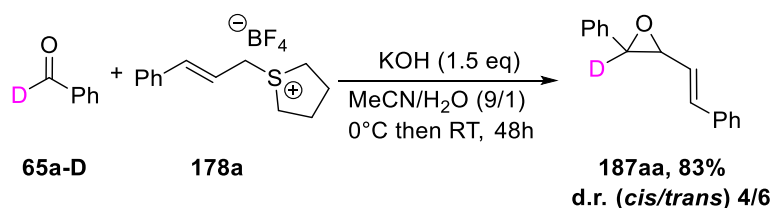
Scheme 5.35: Synthesis of **187aa-D**

The epoxide was rearranged using our classic reaction conditions with copper tetrafluoroborate(II) as the catalyst. The analysis of the ^{1}H NMR spectrum of the crude reaction mixture revealed that the rearrangement occurs selectively via the 1,2-migration of the phenyl group (**Path A**) (Scheme 5.36). This result is similar to our observations for the rearrangement of vinylcyclopropanes and can be explained by the selectivity of the opening step. Indeed, the positive charge created by the heterolytic ring-opening of **187aa-D** is better stabilised in the zwitterion intermediate involved in path A (**220aa-D-LA**) whereas the positive charge in delocalised on more atoms.
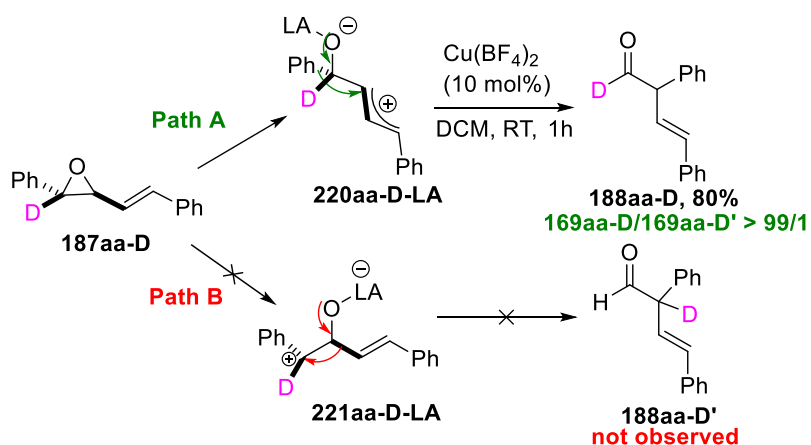
Scheme 5.36: Rearrangement of **187aa-D** lead to the selective formation of **188aa-D**

This result indicates that the origin of the partial stereospecificity of the Meinwald rearrangement step is not linked to the occurrence of two different mechanisms.

Our remaining hypothesis is that the rearrangement of **187aa-trans** occurs via the *cis* and *trans* diastereoisomers of the transition state **TS_{migEpox}aa**. It would be interesting to use DFT calculations to investigate this by creating a model containing all the molecules depicted in Scheme 6.32. Unfortunately, it could not be carried out in the context of this PhD thesis due to a lack of time.
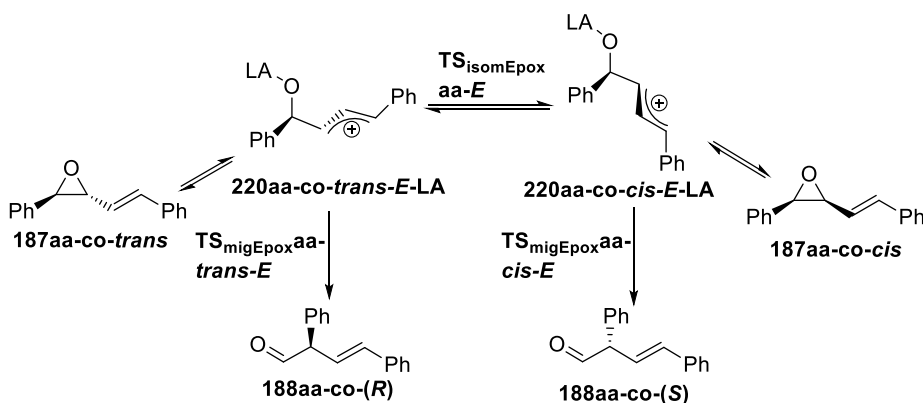
Scheme 5.37: Theoretical model for the investigation of the partial stereospecificity of the rearrangement step

5.6. Conclusions

5.6.1. Development of the methodology

After exploring further the rearrangements of vinylcyclopropanes and the obtaining of skipped dienes, we decided to use the gained knowledge to develop new methodologies. The first one we explored consists in a two-step strategy leading to β,γ-unsaturated aldehydes **188**. Indeed, we successfully developed a one-carbon homologation methodology of α,β-unsaturated aldehydes **186** by insertion of a CHAr fragment coming from benzylic sulfonium salts **185** and going through the Meinwald rearrangement of vinylepoxides **187** (Scheme 5.38). This methodology allows for the selective synthesis of α-aryl β,γ-unsaturated aldehydes using mild reaction conditions preventing their isomerisation to the corresponding α-aryl α,β-unsaturated aldehydes. This work broadens the scope of the previously reported synthesis of such aldehydes which was limited to R^3 = TMS and uses milder reaction conditions than the hydroformylation of 1,3-dienes (see 5.1.1.).
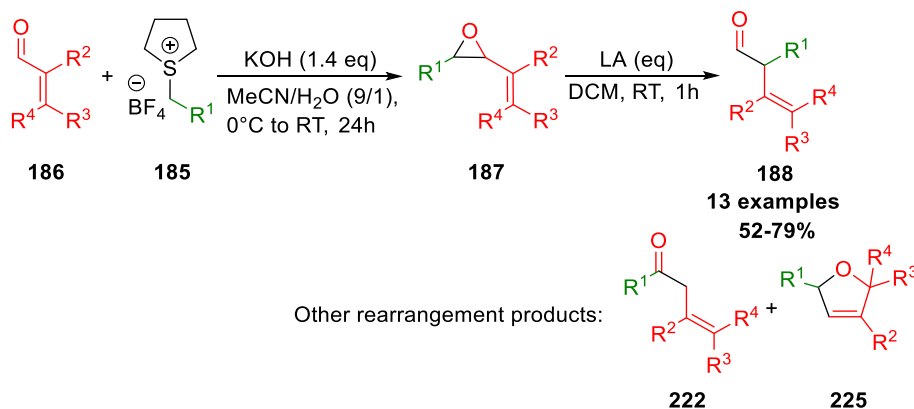
Scheme 5.38: Developed one-carbon homologation of α,β-unsaturated aldehydes methodology

A total of 13 β,γ-unsaturated aldehydes were obtained with a global isolated yield varying from 52 to 79%. Unfortunately, some of the epoxides investigated led to the formation of complex mixtures containing the desired products but together with the formation of side products such as the corresponding β,γ-unsaturated ketone **222**

(R^1 = electron poor aryls) or the dihydrofuran **225** (R^3 = *p*-MeOC$_6$H$_4$). Aldehydes with R^1 = alkyl group could not be isolated either as the hydrogen was found to undergo the 1,2-migration reaction faster than alkyl groups.

5.6.2. Derivatisation of the obtained aldehydes

The derivatisation of the β,γ-unsaturated aldehydes was explored. We were able to develop methodologies for the isomerisation of the β,γ-unsaturated aldehyde **188aa** into its corresponding α,β-unsaturated aldehyde **191aa**, for the reduction of the aldehyde into a primary homoallylic alcohol **192** and formation of a secondary homoallylic alcohol, **190aad**, via an allylation reaction (Scheme 5.39). The olefination and the addition of organometallic reagent reactions never afforded the desired product. This demonstrates the sensitivity of the α-aryl β,γ-unsaturated aldehydes to isomerisation due to their acidic proton in the α position. An analysis of the literature suggested that the presence of the aryl group in the α position (R^1), by increasing the acidity of the purple proton in our substrates, is a major problem for these derivatisation reactions using basic reagents, as these reactions were already reported for R^1 = H and Me groups.
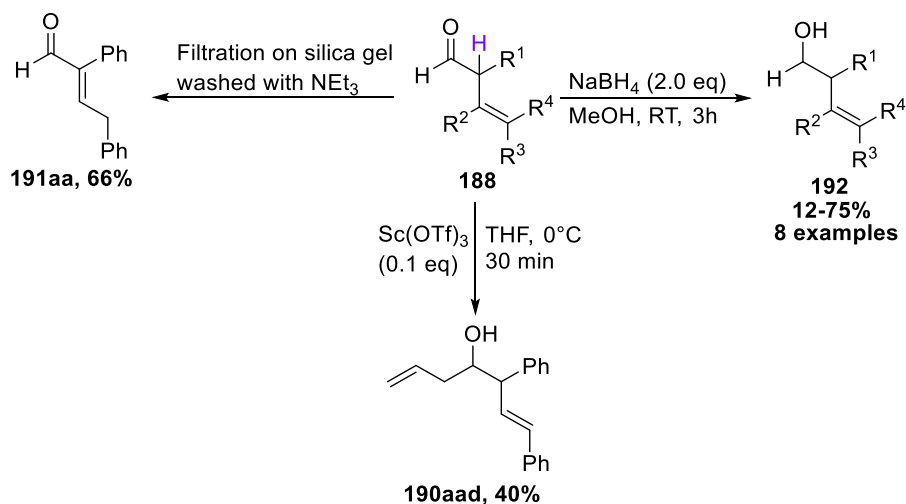
Scheme 5.39: Successful derivatisation of β,γ-unsaturated aldehyde **188**

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5.6.3. Enantioselective version

Similarly to our work on skipped dienes, we attempted to develop an enantioselective version of the methodology using chiral sulfonium salts. Due to the low stability of β,γ-unsaturated aldehydes, enantioselectivities were measured on the homoallylic alcohol **192aa**, obtained after reduction by NaBH$_4$ (Scheme 5.40).
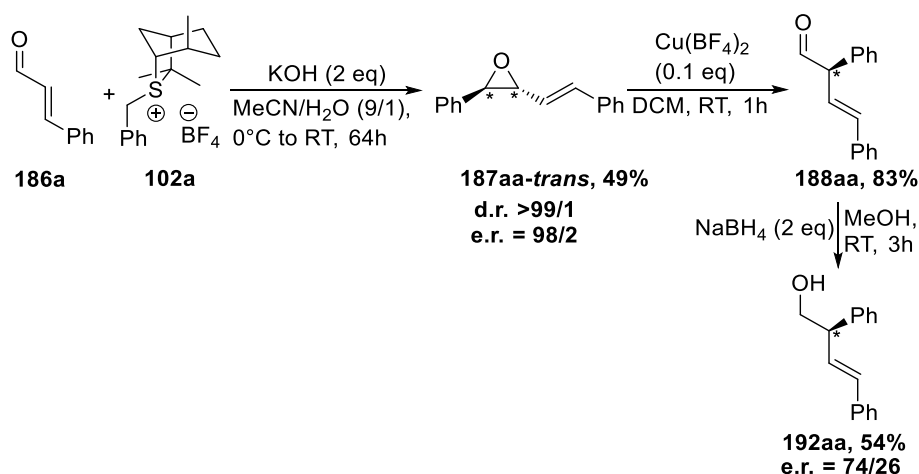
Scheme 5.40: Enantioselective synthesis of alcohol **192aa**

Unfortunately, the high stereospecificity of the rearrangement required for the strategy to work was not observed. Indeed, the e.r. of **192aa** was measured by chiral HPLC to be 74/26 while the corresponding epoxide showed an e.r. of 98/2. Multiple test reactions were performed to investigate factors which could impact the enantioselectivity. The catalyst loading and the time of the Meinwald rearrangement reaction were found to have no impact on the enantiomeric ratio. The reaction conditions used for the reduction reaction were also ruled out as a possible explanation. The investigation of another substitution pattern on the epoxide showed similar measured e.r. Another possible explanation for this partial stereospecificity was that the formation of the β,γ-unsaturated aldehydes is explained by the occurrence of two concomitant mechanisms. A deuteration experiment refuted that hypothesis by showing that the aldehyde was selectively obtained by one mechanism.

Scheme 5.40: Enantioselective synthesis of alcohol **172aa**

Unfortunately, the high stereospecificity of the rearrangement required for the strategy to work was not observed. Indeed, the e.r. of **172aa** was measured by chiral HPLC to be 74/26 while the corresponding epoxide showed an e.r. of 98/2. Multiple test reactions were performed to investigate factors which could impact the enantioselectivity. The catalyst loading and the time of the Meinwald rearrangement reaction were found to have no impact on the enantiomeric ratio. The reaction conditions used for the reduction reaction were also ruled out as a possible explanation. The investigation of another substitution pattern on the epoxide showed similar measured e.r. Another possible explanation for this partial stereospecificity was that the formation of the β,γ-unsaturated aldehydes is explained by the occurrence of two concomitant mechanisms. A deuteriation experiment refuted that hypothesis by showing that the aldehyde was selectively obtained by one mechanism.

Chapter 6: Homologation of activated olefins

Despite being a challenge in organic synthesis, the one-carbon homologation of alkenes is an important transformation.

Homologation of small molecules by metathesis with silica supported metals (Fe, Ru, Os) was reported.[107] Multistep strategies have also been developed. Typical strategies include hydroboration/oxidation/Wittig, hydrophosphination/Wittig and metathesis/reduction of allylic carbonate cascade.[108]

All these methods have however a common limitation: the one-carbon fragment inserted is a methylene. Homologation strategies with the insertion of a CHR fragment remain a challenge. One recent example of such process is the homologation of vinylboronates developed by Mattesson and Aggarwal.[109]

We proposed to investigate the homologation of activated olefins, Knoevenagel adducts. Our strategy is a formal homologation of the olefin **177** by the insertion of the CHR^2 fragment coming from the sulfonium salt. The two-step homologation process involving a cyclopropanation reaction followed by a Lewis acid promoted 1,2-migration reaction is depicted in Scheme 6.1.
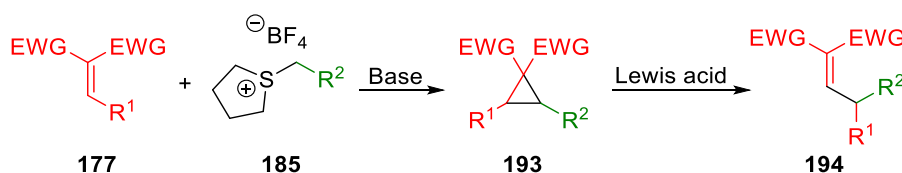
Scheme 6.1: Formal one-carbon homologation of activated olefin **177** by the insertion of a CHR^2 fragment

The difference with our previously discussed homologation of 1,3-diene (see Chapter 2 and 5) strategy is the replacement of the 1,3-dienes by activated olefins (Figure 6.1).

184   replaced by   **177**
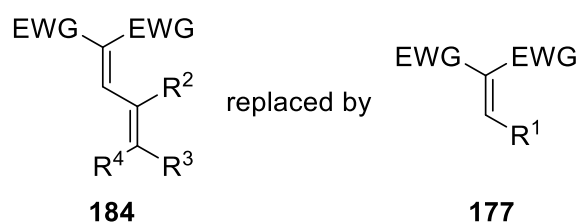
Figure 6.1: 1,3-Dienes are replaced by activated olefins

As discussed in the introduction, Lewis acid triggered ring-opening/1,2-migration sequence of DACPs has already been reported (see 1.1.3.2.). The resulting formal one-carbon homologation was however limited to the insertion of a methylene group. Our work aims at broadening the scope to the insertion of CHAr groups and study the influence of the nature on R^1 and R^2 on the rearrangement reaction. An enantioselective version of the methodology for allowing the insertion of a CHR fragment of defined stereochemistry is another point of interested in this chapter.

6.1. Optimisation

We first showed the feasibility of the methodology and optimised the two steps of the proposed methodology on model substrates: benzylic sulfonium salt **185a** and the olefin bearing a phenyl group (**177a**) (Scheme 6.2).

177a   **185a**   **193aa**   **194aa**
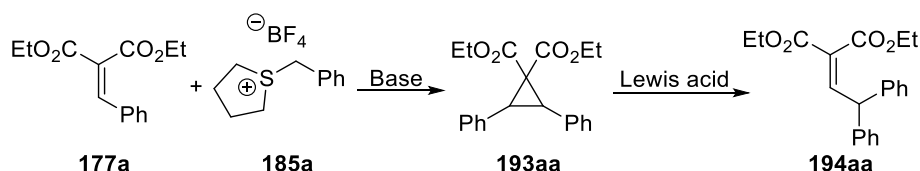
Scheme 6.2: Model system chosen for the optimisation process

This work was carried out by Julien Janssens in the context of his Master's thesis and expanded upon by Thomas Vanhosmael during his internship.[83,110]

CHAPTER 6: HOMOLOGATION OF ACTIVATED OLEFINS

6.1.1. Cyclopropanation reaction

The first reaction investigated during this optimisation process was the cyclopropanation reaction. LiHMDS conditions used for the formation of vinylcyclopropanes could be utilised as such for the cyclopropanation reaction of **177a** and **185a**. The cyclopropane **193aa** is obtained in a good yield and a d.r. slightly in favour of the *cis* isomer (Scheme 6.3).
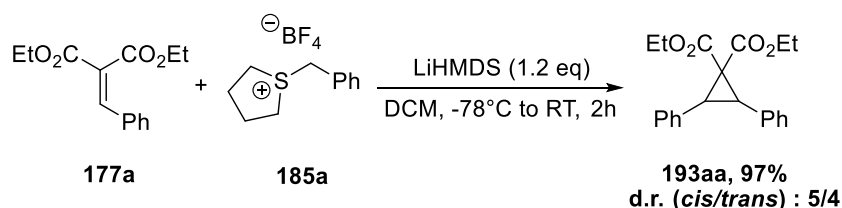
Scheme 6.3: Synthesis of **193aa**

The optimisation process for the cyclopropanation reaction was stopped at this point and we then concentrated our efforts on finding suitable reaction conditions for the second step of the process, the rearrangement of the cyclopropane into the corresponding homologated olefin.

6.1.2. Lewis acid promoted rearrangement

After obtaining the cyclopropane **193aa**, we became interested in its rearrangement into the targeted olefin **194aa**. Thomas Vanhosmael investigated different Lewis acids for this transformation (Table 6.1).[110]

CHAPTER 6: HOMOLOGATION OF ACTIVATED OLEFINS

<u>Table 6.1</u>: Optimisation of the rearrangement step by varying the Lewis acid
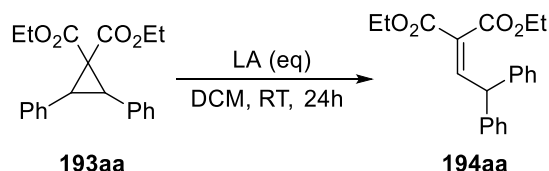
Entry	LA (eq)	193aa/194aa[a]	Yield (%)[b]
1	Cu(BF$_4$)$_2$ (1 eq)	100/0[c]	n.d.
2	Sc(OTf)$_3$ (1 eq)	99/1	n.d.
3	MgI$_2$ (1 eq)	99/1	n.d.
4	Fe(OTf)$_3$ (1 eq)	83/17	n.d.
5	SnCl$_4$ (1 eq)	34/66	n.d.
6	TiCl$_4$ (1 eq)	11/89	n.d.
7	FeCl$_3$ (1 eq)	17/83	n.d.
8	TiCl$_4$ (3 eq)	0/100	91
9	FeCl$_3$ (3 eq)	0/100	85

[a] Determined by ^{1}H NMR on the crude mixture. [b] Yield in pure isolated compound of **194aa** (only determined when the conversion was complete). [c] No *cis-trans* isomerisation of **193aa** was observed.

For the first part of this study, every Lewis acid was loaded with 1 equivalent and the reaction was carried out at room temperature for 24 hours. The obtained reagent/product (**193aa/194aa**) ratio was determined by ^{1}H NMR on the crude mixture.

The Lewis acid used in our homologation of α,β-unsaturated aldehydes methodology (see Chapter 5) is not a suitable catalyst for this reaction: no formation of the desired product or *cis-trans* isomerisation of **193aa** is observed (entry 1). Some Lewis acids, Sc(OTf)$_3$ and MgI$_2$, did not lead to the formation of **194aa** in more than traces amount, but in these cases the *cis-trans* isomerisation of **193aa** was complete and only **193aa-*trans*** was recovered after the work up (entries 2 and 3).

The best conversions for this transformation were obtained with TiCl$_4$ and FeCl$_3$ (entries 6 and 7), our Lewis acid of choice for the rearrangement of vinylcyclopropanes (see Chapter 4). However, these reaction conditions did not lead to the full conversion of **193aa**. We then increased the loading of the two Lewis acids up to 3 equivalents, keeping the same reaction time and temperature (entries 8 and 9), which led to full conversions and the obtaining of **194aa** in good yields (91% and 85% for TiCl$_4$ and FeCl$_3$, respectively).

6.1.3. One-pot version

After optimising separately the two reactions involved in our homologation methodology, we investigated the possibility of developing a one-pot version combining the two reactions in one synthetic step, without the need of isolating **193aa** (Scheme 6.4).
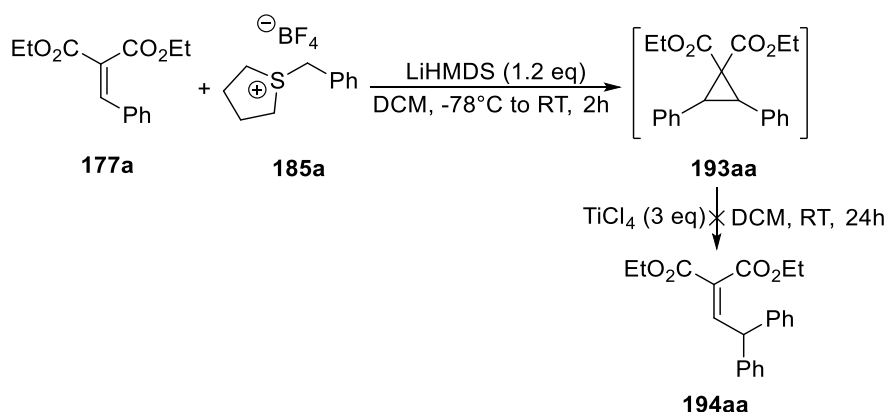
Scheme 6.4: Failed attempt at developing a one-pot version of the methodology

Unfortunately, in our first attempt, the desired olefin **194aa** was not observed in the crude reaction mixture. Instead, the cyclopropane **193aa** was present with other unidentified side products.

We went on to perform control experiments to try to understand the reasons explaining this result. The rearrangement reaction was carried out from purified samples of **193aa** in the presence of either 1 equivalent of the sulfur auxiliary released during

the cyclopropanation reaction, THT, or of HMDS, the conjugated acid of the base used to deprotonnate the benzylic sulfonium salt **185a** (Table 6.2)

Table 6.2: Rearrangement of **193aa** in the presence of either 1 eq of HMDS or tetrahydrothiophene
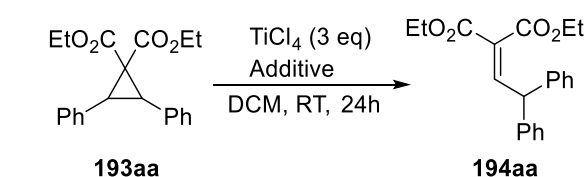
Entry	Additive	Observations
1	HMDS (1 eq)	**193aa-*trans***
2	THT (1 eq)	**193aa-*trans*** + side products

The reaction in the presence of 1 equivalent of HMDS led exclusively to the isomerisation of **193aa** to provide a fully **193aa-*trans*** sample. Thus, the presence of this additive prevents the desired rearrangement reaction. This problem could potentially be solved by switching the nature of the base to one having a conjugated acid which is not detrimental to the rearrangement reaction. However, the presence of 1 equivalent of the sulfur auxiliary was also observed to be detrimental to the obtaining of the homologated olefin **194aa**, as **193aa-*trans*** was recovered among side products after the test reaction. This was at first surprising since we were able to develop a one-pot version of our homologation of 1,3-dienes methodology using TiCl$_4$ as the Lewis acid (see Chapter 2). The main difference between these two methodologies is the reaction time of the Lewis acid triggered rearrangement step. The formation of the skipped diene was complete after 15 minutes whereas the reaction investigated during this chapter takes 24 hours in the presence of three times the amount of Lewis acid. We hypothesised that the formation of the side product is not fast enough to be observed after 15 minutes of reaction but can disrupt the reaction if it takes longer reaction time.

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During his PhD thesis, Dr. Maximilien Richald attempted to develop a one-pot version of his methodology towards cyclopentenes (Scheme 6.5).[80]
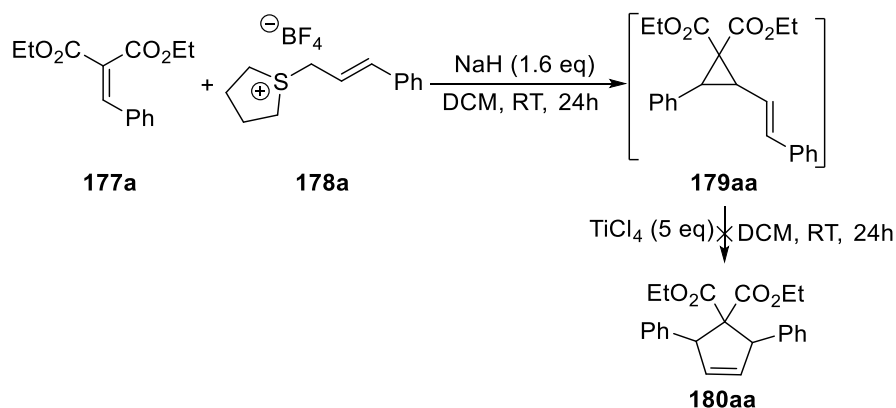
Scheme 6.5: Investigation of a one-pot version of the methodology for the synthesis of cyclopentenes by Dr. Maximilien Richald

Similarly, to the methodology described in this chapter, this reaction takes 24 hours and in the presence of even more equivalents of the Lewis acid. This time, the conjugated acid of the base, H_2, is not contaminating the reaction but it failed to provide cyclopentene **180aa** nonetheless. Maximilien hypothesised that the zwitterion intermediate **182aa-TiCl₄** could be quenched by the sulfur auxiliary and that product **232aa** could be obtained after a protonation occurring during the acidic workup (Scheme 6.6).
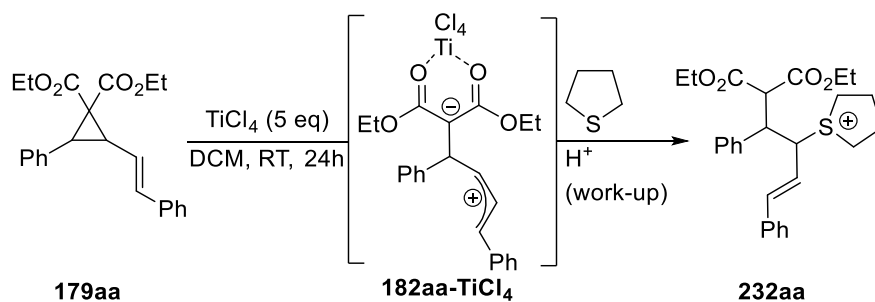
Scheme 6.6: Quenching of the zwitterion intermediate **182aa-TiCl₄** by THT

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This hypothesis was backed by a HRMS analysis of the crude mixture which detected the mass of the product **232aa** in the reaction mixture. Similarly, the quenching of zwitterion intermediate **233aa** by THT could explain our result (Scheme 6.7)
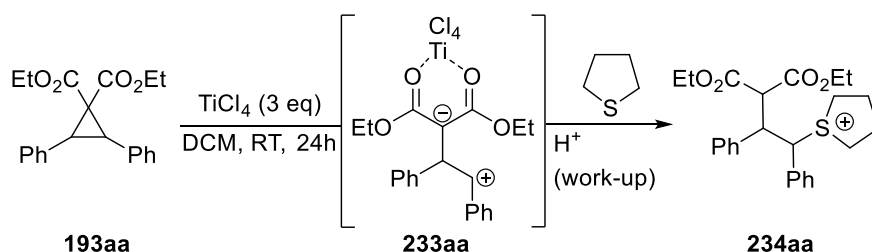
Scheme 6.7: Hypothetical quenching of the zwitterion intermediate **233aa-TiCl₄** by THT

Considering that the release of THT during the cyclopropanation step is hardly avoidable as its poisoning of the second step, the investigation on the one-pot version was stopped at this point.

6.2. Exploration of the scope

The scope of this methodology was then explored by varying the nature of the substituents brought by the activated olefin **177** and the benzylic sulfonium salt **185**. This exploration was carried out in collaboration with Julien Janssens, Madeline De Roose and Thomas Vanhosmael using the previously developed two-step methodology.[83,111,110]

6.2.1. Cyclopropanation

The previously developed reaction conditions were used to produce a library of 18 donor-acceptor cyclopropanes (Table 6.3). The studied sbustituents were electron-donor and –acceptor aryls, alkyls, 2-naphthyl and heteroaryls. Cyano groups as EWGs were also investigated.

Table 6.3: Synthesis of donor-acceptor cyclopropanes **193**
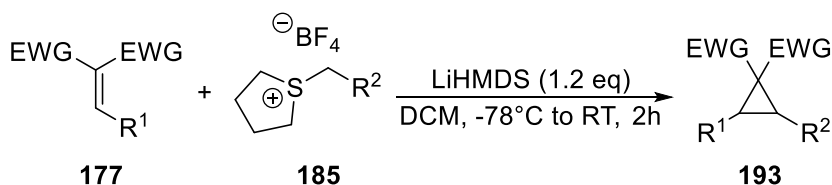
Entry	DACPs	EWG	R^1	R^2	Yield (%)[a]	d.r. (*cis/trans*)[b]
1	**193kk**	CO_2Et	p-MeOC$_6$H$_4$	p-MeOC$_6$H$_4$	quant	67/33
2	**193ka**	CO_2Et	p-MeOC$_6$H$_4$	Ph	quant	67/33
3	**193la**	CO_2Et	p-MeC$_6$H$_4$	Ph	quant	60/40
4	**193ap**	CO_2Et	Ph	p-FC$_6$H$_4$	34 (70)	50/50
5	**193fa**	CO_2Et	p-CO$_2$MeC$_6$H$_4$	Ph	23 (56)	50/50
6	**193ca**	CO_2Et	m-OMeC$_6$H$_4$	Ph	78	67/33
7	**193as**	CO_2Et	Ph	m-ClC$_6$H$_4$	77 (99)	75/25
8	**193ab**	CO_2Et	Ph	o-MeC$_6$H$_4$	60 (84)	75/25
9	**193at**	CO_2Et	Ph	o-FC$_6$H$_4$	60	80/20
10	**193oa**	CO_2Et	2-naphtyl	Ph	86	50/50
11	**193na**	CO_2Et	2-furyl	Ph	51 (67)	33/67
12	**193va**	CO_2Et	2-Py	Ph	31 (65)	33/67
13	**193ha**	CO_2Et	Me	Ph	68 (97)[c]	60/40
14	**193da**	CO_2Et	t-Bu	Ph	47	0/100
15	**193ea**	CO_2Et	Cyclopropyl	Ph	65	33/67
16	**193aj**	CO_2Et	Ph	H	63[d]	-
17	**193aa-CN**	CN	Ph	Ph	38 (57)	67/33
18	**193ka-CN**	CN	p-MeOC$_6$H$_4$	Ph	quant	60/40

[a] Yield in pure isolated compound. In brackets, crude yield determined by ^{1}H NMR using an internal standard (DMT). [b] Determined by ^{1}H NMR on the crude reaction mixture. [c] A 15-minute delay was applied between the additions of the base and of the olefin. [d] A special procedure with a sulfoxonium salt was used to obtain this cyclopropane (*vide infra*).

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The yields for this reaction range from 38% to quantitative and the d.r. (*cis/trans*) varies a lot in these examples, from the *cis* diastereosisomer being the major product (10 of the 18 cyclopropanes) to exclusive *trans* selectivity. This selectivity for the *cis* diastereoisomer was never observed during our research on the vinylcyclopropanes (see 5.1.1.). The *trans* configuration is the most stable configuration of the product and we then hypothesised that the reason for these results is rooted in kinetics. The cyclopropanes obtained cover different substitution patterns of the two aryl groups, as well as DACPs with one alkyl and a phenyl group. Cyclopropanes bearing heteroaryl and 2-napthyl groups were also obtained. The example from entry 16 required the use of a special procedure for the isolation of cyclopropane **193aj** using NaH as a base and the trimethylsulfoxonium iodide **31j** as the methylene source (Scheme 6.8).
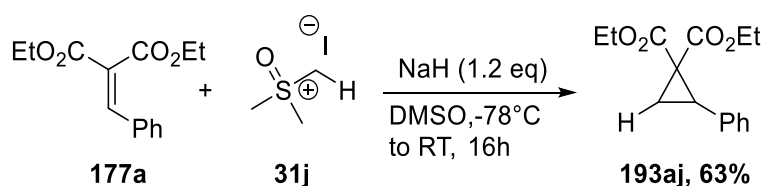
Scheme 6.8: Special procedure for the synthesis of **193aj**

6.2.2. Rearrangement reactions

The obtained cyclopropanes were then rearranged in the presence of a Lewis acid in order to investigate the reactivity towards the formation of the desired olefin **194** and the potential limitations of our methodology. The following results were obtained in collaboration with Julien Janssens, Madeline De Roose and Thomas Vanhosmael (Table 6.4).[83,111,110]

Table 6.4: Lewis acid triggered rearrangement of **193** to **194** or **235**
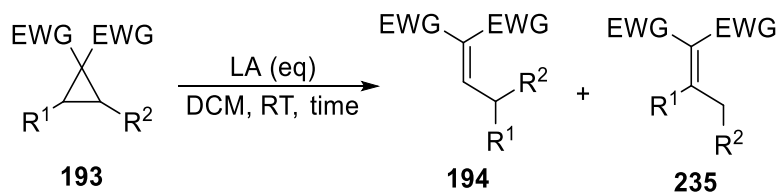
Entry	Olefin	EWG	R^1	R^2	LA (eq)	Time	Yield (%)[a] 194	Yield (%)[a] 235
1	**194kk**	CO_2Et	p-$MeOC_6H_4$	p-$MeOC_6H_4$	$TiCl_4$ (0.4 eq)	1h	90	0
2	**194ka**	CO_2Et	p-$MeOC_6H_4$	Ph	$TiCl_4$ (0.4 eq)	2h	88	0
3	**194la**	CO_2Et	p-MeC_6H_4	Ph	$TiCl_4$ (3 eq)	24h	68	0
4	**194ap**	CO_2Et	Ph	p-FC_6H_4	$TiCl_4$ (3 eq)	24h	88	0
5	**194fa**	CO_2Et	p-$CO_2MeC_6H_4$	Ph	$TiCl_4$ (3 eq)	24h	21	0
6	**194ca**	CO_2Et	m-$OMeC_6H_4$	Ph	$TiCl_4$ (3 eq)	24h	7(43)	0
7	**194as**	CO_2Et	Ph	m-ClC_6H_4	$TiCl_4$ (6 eq)	72h	58	0
8	**194ab**	CO_2Et	Ph	o-MeC_6H_4	$TiCl_4$ (3 eq)	24h	98	0
9	**194at**	CO_2Et	Ph	o-FC_6H_4	$TiCl_4$ (3 eq)	48h	94	0
10	**194oa**	CO_2Et	2-naphtyl	Ph	$TiCl_4$ (3 eq)	24h	89	0
11	**194na**	CO_2Et	2-furyl	Ph	$TiCl_4$ (3 eq)	24h	0[b]	0
12	**194va**	CO_2Et	2-Py	Ph	$TiCl_4$ (3 eq)	24h	0[b]	0
13	**194ha**	CO_2Et	Me	Ph	$FeCl_3$ (3 eq)	24h	0	77
14	**194da**	CO_2Et	t-Bu	Ph	$TiCl_4$ (1 eq)	16h	74	0
15	**194ea**	CO_2Et	Cyclopropyl	Ph	$TiCl_4$ (1 eq)	45 min	95	0
16	**194aj**	CO_2Et	Ph	H	$FeCl_3$ (3 eq)	24h	70	0
17	**194aa-CN**	CN	Ph	Ph	$TiCl_4$ (6 eq)	48h	57	0
18	**194ka-CN**	CN	p-$MeOC_6H_4$	Ph	$TiCl_4$ (6 eq)	24h	76	0

[a] Yield in pure isolated compound. In brackets, crude yield determined by ^{1}H NMR using an internal standard (DMT). [b] Degradation.

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Using the reaction conditions developed with our model substrate, the isolated yields for the rearrangement step are good for most of the obtained olefins. Entries 5 and 6 are the only examples were the desired product was recovered in a low yield.

The conditions allowing for the isolation of **194kk** are significantly milder than the one used on our model substrate **194aa**. Indeed, the presence of the methoxy group on the two aryls groups facilitates the ring-opening by stabilising the positive charge and the migrating group also possesses a better migrating ability than the phenyl group. Mild reaction conditions were also used for the formation of **194ka**, the non-symmetric cyclopropane with a Ph and a p-MeOC$_6$H$_4$ group as substituents.

Other *para* substituents on one of the two aryl groups were also investigated during this exploration. The presence of a methyl or a fluoride group at this position allowed us to isolate the desired product with a good yield (entries 3 and 4). Entry 5 shows that a strong withdrawing group led to the formation of the homologated olefin but in a low yield of 21%. The *meta* position was investigated next (entries 6 and 7). The two electron-withdrawing groups were tolerated and the desired product was isolated but in a moderate yield for m-ClC$_6$H$_4$ and a very low yield for m-MeOC$_6$H$_4$. Finally, the influence of a mild donor and a mild withdrawing group at the *ortho* position was studied. The two olefins were isolated in excellent yields (entries 8 and 9).

The olefin with a 2-napthyl group was successfully obtained in good yield (entry 10). Despite Madeline's best efforts, she was not able to isolate the olefins bearing heteroaryls groups (entries 11 and 12). The conditions developed during the optimisation process led to the degradation of the cyclopropanes. She investigated lower temperatures (0°C and -78°C) but was still unable to isolate the desired products **194na** and **194va**. At -78°C only partial *cis-trans* isomerisation of the cyclopropanes occured and the formation of an unidentified side product was observed for the rearrangement reaction of **193va**. The rearrangement carried out at 0°C also led to the degradation of the cyclopropane.

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The rearrangement of cyclopropanes with one alkyl group and a phenyl substituent were investigated. Similarly to our two previously developed methodologies (see Chapter 4 and 5), the migration of the methyl group was not observed and the olefin resulting from the migration of the H, **235ha**, was isolated. This example required us to switch to our conditions involving $FeCl_3$. The rearrangement promoted by $TiCl_4$ was attempted but led to a mixture of **235ha** and a lactone, **236ha** (Figure 6.2).
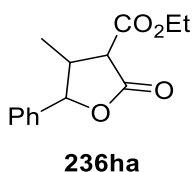
236ha

Figure 6.2: Lactone **236ha**

This type of side product was already observed during our exploration of the scope of the vinylcyclopropane-skipped diene rearrangement (see 4.3.2.3.).

The desired homologated olefin with *t*-Bu and cyclopropyle were obtained in good yields using milder reaction conditions than for the rearrangement of most diaryl cylclopropanes (entries 3-10, 16-18). This reactivity is similar to our rearrangement of vinylcyclopropanes and then differs from the Meinwald rearrangement of epoxides where the H was found to migrate preferentially over these two alkyl groups. Regarding the mechanism explaining the formation of **194ea**, we hypothesised that the heterolytic ring-opening occurs on the cyclopropyl side and the migration of phenyl group explains the formation of the product. Entry 16 shows that **194aj** could also be isolated in a good yield with the reaction conditions using $FeCl_3$ as the Lewis acid. When the titanium chloride was used as the catalyst for this transformation, a chlorinated product was obtained as the main product (**237aj**, Figure 6.3).
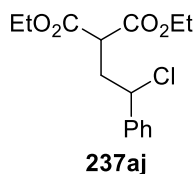
237aj

Figure 6.3: Chlorinated compound **237aj**

Contrary to the rearrangement of vinylcyclopropanes, the 1,2-migration type rearrangement of cyclopropanes **194** succesfully led to the formation of the homologated olefin bearing cyano groups as electron-withdrawing groups. The olefins **194aa-CN** and **29ka-CN** were obtained in good yields with twice the amount of Lewis acid as the previously optimised conditions. This can be accounted for by the need of two molecules of Lewis acid to complex the two cyano groups (**233aa-CN-TiCl₄**, Figure 7.4), for geometric reasons, whereas only one molecule of Lewis acid is sufficient to complex two ester groups (**233aa-TiCl₄**, Figure 6.4).

233aa-CN-TiCl₄   **233aa-TiCl₄**
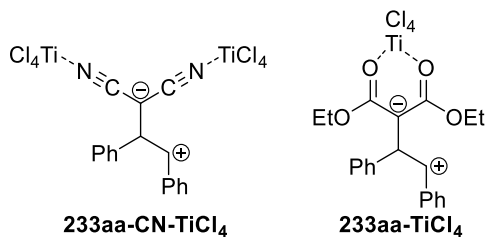
Figure 6.4: Zwitterion intermediates **233aa-CN-TiCl₄** and **233aa-TiCl₄**

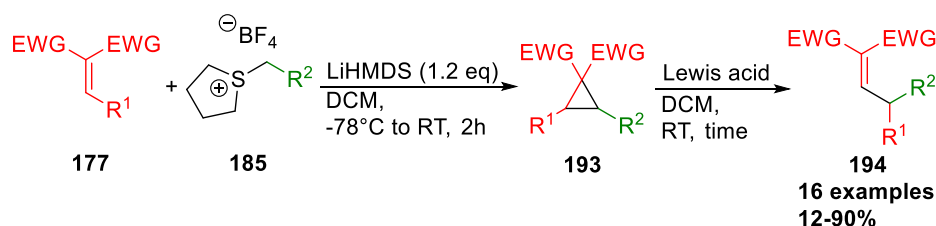## 6.2.3. Conclusions on the exploration of the scope

We were able to successfully use this methodology to obtain 16 homologated olefins with global yields varying from 12 to 90% (Scheme 6.9).

<u>Scheme 6.9:</u> One-carbon homologation of activated olefins methodology

Our exploration of the scope showed that aryl groups with donor or acceptor groups at every position are tolerated even if the conditions need to be harsher for some examples with electron-withdrawing groups. On the other hand, the conditions for the obtaining of **194** with one or two p-MeOC$_6$H$_4$ aryl group were significantly milder. The olefin with a 2-napthyl group can also be obtained.

Heteroaryl groups were also investigated during this work. Unfortunately, the heteroaromatic groups, 2-furyl and 2-Py, are not compatible with the methodology. The nature of the alkyl group has an impact on the outcome of the reaction. Indeed, the t-Bu substituent and the cyclopropyl group allow for the formation of the desired product whereas the methyl group is not migrating and loose the competition with the H being on the same carbon. These reactivity trends are similar to those observed for alkyl groups in the rearrangement of vinylcyclopropanes (see Chapter 4).

With this methodology, we were able to obtain the desired products bearing different electron-withdrawing groups than esters; the lack of a competitive cyclisation reaction (as in the rearrangement of vinylcyclopropane) is explaining this result.

One question is not answered by this exploration: in the case cyclopropanes with two different substituents, which one is the migrating group? Is it possible that two mechanisms operate concurrently?

6.3. Mechanistic studies

Experimental and computational investigations were carried out with the goal of gaining a better understanding of the factors governing reactivity and selectivity in the rearrangement of the donor-acceptor cyclopropanes **193**.

6.3.1. Experimental investigations

As discussed earlier in this manuscript (see 6.2.3.), the experimental data are not sufficient to identify which group is migrating in the rearrangement when the cyclopropane **193** carries two different groups; the product being the same in both cases. In order to clarify this point, we performed a deuteration experiment investigating the rearrangement of **193ak-D**. The latter was obtained by reaction between **177a-D** and the sulfonium salt **185k** (Scheme 6.10)
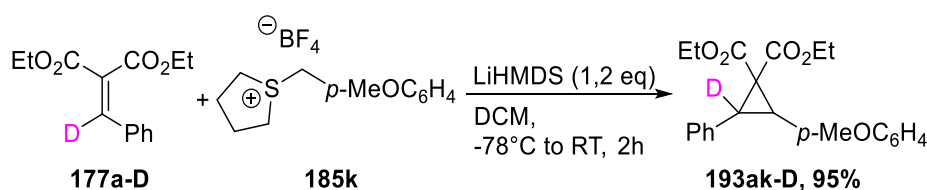
Scheme 6.10: Synthesis of **193ak-D**

The two potential pathways for the formation of the homologated olefin are shown in Scheme 6.11. Pathway A involves the ring-opening on the *p*-MeOC$_6$H$_4$ side which can better stabilise the positive charge resulting from the heterolytic opening of **193ak-D** and then the migration of the phenyl group. Pathway B, on the other hand, consists in the ring-opening of the cyclopropane on the phenyl side followed by the migration of the best migrating group, *p*-MeOC$_6$H$_4$ (see the migration scale calculated for the vinylcyclopropane rearrangement, section 4.3.3.1.1.). The presence of a deuterium atom on the cyclopropane enables the differentiation the product of pathways A and B with the deuterium positioned on the double bond or on the benzydryl position, respectively.
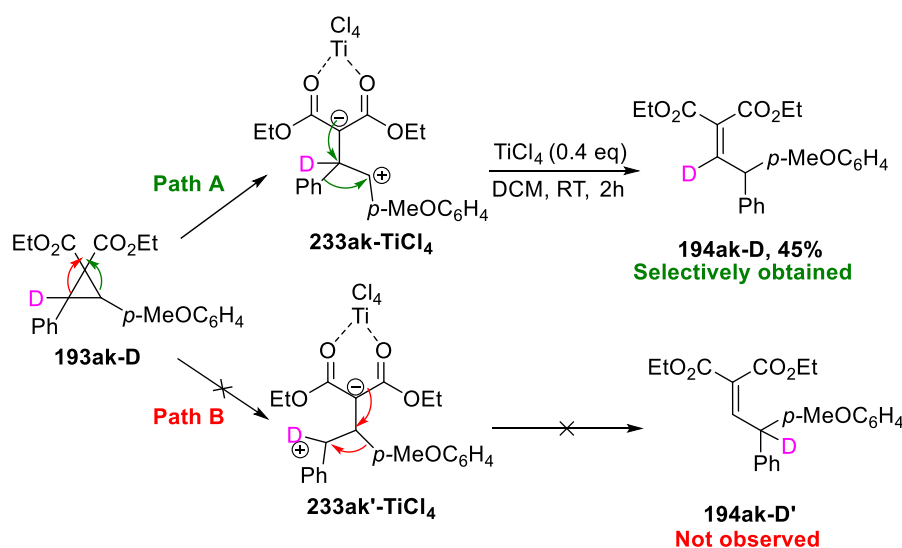
Scheme 6.11: TiCl$_4$-promoted rearrangement of **193ak-D**

The rearrangement of **193ak-D** was carried out in the presence of TiCl$_4$. The analysis of the ^{1}H NMR spectrum of the crude mixture showed the formation of compound **194ak-D** with the deuterium atom being on the olefin moiety of the final product. The product was obtained with a 45% isolated yield.

During our investigations of the non-deuteriated rearrangement of **193ak**, we observed that the signal for the H of the olefin moiety of **194ak** was slightly overlapping with the edge of an aromatic massif. We can see the disappearance of this peak on the ^{1}H NMR spectrum of the rearrangement of **193ak-D**, indicating the position of the deuterium atom in the corresponding olefin. However, the presence of the edge of the aromatic massif prevents us from seeing hypothetical traces of this doublet (which would corresponds to **194ak-D'**) and hence quantify accurately the selectivity **194ak-D/194ak-D'**. We can only confirm that **194ak-D** is by far the main product.

This result indicates that formation of **194ak** occurs mainly (or exclusively) via pathway A involving the intermediate with the best stabilisation of the positive charge created by the ring-opening (**233ak-**

TiCl₄). It would be interesting to carry out the same experiment on cyclopropanes with aryls of more similar electronic proprieties.

It is important to note that the selectivity between pathways A and B is a key point for the development of an enantioselective version of our methodology. Indeed, these two pathways lead to the same homologated product but not the same stereoisomer (Scheme 6.12).
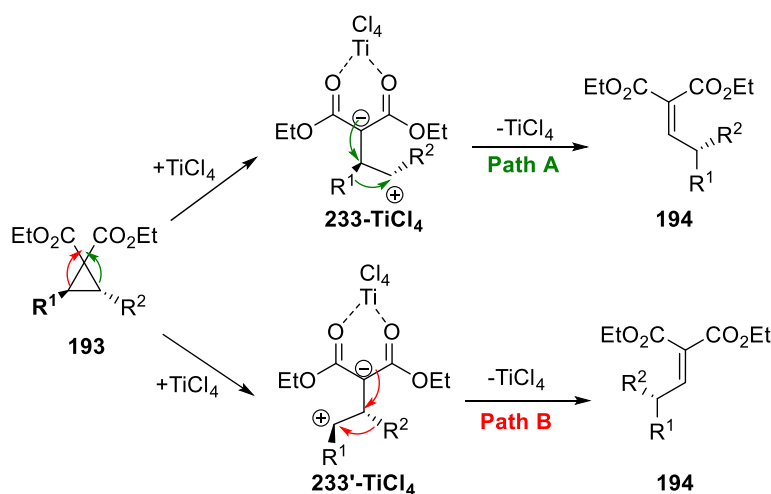
Scheme 6.12: Impact of the migration pathway on the enantiomer obtained

6.3.2. Computational investigations

6.3.2.1. Model established on the model substrate

The mechanism of the rearrangement step for the homologation of Knoevenagel adducts was also studied by computational methods using the same level of theory as for the one chosen for the rearrangement of vinylcyclopropanes (see 4.3.1).

$$M06\text{-}2X/6\text{-}311+G^{**}(CH_2Cl_2)//M06\text{-}2X/6\text{-}31+G^*(CH_2Cl_2)$$
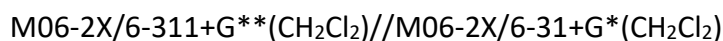
The following model was established by optimising the structure of every reactants, products, intermediates and transition states before calculating the free energy of all the molecules.
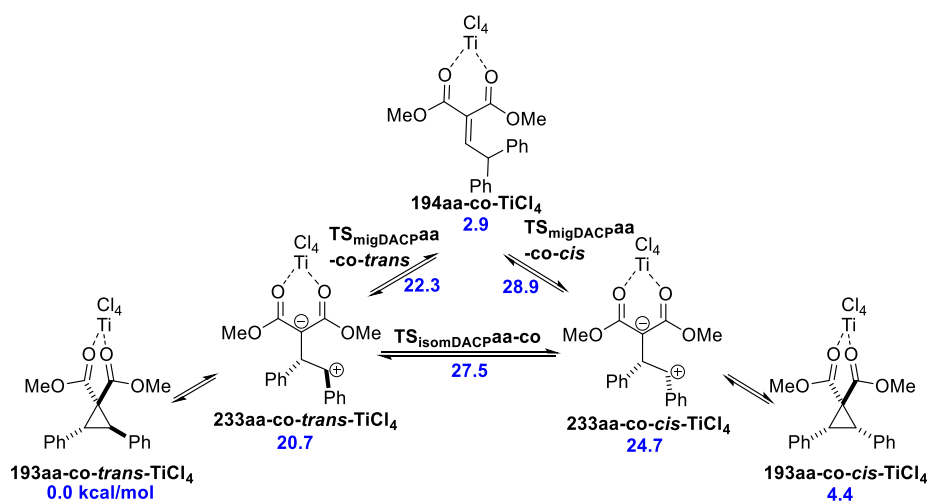
Scheme 6.13: Mechanism of the rearrangement. Relative free energies (in kcal/mol) obtained at the M06-2X/6-311+G**(CH$_2$Cl$_2$)//M06-2X/6-31+G*(CH$_2$Cl$_2$)

Our results show that the zwitterion intermediates **233aa-co-TiCl$_4$** lie higher in free energy as compared to the one involved in the rearrangement of vinylcyclopropanes (see 5.3.2.), due to a lower stabilisation of the positive charge by the phenyl group than by a styryl group. The consequence of this effect is an augmentation of the global migration free energy barrier (**TS$_{migDACP}$aa-co-*trans*** lies at 22.3 kcal/mol). This is consistent with the experimental data as the rearrangement needs to be carried out under harsher reaction conditions (3 equivalents of TiCl$_4$ for a reaction time of 24 hours for the rearrangement of donor-acceptor cyclopropanes, 1 equivalent of TiCl$_4$ for a reaction time of 15 minutes for the rearrangement of vinylcyclopropanes).

Similarly to our investigations regarding the rearrangement of VCP (see 4.3.2.), the model seems to overestimate the free energy of the migration product, **194a-TiCl$_4$** in this case. The isomerisation barrier **TS$_{isomDACP}$aa-co** is predicted to be higher than **TS$_{migDACP}$aa-co-*trans***, which is not consistent with the experimental data showing a full *cis-trans* isomerisation of **193aa-*cis*** before the formation of **194aa**. We decided however not to search for a new level of theory.

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The transition state **TS_{migDACP}aa-co-*cis*** is predicted to be significantly higher in energy than its *trans* counterpart. The origin of this effect can be found by visualising the transition state in three dimensions. Indeed, there is a proximity between the non-migrating phenyl group and one of the ester groups which induces an important steric clash in **TS_{migDACP}aa-co-*cis*** and hence an augmentation of the free energy (Figure 6.5).
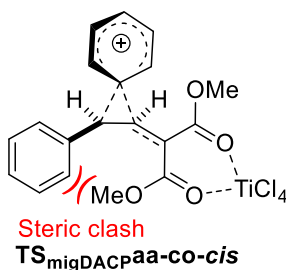
Figure 6.5: Steric clash between the phenyl group and one ester in **TS_{migDACP}aa-co-cis**

The significant energy difference (6.6 kcal/mol) predicts a total selectivity for the path involving the *trans* isomer of the transition state. This is an important data concerning the stereospecificity of the rearrangement. Indeed, when the two aryl groups are different, the two possible paths for the rearrangement of **193-*trans*-TiCl₄** lead to the formation of the enantiomers of opposite stereochemistry (Scheme 7.14). We hypothesise that the significant difference in free energy between **TS_{migDACP}-*trans*** and **TS_{migDACP}-*cis*** carries over to other examples, with two different substituents.
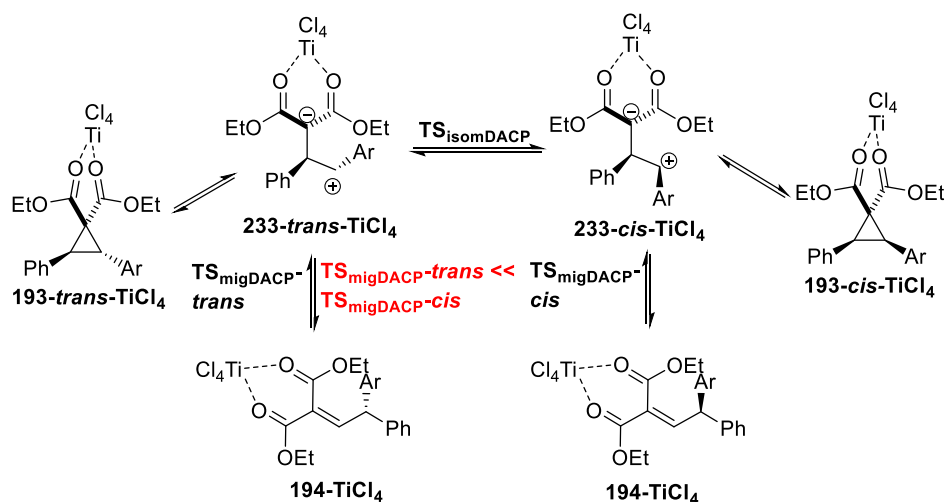
Scheme 6.14: Rearrangement of a **193-*trans*** of fixed stereochemistry

6.4. Enantioselective version

6.4.1. Strategy

The development of an enantioselective version of our homologation of activated olefins methodology was envisaged. As for the previously discussed works (see 5.5. and 6.4.), our strategy relied on the use of a chiral sulfonium salt for the cyclopropanation step (Scheme 6.15).
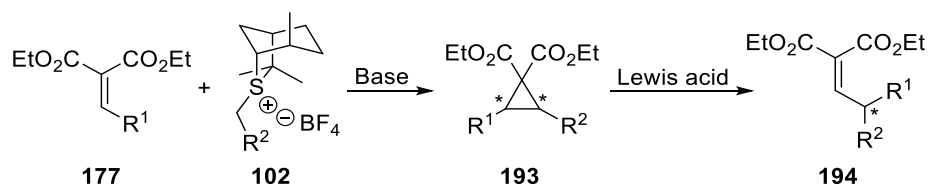
Scheme 6.15: Envisioned strategy for the synthesis of enantioenriched homologated olefins

The deprotonation of the chiral sulfonium salt leads to the formation of the corresponding sulfonium ylide (Figure 7.6).
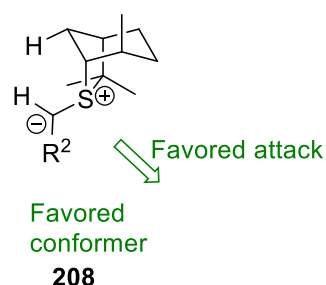
Figure 6.6: Sulfonium ylide **208** and preferred face for attack

As already discussed (see 4.4.1.), the ylide will add on the olefin exclusively on its *Re* face since the *Si* face is hindered by a methyl group. The two orientations of the olefin lead to the formation of the following isomers of **193** as rationalised by Aggarwal's model (Figure 6.7). The *cis* and *trans* diastereoisomers differ by the configuration of the carbon brought by the olefin.
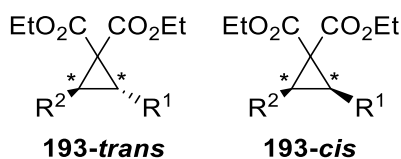
Figure 6.7: **193-*trans*** and **193-*cis*** obtained by the cyclopropanation step using chiral sulfonium salts **102**

The rearrangement step is performed exactly as it is carried out for the racemic version of the methodology (see 6.2.2.) (Scheme 6.15) and then needs to be stereospecific for this strategy to work. The points of attention for the stereospecifity are the following.

The transformation needs to occur via only one of the two possible mechanisms as previously discussed (see 6.3.1.).

The rearrangement must go selectively through **TS$_{migDACP}$-*trans*; TS$_{migDACP}$-*cis*** leading to the other enantiomer. According to our previous results (see 6.3.2.), this should be the case.

If a cyclopropane is obtained with a *cis/trans* ratio, the isomerisation of **193-*cis*** must occur through only one pathway. Indeed, Scheme 6.16 shows that the two potential pathways (A or B)

lead to two different enantiomers of **193-*trans*** and hence to different enantiomers of the homologated olefin **194**. It is important that the *cis* and *trans* cyclopropanes differ by the stereochemistry of the carbon with the substituent involved in the isomerisation process (Path A, Scheme 6.16). In that case, the *cis-trans* isomerisation of the sample triggered by TiCl$_4$ leads to one single enantiomer of **193-*trans*** before the 1,2-migration step.
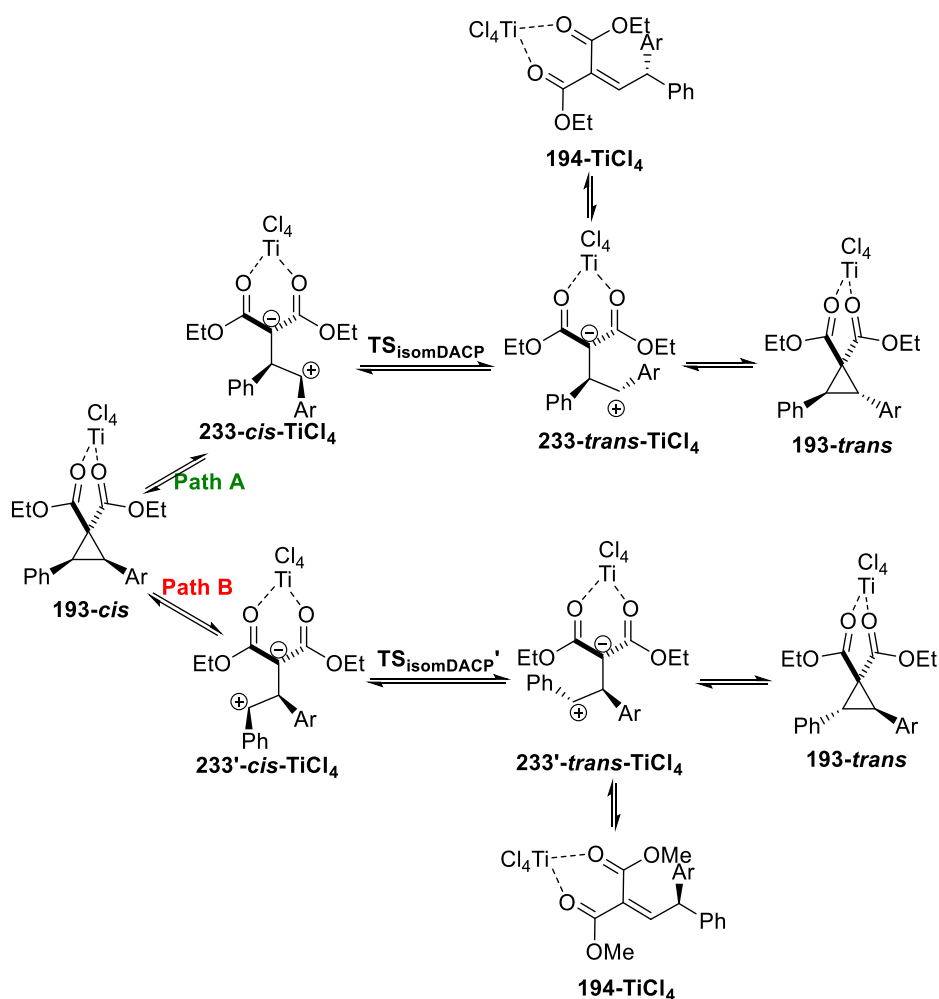
Scheme 6.16: Two paths for the *cis-trans* isomerisation of a **193-*cis*** of fixed stereochemistry

6.4.2. Results

6.4.2.1. Synthesis

During her Master's thesis, Madeline De Roose started working on an enantioselective version of our methodology.[72] She decided to target the enantioselective synthesis of the homologated olefin **194ka**.

This target was chosen because we had experimental proof that the rearrangement was taking place selectively by the pathway involving the best stabilisation of the positive charge created by the heterolytic ring-opening of **193ka** (see 6.3.1.). Knowing the mechanism explaining the transformation was also important for the choice of the substrates used to synthesise **193ka**. Indeed, the p-MeOC$_6$H$_4$ and Ph groups can be brought either by the olefin or by the sulfonium salt. In accordance with the model presented in section 6.4.1., it was decided that the p-MeOC$_6$H$_4$ would come from the activated olefin substrate (Scheme 6.17).
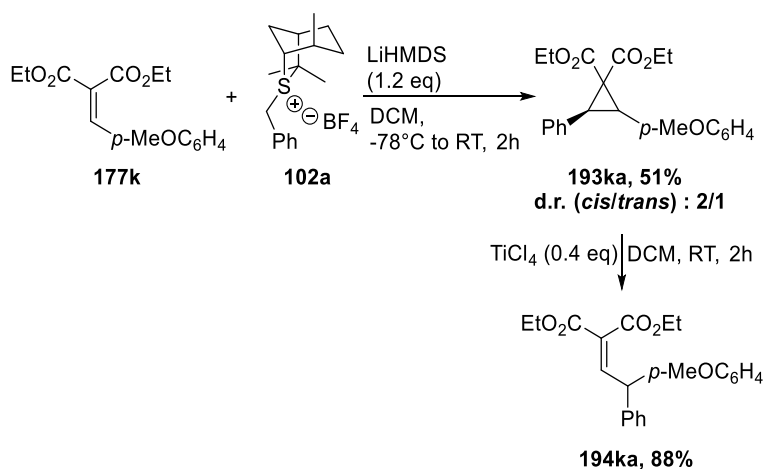
Scheme 6.17: Enantioselective synthesis of **194ka**

The cyclopropane was obtained with an isolated yield of 51% and a d.r. (*cis/trans*) of 2/1 using the same reaction conditions used for the racemic version. The cyclopropane was then successfully rearranged into the desired olefin **194ka** in the presence of TiCl$_4$ with a good isolated yield.

6.4.2.2. Analysis

The e.r. of the desired olefin **194ka** was measured to be 98/2 by chiral HPLC by Laurent Collard. This result shows that the rearrangement of this cyclopropane is highly stereospecific. The e.r. of the cyclopropane was not determined by chiral HPLC during Madeline's work and can only be estimated to be ≥ 98/2.

No analysis of the structure of the molecule obtained by Madeline was carried out during her Master's thesis to identify which enantiomer was obtained. According to the model developed by Aggarwal, one can however predict the main enantiomer to be **194ak-(*S*)** (Figure 6.8).

175ka-(*S*), 88%
e.r. : 98/2
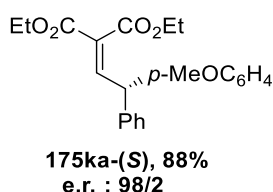
Figure 6.8: **194ka-(*S*)**

6.5. Conclusions

6.5.1. Development of the methodology

A new methodology for the one-carbon homologation of Knoevenagel adducts was successfully developed (Scheme 7.8). This strategy broadens the scope of previous studies (see 1.1.3.2.) and allows for the homologation of the activated olefins by insertion of CHAr fragments brought by the benzylic sulfonium salt **185**. The scope in respect to the nature of the olefin was also extended to R^1 = Alk and EWG = CN groups.
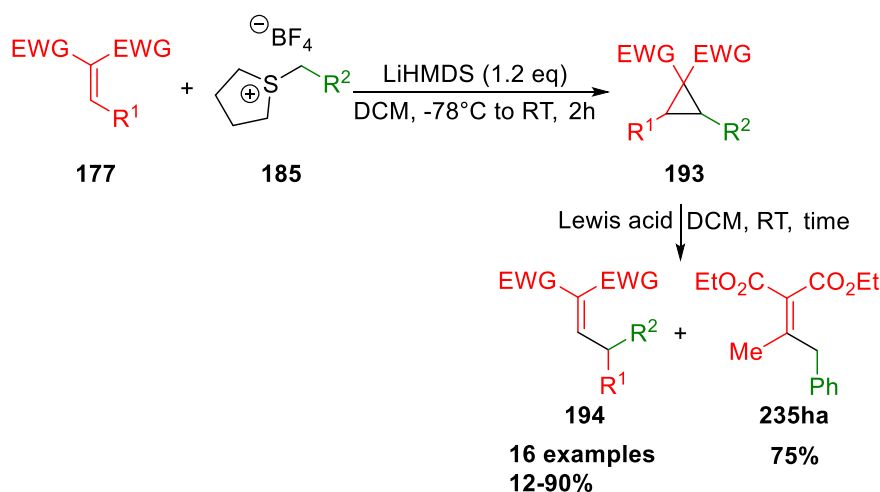
<u>Scheme 6.18:</u> Developed one-carbon homologation of activated olefins methodology

The global yields range from 12 to 90% for the 16 examples we obtained. The R^1 and R^2 substituents that led to the formation of the desired product were electron-donor and -acceptor aryls, H and alkyl groups such a *t*-Bu and cyclopropyl. Similarly to our vinylcyclopropane rearrangement, the methyl group is not migrating and loses the competition against the hydrogen atom to form the isomeric olefin **235ha**. Concerning the EWG, both ester and cyano groups are tolerated.

6.5.2. Mechanistic studies

A combined experimental and computational study of the rearrangement step was performed. It allowed us to gain a better insight into the mechanism of the transformation and understand factors controlling the stereospecificity.

6.5.3. Enantioselective version of the methodology

The stereospecificity of the rearrangement is a key factor in the perspective of developing an enantioselective version of the methodology using chiral suilfonium salts. Indeed, the chiral information would be introduced during the cyclopropanation step and must be transferred to the desired product during the second step of the process.

CHAPTER 6: HOMOLOGATION OF ACTIVATED OLEFINS

The olefin **194ka-(S)** was successfully obtained using the intended strategy with chiral sulfonium salts to induce an enantioselectivity during the cyclopropanation step (Scheme 6.19). Observed high enantiomeric ratio (98/2) confirms the high stereospecificity of the second step of the process.
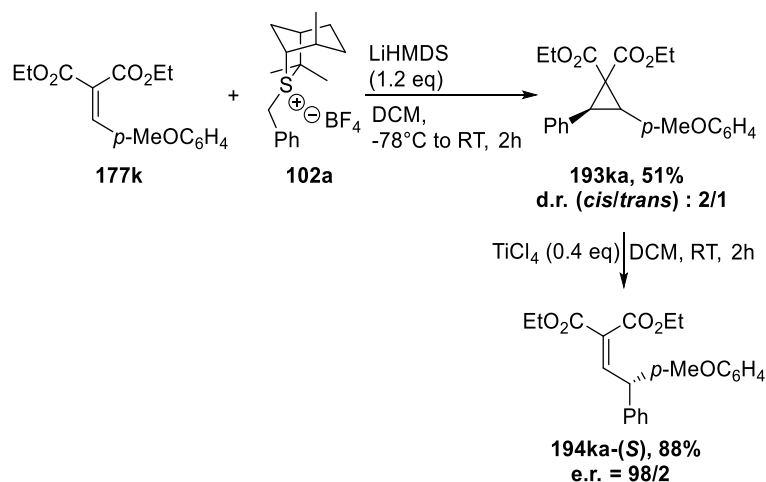
Scheme 6.19: Enantioselective synthesis of **194ka-(S)**

Chapter 7: Divergent rearrangements of divinylcyclopropanes

After developing methodologies involving vinylcyclopropanes, epoxides and donor-acceptor cyclopropanes, we turned our attention to divinylcyclopropane intermediates **195**. They could easily be obtained from 1,3-dienes **184** and allylic sulfonium salts **159**, both reagents which were used to bring the unsaturation to our vinylcyclopropanes (see Chapter 2).

The divergent rearrangements of these divinylcyclopropanes into 1,4,4'-trienes **196** via a 1,2-migration reaction in the presence of a Lewis acid or to cycloheptadiene **197** via a thermally induced Cope rearrangement will be studied (Scheme 7.1).
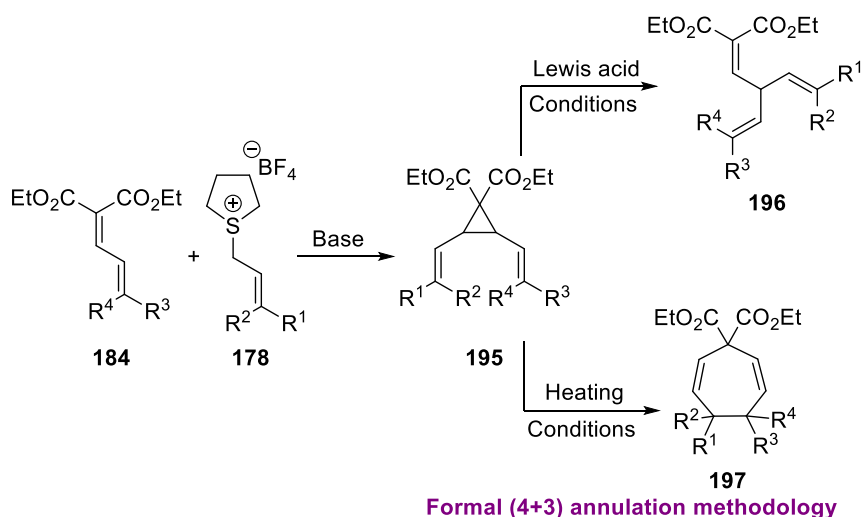
Scheme 7.1: Targeted divergent rearrangements of diVCPs to 1,4,4'-trienes and cycloheptadienes

Interestingly, the overall process to cycloheptadienes is a formal (4+3) annulation strategy. Despite the importance of the seven membered carbocycles in organic synthesis and their presence in a number of natural products,[22,112] very few (4+3) cycloaddition/annulation methodologies have been reported thus far in the literature.[23-25,113] Accordingly, we propose to develop a new

strategy which has the advantage of not requiring transition metals and being easy to carry out.

7.1. Synthesis of divinylcyclopropanes

The work on divinylcyclopropanes started by their synthesis. We applied the same LiHMDS protocol as developed previously (see Chapter 4) but starting from 1,3-dienes **184** and sulfonium salt **159a** (Table 7.1).

Table 7.1: Synthesis of divinylcyclopropanes
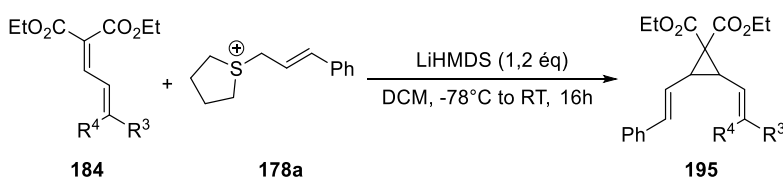
Entry	diVCP	R³	R⁴	Yield (%)ᵃ	d.r. (*cis/trans*)ᵇ
1	**195aa**	H	Ph	90	70/30
2	**195ba**	Me	Me	25ᶜ	40/60

ᵃ Yield in pure isolated compound. ᵇ Measured on the ¹H NMR spectrum of the crude mixture. ᶜ A 15-minute delay was applied between the additions of the base and of the 1,3-diene.

Under these reaction conditions, both divinylcyclopropanes **195aa** and **195ba** were obtained. The latter required a purification by flash chromatography explaining the lower isolated yield. Interestingly, **195aa** presented a *cis/trans* ratio in favour of the *cis* diastereomer (70/30), something that was observed with cyclopropanes (see Chapter 6) but never with vinylcyclopropanes (see Chapter 4). In the case of **195ba**, a low selectivity for the *trans* isomer is observed.

7.2. Preparation of 1,4,4'-trienes

The TiCl₄-catalysed rearrangement of divinylcyclopropanes **195** into **196** was studied under similar conditions as those developed in Chapter 5 (Table 7.2).

CHAPTER 7: DIVERGENT REARRANGEMENTS OF DIVINYLCYCLOPROPANES

Table 7.2: TiCl₄ promoted rearrangement of diVCP **195** to 1,4,4'-triene **196**
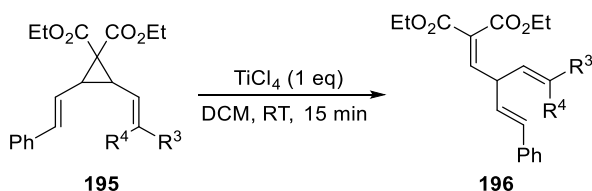
Entry	Triene	R³	R⁴	Yield (%)[a]
1	**196aa**	Ph	H	80
2	**196ba**	Me	Me	54

[a] Yield in pure isolated compound.

The Lewis acid promoted rearrangement of diVCPs **196aa-ba** produced the desired branched 1,4,4'-trienes in good yields.

Since, in our previous investigations (see Chapters 2 and 4), the formation of the 1,4-dienes was, in most cases, not the end point of the rearrangement of vinylcyclopropanes, we investigated the rearrangement of **195aa** for longer time than 15 min (Table 7.3).

Table 7.3: Investigation of longer reaction times for the Lewis acid triggered rearrangement of **195aa**
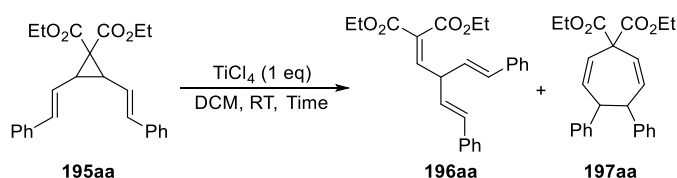
Entry	Time	Observations
1	20h	Complex mixture containing **196aa** and **197aa**
2	28h	Mixture containing **197aa** as the main product
3	48h	Mixture containing **197aa** as the main product

Carrying out the reaction for longer reaction times led to the obtaining of complex mixtures of products. After 20h of rearrangement, the 1,4,4'-triene **196aa** was still present in the mixture but the cycloheptadiene **197aa** could also be detected by ¹H NMR in

the crude mixture (entry 1). The triene **196aa** fully disappeared of the NMR spectrum after 28h of reaction and the proportion of **197aa** increased to become the main product (entry 2). Leaving the reaction for 20 additional hours did not lead to a significant change. Surprisingly, no trace of cyclopentene was observed during this study.

Interestingly, alongside these experiments, we also observed that the Cope rearrangement of **195aa-*cis*** to cycloheptadiene **197aa** is spontaneous at room temperature as the formation of this latter was detected in a sample of diVCP **195aa** left overnight on our bench. Analysing a sample of **195aa** after 2 years in the fridge revealed a mixture of **195aa-*trans*** and **197aa** in a ratio corresponding to the d.r. of the obtained **195aa** sample (d.r. (*cis/trans*) = 70/30).
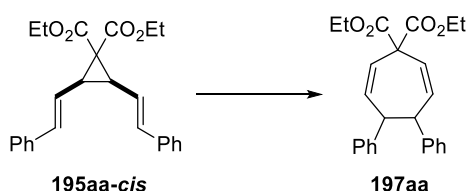
Scheme 7.2: Cope rearrangement of **195aa-*cis*** to **197aa**

The mechanism and optimisation of the formation of **197aa** is detailed in the next section.

7.3. Cope rearrangement

Our investigation of the TiCl$_4$-catalysed rearrangement of diVCPs **195** as well as our stability studies led to the observation of cycloheptadiene formation. Accordingly, we turned our attention to the rearrangement of diVCPs **195** for the obtaining of cycloheptadienes **197** (Scheme 7.3).
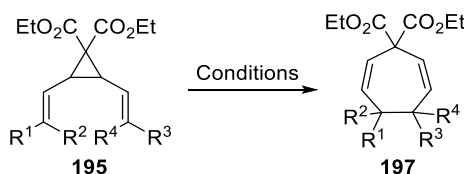
Scheme 7.3: Cope rearrangement of **195** into cycloheptadiene **197**

7.3.1. Mechanism

The mechanism explaining the formation of cycloheptadienes from divinylcylopropanes consists in a Cope rearrangement as previously reported.[114] The mechanism of the Cope rearrangement of **134-*cis*** into **135** was computationally studied by Özkan *et al.* at the (U)B3LYP/6-31G* level (Scheme 7.4).[134] The rearrangement requires the two vinyl groups to be in the *cis* configuration for the reaction to occur. However, different orientations of the two vinyl groups are possible (conformers **134-*cis-exo/exo*, 134-*cis-exo/endo*** and **134-*cis-endo/endo***). The reaction can however only occur via the third path (starting from the least stable conformer of **134-*cis***, with the two vinyls in endo positions) where the vinyl groups are properly positioned to lead to the formation of two *cis* unsaturation in the final product, via the transition state **TS_{Cope}-*endo/endo***. The 3,3-sigmatropic rearrangement of divinylcyclopropanes favours the boat transition state **TS_{Cope}-*endo/endo***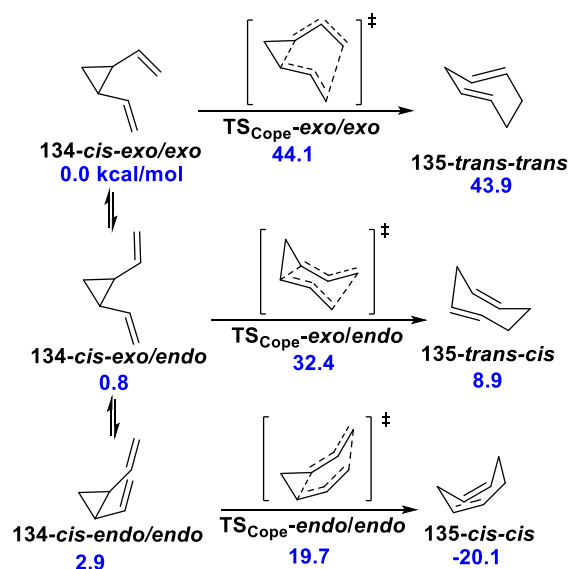 which is different behaviour than the classic Cope rearrangement favouring chair transition states.[114] The barrier predicted by the calculations (19.7 kcal/mol) is consistent with the experimental value: 20.0 kcal/mol.[68,135]

134-*cis-exo/exo*
0.0 kcal/mol

TS_{Cope}-*exo/exo*
44.1

135-*trans-trans*
43.9

134-*cis-exo/endo*
0.8

TS_{Cope}-*exo/endo*
32.4

135-*trans-cis*
8.9

134-*cis-endo/endo*
2.9

TS_{Cope}-*endo/endo*
19.7

135-*cis-cis*
-20.1

Scheme 7.4: Mechanism of the Cope rearrangement of diVCP **134-*cis*** studied at the (U)B3LYP/6-31G* level of theory

8.3.2. Optimisation

The diVCP **195aa** was chosen as a model substrate for the optimisation process. As previously discussed, the divinylcylopropane was obtained with a *cis/trans* diastereoisomeric ratio of 7/3. Accordingly, the reaction conditions need to allow the isomerisation of **195aa-trans** into **195aa-cis** for a full conversion of the diVCP to the desired cycloheptadiene **197aa**.

Table 7.4: Optimisation of the Cope rearrangement of **197aa**

176aa
d.r. (*cis/trans*) = 70/30

178aa
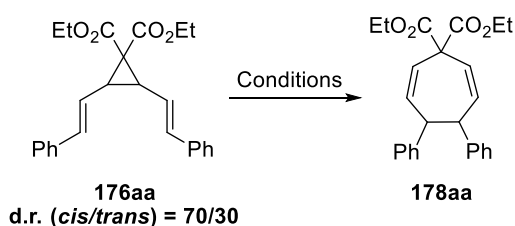
Entry	Conditions	195aa/197aa[a]	Yield (%)[b]
1	Toluene, 110°C, 48h	30/70	70[c]
2	Xylene mix, 130°C, 16h	0/100	22
3	Xylene mix, 110°C, 16h	30/70	70[c]
4	ZnCl$_2$ (0.1 eq), toluene, 110°C, 16h	1/99	19

[a] Determined on the ^{1}H NMR spectrum of the crude mixture. [b] Yield in pure isolated compound. [c] Determined by ^{1}H NMR on a mixture of **195aa** and **197aa** which are not separable on silica gel.

Our first attempt was carried out in toluene at reflux (110°C) for 48h (Table 7.4). Satisfyingly, the analysis of the crude reaction mixture showed a 7/3 ratio of the desired product **197aa** and **195aa-trans**, with no traces of **195aa-cis** or side products. This ratio corresponds to the d.r. of the starting diVCP **195aa**, indicating that all the *cis* isomer was converted into **197aa** but the reaction conditions are not promoting the isomerisation of **195aa-trans** into **195aa-cis**. Unfortunately, the two products were found to co-eluate and then be impossible to isolate on silica gel.

In order to favour the *cis/trans* isomerisation, we then decided to use a solvent with a higher boiling point, the xylene mix (130°C).

Interestingly, no remaining traces of diVCP **195aa-*trans*** could be observed in the crude mixture after 16 hours, suggesting that the isomerisation took place at that temperature. However, the presence of sides products was observed, explaining the low isolated yield of 22%. Lowering the temperature from 130°C to 110°C with the same solvent led to the same result as with toluene (see entries 1 and 3).

We then went back to the use of toluene as the solvent but added 0.1 equivalent of $ZnCl_2$. Indeed, this Lewis acid was found to catalyse the isomerisation of vinylcyclopropanes but not their rearrangement into skipped diene.[97] The desired goal of isomerising **195aa-*trans*** was thus achieved. However, the presence of $ZnCl_2$ led to the observation of traces of the corresponding 1,4,4'-triene **196aa**. This can be explained by the better migration aptitude of the styryl group (see 4.3.3.1.1.) and/or the higher temperature. The mass of product recovered after the work-up was already low, which explains the low isolated yield of 19%, a similar result to entry 2.

For a question of time, we stopped our investigations at this point. The optimisation process is not finished but we were able to provide a proof of concept to the obtaining of the cycloheptadiene **197aa** from the divinylcyclopropane **195aa**.

7.4. Conclusions

We successfully developed the divergent rearrangements of divinylcyclopropanes into 1,4,4'-trienes under Lewis acid conditions and to cycloheptadienes upon heating (Scheme 7.5).

CHAPTER 7: DIVERGENT REARRANGEMENTS OF DIVINYLCYCLOPROPANES

New rearrangement of diVCPs
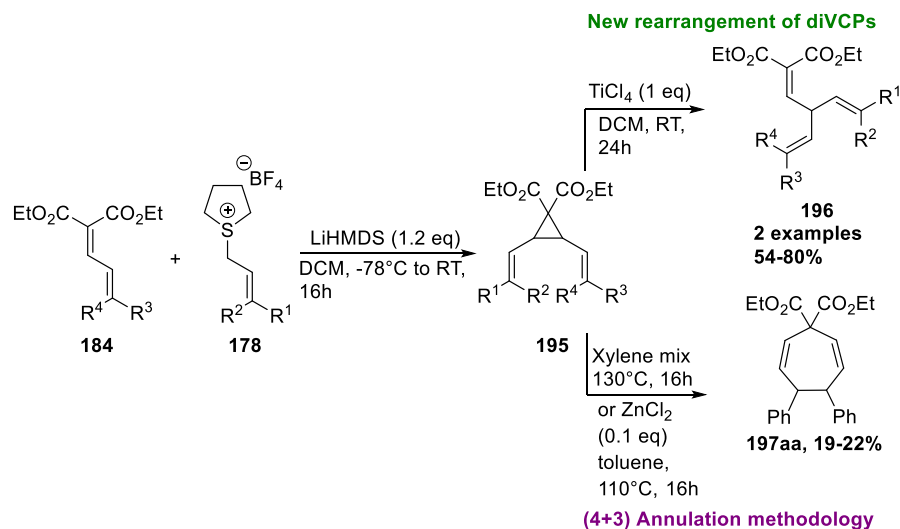
Scheme 7.5: Divergent rearrangements of divinylcyclopropanes

The Lewis acid promoted rearrangement of these substrates was successfully investigated and allowed us to isolate two trienes **196** in good yields. This represents a new rearrangement of these divinylcyclopropanes.

The reported [3,3]-sigmatropic rearrangement of divinylcyclopropanes was also used in a new formal (4+3) annulation strategy for the formation of seven membered carbocycles. The first attempts of Cope rearrangement of diVCP **195aa** were successful but the isolated yield of **197aa** is low, around 20%. This work provided however a proof of concept of our initial idea which adds to the few (4+3) annulation strategy reported in the literature and has the advantage of not involving transition metals and being atom efficient. Additional work is required on this reaction in order to optimise the yield. After that, the scope of the (4+3) annulation methodology could be explored.

Chapter 8: Conclusions and perspectives

During this work, we carried out investigations on the rearrangement of vinylcyclopropanes into skipped dienes and then focused on the development of related new methodologies. We explored methodologies involving the rearrangement of diverse type of three membered ring moieties: vinylcyclopropanes, vinylepoxides, arylcyclopropanes and divinylcyclopropanes. The objectives were to develop these methodologies, explore their limitations, carry out mechanistic studies and investigate enantioselective versions.

8.1. Rearrangement of vinylcyclopropanes

8.1.1. Conclusions

The scope of the VCP rearrangement into skipped dienes was explored further during this PhD thesis. The data obtained completed the one previously obtained (see Chapter 2) to provide a more thorough analysis of the effect of the substituents on the skipped diene/CP selectivity (Scheme 8.1).

Strategies to slow down the cyclisation reaction (R^3 = alkyls or p-$CO_2MeC_6H_4$) were successfully used, which allowed us to investigate the migration of poor migrating groups. This led to the formation of skipped dienes **204** coming from the migration of a hydrogen instead of the R^1 group in the case of very poor migrating group (Me, i-Bu, i-Pr).

The experimental exploration of the scope was completed with a computational study of the effect of the substituents on the outcome of the Lewis acid triggered rearrangement of VCPs. These combined studies allowed us to get insights into the origin of the effect of the substituents on the skipped diene/CP selectivity. The reactivity of the Lewis acid triggered rearrangements of donor-acceptor VCPs is now well understood.
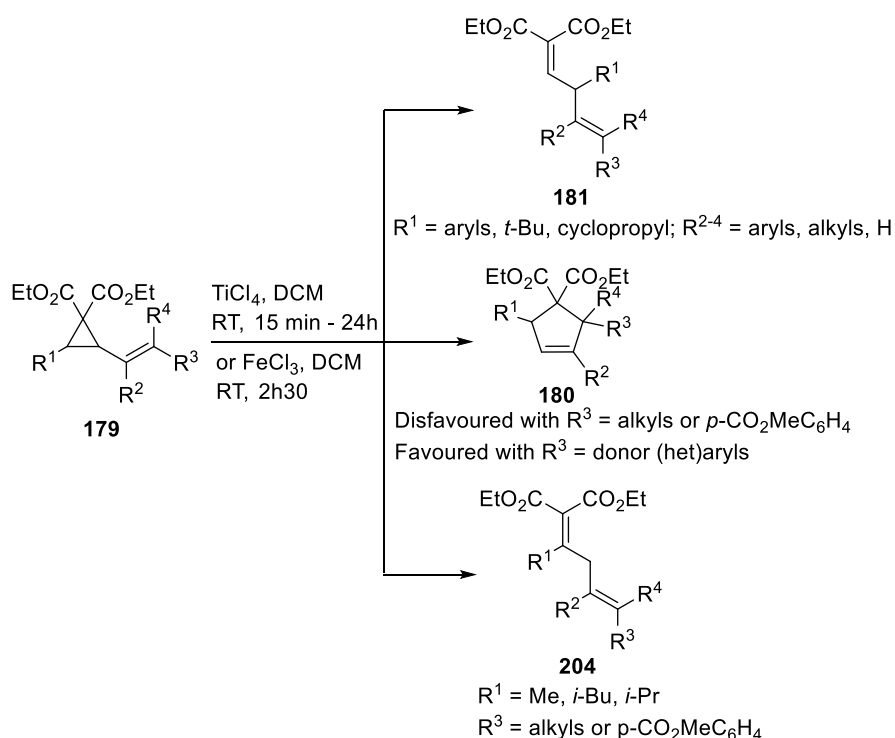
Scheme 8.1: Exploration of the scope of the rearrangement

Unfortunately, our attempts to develop an enantioselective version of the methodology failed due to issues related to the analysis of the samples of VCPs and skipped dienes by chiral HPLC.

8.1.2. Perspectives

Further work could be carried out on the enantioselective version of the methodology such as the investigation of derivatisation reactions to obtain molecules that are easier to analyse by chiral HLPC. Reactions on the ester groups of both the VCP and the skipped diene to transform these groups to carboxylic acid or alcohols could be envisaged.

The derivatisation of our skipped dienes could be explored in the future. Some possible reactions are shown in Scheme 8.3. The skipped dienes **181** possess an activated olefin moiety that could be engaged in a Michael addition reaction with a nucleophile. This could be interesting on optically active dienes as it could lead to a

diastereoselective addition creating two contiguous stereocenters. If the nucleophile reagent is an allylic sulfonium ylide could be involved in a second cyclopropanation/rearrangement sequence, which repeated in an iterative way, could lead to a new example of assembly line synthesis.[117] As mentioned previously, reaction on the ester groups of the skipped dienes **181** could also be explored.
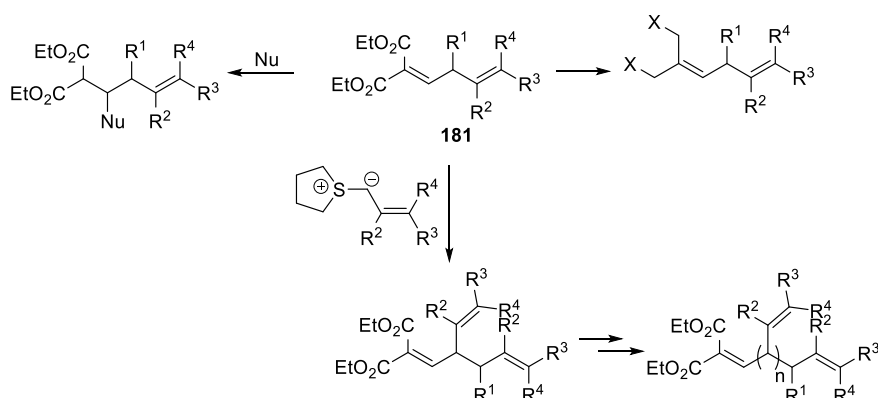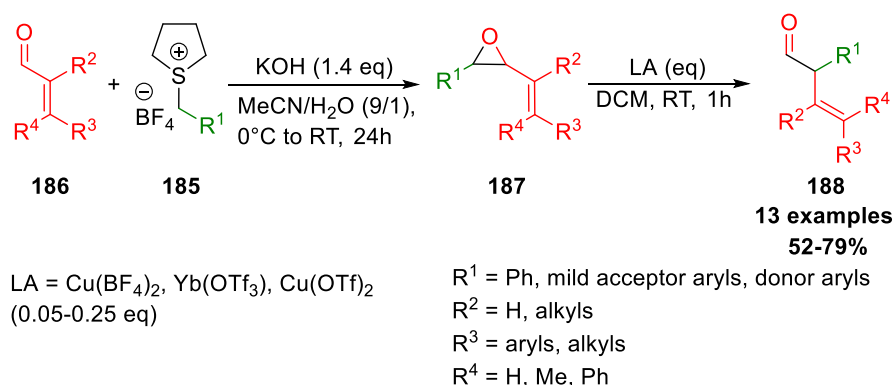

Scheme 8.3: Possible derivatisation reactions of skipped diene **181**

8.2. Homologation of α,β-unsaturated aldehydes

8.2.1. Conclusions

Inspired by our one-carbon homologation of 1,3-dienes methodology, we developed a new homologation strategy leading to the selective synthesis of α-aryl β,γ-unsaturated aldehydes using mild reaction conditions (Scheme 8.4). Our methodology provides a new route toward this challenging scaffold and expands the scope of the Meinwald rearrangement of vinylepoxides in respect to the substitution pattern on the unsaturation (R^{2-4}). The effect of the substituents on the Meinwald reaction was studied and we observed the formation of side products (ketone and dihydrofuran) which limited the scope of this transformation.

LA = Cu(BF$_4$)$_2$, Yb(OTf$_3$), Cu(OTf)$_2$
(0.05-0.25 eq)

R^1 = Ph, mild acceptor aryls, donor aryls
R^2 = H, alkyls
R^3 = aryls, alkyls
R^4 = H, Me, Ph

Scheme 8.4: Developed one-carbon homologation of α,β-unsaturated aldehydes

The obtained aldehydes were found to be poorly stable and we then investigated derivatisation reactions. Successful investigations allowed us to develop new synthetic routes for both primary homoallylic alcohols and α-aryl α,β-unsaturated aldehydes by adding a simple isomerisation or reduction step to the one-carbon homologation strategy. These results are interesting considering the ease of use of these new methodologies and the fact that few strategies were reported for the preparation of these two structures.

The preliminary investigations toward an enantioselective version of the methodology were carried out. Unfortunately, the Meinwald rearrangement step was found not to display the required stereospecificity for the success of our strategy using chiral sulfonium salts.

8.2.2. Perspectives

Further work could be carried out on the enantioselective version of the methodology. Other reaction parameters for the rearrangement of **187aa** to **188aa** could be investigated such as the nature of the Lewis acid or the temperature. If these parameters allow for the obtaining of better e.r., these found conditions could be applied to other epoxides.

Additionally, exploring the Meinwald rearrangement step by means of DFT calculations could help gaining more insight on the

factors explaining the partial stereospecificity of the 1,2-migration step.

The addition of nucleophilic derivatives on the β,γ-unsaturated could be explored further by the study of organoalluminium derivatives. Indeed, these organometallic compounds react on carbonyl compounds and have a better functional group tolerance than organolithium or Grignard reagents.[118] Enantioselective additions of these derivatives in the presence of chiral ligands was achieved with good e.e.[119]

8.3. Homologation of activated olefins

8.3.1. Conclusions

Cognizant of the reactivity similarities between donor-acceptor vinylcyclopropanes and DACPs, we developed a one-carbon homologation of activated olefins inspired by our work on VCPs (Scheme 8.8). This new homologation methodology of olefins has the advantage of allowing the insertion of CHR fragment. These strategies are far scarcer than those allowing the insertion of a methylene group.
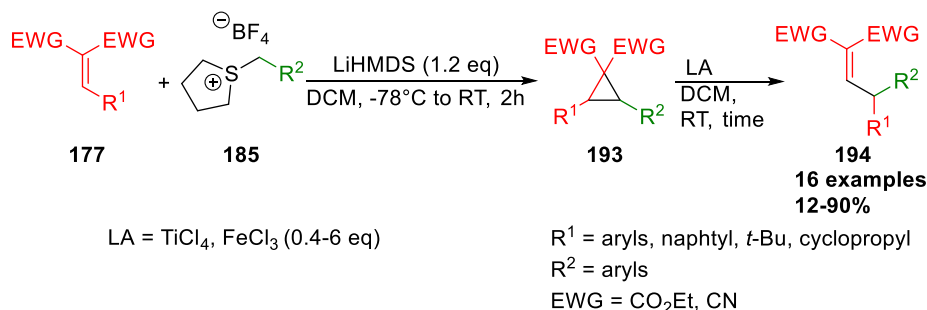
Scheme 8.8: Developed one-carbon homologation of activated olefins methodology

The scope of this methodology was explored and the observed limitation is that it is not compatible with the migration of a methyl group. Our studies provides a better look at the Lewis acid triggered rearrangement of DACPs which was previously limited to the migration of a hydrogen from cyclopropanes only activated by esters groups as EWGs.

CHAPTER 8: CONCLUSIONS AND PERSPECTIVES

We combined experimental and DFT methods to investigate the mechanism of the 1,2-migrating step what allowed us to improve our understanding of the factor governing reactivity and selectivity in the process. This work enabled us to choose the right target for the start of our investigation on the enantioselective version of this methodology using chiral sulfonium salts. We successfully obtained the olefin **194ka-(S)** with a e.r. of 98/2 (Figure 8.1).
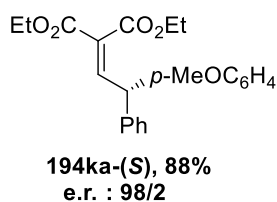
EtO_2C CO_2Et

p-$MeOC_6H_4$

Ph

194ka-(*S*), 88%
e.r. : 98/2

Figure 8.1: Enantioselective synthesis of **194ka-(*S*)**

8.3.2. Perspectives

It would be interesting to determine the enantiomeric ratio of the cyclopropane **193ka** to have a full data set for this system. The exploration of the scope of the enantioselective version could be explored further to investigate the influence of the substituents on the stereospecificity of the rearrangement. This would increase the number of examples of one-carbon homologation by insertion of CHR fragment of defined stereochemistry. Cyclopropanes **193** with two aryls of similar electronic proprieties could be a major limitation. Indeed, these cyclopropanes could be found to undergo the *cis-trans* isomerisation and form the olefins **194** by 1,2-migration via two concomittant pathways, which would lead to a mixture of enantiomers of the desired olefin.

The derivatisation of the homologated olefins could be carried out as well. One example of a derivatisation reaction is the formation of the naphthalenols **238** that was already briefly investigated by Madeline De Roose at the end of her Master's thesis (Scheme 8.6).[111] The formation of **238ka** was observed but this strategy requires more work to be optimised.
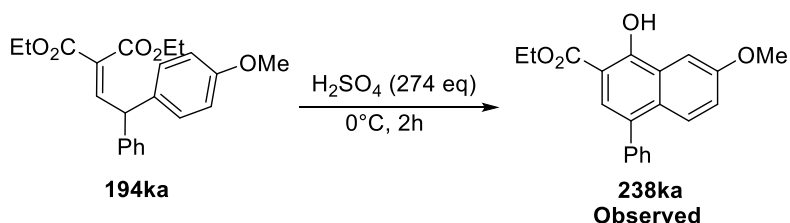
Scheme 8.6: Formation of naphtalenol **238ka**

Other possible derivatisation include the following reactions (Scheme 8.7). The activated olefin **194** obtained via our homologation methodology is a Michael acceptor which could be attacked a nucleophile. The diastereoselective addition of a nucleophile on enantioenriched olefins could lead to the formation of two stereocenters on vicinal carbons. If the nucleophile reagent is a benzylic sulfonium ylide, it could lead to a second cyclopropanation/rearrangement sequence, which repeated in an iterative way, would lead to a new example of assembly line synthesis.[117]
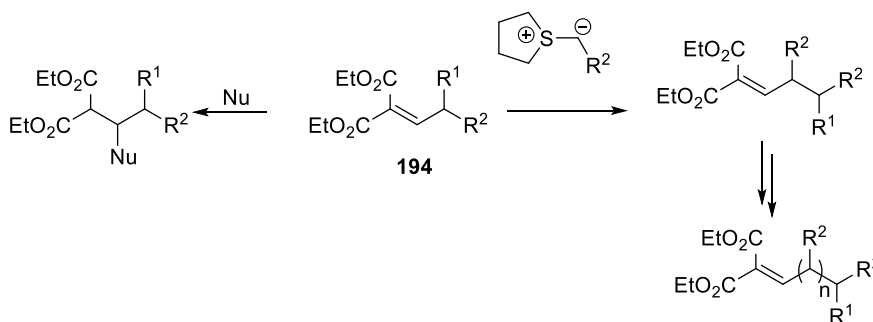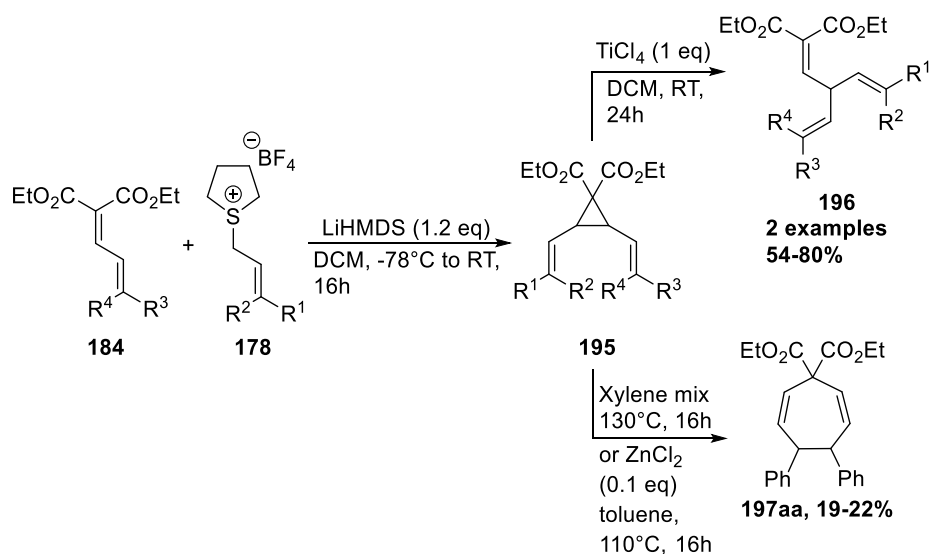

Scheme 8.7: Possible derivatisation reactions of the activated olefin **194**

8.4. Divergent rearrangements of divinylcyclopropanes

8.4.1. Conclusions

The last topic covered by this work was the obtaining and divergent rearrangements of divinylcyclopropanes into 1,4,4'-trienes and cycloheptadienes (Scheme 8.8).

Scheme 8.8: Divergent rearrangement of divinylcyclopropanes

We successfully applied our previously developed TiCl$_4$-promoted rearrangement conditions to obtain the desired trienes (**196**). The first attempts of Cope rearrangement of diVCP **195** were successful but the isolated yield of **197aa** is low, around 20%. The obtaining of the cycloheptadiene is a formal (4+3) annulation reaction methodology which adds to the limited amount of (4+3) annulation methodologies in the literature. This work only provides proof of concept of our initial idea, additional work is required for the development of this new strategy.

8.4.2. Perspectives

The optimisation of this reaction should be pursued to find suitable reaction conditions (Scheme 8.9). These conditions need to enable the promotion of the *trans-cis* isomerisation of the diVCP. Possible ideas include the use of a more polar solvent, the catalysis of the isomerisation by a Lewis acid and the use of microwave irradiation to help the reaction.
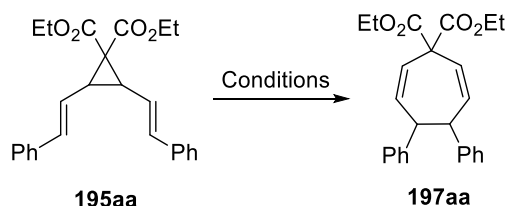
Scheme 8.9: Further optimising the reaction conditions for the formation of **197aa**

After this process, the scope of this transformation could be explored by varying the substitutions of the two unsaturations. The nature of R^7 and R^8 could be varied as well since the Cope rearrangement does not necessitate the groups at this position to be electron-withdrawing groups (Scheme 8.10).
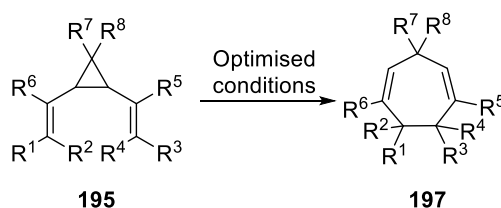
Scheme 8.10: Further exploring the scope of the Cope rearrangement

8.5 General conclusions

We developed new synthetic methods targeting the formation of important but synthetically challenging scaffolds: skipped dienes, β,γ-unsaturated aldehydes, primary homoallylic alcohols, α-aryl α,β-unsaturated aldehydes and cycloheptadienes. We also developed a new one-carbon homologation of Knoevenagel adducts enabling the insertion of a CHR group. All these methodologies are atom economic, easy to use and are performed under mild and transition metal free reaction conditions from cheap or readily available reagents.

The effects of the substituents in the key 1,2-migration shared by almost all methodologies was investigated by a combination of experimental and computational methods. This allowed us to improve our understanding of the mechanisms at play and the factors controlling reactivity and selectivity in these processes. This combined

studies provide a better insights into the Lewis acid triggered rearrangement of donor-acceptor vinylcyclopropanes, vinylexpoxides and DACPs.

The enantioselective version of some of these methodologies using chiral sulfonium salts was investigated with mixed results. Further work has to be performed on this to explore the scope of these enantioselective transformations or to understand the low stereospecificity of the Meinwald rearrangement of vinylepoxides.

Chapter 9: Experimental part

9.1 Numbering of the molecules

The following section details the method for numbering throughout this manuscript.

Every vinylcyclopropane has been attributed two letters. The logic is illustrated on **179ac** in Scheme 9.1. The first letter corresponds to the **R^1** substituent whereas the second letter is determined by the nature of the vinyl side of the VCP (**R^2-R^4**). The letters have been assigned by order of appearance in the manuscript (including the molecules studied by DFT). The substrates (1,3-dienes, olefins, sulfonium salts) have been assigned only one letter, corresponding to the substitution they bring to the resulting vinylcyclopropane.
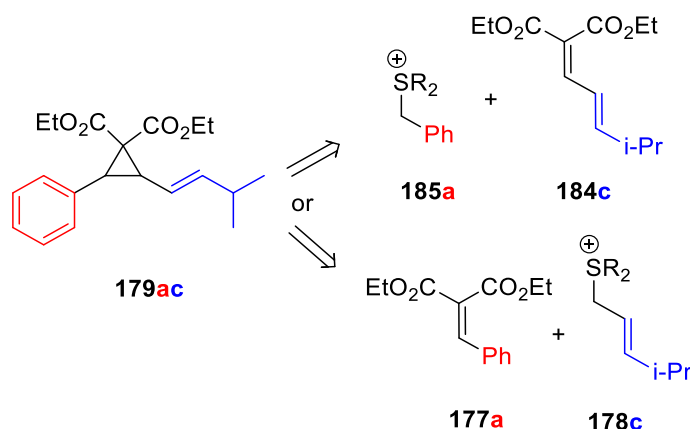
Scheme 9.1: Example of the numbering logic of **179ac**

Vinylcyclopropanes with different EWG were named with the two letters corresponding to their substitution pattern: **–CN** or **–COMe** was added in the naming of the molecules (ex: **179aa-CN).**

The attributed letters were kept consistent during the following chapters focussing on vinylepoxides, cyclopropanes, divinylcyclopropanes and their respective rearrangement products.

9.2. Synthesis of the substrates

The synthesis of the substrates used in our different methodologies is an important part of this work. This section describes the synthesis of sulfonium salts, 1,3-dienes, activated olefins and α,β-unsaturated aldehydes used to synthetise various cyclopropanes and epoxides. The numbering logic used for the molecules in this manuscript is detailed in section 10.1.

9.2.1. Sulfonium salts

Sulfonium salts are used to *in situ* generate the corresponding sulfonium ylides in the presence of a base. During this work, chiral and non-chiral salts were synthesised.

9.2.1.1. Non-chiral sulfonium salts

The development of new methodologies using sulfonium ylides requires the synthesis of the corresponding benzylic and allylic sulfonium salts. The sulfide used for the synthesis of the non chiral salts is the commercially available tetrahydrothiophene (Figure 9.1).
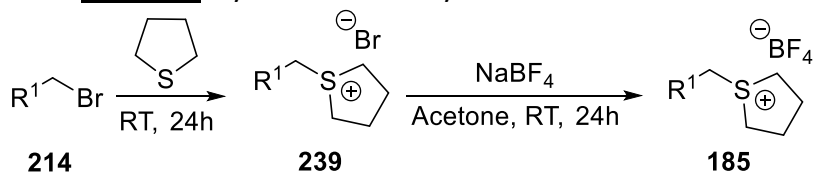

Figure 9.1: Tetrahydrothiophene

9.2.1.1.1. Benzylic sulfonium salts

Some of the benzylic sulfonium salts used during this work necessitated their synthesis. They could be obtained via a two steps procedure starting from commercially available bromide derivatives **214** (Table 9.1).[120]

Table 9.1: Synthesis of benzylic sulfonium salts **185**

Entry	Salt	R^1	Yield (%)[a]
1	**185a**	Ph	48
2	**185f**	p-$CO_2MeC_6H_4$	32
3	**185p**	p-FC_6H_4	63
4	**185q**	p-BrC_6H_4	67
5	**185r**	m-$CO_2MeC_6H_4$	25

[a] Yield in pure isolated compound.

The first step is a S_N2 type reaction between the THT acting as the nucleophile and the bromide compounds. This led to the formation of a sulfonium salt with a bromide as counter-ion, **239**. The bromide is then replaced by another counter-ion, BF_4^-, by diluting **239** in acetone and adding $NaBF_4$. After 24 hours at room temperature, the NaBr formed by the ion exchange is removed by filtration. The filtrate is concentrated to give the sulfonium salt, which is then purified by precipitation with MeOH/diethylether.

The benzylic salts **185a** and **185p** were synthesised by Boris Takam during his Master's thesis.[96] Sulfonium salts with R^1 = p-MeC_6H_4, p-$MeOC_6H_4$, o-MeC_6H_4, m-$MeOC_6H_4$, m-ClC_6H_4, o-FC_6H_4 were available in our laboratory and did not require to be resynthesised.

9.2.1.1.2. Allylic sulfonium salts

9.2.1.1.2.1. Allylic alcohols

The synthesis of allylic sulfonium salts is not starting from bromide compounds like their benzylic counterparts, but from allylic alcohols **240**. **240c** was obtained by the reduction of the corresponding commercially available α,β-unsaturated aldehyde **186c** with $LiAlH_4$ (Scheme 9.2).
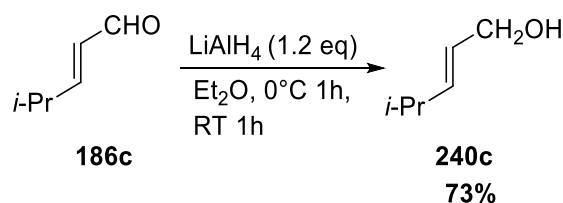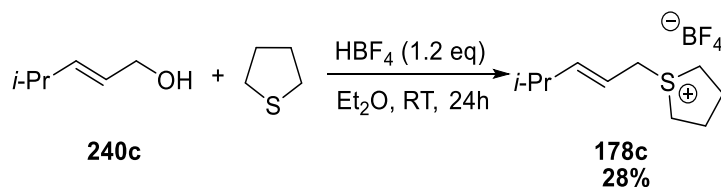
Scheme 9.2: Reduction of aldehyde **186c** to the corresponding alcohol **240c**

9.2.1.1.2.1. Allylic sulfonium salts

Allylic sulfonium salts **178c** was obtained via a reaction between **181c** and tetrahydrothiophene in the presence of 1.2 eq of an acid, HBF$_4$ (Scheme 9.3).


Scheme 9.3: Synthesis of allylic sulfonium salt **178c**

Allylic sulfonium salt **178a,h**, with R^3 = Ph and p-CO$_2$MeC$_6$H$_4$ respectively, were already available in our lab and did not necessitated their synthesis during this work.

9.2.1.2. Chiral sulfonium salts

In order to develop enantioselective versions of our various methodologies using sulfonium ylides, we chose to induce enantioselectivity in the three membered ring formation reactions (cyclopropanation or epoxidation) by using chiral sulfonium ylides. Among the different reported chiral sulfide auxiliaries, the group of Prof. V. K. Aggarwal showed that isothiocenol **211** was the best candidate for the formation of three member rings.[50] Moreover, this sulfide has been successfully used by our laboratory in the development of an enantioselective (4+1) methodology (see 1.2.3.1.1.).[49]

CHAPTER 9: EXPERIMENTAL PART

211
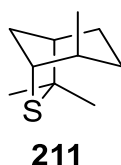
Figure 9.2: Isothiocenol **211**

9.2.1.2.1 Synthesis of the chiral auxiliary

The chiral sulfur auxiliary used during this work is not commercially available and was synthesised by our laboratory. It was obtained in a sufficient amount by Dr. Maximilien Richald during his PhD thesis[80] using a methodology developed by the group of Prof. V. K. Aggarwal (Scheme 9.4).[50]


211
37%
e.e.: 99%
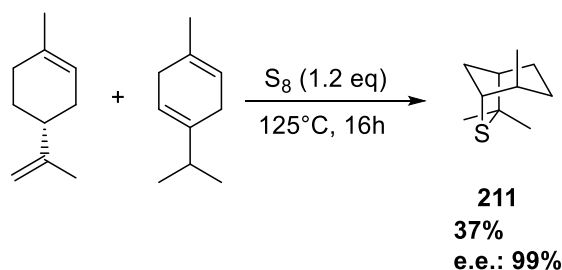
Scheme 9.4: Synthesis of the chiral auxiliary isothiocenol **211**

(+)-limonene is heated up at 125°C for 16 hours in the presence of γ-terpinene and elemental sulfur. The product is obtained in a moderate yield after purification by fractional distillation but shows a high enantiomeric excess.

9.2.1.2.1. Chiral benzylic sulfonium salts

Chiral sulfonium salt **102a** was the only chiral benzylic salt used during this work and we did not need to resynthesise it. **102a** was obtained by Dr. Sébastien Clergue starting from benzyl alcohol **64a** and chiral sulfur auxiliary **211** (Scheme 9.5). [121]
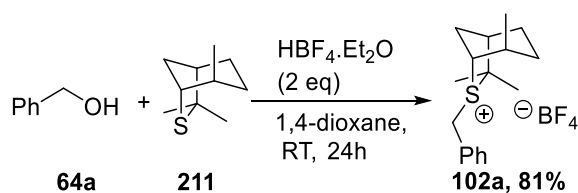
Scheme 9.5: Synthesis of the chiral sulfonium salt **102a**

9.2.2. α,β-unsaturated aldehydes

α,β-unsaturated aldehydes will be engaged in epoxidation reaction (see Chapter 5) or in Knoevenagel condensation to afford 1,3-dienes (see 4.3.). Most aldehydes were commercially available but four of them needed to be synthesised. Our strategy involved the Swern oxidation of an allylic alcohol **240**.

9.2.2.1. Synthesis of allylic alcohols

Allylic alcohols were obtained during this work with the aim of oxidising them and obtaining α,β-unsaturated aldehydes. Two alcohols were synthesised by the reduction of the corresponding ester **241** by LiAlH$_4$ (Table 9.2).

Table 9.2: Reduction of esters **240** to the corresponding allylic alcohol by LiAlH$_4$
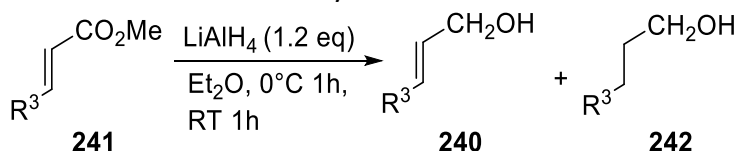
Entry	Alcohol	R^3	240/242	Total Yield (%)^a
1	**240m**	p-MeC$_6$H$_4$	7/1	85
2	**240l**	p-FC$_6$H$_4$	3/1	75

^{a} The total yield has been calculated from the mass of product recovered compared to the theoretical mass for **181**. This makes the approximation that the two products have the same molecular weight.

The desired alcohols **240m,l** were obtained, but in both cases, the saturated alcohols **242m,l** were also observed. Considering the high purity of these samples, except for the presence of **242**, we decided not to purify the alcohols and engaged them directly in a

Swern oxidation and separate the two corresponding aldehydes by chromatography at that stage (*vide infra*).

9.2.2.2. Swern oxidation

Table 9.3 shows the four aldehydes **186** obtained via the Swern oxidation of allylic alcohols **240**.

Table 9.3: Swern oxidation of allylic alcohols to the corresponding aldehydes

Entry	Aldehyde	R^2	R^3	Yield (%)[a]
1	**186h**	H	$p\text{-}CO_2MeC_6H_4$	13
2	**186m**	H	$p\text{-}MeC_6H_4$	41
3	**186l**	H	$p\text{-}FC_6H_4$	13
4	**186n**	CO_2Me	Ph	30

[a] Yield in pure isolated compound.

The isolated yield in aldehyde is, in all cases, low. For entries 1 and 4, it can be explained by the complex crude mixtures obtained after the Swern oxidation. The crude mixtures for entries 2 and 3 were cleaner but the necessity to separate the saturated and unsaturated aldehydes that were close in polarity led to the loss of a fraction of the desired products during the purification process.

9.2.3. 1,3-dienes

1,3-dienes are important substrates for the exploration of the scope of the vinylcyclopropane/skipped diene rearrangement methodology.

9.2.3.1. EWG = CO₂Et

The synthesis of 1,3-dienes was an important part of our Master's thesis work.[81] Most of the 1,3-dienes used during this work were thus already available in our laboratory. These 1,3-dienes are

obtained via a simple Knoevenagel condensation, the reaction conditions vary depending on the product. Two new electron-poor 1,3-dienes were obtained in the context of this work (Table 9.4).

Table 9.4: Synthesis of new 1,3-diene **184** by Knovenagel condensation
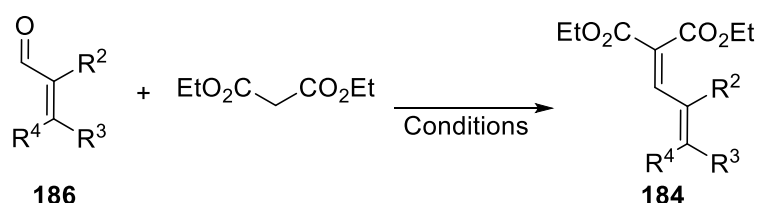
Entry	Dienes	R^2	R^3	R^4	Conditions	Yield (%)[a]
1	**184c**	H	Ph	Ph	Piperidine (0.1 eq), AcOH (0.1 eq), Ethanol, Reflux 48h	90
2	**184f**	H	*i*-Pr	H	Piperidine (0.1 eq), Toluene, RT, 16h	12

[a] Yield in pure isolated compound.

Entry 1 details the obtaining of 1,3-diene with the Knoevenagel protocol most commonly used in our laboratory for the synthesis of 1,3-dienes or activated olefins. The product was purified by distillation under reduced pressure. 1,3-Dienes with an alkyl group were found to be more sensitive to high temperature and were synthesised with a protocol in which the reaction is carried out at room temperature. Under these conditions, the conversion was not complete and the reactants needed to be removed by chromatography, explaining the lower isolated yields (entry 2).

9.2.3.2. Other EWG

Vinylcyclopropanes bearing other electron-withdrawing groups than CO_2Et were part of the exploration of the scope of the VCP-skipped diene rearrangement. In our primary strategy of interest, these EWG are brought by a 1,3-diene.
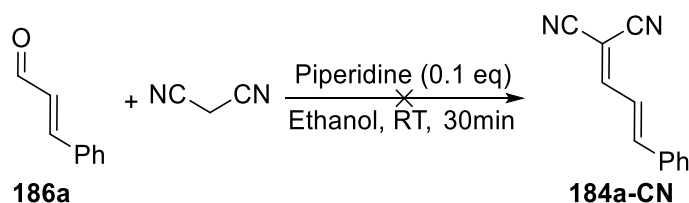
9.2.3.2.1. EWG = CN

The synthesis of electron-poor diene **184a-CN** with cyano groups was investigated using the Knoevenagel protocol used by our

lab for the formation of activated olefin bearing cyano groups (see 9.2.4.3.) (Scheme 9.6).[121]

Scheme 9.6: Failed attempt at synthesising **184a-CN**

Unfortunately, the obtained orange solid could not be purified by recrystallisation as described in the protocol. Accordingly, we decided to use the complementary strategy for the obtaining of vinylcylopropanes, in which the EWG are brought by an activated olefin since the cyano-bearing olefin was available in large amount in our laboratory to perform the first tests of rearrangements of a cyanated VCP. The desired skipped diene was never observed during these tests (see 4.3.3.) and we never resumed investigating the synthesis and purification of 1,3-dienes with cyano groups.

9.2.3.2.2. EWG = COMe

Ketone groups (COMe) were also investigated. 1,3-Diene **184a-COMe** coming from the Knoevenagel condensation of acetylacetone and cinnamaldehyde **186a** was obtained using the protocol in which the reaction is performed in toluene at room temperature (Scheme 9.7).
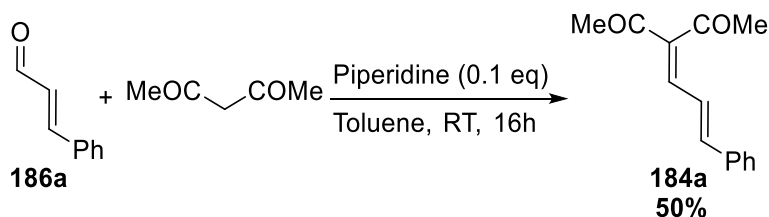
Scheme 9.7: Synthesis of the 1,3-diene **184a-COMe** by Knovenagel condensation

9.2.4. Activated olefins

Activated olefins were used in the exploration of the vinylcyclopropane/diene rearrangement to access R^1 group which were difficult to obtain if they were put on a sulfonium salt moiety (see Chapter 4). These olefins are also substrate for the homologation of activated olefins methodology (see Chapter 6).

9.2.4.1. Esters substituted olefins

Olefins activated by the presence of two ester groups could be obtained via a simple Knoevenagel condensation between **65** and diethyl malonate. These olefins were obtained by Julien Janssens (**177e,d**) and Madeline De Roose (**177r,o**) in the context of their respective Master's theses (Table 9.5).[83,111]

Table 9.5: Synthesis of Knoevenagel adducts

| Entry	Olefins	R^1	Conditions	Yield (%)
1	**177r**	m-MeOC$_6$H$_4$	Piperidine (0.1 eq), AcOH (0.1 eq), ethanol, reflux 66h	67
2	**177e**	Cyclopropyl	Piperidine (0.1 eq), EtOH, RT, 16h	87
3	**177d**	t-Bu	ZnCl$_2$ (0.15 eq), Ac$_2$O (1.25 eq), reflux 72h	65
4	**177o**	2-naphtyl	Piperidine (0.15 eq), AcOH (0.15 eq), toluene, reflux 66h	23

The protocol used by Dr. Maximilien Richald for obtaining the activated olefins[80] was used to obtain the olefin **177r** ($R^1 = m$-MeOPh) in a good yield. The other olefins required special protocols (entries 2-4) but the products were obtained in good yields except for the olefin with R^1 = 2-napthyl (entry 4). The conversion in the reaction forming **177o** was never complete and it was decided to isolate the product by flash chromatography nonetheless, which explains the low yield.

Olefins with R^1 = Ph, *p*-MeC$_6$H$_4$, *p*-CO$_2$MeC$_6$H$_4$, *p*-MeOC$_6$H$_4$, Me, *i*-Pr, *i*-Bu were available in our laboratory and were not synthesised during this work.

9.2.4.2. Deuteriated activated olefin

In order to carry out experimental mechanistic studies of the cyclopropane rearrangement involved in the homologation of activated olefins methodology, a deuteriated olefin was synthesised starting from deuteriated benzaldehyde **65a-D**. This latter was obtained by Julien Janssens using a Knoevenagel condensation (Scheme 9.8).[83]
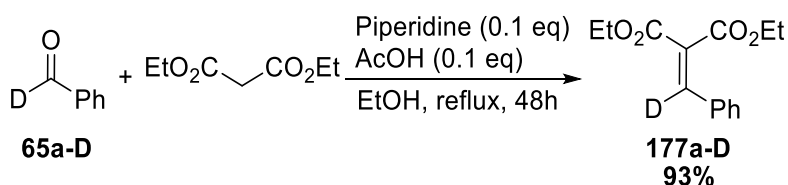
Scheme 9.8: Knoevenagel condensation of **65a-D** and diethylmalonate

The deuteriated benzaldehyde **65a-D** is a commercially available product. However, during our PhD the supplier who delivered the first batch stopped selling the product and the shipping delays were too long for the other suppliers. We then decided to obtain it via an oxidation of the deuteriated benzyl alcohol **58a-D** using the Dess-Martin periodinane (Scheme 9.9).
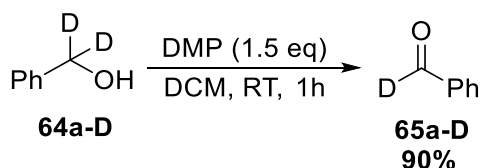
Schema 9.9: Dess-Martin oxidation of **65a-D** to **65a-D**

9.2.4.3. Other EWG

Activated olefins were used for obtaining vinylcylopropanes bearing other electron-withdrawing groups than CO$_2$Et.

9.2.4.3.1 EWG = CN

Olefins activated by cyano groups were obtained by Dr. Sébastien Clergue's during his PhD thesis and were available in sufficient amount to carry out this work.[121] These olefins were synthesised by a Knoevenagel condensation between malonitrile and a benzaldehyde derivative **59** (Scheme 4.9)
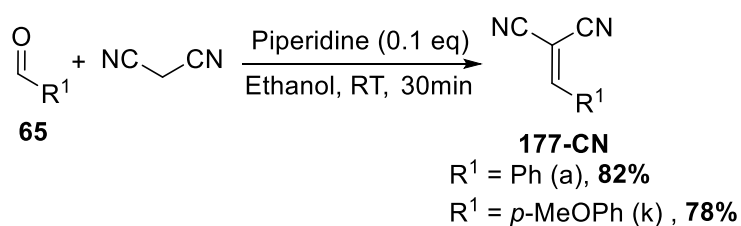
Scheme 9.10: Synthesis of **177a-CN** and **177k-CN** by Knoevenagel condensation

9.2.4.3.2. EWG = COMe

As for 1,3-dienes, the third EWG group investigated was COMe. The corresponding activated olefin **177a-COMe** was synthesised using the same protocol as for the electron-poor diene bearing two ketone groups (*vide supra*) (Scheme 9.11).
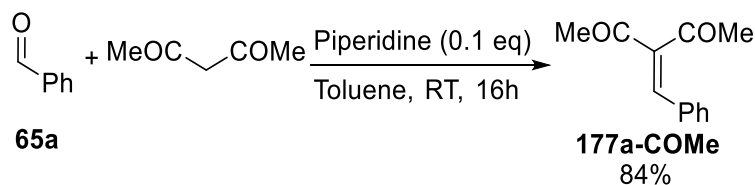
Scheme 9.11: Synthesis of **177a-COMe** by Knoevenagel condensation

9.3. General

Solvents: all solvents (for reactions, extractions and purification by chromatography) were obtained from commercial sources and used without further purification, unless mentioned otherwise.

Reactants and reagents: commercially available reagents were used as purchased, unless mentioned otherwise.

NaH dispersed in mineral oil: The %wt of the NaH in the mineral oil was determined by ^{1}H NMR titration with diethyl diethylephosphonacetate as titrating agent. The mineral oil was washed off with three portions of *n*-hexane before every reaction to prevent the mineral oil from being in our samples.

Temperatures: the reactions requiring a temperature higher than room temperature were carried out using a silicon oil bath. The temperature was controlled by a temperature probe. The reactions requiring a temperature of -78°C were carried out using an acetone/dry ice bath. The temperature of 0°C was achieved with the use of ice baths.

Anhydrous conditions: Reactions requiring anhydrous conditions were performed in glassware previously flame-dried by a Bunsen burner under reduced pressure and then cooled down under argon atmosphere.

Thin layer chromatography (TLCs): TLCs were carried out on Merck Silica gel 60 F254 aluminium backed plates using UV light and potassium permanganate for revelation.

Flash chromatography: flash chromatography was performed using Merck Silica gel 60Å (40-63 μm).

Nuclear Magnetic Resonance (NMR) spectroscopy: NMR spectra were recorded on a *Bruker avance II 300* operating at 300 MHz for proton-^{1}H and 75 MHz for carbon-^{13}C or on a Bruker Avance 500 spectrometer operating at 500 MHz for ^{1}H and 125 MHz for ^{13}C. Solvents are indicated case-by-case. Chemical shifts (δ) are reported in ppm relative to the reference signal (TMS) and coupling constants are given in Hertz (Hz). For some molecules, the ^{1}H and ^{13}C signals attributions required additional analyses (COSY, HMQC, HMBC, ^{13}C DEPT-Q). NMR multiplicities are abbreviated as follow: s = singlet, d = doublet, t = triplet, q = quadruplet, sep = septet, m = multiplet.

Mass spectrometry: mass spectra and high-resolution mass spectra were recorded by the ASM platform on a *Thermo Orbitrap Exactive* device. The mass values are given in Dalton.

IR spectrophotometry: IR spectrum were recorded with an infrared spectrophotometer *PerkinElmer Spectrum UATR Two.* The wave numbers are given in cm^{-1}.

Melting point: Melting points were recorded with a *Büchi melting point B-540.* Given temperatures are in Celsius.

Chiral HPLC: HPLC experiments were carried out at room temperature on a quaternary pump *Waters 600* equipped with a *Waters 996* DDA photodiodes array detector. The CHIRALPAK IA and IB columns used have particles of 5 µm of size. The dimension of the two columns is 4.6 mm x 250 mm.

9.4. Procedures and compounds characterisation
9.4.1. Synthesis of benzylic sulfonium salts
### *9.4.1.1. General procedure*
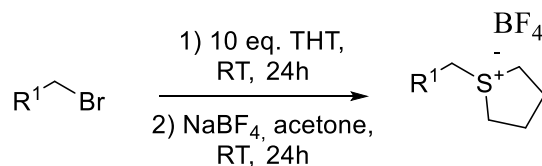
In a round-bottom flask are added the bromide derivative (1 eq.) and tetrahydrothiophene (11 eq.). After stirring for 24 h at room temperature, the resulting solid is washed with cyclohexane in order to remove the excess of tetrahydrothiophene. The crude bromide derivative is then diluted with acetone (2mL/mmol of bromide derivative), followed by the addition of NaBF$_4$ (1 eq.). After stirring for 24 h at room temperature, the reaction mixture is filtered in order to remove precipitated NaBr. The solution is then concentrated under reduced pressure. The sulfonium salt is purified by precipitation in a MeOH/Et$_2$O mixture.

9.4.1.2. Product descriptions

9.4.1.2.1. 1-Benzylthiolan-1-ium trifluoroborane fluoride (185a)
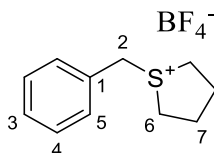
Chemical Formula: $C_{11}H_{15}SBF_4$
Molecular Weight: 266.10

CAS: 1478-78-0
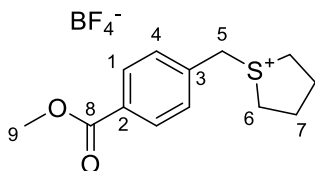**Aspect:** White powder
Melting point: 120 – 121°C
Yield: 48%

^{1}H NMR (300 MHz, (CD$_3$)$_2$CO): δ = 7.70 (m, 2H, H^{arom}), 7.54 (m, 3H, H^{arom}), 4.81 (s, 2H, H^2), 3.80 to 3.65 (m, 4H, H^6), 2.48 (m, 4H, H^7)

^{13}C NMR (75 MHz, (CD$_3$)$_2$CO): δ = 131.1, 130.4, 130.1, 129.9, 46.2, 43.2, 28.9

HRMS (APCI): Calculated for $C_{11}H_{15}{}^{32}S^+$: 179.08890, found: 179.08889

9.4.1.2.2. 1-{[4-(Methoxycarbonyl)phenyl]methyl}thiolan-1-ium trifluoroborane fluoride (185f)

Chemical Formula: $C_{13}H_{17}O_2SBF_4$
Molecular Weight: 324.14

CAS: 1028204-21-3
Yield: 32%
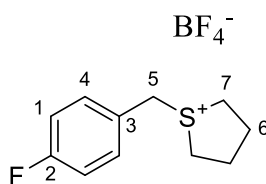**Aspect:** White powder
Melting point: 121°C

^{1}H NMR (300 MHz, CD$_2$Cl$_2$): δ = 8.08 (d, 2H, *J* = 8.4 Hz, H^1), 7.58 (d, 2H, *J* = 8.4 Hz, H^4), 4.59 (s, 2H, H^5), 3.91 (s, 3H, H^9), 3.64 to 3.38 (m, 4H, H^6), 2.48 to 2.22 (m, 4H, H^7)

¹³C NMR (75 MHz, CD₂Cl₂): δ = 166.2, 132.9, 132.5, 131.2, 131.0, 52.7, 46.2, 43.3, 29.0

HRMS (APCI): Calculated for $C_{13}H_{18}O_2{}^{32}S^+$: 237.09438, found: 237.09434

9.4.1.2.3. 1-[(4-Fluorophenyl)methyl]thiolan-1-ium trifluoroborane fluoride (185p)

Chemical Formula: $C_{11}H_{14}F_5SBF$
Molecular Weight: 284.10

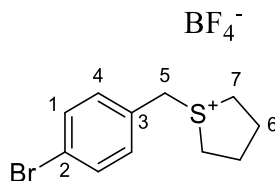**CAS:** 1028204-22-4
Yield: 63%
Aspect: White powder
Melting point: 109°C

¹H NMR (300 MHz, CD₂Cl₂): δ = 7.56 to 7.44 (m, 2H, H⁴), 7.20 to 7.07 (m, 2H, H¹), 4.50 (s, 2H, H⁵), 3.58 to 3.33 (m, 4H, H⁷), 2.44 to 2.18 (m, 4H, H⁶)

¹³C NMR (75 MHz, CD₂Cl₂): δ = 183.1 (d, J = 250.3 Hz), 133.0 (d, J = 8.7 Hz), 124.5 (d, J = 3.2 Hz), 117.2 (d, J = 22.1 Hz) , 45.8, 42.9, 28.9

HRMS (APCI): Calculated for $C_{11}H_{14}F^{32}S^+$: 197.07948, found: 197.07946

9.4.1.2.4. 1-[(4-Bromophenyl)methyl]thiolan-1-ium trifluoroborane fluoride (185q)

Chemical Formula: $C_{11}H_{14}F_4SBBr$
Molecular Weight: 345.00

Yield: 67%
Aspect: White powder
Melting point: 120°C

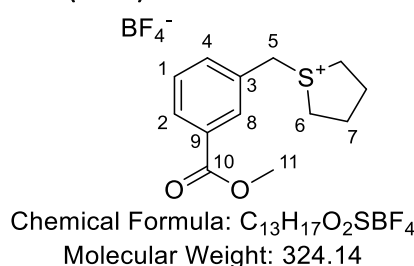**^{1}H NMR (300 MHz, CD$_2$Cl$_2$)**: δ = 7.56 to 7.44 (m, 2H, H^4), 7.20 to 7.07 (m, 2H, H^1), 4.50 (s, 2H, H^5), 3.58 to 3.33 (m, 4H, H^7), 2.44 to 2.18 (m, 4H, H^6)

^{13}C NMR (75 MHz, CD$_2$Cl$_2$): δ = 133.1, 133.0, 129.4, 124.1, 45.4, 43.3, 28.8.

HRMS (APCI): Calculated for C$_{11}$H$_{14}$Br^{32}S$^+$: 256.99941, found: 256.99916

9.4.1.2.2. 1-{[3-(Methoxycarbonyl)phenyl]methyl}thiolan-1-ium trifluoroborane fluoride (**185r**)

Chemical Formula: C$_{13}$H$_{17}$O$_2$SBF$_4$
Molecular Weight: 324.14

Yield: 25%
Aspect: White powder
Melting point: 121°C

^{1}H NMR (300 MHz, CD$_2$Cl$_2$): δ = 8.08 (d, 2H, *J* = 8.4 Hz, H^1), 7.58 (d, 2H, *J* = 8.4 Hz, H^4), 4.59 (s, 2H, H^5), 3.91 (s, 3H, H^9), 3.64 to 3.38 (m, 4H, H^6), 2.48 to 2.22 (m, 4H, H^7)

^{13}C NMR (75 MHz, CD$_2$Cl$_2$): δ = 166.0, 135.4, 131.9, 131.6, 130.9, 130.7, 130.4, 52.2, 45.6, 43.4.

HRMS (APCI): Calculated for C$_{13}$H$_{18}$O$_2$^{32}S$^+$: 237.09438, found: 237.09434

9.4.2. Synthesis of allylic sulfonium salt

9.4.2.1. (E)-4-Methylpent-2-en-1-ol (240c)
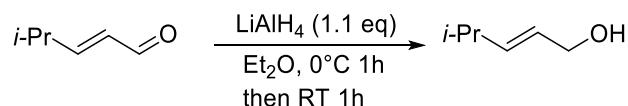

In a dry round bottom flask, under argon atmosphere, a solution of (*E*)-4-methylpent-2-enal (2.5 mL, 21.5 mmol, 1 eq.) dissolved in diethyl ether (10 mL) is added dropwise to a solution of LiAlH$_4$ (1.07 g, 60 mmol, 1.1 eq.) in diethyl ether (30 mL) at 0°C in a second dry round bottomed flask under argon atmosphere. The mixture is stirred for 1h at 0°C and then allowed to

warm up to room temperature and stirred for one additional hour. The reaction is stopped by the dropwise addition of 20 mL of a saturated solution of potassium sodium tartrate. The layers are separated and the aqueous layer is extracted twice with diethylether. The combined organic layers are dried over $MgSO_4$ and the desired product (1.596 g) is obtained after evaporation of the solvent under reduced pressure.
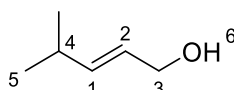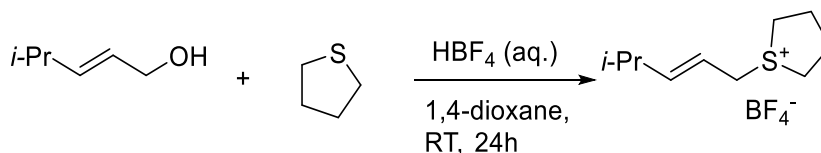

Chemical Formula: $C_6H_{12}O$
Molecular Weight: 100.16

CAS: 69143-05-1
Yield: 73%
Aspect: colorless oil

**¹H NMR (300 MHz, (CD₃)₂CO)**: δ= 5.57 (m, 2H, H[1 and 2]), 4.04 (d, *J* = 5.4 Hz, 2H, H[3]), 2.27 (m, 1H, H[4]), 2.07 (bs, 1H, H[6]), 0.96 (d, *J* = 6.8 Hz, 6H, H[5]).

9.4.2.2. 1-[(2E)-4-Methylpent-2-en-1-yl]thiolan-1-ium; tetrafluoroboranuide (178c)

(*E*)-4-Methylpent-2-en-1-ol (1.578g, 15.8 mmol, 1 eq.), tetrahydrothiophene (1.4 mL, 16.7 mmol, 1.06 eq.) and 1,4-dioxane (4mL) are introduced in a round-bottom flask. An aqueous solution of tetrafluoroboric acid (1.8 mL, 17.5 mmol, 1.1 eq.) is added slowly. After 24 hours of stirring at room temperature, the solvent is evaporated. Azeotropic evaporation with EtOH was performed to remove the water. The residue is then dissolved in dichloromethane. A solution of 1M HCl is then added. The two layers are separated and the aqueous one is extracted twice with dichloromomethane. The combined organic layers are washed with brine, dried over $MgSO_4$ and concentrated under reduced pressure. The sulfonium salt (1.142 g) is obtained as a brown oil.
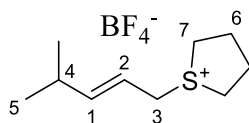
Chemical Formula: $C_{10}H_{19}SBF_4$
Molecular Weight: 258.12

Yield: 28 %
Aspect: brown oil

^{1}H NMR (300 MHz, (CD$_3$)$_2$CO): δ = 6.11 (ddt, 1H, J = 15.4, 6.7, 1.1 Hz, H^1), 5.55 (ddt, 1H, J = 15.3, 7.6, 1.4 Hz, H^2), 4.02 (d, 2H, J = 7.7 Hz, H^3), 3.58 (m, 2H, H^7), 3.66-3.44 (m, 2H, H^7), 2.41-2.19 (m, 5H, H^{4,6}), 1.02 (d, 6H, J = 6.8 Hz, H^5)
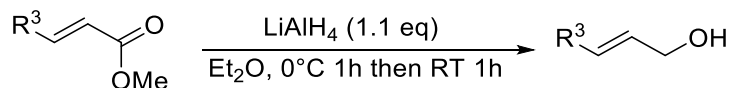
^{13}C NMR (75 MHz, (CD$_3$)$_2$CO): δ = 152.5, 113.3, 44.8, 41.9, 31.8, 29.1, 22.1

HRMS (ESI): calculated for $C_{10}H_{19}{}^{32}S^+$: 171.12020 found: 171.12024

9.4.3. Synthesis of α,β-unsaturated aldehydes

9.4.3.1. Synthesis of allylic alcohols

9.4.3.1.1. General procedure

In a dry round bottom flask, under argon atmosphere, a solution of the ester (1 eq.) dissolved in diethyl ether (11 mL/g of ester) is added dropwise to a solution of LiAlH$_4$ (1.1 eq.) in diethyl ether (30 mL/g of ester) at 0°C in a second dry round bottomed flask under argon atmosphere. The mixture is stirred for 1h at 0°C and then allowed to warm up to room temperature and stirred for one additional hour. The reaction is stopped by the dropwise addition of 20 mL of a saturated solution of potassium sodium tartrate. The layers are separated and the aqueous layer is extracted twice with diethylether. The combined organic layers are dried over MgSO$_4$ and the desired product is obtained after evaporation of the solvent under reduced pressure.

9.4.3.1.2. Product descriptions

9.4.3.1.2.1. (*E*)-3-(*p*-Tolyl)prop-2-en-1-ol (**240m**)
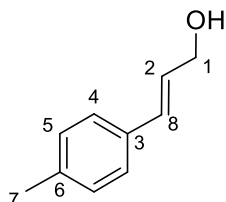
Chemical Formula: $C_{10}H_{12}O$
Molecular Weight: 148.21

CAS: 122058-30-4
Yield: 85%
Aspect: colorless liquid

^{1}H NMR (300 MHz, CDCl$_3$) δ = 7.30 (m, 2H, H^4), 7.14 (m, 2H, H^5), 6.61 (dt, 1H, *J* = 15.9, 1.5 Hz, H^8), 6.34 (dt, 1H, *J* = 15.9, 5.8 Hz, H^2), 4.33 (dd, 2H, *J* = 5.8, 1.5 Hz, H^1), 2.36 (s, 3H, H^7)

^{13}C NMR (75 MHz, CDCl$_3$): δ = 137.7, 134.0, 131.3, 129.4, 127.5, 126.5, 64.0, 21.3

HRMS (ESI): Calculated for $C_{10}H_{13}O$: 149.09609, found: 149.09607

9.4.3.1.2.2. (*E*)-3-(4-Fluorophenyl)prop-2-en-1-ol (**240l**)
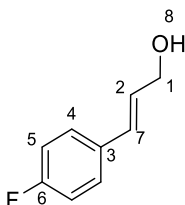
Chemical Formula: C_9H_9OF
Molecular Weight: 152.17

CAS: 124980-95-6
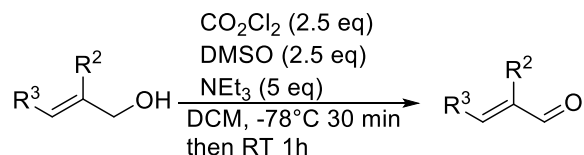**Yield**: 75%
Aspect: colorless liquid

^{1}H NMR (300 MHz, CDCl$_3$) δ = 7.44 − 6.89 (m, 4H, H^{arom}), 6.59 (d, *J* = 15.9 Hz, 1H, H^7), 6.29 (dt, *J* = 15.9, 5.7 Hz, 1H, H^2), 4.32 (d, *J* = 5.1 Hz, 2H, H^1), 1,25 (s, 1H, H^8).

9.4.3. Synthesis of α,β-unsaturated aldehydes

9.4.3.1. General procedure

In a dry round-bottom flash under inert atmosphere at -78°C, dry dichloromethane (10 mL/g of alcohol), oxalyl chloride (2.5 eq.) and DMSO (2.5 eq.) diluted in 1 mL of dry dichloromethane are added dropwise in that order. After 5 minutes of stirring, the allylic alcohol (1 eq.) dissolved in 5 mL of dry dichloromethane is added dropwise. After 10 minutes of stirring, trimethylamine (5 eq.) is added dropwise. The mixture is stirred for 15 min at -78°C and for 1h at room temperature. Water is added to stop the reaction. The phases are separated and the aqueous one is extracted twice with dichloromethane. The combined organic layers are washed with brine, dried over $MgSO_4$ and concentrated under reduced pressure. The crude mixture is purified by flash chromatography to give the desired aldehyde.

9.4.3.2. Product descriptions

9.4.3.1.2.1. (*E*)-3-(*p*-Tolyl)acrylaldehyde (**186m**)
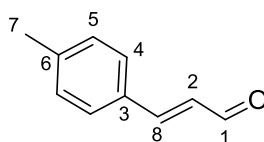
Chemical Formula: $C_{10}H_{10}O$
Molecular Weight: 146.19

CAS: 56578-35-9
Eluent for purification: 85/15 *n*-hexane/AcOEt
Yield: 41%
Aspect: colorless liquid

^{1}H NMR (300 MHz, CDCl₃) δ = 9.65 (d, *J* = 7.7 Hz, 1H, H[1]), 7.47 − 7.38 (m, 3H, H[4 and 8]), 7.21 (d, *J* = 8.1 Hz, 2H, H[5]), 6.66 (dd, *J* = 15.9, 7.7 Hz, 1H, H[2]), 2.37 (s, 3H, H[7]).

9.4.3.1.2.2. (*E*)-3-(4-Fluorophenyl)acrylaldehyde (**186l**)
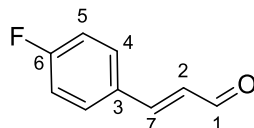
Chemical Formula: C_9H_9OF
Molecular Weight: 152.17

CAS: 51791-26-5
Eluent for purification: 85/15 *n*-hexane/AcOEt
Yield: 13%
Aspect: colorless liquid

^{1}H NMR (300 MHz, CDCl$_3$) δ = 9.69 (d, *J* = 7.6 Hz, 1H, H^1), 7.62 – 6.87 (m, 5H, H^{arom} + H^7), 6.65 (dd, *J* =16.0, 7.6, 1H, H^2).

9.4.3.1.2.3. Methyl (*E*)-4-(3-oxoprop-1-en-1-yl)benzoate (**186h**)

Chemical Formula: $C_{11}H_{10}O_3$
Molecular Weight: 190.20

Eluent for purification: 75/25 *n*-hexane/AcOEt
Yield: 13%
Aspect: colorless liquid

^{1}H NMR (300 MHz, CDCl$_3$) δ = 9.75 (d, *J* = 7.6 Hz, 1H, H^1), 8.10 (d, *J* = 8.4 Hz, 2H, H^5), 7.64 (d, *J* = 8.3 Hz, 2H, H^4), 7,51 (d, *J* = 16.0 Hz, 1H, H^7), 6,78 (dd, *J* = 16.0, 7.6 Hz, 1H, H^2), 3.95 (s, 3H, H^9).

9.4.3.1.2.4. Methyl (*E*)-4-(3-oxoprop-1-en-1-yl)benzoate (**186n**)

Chemical Formula: $C_{11}H_{10}O_3$
Molecular Weight: 190.20

CAS: 113549-37-4
Eluent for purification: 80/20 *n*-hexane/AcOEt
Yield: 30%
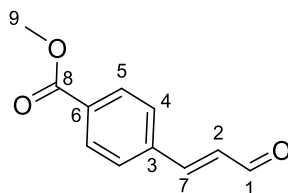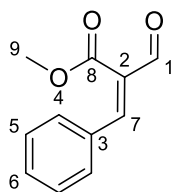**Aspect:** colorless liquid

^{1}H NMR (300 MHz, CDCl$_3$) δ = 9.61 (s, 1H, H^1), 7.56 − 7.39 (m, 6H, H^{arom} + H^7), 3.89 (s, 3H, H^9).

9.4.4. Synthesis of 1,3-dienes

9.4.4.1. Diethyl 2-(3,3-diphenylallylidene)malonate (184f)
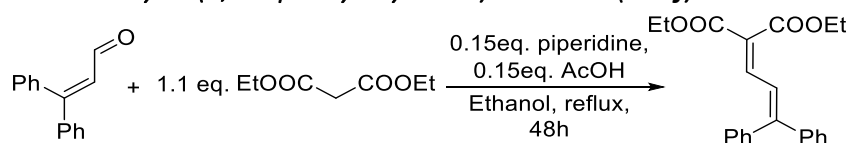
β-Phenyl cinnamaldehyde (0.73 g, 3.51 mmol, 1 eq.), 1,3-diethyl propandioate (0.53 mL, 3.86, 1.1 eq.), piperidine (0.03 mL, 0.15 eq.), glacial acetic acid (0.02 mL, 0.15 eq) and absolute ethanol (4 mL) are introduced in a round-bottom flask with a condenser. The mixture is heated at reflux for 48 hours. Then, the solvent is evaporated and the crude product is distilled under reduced pressure (T°$_{oil\ bath}$= 200°C) and the desired product (1.044 g) is obtained as the distillation residue.

Chemical Formula: C$_{22}$H$_{22}$O$_4$
Molecular Weight: 350.41
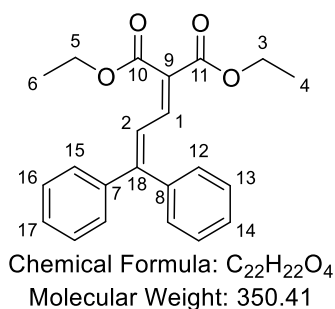
Yield: 85%
Aspect: brown oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.48 − 7.28 (m, 9H, H$^{arom\ and\ 1}$), 7.24 − 7.18 (m, 2H, H^{arom}), 7.14 (d, *J* = 12.1 Hz, 1H, H^2), 4.37 (q, *J* = 7.1 Hz, 2H, H$^{5\ or\ 3}$), 4.20 (q, *J* = 7.1 Hz, 2H, H$^{3or\ 5}$), 1.37 (t, *J* = 7.1 Hz, 1H, H$^{6\ or\ 4}$), 1.24 (t, *J* = 7.1 Hz, 1H, H$^{4\ or\ 6}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 165.9, 165.0, 154.9, 142.2, 141.3, 138.2, 130.8, 129.4, 128.9, 128.7, 128.5, 128.5, 125.9, 122.1, 61.5, 61.3, 14.4, 14.2.

HRMS (APCI): Calculated for $C_{22}H_{23}O_4$: 351.15909, found: 351.15896

9.4.4.2. Diethyl (E)-2-(4-methylpent-2-en-1-ylidene)malonate (184c)
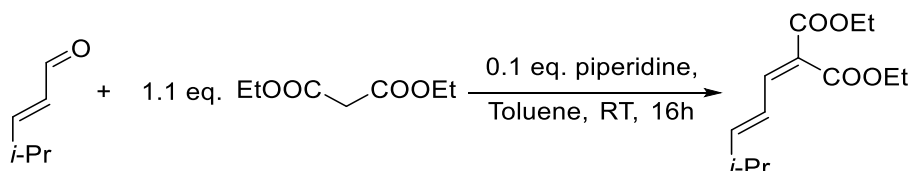
(*E*)-4-Methylpent-2-enal (1 mL, 8.6 mmol, 1 eq.), 1,3-diethyl propandioate (1.3 mL, 9.5 mmol, 1.1 eq.), piperidine (0.1 mL, 1.3 mmol, 0.15 eq) and toluene (4 mL) are introduced in a round-bottom flask. The reaction is stirred at room temperature for 16 hours. Then, the solvent is evaporated and the crude product is purified by flash chromatography on silica gel with 82/18 *n*-hexane/AcOEt as eluent and recovered as a yellow oil (0.2421 g).

Chemical Formula: $C_{13}H_{20}O_4$
Molecular Weight: 240.30
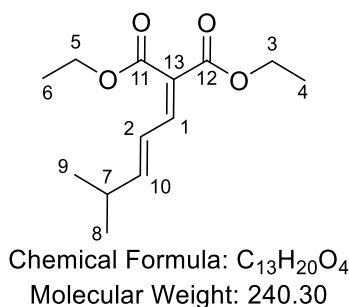
Yield: 12%
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.32 (d, *J* = 11.4 Hz, 1H, H^1), 6.47 (ddd, *J* = 15.1, 11.4, 1.2 Hz, 1H, H^2), 6.26 (dd, *J* = 15.3, 6.7 Hz, 1H, H^{10}), 4.31 (q, *J* = 7.2 Hz, 2H, H$^{5 \text{ or } 3}$), 4.23 (q, *J* = 7.1 Hz, 2H, H$^{3 \text{ or } 5}$), 2.55 − 2.36 (m, 1H, H^7), 1.33 (t, J = 7.1 Hz 3H, H$^{6 \text{ or } 4}$), 1.28 (t, J = 7.1 Hz, 3H, H$^{4 \text{ or } 6}$), 1.04 (d, *J* = 6.8 Hz, 6H, H$^{8 \text{ and } 9}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 165.6, 183.9, 156.2, 145.9, 123.9, 123.0, 61.3, 61.3, 32.1, 21.7, 14.3. *C^9 and C^8 signals are overlapping. C^6 and C^4 are overlapping.*

HRMS (APCI): Calculated for $C_{12}H_{19}O_4$: 241.14344, found: 241.14361

9.4.5. Synthesis of activated olefins

9.4.5.1. General procedure
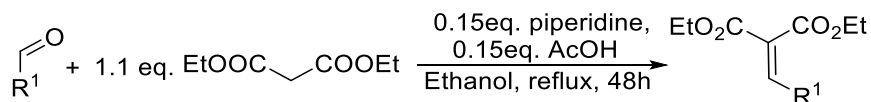
Starting aldehyde (1eq.), 1,3-diethyl propandioate (1.1 eq.), piperidine (0.15 eq.), glacial acetic acid (0.15 eq) and absolute ethanol (10 mL/mmol of aldehyde) were introduced in a round-bottom flask with a condenser. The mixture is heated at reflux for 48 hours. Then, the solvent is evaporated and and the crude product is distilled under reduced pressure (T°$_{oil\ bath}$= 200°C) and the desired product is obtained as the distillation residue.

9.4.5.2. Products descriptions

9.4.5.2.1. Benzaldehyde-α-d^1 (**65a-D**)
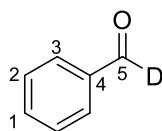
Chemical Formula: C$_7$H$_5$DO
Molecular Weight: 107.13

Procedure:
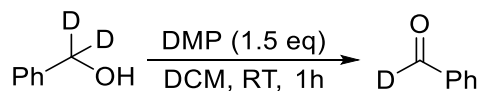
Alcohol (0.4 mL, 3.87 mmol) and dry dichloromethane (20 mL) are introduced in a dry round-bottom flask under argon. Then, Dess–Martin periodinane (2.460 g, 5.8 mmol) is added and the mixture is stirred at room temperature for 1h (Reaction completion was monitored by TLC). Water is added to stop the reaction. The two layers are separated and the aqueous one is extracted twice with dichloromethane. The combined organic layers are washed with brine, dried over MgSO$_4$ and concentrated under reduced pressure.

Yield: 90%
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.95 − 7.83 (m, 2H, H^3), 7.68 − 7.60 (m, 1H, H^1), 7.58 − 7.48 (m, 2H, H^2).

Due to a lack of time, no further analysis were carried out on this compound.

9.4.5.2.2. 1,3-Diethyl 2-[phenyl(2H)methylidene]propanedioate (**177a-D**)

Chemical Formula: $C_{14}H_{15}DO_4$
Molecular Weight: 249.28
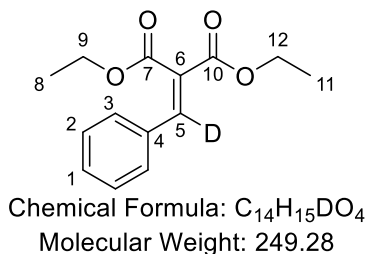
Yield: 93%
Aspect: brown oil

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.37 to 7.18 (m, 5H, H^{arom}), 4.20 (m, 4H, H^{9,12}), 1.18 (m, 6H, H^{8,11}).

9.4.5.2.3. Diethyl 2-(3-methoxybenzylidene)malonate (**177r**)

Chemical Formula: $C_{15}H_{18}O_5$
Molecular Weight: 278.30
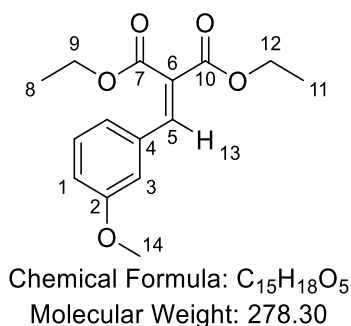
Yield: 67%
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.70 (s, 1H, H^{13}), 7.35 − 6.83 (m, 4H, H^{arom}), 4.32 (q, J = 7.1 Hz, 2H, H$^{12\ or\ 9}$), 4.32 (q, J = 7.1 Hz, 2H, H$^{9\ or\ 12}$), 3.80 (s, 3H, H^{14}), 1.34 (t, J = 7.1 Hz, 3H, H$^{11\ or\ 8}$), 1.30 (t, J = 7.1 Hz, 3H, H$^{8\ or\ 11}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 167.2, 166.6, 159.7, 141.8, 134.1, 129.7, 126.5, 121.9, 116.4, 114.2, 61.6, 61.6, 55.1, 14.1, 14.1.

HRMS (APCI) calculated for $C_{15}H_{19}O_5$: 279.12253, found: 279.12270.

9.4.5.2.4. Diethyl 2-(naphthalen-2-ylmethylene)malonate (177o)
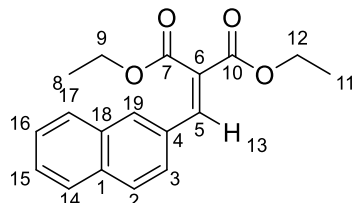
Chemical Formula: $C_{18}H_{18}O_4$
Molecular Weight: 298.34

Special procedure:
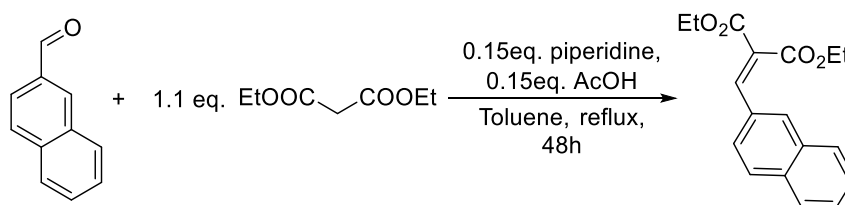
2-Naphtaldehyde (0.5 g, 3.2 mmol, 1.1 eq.), 1,3-diethyl propandioate (0.44 mL, 2.91 mmol, 1 eq.), piperidine (0.04 mL, 0.44 mmol, 0.15 eq.), glacial acetic acid (0.02 mL, 0.44 mmol, 0.15 eq) and toluene (25 mL) are introduced in a round-bottom flask with a Dean-Stark apparatus and a condenser. The mixture is heated at reflux (110°C) for 66 hours. Then, 1M HCl is added and the phases are separated. The aqueous phase is extracted twice with toluene. The combined organic layers are washed with brine, dried over $MgSO_4$. The solvent is evaporated under reduced pressure. The product is purified by chromatography on silica gel with a mixture n-hexane/AcOEt 95/5 as the eluent. 216 mg of the desired Knoevenagel adduct are obtained.

Yield: 23%
Aspect: orange oil

^{1}H NMR (300 MHz, CDCl$_3$): δ= 7.70 (s, 1H, H^{13}), 7.35 – 6.83 (m, 4H, H^{arom}), 4.32 (q, J = 7.1 Hz, 2H, H$^{12\,or\,9}$), 4.32 (q, J = 7.1 Hz, 2H, H$^{9\,or\,12}$), 3.80 (s, 3H, H^{14}), 1.34 (t, J = 7.1 Hz, 3H, H$^{11\,or\,8}$), 1.30 (t, J = 7.1 Hz, 3H, H$^{8\,or\,11}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 167.2, 166.6, 159.7, 141.8, 134.1, 129.7, 126.5, 121.9, 116.4, 114.2, 61.6, 61.6, 55.1, 14.1, 14.1.

HRMS (APCI) calculated for $C_{15}H_{19}O_5$: 279.12253, found: 279.12270.

9.4.5.2.5. Diethyl 2-(2,2-dimethylpropylidene)malonate (**177d**)
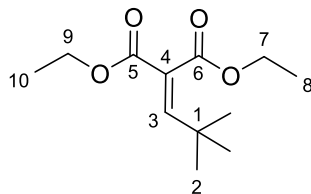
Chemical Formula: $C_{12}H_{20}O_4$
Molecular Weight: 228.29

Special procedure :
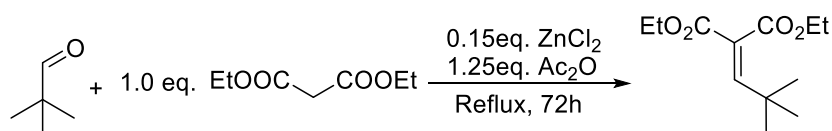
Pivaldehyde (2.2 mL, 19.9 mmol, 1eq.), diethyl malonate (3 mL, 19.9 mmol, 1 eq.), $ZnCl_2$ (0.384g, 2.8 mmol, 0.15 eq.), acetic anhydride (1.25 eq) are introduced in a dry round-bottom flask under argon atmosphere with a condenser. The mixture is heated at reflux for 72 hours. The reaction mixture is dissolved in toluene and washed three times with water. The combined aqueous layers are washed with toluene two times. The combined organic layers are dried with $MgSO_4$ and then filtrated on silica to afford the desired product. 2.949g of the desired Knoevenagel adduct are obtained.

Yield: 65%
Aspect: yellow oil

¹H NMR (300 MHz, CDCl₃) δ 6.86 (s, 1H, H³), 4.27 (q, J = 7.1 Hz, 2H, H⁷ ᵒʳ ⁹), 4.20 (q, J = 7.1 Hz, 2H, H⁹ ᵒʳ ⁷), 1.32 (t, J = 7.2 Hz, 3H, H⁸ ᵒʳ ¹⁰), 1.26 (t, J = 7.2 Hz, 3H, H ¹⁰ ᵒʳ ⁸), 1.13 (s, 9H, H²).

¹³C NMR (75 MHz, CDCl₃) δ 166.9, 183.5, 155.0, 125.3, 61.4, 61.3, 34.2, 28.9, 14.0, 13.9.

HRMS (APCI) calculated for $C_{12}H_{20}O_4$: 229.14363, found: 229.14344.

9.4.5.2.6. Diethyl 2-(cyclopropylmethylene)malonate (**177e**)
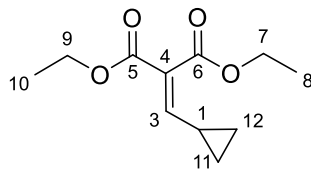
Chemical Formula: $C_{11}H_{16}O_4$
Molecular Weight: 212.26

Yield: 87%
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 6.34 (d, J = 11.3 Hz, 1H, H^3), 4.31 (q, J = 7.1 Hz, 2H, H$^{7 \text{ or } 9}$), 4.21 (q, J = 7.1 Hz, 2H, H$^{9 \text{ or } 7}$), 2.04 − 1.86 (m, 1H, H^1), 1.33 (t, J = 7.1 Hz, 3H, H$^{7 \text{ or } 8}$, 1.27 (t, J = 7.1 Hz, 3H, H$^{10 \text{ or } 8}$), 1.07 (m, 2H, H$^{11a \text{ and } 12a}$), 0.78 − 0.70 (m, 2H, H$^{11b \text{ and } 12b}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 165.8, 183.3, 156.1, 125.5, 61.1, 61.0, 14.1, 14.1, 13.0, 9.8.

HRMS (APCI) calculated for $C_{11}H_{16}O_4$: 213.11214, found: 213.11244.

9.4.6. Synthesis of vinylcyclopropanes

9.4.6.1. Strategy from 1,3-dienes: Procedure A

In a dry round-bottomed flask, under an inert atmosphere, sulfonium salt (1.2 eq.) is dissolved in dichloromethane (1 mL/20mg of sulfonium salt). LiHMDS (1.0M in THF, 1.2 eq.) is added dropwise at -78°C. The diene is then added dropwise. The mixture is stirred at -78°C for 1 h and 1h at room temperature. Water is added to stop the reaction. An aqueous solution of hydrochloric acid (1M) is added. The two layers are separated and the aqueous one is extracted two times with dichloromethane. The combined organic layers are washed with brine, dried over MgSO$_4$ and concentrated under reduced pressure. The vinylcylopropane is then purified by flash column chromatography to yield a mixture of *trans* and *cis* isomers.

The eluent used for the chromatography column depends on the product and is given for each synthesised vinylcyclopropane in the next section.

9.4.6.2. Strategy from activated olefins: Procedure B

In a dry round-bottomed flask, under an inert atmosphere, sulfonium salt (1.2 eq.) is dissolved in dichloromethane (1 mL/20mg of sulfonium salt). LiHMDS (1.0M in THF, 1.2 eq.) is added dropwise at -78°C. The olefin is then added dropwise. The mixture is stirred at -78°C for 1 h and 1h at room temperature. Water is added to stop the reaction. An aqueous solution of hydrochloric acid (1M) is added. The two layers are separated and the aqueous one is extracted two times with dichloromethane. The combined organic layers are washed with brine, dried over $MgSO_4$ and concentrated under reduced pressure. The vinylcylopropane is then purified by flash column chromatography to yield a mixture of *trans* and *cis* isomers.

The eluent used for the chromatography column depends on the product and is given for each synthesised vinylcyclopropane in the next section.

9.4.6.3. Products descriptions

9.4.6.3.1. 1,1-Diethyl 2-phenyl-3-[(1*E*)-1-phenylprop-1-en-2-yl]cyclopropane-1,1-dicarboxylate (**179ad**)
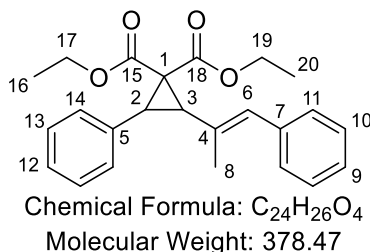
Chemical Formula: $C_{24}H_{26}O_4$
Molecular Weight: 378.47

The characterisation of this compound was made on a mixture of cis and trans diastereomers

Procedure: A
Eluent for purification: *n*-hexane/AcOEt (9/1)
Yield: 45 %
d.r. (*cis/trans*): 4/6
Aspect: colorless oil

^{1}H NMR (300 MHz, CDCl$_3$): δ= 7.17 (m, 20H, H$^{arom}_{cis, trans}$), 6.41 (s, 2H, H$^6_{cis, trans}$), 4.29 to 3.77 (m, 8H, H$^{17,20}_{cis, trans}$), 3.63 (d, 1H, *J* = 8.6 Hz, H$^2_{trans}$), 3.26 (d, 1H, *J* = 8.5 Hz, H$^3_{trans}$), 3.06 (d, 1H, *J* = 10.3 Hz, H$^2_{cis}$), 2.76 (dd, 1H, *J* = 10.2, 0.9 Hz, H$^3_{cis}$), 1.91 (s, 3H, H$^8_{cis\ or\ trans}$), 1.89 (s, 3H, H$^8_{cis\ or\ trans}$), 1.24 (t, 3H, *J* = 7.1 Hz, H$^{16\ or\ 19}_{cis}$), 1.16 (t, 3H, *J* = 7.1 Hz, H$^{16\ or\ 19}_{trans}$), 0.96 (t, 3H, *J* = 7.1 Hz, H$^{16\ or\ 19}_{cis}$), 0.87 (t, 3H, *J* = 7.1 Hz, H$^{16\ or\ 19}_{trans}$)

^{13}C NMR (75 MHz, CDCl$_3$): δ= 177.0, 167.4, 167.2, 166.5, 138.0, 137.7, 135.2, 134.6, 131.9, 131.5, 130.1, 130.0, 129.2, 129.1, 128.6, 128.5, 128.4, 127.9, 127.7, 127.1, 126.9, 126.7, 62.4, 61.9, 61.7, 61.4, 44.9, 41.4, 39.8, 38.9, 35.8, 34.9, 19.7, 18.8, 14.6, 14.4, 14.2, 14.1

HRMS (ESI): Calculated for C$_{24}$H$_{27}$O$_4$: 379.19039, found: 379.19032

9.4.6.3.2. Diethyl (*E*)-2-(4-bromostyryl)-3-phenylcyclopropane-1,1-dicarboxylate (**179ae**)

Chemical Formula: C$_{23}$H$_{23}$BrO$_4$
Molecular Weight: 443.38

This description for a mixture of cis and trans vinylcyclopropane isomers

Procedure: A
Eluent for purification: *n*-hexane/AcOEt (85/15)
Yield: 82%
d.r. (*cis/trans*): 4/6
Aspect: Colorless oil

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.46 − 7.13 (m, 18H, H^{arom}), 6.72 (d, *J* = 15.8 Hz, 1H, H6x), 6.65 (d, *J* = 15.9 Hz, 1H, H^6_x), 6.22 (dd, *J* = 15.9, 10.3 Hz, 1H, H$^5_{cis}$), 6.04 (dd, *J* = 15.8, 8.7 Hz, 1H, H$^5_{trans}$), 4.40 − 4.01 (m, 6H, H$^{19\ or\ 16}_{cis\ and\ trans}$), 3.99 − 3.82 (m, 2H, H$^{16\ or\ 19}_{trans}$), 3.47 (d, *J* = 7.9 Hz, 1H, H$^2_{trans}$), 3.39 (d, *J* = 9.8 Hz, 1H, H$^2_{cis}$), 3.30 (t, *J* = 8.3 Hz, 1H, H$^3_{trans}$), 2.78 (t, *J* = 10.1 Hz, 1H, H$^3_{cis}$), 1.32 (t, *J* = 7.1 Hz, 3H, H$^{15\ or\ 18}_{cis}$), 1.24 (t, *J* = 7.1 Hz, 3H, H$^{15\ or\ 18}_{trans}$), 1.16 (t, *J* = 7.1 Hz, 3H, H$^{15\ or\ 18}_{cis}$), 0.92 (t, *J* = 7.1 Hz, 3H, H$^{15\ or\ 18}_{trans}$).

^{13}C NMR (75 MHz, CDCl$_3$): δ= 170.0, 167.6, 166.4, 136.2, 135.8, 134.4, 133.2, 132.8, 132.2, 131.8, 131.7, 130.5, 128.7, 128.4, 128.3, 127.8, 127.8, 127.6, 127.5, 125.4, 125.2, 121.4, 121.2, 62.2, 62.0, 61.6, 61.4, 44.8, 40.4, 36.8, 35.6, 35.2, 33.5, 14.3, 14.2, 14.1, 13.9.

HRMS (APCI): Calculated for C$_{23}$H$_{24}$O$_4$Br: 443.08580, found: 443.08562

9.4.6.3.3. 1,1-Diethyl 2-[(1*E*)-3-methylbut-1-en-1-yl]-3-phenylcyclopropane-1.1-dicarboxylate (**179ac**)

Chemical Formula: C$_{20}$H$_{26}$O$_4$
Molecular Weight: 330.42

The characterisation of this compound was made on a mixture of cis and trans diastereomers

Procedure: A
Eluent for purification: *n*-hexane/AcOEt (85/15)
Yield: 45%
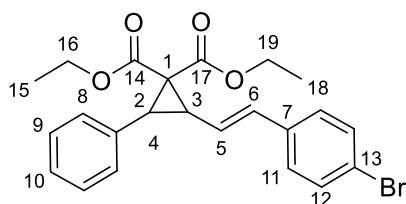**d.r. (*cis/trans*):** 1/1
Aspect: colorless oil

^{1}H NMR (300 MHz, CDCl$_3$): δ= 7.34 to 7.17 (m, 10H, H^{arom}), 5.84 (ddd, 2H, *J* = 15.5, 6.7, 0.8 Hz, H^5), 5.80 (dd, 1H, *J* = 15.1, 6.4 Hz, H$^5_{cis}$), 5.36 (ddd, 1H, *J* = 15.5, 10.1, 1.4 Hz, H$^4_{cis}$), 5.22 (ddd, 1H, *J* = 15.4, 8.1, 1.4 Hz, H$^4_{trans}$), 4.25 (m, 2H, H^{10,13}), 4.07 (m, 2H, H$^{10 \, or \, 13}$), 3.88 (m, 2H, H$^{10 \, or \, 13}$), 3.32 (d, 1H, *J* = 8.0 Hz, H$^2_{trans}$), 3.20 (d, 1H, *J* = 9.9 Hz, H$^2_{cis}$), 3.08 (dd, 1H, *J* = 8.1 Hz, H$^3_{trans}$), 2.64 (dd, 1H, *J* = 10 Hz, H$^3_{cis}$), 2.30 (m, 2H, H^6), 1.29 (m, 6H, H$^{9 \, and/or \, 12}$), 1.13 (t, 3H, *J* = 7.1 Hz, H$^{9 \, or \, 12}$), 0.98 (m, 6H, H^7), 0.90 (t, 3H, *J* = 7.1 Hz, H$^{9 \, or \, 12}$)

^{13}C NMR (75 MHz, CDCl$_3$): δ= 170.7, 167.8, 167.0, 142.9, 142.1, 135.1, 133.9, 130.8, 129.0, 128.4, 128.1, 127.5, 127.3, 121.3, 121.2, 110.3, 62.2, 61.9, 61.6, 61.3, 44.7, 39.8, 36.5, 35.4, 34.9, 33.2, 31.5, 31.5, 22.7, 14.7, 14.4, 14.3, 14.1

HRMS (APCI): calculated for C$_{20}$H$_{27}$O$_4$: 331.19039 found: 331.19025

IR (cm^{-1}): 2960, 1723, 1093, 697

9.4.6.3.4. Diethyl 2-(2-methylprop-1-en-1-yl)-3-phenylcyclopropane-1,1-dicarboxylate (**179ab**)
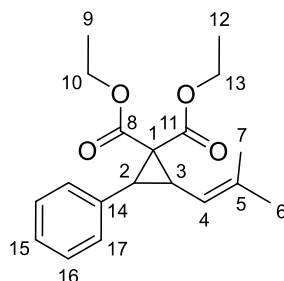
Chemical Formula: $C_{19}H_{24}O_4$
Molecular Weight: 316.40

The characterisation of this compound was made on a mixture of cis and trans diastereomers

Procedure: A
Eluent for purification: *n*-hexane/AcOEt (85/15)
Yield: 44%
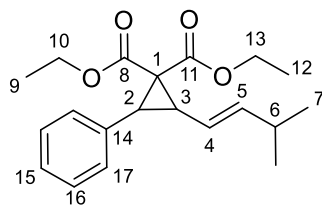**d.r. (*cis/trans*):** 1/1
Aspect: colorless oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.32 − 7.19 (m, 10H), 5.31-5.20 (m, 1H, H$^4_{cis}$), 5.03 − 4.94 (m, 1H, H$^4_{trans}$), 4.35–4.19 (m, 4H, H$^{10 \text{ or } 13}_{cis \text{ and } trans}$), 4.08 (m, 2H, H$^{10 \text{ or } 13}_{cis}$), 3.95–3.85 (m, 2H, H$^{10 \text{ or } 13}_{trans}$), 3.32–3.15 (m, 3H, H$^2_{cis \text{ and } trans}$ and H$^3_{trans}$), 2.79 (t, *J* = 9.6 Hz, 1H, H$^3_{cis}$), 1.85 (d, *J* = 1.1 Hz, 3H, H$^{6 \text{ or } 7}_{trans}$), 1.77 (d, *J* = 1.0 Hz, 6H, H$^{6 \text{ and } 7}_{cis}$), 1.75 (s, 3H, H$^{6 \text{ or } 7}_{trans}$), 1.31 (t, *J* = 7.1 Hz, 3H, H$^{9 \text{ or } 12}$), 1.28 (t, *J* = 7.1 Hz, 3H, H$^{9 \text{ or } 12}$), 1.11 (t, *J* = 7.1 Hz, 3H, H$^{9 \text{ or } 12}$), 0.92 (t, *J* = 7.1 Hz, 3H, H$^{9 \text{ or } 12}$).

^{13}C NMR (75 MHz, CDCl$_3$): δ 170.7, 167.9, 166.9, 166.6, 138.2, 136.9, 135.1, 134.0, 130.3, 128.8, 128.2, 127.9, 127.3, 126.9, 118.8, 117.1, 62.0, 61.6, 61.3, 61.0, 44.7, 39.6, 37.2, 35.0, 31.4, 29.7, 26.1, 25.7, 18.9, 18.6, 14.4, 14.2, 14.0, 13.9.

HRMS (APCI): calculated for $C_{20}H_{27}O_4$: 317.17474 found: 317.17484

9.4.6.3.5. Diethyl 2-(2,2-diphenylvinyl)-3-phenylcyclopropane-1,1-dicarboxylate (**179af**)

Chemical Formula: $C_{29}H_{28}O_4$
Molecular Weight: 440.54

The characterisation of this compound was made on a mixture of cis and trans diastereomers

Procedure: A
No purification required
Yield: 69%
d.r. (*cis/trans*): 4/6
Aspect: colorless oil

¹H NMR (300 MHz, CDCl₃) δ 7.50 − 7.06 (m, 30H, H^{arom}), 6.19 (d, *J* = 10.2 Hz, 1H, H$^4_{cis}$), 5.87 (d, *J* = 9.3 Hz, 2H, H$^4_{trans}$), 4.43 − 4.04 (m, 6H, H$^{10\,and\,13}_{cis\,and\,trans}$), 3.91 − 3.79 (m, 2H, H$^{10\,or\,13}_{trans}$), 3.48 (d, *J* = 8.0 Hz, 1H, H$^2_{trans}$), 3.33−3.21 (m, 2H, H$^2_{cis}$ and H$^3_{trans}$), 2.70 (t, *J* = 10.0 Hz, 1H, H$^3_{cis}$), 1.34−1.26 (m, 6H, H$^{12\,or\,9}_{trans\,and\,cis}$), 1.15 (t, *J* = 7.1 Hz, 3H, H$^{9\,or\,12}_{cis}$), 0.86 (t, *J* = 7.1 Hz, 3H, H$^{12\,or\,9}_{trans}$).

¹³C NMR (75 MHz, CDCl₃): δ 169.8, 167.8, 166.4, 166.1, 146.1, 144.7, 142.3, 142.0, 139.5, 139.4, 134.3, 133.4, 130.3, 130.3, 130.2, 128.6, 128.5, 128.3, 128.3, 128.2, 128.1, 127.8, 127.7, 127.6, 127.5, 127.5, 127.4, 127.2, 126.9, 125.5, 123.3, 122.4, 61.9, 61.8, 61.2, 45.3, 40.9, 37.8, 35.6, 33.2, 31.6, 14.3, 14.2, 14.0, 13.7.

HRMS (APCI): calculated for $C_{29}H_{29}O_4$: 441.20608 found: 441.20604

9.4.6.3.6. Diethyl-(*E*)-2-(2-(furan-2-yl)vinyl)-3-phenylcyclopropane-1,1-dicarboxylate (**179ag**)
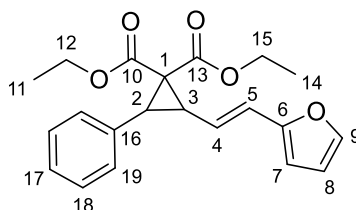
Chemical Formula: $C_{21}H_{22}O_5$
Molecular Weight: 354.40

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Procedure: A
Eluent for purification: *n*-hexane/AcOEt (83/17)
Yield: 13%
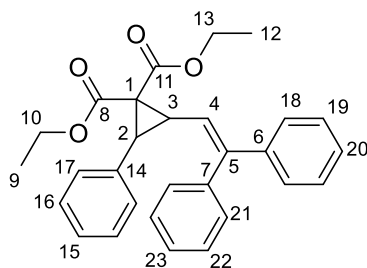**d.r. (*cis/trans*):** 3/7
Aspect: colorless oil

^{1}H NMR (300 MHz, CDCl$_3$: δ = 7.34-7.21 (m, 5H, H^{arom,9}), 6.58 (d, 1H, *J* = 15.9 Hz, H$^5_{trans}$), 6.52 (d, 1H, *J* = 16.0 Hz, H$^5_{cis}$), 6.34 (m, 2H, H$^{7\ or\ 8}_{cis\ and\ trans}$), 6.21 (m, 2H, H$^{8\ or\ 7}_{cis\ and\ trans}$), 6.18 (m, 1H, H$^4_{cis}$), 5.98 (dd, 1H, *J* = 15.8, 8.8 Hz, H$^4_{trans}$), 4.26 (m, 4H, H$^{12\ or\ 15}_{cis\ and\ trans}$), 4.09 (m, 2H, H$^{12\ or\ 15}_{cis}$), 3.90 (m, 2H, H$^{15\ or\ 12}_{trans}$), 3.46 (d, 1H, *J* = 7.9 Hz, H$^2_{trans}$), 3.35 (d, 1H, *J* = 9.6 Hz, H$^2_{cis}$), 3.25 (m, 1H, H$^3_{trans}$), 2.73 (m, 1H, H$^3_{cis}$), 1.31 (t, 3H, *J* = 7.1 Hz, H$^{11\ or\ 14}_{cis}$), 1.26 (t, 3H, *J* = 7.1 Hz, H$^{11\ or\ 14}_{trans}$), 1.14 (t, 3H, *J* = 7.1 Hz, H$^{14\ or\ 11}_{cis}$), 0.92 (t, 3H, *J* = 7.1 Hz, H$^{14\ or\ 11}_{trans}$)

^{13}C NMR (75 MHz, CDCl$_3$): δ = 170.2, 167.5, 166.5, 152.5, 151.7, 142.1, 134.5, 133.2, 130.5, 128.7, 128.3, 128.2, 127.5, 127.4, 123.0, 122.9, 122.2, 121.5, 111.4, 107.7, 107.3, 61.1, 61.9, 61.5, 61.3, 44.9, 36.8, 35.7, 35.3, 33.5, 14.3, 14.2, 14.0, 13.9

HRMS (APCI): Calculated for $C_{21}H_{23}O_5$: 355.15400 found: 355.15390

9.4.6.3.7. 1,1-Diethyl 2-(3-methoxyphenyl)-3-[(*E*)-2-phenylethenyl]cyclopropane-1,1-dicarboxylate (**179ca**)
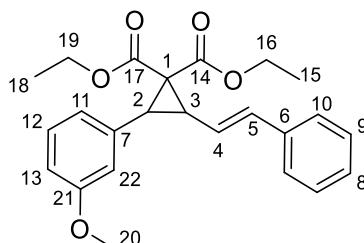
Chemical Formula: $C_{24}H_{26}O_5$
Molecular Weight: 394.47

The characterisation of this compound was made on a mixture of cis and trans diastereomers

Procedure: A
Eluent for purification: *n*-hexane/AcOEt (90/10)
Yield: 37%
d.r. (*cis/trans*): 4/6
Aspect: Yellow oil

^{1}H NMR (300 MHz, CDCl$_3$): δ 7.40 – 7.16 (m, 10H, H^{arom}), 6.96 – 6.68 (m, 6H, H^{arom}, H^4$_{cis and trans}$), 6.27 (dd, *J* = 15.9, 10.3 Hz, 1H, H^5$_{cis}$), 6.04 (dd, *J* = 15.8, 8.7 Hz, 1H, H^5$_{trans}$), 4.36 – 4.05 (m, 6H, H$^{19 and 11}$ $_{cis and trans}$), 4.03 – 3.89 (m, 2H, H$^{19 or 16}$ $_{cis or trans}$), 3.80 (s, 3H, H^{20}$_{trans}$), 3.75 (s, 3H, H^{20}$_{cis}$), 3.47 (d, *J* = 7.9 Hz, 1H, H^2$_{trans}$), 3.37 (dd, *J* = 9.8, 1.0 Hz, 1H, H^2$_{cis}$), 3.30 (t, *J* = 8.7 Hz, 1H, H^3$_{trans}$), 2.80 (t, *J* = 10.3 Hz, 1H, H^3$_{cis}$), 1.33 (t, *J* = 7.1 Hz, 3H, H$^{18 or 15}$ $_{cis}$), 1.26 (t, *J* = 7.1 Hz, 3H, H$^{18 or 15}$ $_{trans}$), 1.18 (t, *J* = 7.1 Hz, 3H, H$^{18 or 15}$ $_{cis}$), 0.98 (t, *J* = 7.1 Hz, 3H, H$^{18 or 15}$ $_{trans}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 167.65, 166.49, 159.59, 136.90, 136.15, 134.04, 133.00, 129.33, 129.18, 128.71, 128.66, 127.70, 127.46, 126.29, 124.42, 124.21, 122.80, 121.01, 115.98, 114.30, 113.28, 62.14, 61.92, 61.54, 61.32, 55.37, 55.29, 44.80, 40.31, 36.79, 35.82, 35.16, 33.84, 14.37, 14.37, 14.23, 14.23, 14.10, 13.96, 13.96.

HRMS (APCI): Calculated for $C_{24}H_{27}O_5$: 395.18530, found: 395.18528

9.4.6.3.8. 1,1-Diethyl (*E*)-2-Tertbutyl-3-styrylcyclopropane-1.1-dicarboxylate (**179da**)
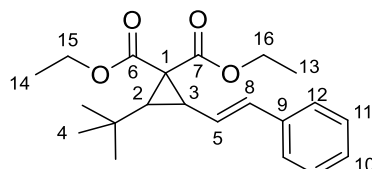
Chemical Formula: $C_{21}H_{28}O_4$
Molecular Weight: 344.45

This description corresponds to the trans diastereomer of the vinylcyclopropane

Procedure: B
No purification required
Yield: quant.
d.r. (*cis/trans*): 0/1
Aspect: Yellow oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.40 – 7.16 (m, 5H, H^{arom}), 6.66 (d, J = 15.8 Hz, 1H, H^8), 5.96 (dd, J = 15.8; 8.7 Hz, 1H, H^4), 4.33 – 4.05 (m, 4H, H$^{15 \text{ and } 16}$), 2.70 (t, J = 8.8 Hz, 1H, H^3), 2.15 (d, J = 8.7 Hz, 1H, H^2), 1.31 (t, J = 7.1 Hz, 3H, H$^{14 \text{ or } 13}$), 1.21 (t, J = 7.1 Hz, 3H, H$^{13 \text{ or } 14}$), 0.97 (s, 9H, H^4).

^{13}C NMR (75 MHz, CDCl$_3$) δ 168.3, 168.2, 137.0, 132.7, 128.5, 127.2, 126.0, 125.8, 61.6, 61., 44.4, 41.8, 31.6, 30.8, 28.5, 14.1, 13.9.

HRMS (APCI) calculated for $C_{21}H_{28}O_4$: 345.20604, found: 345.20633.

9.4.6.3.9. Diethyl (*E*)-3-styryl-[1,1'-bi(cyclopropane)]-2,2-dicarboxylate (**179ea**)
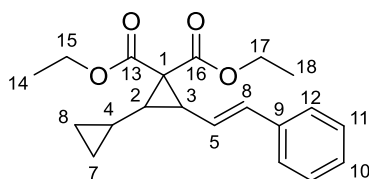
Chemical Formula: $C_{20}H_{24}O_4$
Molecular Weight: 328.41

The characterisation of this compound was made on a mixture of cis and trans diastereomers

Procedure: B
Eluent for purification: *n*-hexane/AcOEt (7/3)
**Yield:** 82%
d.r. (*cis/trans*): 3/7
Aspect: Yellow oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.46 – 7.12 (m, 10H, H^{arom}), 6.70 (d, *J* = 15.8 Hz, 1H, H$^8_{cis}$), 6.63 (d, *J* = 15.8 Hz, 1H, H$^8_{trans}$), 6.25 (dd, *J* = 15.8; 9.8 Hz, 1H, H$^5_{cis}$), 5.85 (dd, *J* = 15.8; 9.0 Hz, 1H, H$^5_{trans}$), 4.39 – 4.03 (m, 8H, H$^{15 \text{ and } 18}_{cis \text{ and } trans}$), 2.71 (dd, *J* = 8.9; 7.6 Hz, 1H, H$^3_{trans}$), 2.56 (t, *J* = 9.7 Hz, 1H, H$^3_{cis}$), 2.06 – 1.80 (m, 1H, H$^2_{trans}$), 1.44 (t, *J* = 9.5 Hz, 1H, H$^2_{cis}$), 1.36 – 1.17 (m, 12H, H$^{14 \text{ and } 17}_{cis \text{ and } trans}$) 0.87 – 0.55 (m, 4H, H$^{6a \text{ and } 12a}$), 0.57 – 0.47 (m, 2H, H^4), 0.47 – 0.25 (m, 4H, H$^{6b \text{ and } 7b}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 170.2, 165.3, 137.3, 136.9, 133.7, 133.1, 128.5, 127.4, 127.3, 126.1, 126.0), 124.9, 123.6, 61.7, 61.1, 42.5, 37.4, 36.4, 35.2, 34.8, 14.2,14.0, 8.4, 6.4, 5.2, 5.0, 4.3, 4.0.

HRMS (APCI) calculated for C$_{20}$H$_{25}$O$_4$: 329.17474, found: 329.17489.

9.4.6.3.10. Diethyl (*E*)-2-(*tert*-butyl)-3-(4-(methoxycarbonyl)styryl)cyclopropane-1,1-dicarboxylate (**179dh**)
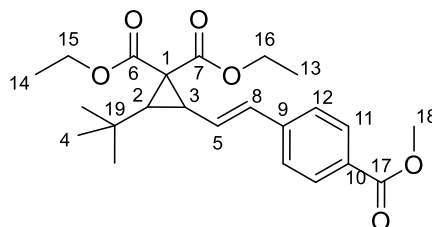
Chemical Formula: C$_{23}$H$_{30}$O$_6$
Molecular Weight: 402.49

This description corresponds to the trans diastereoisomer of the vinylcyclopropane

Procedure: B
Eluent for purification: *n*-hexane/AcOEt (95/5)
Yield: 76%
d.r. (*cis/trans*): 0:1
Aspect: White powder

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.95 (d, *J* = 8.4 Hz, 2H, H^{11}), 7.36 (d, *J* = 8.4 Hz, 2H, H^{12}), 6.69 (d, *J* = 15.9 Hz, 1H H^8), 6.10 (dd, *J* = 15.8; 8.8 Hz, 1H, H^5), 4.31 – 4.09 (m, 4H, H$^{15 \text{ and } 16}$), 3.90 (s, 3H, H^{18}), 2.71 (t, *J* = 8.7 Hz, 1H, H^3), 2.17 (d, *J* = 8.8 Hz, 1H, H^2), 1.31 (t, *J* = 7.1 Hz, 3H, H$^{14 \text{ or } 13}$), 1.21 (t, *J* = 7.1 Hz, 3H, H$^{13 \text{ or } 14}$), 0.97 (s, 9H, H^4).

^{13}C NMR (75 MHz, CDCl$_3$) δ 168.3, 168.0, 166.9, 141.5, 131.8, 129.9, 128.9, 128.7, 125.9, 61.7, 61.6, 52.0, 44.6, 42.0, 31.7, 31.0, 28.5, 14.1, 14.0.

HRMS (APCI) calculated for C$_{23}$H$_{31}$O$_6$: 403.21152, found : 403.21202.

9.4.6.3.11. Diethyl (*E*)-2-isopropyl-3-(4-(methoxycarbonyl)styryl)cyclopropane-1,1-dicarboxylate (**179gh**)
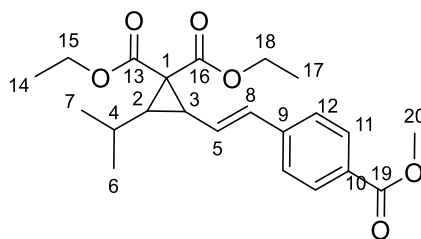
Chemical Formula: C$_{22}$H$_{28}$O$_6$
Molecular Weight: 388.46

This description corresponds to the trans diastereoisomer of the vinylcyclopropane

Procedure: B
Eluent for purification: *n*-hexane/AcOEt (95/5)
Yield: 48%
d.r. (*cis/trans*): 4/6
Aspect: Colorless oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.96 (d, *J* = 8.4 Hz, 2H, H^{11}), 7.36 (d, *J* = 8.4 Hz, 2H, H^{12}), 6.65 (d, *J* = 15.8 Hz, 1H, H^8), 5.99 (dd, *J* = 15.8; 9.0 Hz, 1H, H^5), 4.34 – 4.07 (m, 4H, H$^{18 \text{ and } 15}$), 3.89 (s, 3H, H^{14}), 2.62 (ddd, *J* = 8.8; 7.8; 0.6 Hz, 1H, H^3), 1.96 (dd, *J* = 10.4; 7.7 Hz, 1H, H^2), 1.29 (t, *J* = 7.1 Hz, 3H, H$^{17 \text{ or } 14}$), 1.21 (t, *J* = 7.1 Hz, 3H, H$^{14 \text{ or } 17}$), 1.06 (d, *J* = 6.6 Hz, 3H, H$^{7 \text{ or } 6}$), 0.99 (d, *J* = 6.6 Hz, 3H, H$^{6 \text{ or } 7}$), *H^4 is hidden by H$^{14 \text{ or } 17}$ signal*

^{13}C NMR (75 MHz, CDCl$_3$) δ 167.9, 167.8, 166.8, 141.3, 131.8, 129.9, 128.7, 128.2, 125.8, 61.5, 52.0, 42.7, 40.8, 35.2, 27.9, 22.1, 21.5, 14.1, 14.1.

HRMS (APCI): calculated for C$_{22}$H$_{29}$O$_6$: 389.19587 found: 389.19602

9.4.6.3.12. Diethyl (*E*)-2-(4-(methoxycarbonyl)phenyl)-3-(3-methylbut-1-en-1-yl)cyclopropane-1,1-dicarboxylate (**179fc**)
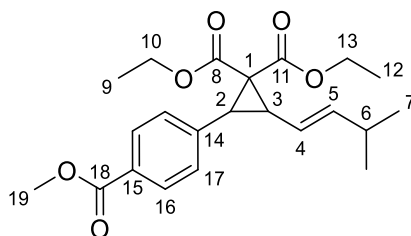
Chemical Formula: $C_{22}H_{28}O_6$
Molecular Weight: 388.46

The characterisation of this compound was made on the cis diastereomer

Procedure: A
Eluent for purification: *n*-hexane/AcOEt (82/18)
Yield: 44%
d.r. (*cis/trans*): 3/7
Aspect: Colorless oil

^{1}H NMR (300 MHz, CDCl$_3$): δ = δ 8.01 − 7.89 (m, 2H, H^{16}), 7.44 − 7.36 (m, 2H, H^{17}), 5.82 (ddd, *J* = 15.5, 6.5, 0.6 Hz, 1H, H^4), 5.28 (ddd, *J* = 15.5, 10.1, 1.4 Hz, 1H, H^5), 4.33 − 4.17 (m, 2H, H$^{10 \text{ or } 13}$), 4.15 − 4.01 (m, 2H, H$^{13 \text{ or } 10}$), 3.91 (s, 3H, H^{19}), 3.19 (dd, *J* = 9.9, 1.0 Hz, 1H, H^2), 2.70 (td, *J* = 10.0, 0.6 Hz, 1H, H^3), 2.44 − 2.21 (m, 1H, H^6), 1.32 (t, *J* = 7.1 Hz, 3H, H$^{9 \text{ or } 12}$), 1.14 (t, *J* = 7.1 Hz, 3H, H$^{12 \text{ or } 9}$), 1.03 − 0.94 (m, 6H, H^7).

^{13}C NMR (75 MHz, CDCl$_3$): δ 170.1, 167.1, 166.3, 142.6, 139.2, 130.6, 129.2, 120.3, 62.2, 61.3, 52.2, 39.6, 35.0, 34.4, 31.4, 22.4, 14.2, 14.1.

HRMS (APCI): calculated for $C_{22}H_{29}O_6$: 389.19587 found: 389.19602

9.4.6.3.13. Diethyl 2-(4-(methoxycarbonyl)phenyl)-3-(2-methylprop-1-en-1-yl)cyclopropane-1,1-dicarboxylate (**179fb**)
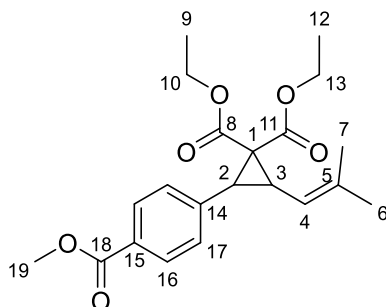
Chemical Formula: $C_{21}H_{26}O_6$
Molecular Weight: 374.43

The characterisation of this compound was made on a 1/2 mixture of trans and cis diastereomers

Procedure: A
Eluent for purification: *n*-hexane/AcOEt (85/15)
Yield: 54%
Aspect: colorless oil
d.r. (*cis/trans*): 3/7

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.92 − 7.82 (m, 2H), 7.30 − 7.21 (m, 3H), 5.18 − 5.06 (m, 1H), 4.93 − 4.83 (m, 0H), 4.27 − 4.08 (m, 3H), 4.10 − 3.91 (m, 2H), 3.83 (s, 5H), 3.27 − 3.12 (m, 1H), 3.09 (d, *J* = 9.9 Hz, 1H), 2.75 (t, *J* = 9.4 Hz, 1H), 1.77 (d, *J* = 1.3 Hz, 1H), 1.67 (dd, *J* = 2.9, 1.4 Hz, 9H), 1.52 (s, 1H), 1.22 (dt, *J* = 12.9, 7.1 Hz, 5H), 1.03 (t, *J* = 7.1 Hz, 4H), 0.86 (t, *J* = 7.1 Hz, 1H).

^{13}C NMR (75 MHz, CDCl$_3$): δ = 170.3, 167.0, 166.1, 139.5, 137.7, 130.1, 129.4, 128.98, 128.7, 128.6, 118.3, 116.3, 62.0, 61.6, 61.4, 61.1, 52.1, 39.6, 36.8, 34.7, 31.2, 29.7, 26.0, 25.6, 18.8, 18.5, 14.2, 14.1, 13.9. *Quaternary carbons from the trans isomer are missing*

HRMS (APCI): calculated for $C_{20}H_{27}O_4$: 375.18022 found: 375.18007

9.4.6.3.14. Diethyl (*E*)-2-isopropyl-3-(3-methylbut-1-en-1-yl)cyclopropane-1,1-dicarboxylate (**179gc**)
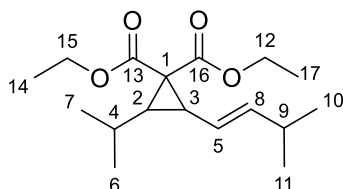
Chemical Formula: $C_{17}H_{28}O_4$
Molecular Weight: 296.41

The characterisation of this compound was made on a mixture of cis and trans diastereomers

Procedure: B
No purification required
Yield: 90%
d.r. (*cis/trans*): 4/6
Aspect: Orange oil

¹H NMR (300 MHz, CDCl₃) δ 5.73 (dd, *J* = 15.3; 6.6 Hz, 1H, H⁸$_{cis\ or\ trans}$), 5.66 (ddd, *J* = 15.5; 6.6; 0.6 Hz, 1H, H⁸$_{trans\ or\ cis}$), 5.17 (ddd, *J* = 15.4; 10.2; 1.3 Hz, 1H, H⁵$_{cis\ ou\ trans}$), 5.03 (ddd, *J* = 15.4; 8.1; 1.3 Hz, 1H, H⁵$_{trans\ or\ cis}$), 4.35 − 4.09 (m, 8H, H¹⁵$^{and\ 12}$$_{cis\ and\ trans}$), 2.44 − 2.16 (m, 2H, H³$_{cis\ et\ trans}$), 1.78 (dd, *J* = 10.4; 7.8 Hz, 1H, H²$_{trans}$), 1.70 − 1.49 (m, 1H, H²$_{cis}$), 1.27 (q, *J* = 7.1 Hz, 6H, H¹⁴$^{and\ 17}$$_{cis\ or\ trans}$), 1.25 (q, *J* = 7.1 Hz, 6H, H¹⁴$^{and\ 17}$$_{trans\ or\ cis}$), 1.15 − 0.87 (m, 12H, H⁶$^{,\ 7,\ 10\ and\ 11,}$), *H⁶ $^{and\ 9}$$_{cis\ and\ trans}$ are hidden by H¹⁴ $^{or\ 17}$ signal*

¹³C NMR (75 MHz, CDCl₃) δ 170.8, 168.5, 168.2, 167.1, 142.3, 141.6, 122.0, 120.1, 77.2, 61.6, 61.4, 61.2, 61.0, 42.2, 40.3, 39.8, 38.8, 34.8, 34.3, 31.4, 31.1, 27.8, 25.3, 22.6, 22.5, 22.5, 22.4, 22.2, 21.8, 21.7, 14.40, 14.3, 14.2.

HRMS (APCI) calculated for $C_{17}H_{28}O_4$: 297.20604, found: 297.20665.

9.4.6.3.15. Diethyl (*E*)-2-methyl-3-(3-methylbut-1-en-1-yl)cyclopropane-1,1-dicarboxylate (**179hc**)
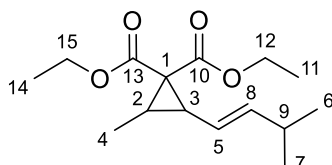
Chemical Formula: $C_{15}H_{24}O_4$
Molecular Weight: 268.35

The characterisation of this compound was made on the trans diastereomer

Procedure: B
Procedure note: A 15 minute-delay was observed between the addition of the base used to deprotonate the sulfonium salt and the activated olefin.
No purification required
Yield: 91%
d.r. (*cis/trans*): 4/6
Aspect: Orange oil

^{1}H NMR (300 MHz, CDCl₃) δ 5.68 (dd, *J* = 15.5; 6.6 Hz, 1H, H^8), 5.03 (ddd, *J* = 15.4; 8.5; 1.3 Hz, 1H, H^5), 4.30 – 4.11 (m, 4H, H$^{15\ and\ 12}$), 2.33 (t, *J* = 8.0 Hz, 1H, H^3), 2.33 – 2.14 (m, 1H, H^9), 2.03 (dq, *J* = 7.5; 6.3 Hz, 1H, H^2), 1.33 – 1.21 (m, 6H, H$^{14\ et\ 11}$), 1.13 (d, *J* = 6.3 Hz, 3H, H^4 $_{trans}$), 1.02 – 0.91 (m, 12H, H$^{6\ and\ 7}$).

^{13}C NMR (75 MHz, CDCl₃) δ 168.1, 168.0, 141.7, 121.7, 61.3, 61.2, 41.9, 36.0, 31.0, 26.7, 22.4, 14.3, 14.3, 12.2.

HRMS (APCI) calculated for $C_{15}H_{24}O_4$: 269.17474, found: 269.17510.

9.4.6.3.16. Diethyl (*E*)-2-(tert-butyl)-3-(3-methylbut-1-en-1-yl)cyclopropane-1,1-dicarboxylate (**179dc**)
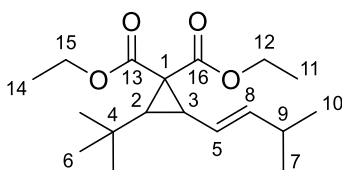
Chemical Formula: $C_{17}H_{28}O_4$
Molecular Weight: 310.43

This description corresponds to the trans diastereomer of the vinylcyclopropane

Procedure: B
No purification required
Yield: quant
d.r. (*cis/trans*): 0/1
Aspect: Yellow oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 5.69 (ddd, *J* = 15.4; 6.6; 0.6 Hz, 1H, H^8), 5.12 (ddd, *J* = 15.4; 7.9; 1.3 Hz, 1H, H^5), 4.30 – 4.07 (m, 4H, H$^{12\ and\ 15}$), 2.50 (dd, *J* = 9.1; 8.1 Hz, 1H, H^3), 2.20 (m, 1H, H^9), 1.99 (d, *J* = 9.0 Hz, 1H, H^2), 1.29 (t, *J* = 7.1 Hz, 1H, H$^{11\ or\ 14}$), 1.23 (t, *J* = 7.1 Hz, 1H, H$^{14\ or\ 11}$), 0.97 – 0.91 (m, 15H, H$^{7,\ 6\ and\ 10}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 168.7, 168.4, 141.5, 122.4, 61.4, 43.9, 41.5, 31.1, 31.0, 30.8, 28.7, 22.5, 22.5, 14.4, 14.1.

HRMS (APCI) calculated for C$_{18}$H$_{30}$O$_4$: 311.22169, found: 311.22157.

9.4.6.3.17. Diethyl (*E*)-3-(3-methylbut-1-en-1-yl)-[1,1'-bi(cyclopropane)]-2,2-dicarboxylate (**179ec**)
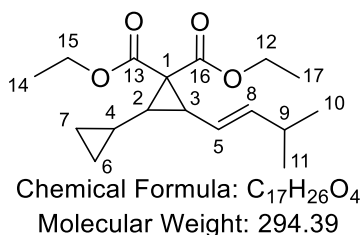
Chemical Formula: C$_{17}$H$_{26}$O$_4$
Molecular Weight: 294.39

The characterisation of this compound was made on a mixture of cis and trans diastereomers

Procedure: B
Eluent for purification: *n*-hexane/AcOEt (98/2)
**Yield:** 41%
Aspect: Yellow oil
d.r. (*cis/trans*): 1/1

^{1}H NMR (300 MHz, CDCl$_3$) δ 5.76 (dd, J = 15.6; 6.4 Hz, 1H, H^8$_{trans}$), 5.67 (ddd, J = 15.5; 6.6; 0.6 Hz, 1H, H^8$_{cis}$), 5.35 (ddd, J = 15.4; 9.5; 1.3 Hz, 1H, H^5$_{trans}$), 5.01 (ddd, J = 15.4; 8.3; 1.3 Hz, 1H, H^5$_{cis}$), 4.23 (q, J = 7.1 Hz, 2H, H$^{15\ or\ 12}$$_{trans}$), 4.19 (q, J = 7.1 Hz, 2H, H$^{15\ or\ 12}$$_{cis}$) 4.15 (q, J = 7.2 Hz, 2H, H$^{12\ or\ 15}$$_{trans}$), 2.51 (dd, J = 9.3; 7.1 Hz, 1H, H^3$_{cis}$), 2.42 – 2.33 (m, 1H, H^3$_{trans}$), 2.36 – 2.28 (m, 1H, H^2$_{trans}$), 2.22 (ddd, J = 13.4; 6.7; 1.3 Hz, 1H, H^2$_{cis}$), 1.71 (t, J = 7,3 Hz, 1H), 1.29 (t, J = 7.1 Hz, 3H, H$^{14\ ou\ 16}$$_{trans}$), 1.26 (m, 6H, H$^{14\ et\ 16}$$_{cis}$), 1.25 (t, J = 7.1 Hz, 3H, H$^{16\ ou\ 14}$$_{trans}$), 1.00 (d, J = 6.8 Hz, 6H, H$^{10\ and\ 11}$$_{trans}$), 0.93 (d, J = 6.8 Hz, 6H, H$^{10\ and\ 11}$$_{cis}$), 0.80 – 0.55 (m, 4H, H$^{6a\ et\ 7a}$$_{cis\ and\ trans}$), 0.52 – 0.43 (m, 2H, H^9$_{cis\ and\ trans}$), 0.43 – 0.20 (m, 4H, H$^{7b\ et\ 6b}$$_{cis\ et\ trans}$). $H^9$$_{cis\ and\ trans}$ *is hidden by* $H^{14\ and\ 17}$.

^{13}C NMR (75 MHz, CDCl$_3$) δ 170.4, 166.9, 142.4, 141.8, 121.5, 120.0, 61.5, 61.2 et 61.2, 60.9, 38.4, 37.0, 35.9, 34.6, 34.3, 31.3, 31.0, 22.4, 22.3, 14.2, 14.0, 8.3, 6.4, 5.0, 4.4, 3.9.

HRMS (APCI) calculated for C$_{17}$H$_{26}$O$_4$: 295.19039, found: 295.19097.

9.4.6.3.18. Diethyl (*E*)-2-isobutyl-3-(3-methylbut-1-en-1-yl)cyclopropane-1,1-dicarboxylate (**179ic**)
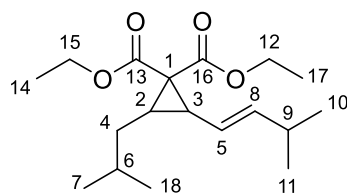
Chemical Formula: C$_{18}$H$_{30}$O$_4$
Molecular Weight: 310.43

This description corresponds to only one diastereoisomer (trans) of the vinylcyclopropane

Procedure: Ab
Procedure note: A 15-minute delay was observed between the addition of the base used to deprotonate the sulfonium salt and the activated olefin.
Eluent for purification: n-hexane/AcOEt (97/3)
Yield: 35%
d.r. (*cis/trans*): 4/6
Aspect: Clear oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 5.67 (ddd, J = 15.4, 6.6, 0.8 Hz, 1H, H^5), 5.03 (ddd, J = 15.4, 8.5, 1.4 Hz, 1H, H^8), 4.31 − 4.09 (m, 4H, H$^{12\text{ and }15}$), 2.35 (t, J = 8.1 Hz, 1H, H^3), 2.32 − 2.15 (m, 1H), 1.98 (td, J = 7.9, 6.3 Hz, 1H, H^2), 1.76 − 1.56 (m, 1H, H^6), 1.43 (dt, J = 13.9, 6.1 Hz, 1H, H^2), 1.32 − 1.19 (m, 6H, H$^{14\text{ and }17}$), 1.13 (dt, J = 13.9, 7.9 Hz, 1H, H$^{4b\text{ or }4a}$), 0.97 − 0.85 (m, 12H, H$^{7,\,10,\,11\text{ and }18}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 168.4, 168.3, 141.8, 121.9, 61.5, 61.4, 41.5, 36.3, 35.6, 31.3, 31.2, 28.3, 22.8, 22.6, 22.5, 22.3, 14.4, 14.4.

HRMS (APCI) calculated for C$_{18}$H$_{31}$O$_4$: 311.22169, found: 311.22172

9.4.6.3.19. 2-Phenyl-3-[(E)-2-phenylethenyl]cyclopropane-1,1-dicarbonirile (**179aa-CN**)
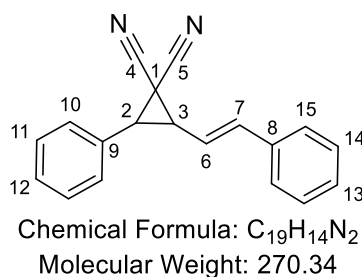
Chemical Formula: C$_{19}$H$_{14}$N$_2$
Molecular Weight: 270.34

The characterisation of this compound was made on a mixture of cis and trans diastereomers

Special procedure:
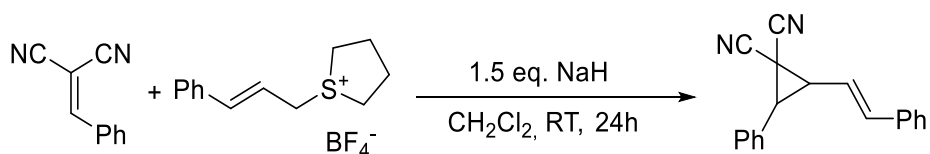
NaH (29wt% in mineral oil, 0.172 g, 2.07 mmol, 1.6 eq.) is introduced into a dry round-bottom flask under argon atmosphere and washed three times with n-hexane. Then, 2-benzylidenemalononitrile (0.196 g, 1.30 mmol, 1 eq.) and dichloromethane (28 mL) are added. The sulfonium salt (0.568 g, 1.95 mmol, 1.5 eq.) is added under stirring at room temperature. After 24h, water is added to stop the reaction. An aqueous solution of hydrochloric acid (1M) is added. The two layers are separated and the aqueous one is extracted twice with dichloromethane. The combined organic layers are washed with brine, dried over MgSO$_4$ and concentrated under reduced pressure. 0.350 g of the vinylcyclopropane are obtained.

No purification required
Yield: quant.
d.r. (*cis/trans*): 3/7
Aspect: Clear oil

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.41 (m, 20H, H$^{arom}_{cis,\,trans}$), 7.00 (d, 1H, J = 5.7 Hz, H$^{7}_{trans}$), 6.95 (d, 1H, J = 5.7 Hz, H$^{7}_{cis}$), 6.08 (dd, 1H, J = 15.7, 8.0 Hz, H$^{6}_{cis}$), 5.67 (dd, 1H, J = 15.7, 10 Hz, H$^{6}_{trans}$), 3.52 (d, 1H, J = 9.7 Hz, H$^{2}_{trans}$), 3.36 (d, 1H, J = 8.4 Hz, H$^{2}_{cis}$), 3.26 (m, 2H, H$^{3}_{cis,\,trans}$)

^{13}C NMR (75 MHz, CDCl$_3$) δ 138.4, 138.2, 135.5, 135.2, 130.5, 130.0, 129.6, 129.2, 129.0, 128.8, 128.6, 128.3, 126.7, 120.3, 118.4, 115.5, 113.6, 112.8, 112.0, 40.3, 38.7, 37.9, 37.7, 14.7, 11.7. *Five aromatic signals of the minor diastereomer are missing, possibly due to overlapping.*

HRMS (APCI): calculated for C$_{19}$H$_{15}$N$_2$: 271.12298 found: 271.12292

9.4.7. Synthesis of 1,4-dienes

9.4.7.1. General procedure A: TiCl$_4$ promoted rearrangement of VCP

Starting vinylcyclopropane (1 eq.) and dry dichloromethane (1 mL/10 mg of vinylcyclopropane) are introduced in a dry round-bottom flask under argon. Then, titanium tetrachloride 1M in dichloromethane *(see product description for number of eq.)* is added and the mixture is stirred at room temperature for a defined time *(see description of the compound)*. Then, water is added to stop the reaction. An aqueous solution of hydrochloric acid (1M) is added. The two layers are separated and the aqueous one is extracted twice with dichloromethane. The combined organic layers are washed with brine, dried over MgSO$_4$ and concentrated under reduced pressure. The obtained crude product is purified by flash chromatography over silica gel.

Number of TiCl$_4$ equivalents, reaction time and eluent for purification depend on the nature of the compound and are reported in the description of each product.

9.4.7.2. General procedure B: FeCl₃ promoted rearrangement of VCP
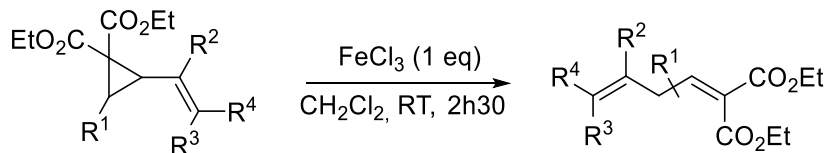
Starting vinylcyclopropane (1 eq.) and dry dichloromethane (1 mL/10 mg of vinylcyclopropane) are introduced in a dry round-bottom flask under argon. Then, 1 equivalent of $FeCl_3$ is added and the mixture is stirred at room temperature for 2h30. Then, water is added to stop the reaction. An aqueous solution of hydrochloric acid (1M) is added. The two layers are separated and the aqueous one is extracted two times with dichloromethane. The combined organic layers are washed with brine, dried over $MgSO_4$ and concentrated under reduced pressure. The obtained crude product is purified by flash chromatography over silica gel.

Eluent for purification depends on the nature of the compound and are reported in the description of each product.

9.4.7.4. Products descriptions

9.4.7.4.1. 1,3-Diethyl 2-[(3E)-3-methyl-2,4-diphenylbut-3-en-1-ylidene]propanedioate (181ad)
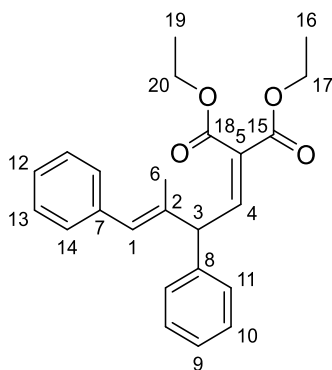
Chemical Formula: $C_{24}H_{26}O_4$
Molecular Weight: 378.47

Procedure A
Eq. of TiCl₄: 0.4 eq.
Reaction time: 15 min
Eluent for purification: *n*-hexane/AcOEt (85/15)
Yield: 54%
Aspect: Colorless oil

¹H NMR (300 MHz, CDCl₃): δ= 7.37 to 7.19 (m, 11H, H^{4,arom}), 6.43 (s, 1H, H^1), 4.58 (d, 1H, *J = 1*0.7 Hz, H^3), 4.32 (q, 2H, *J = 7*.1 Hz, H$^{17\,or\,20}$), 4.26 (q, 2H, *J = 7*.1 Hz, H$^{20\,or\,17}$), 1.78 (d, 3H, *J = 1*.3 Hz, H^6), 1.31 (td, 6H, *J = 7*.1 Hz, H^{16,19})

¹³C NMR (75 MHz, CDCl₃): δ= 148.0, 129.0, 128.8, 128.2, 128.2, 128.1, 127.2, 126.5, 61.5, 61.4, 53.7, 17.1, 14.2, 14.1. *Quartenary carbons are missing*

HRMS (ESI): Calculated for C₂₄H₂₇O₄: 379.19039, found: 379.19038

IR (cm⁻¹): 2924, 2853, 1730, 1447, 1238, 740, 699

9.4.7.4.2. 1,3-Diethyl 2-[(3*E*)-2-(2-methylphenyl)-4-phenylbut-3-en-1-ylidene]propanedioate (**181ba**)
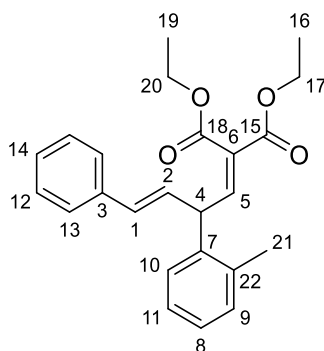
Chemical Formula: C₂₄H₂₆O₄
Molecular Weight: 378.47

Procedure A
Eq. of TiCl₄: 1 eq.
Reaction time: 15 min
Eluent for purification: *n*-hexane/AcOEt (9/1)
Yield: 25%
Aspect: Yellow oil
¹H NMR (300 MHz, CDCl₃): δ= 7.37 – 7.11 (m, 10H, H$^{5\,and\,arom}$), 6.43 (d, *J* = 16.1, 1H, H^1), 6.33 (dd, *J* = 16.0, 5.5 Hz, 1H, H^2), 4.91 (ddd, *J* = 9.8, 5.5, 1.0 Hz, 1H, H^4), 4.34 – 4.16 (m, 4H, H$^{20\,and\,17}$), 2.35 (s, 3H, H^{21}), 1.29 (t, *J* = 7.1 Hz, 3H, H$^{19\,or\,16}$), 1.28 (t, *J* = 7.1 Hz, 3H, H$^{16\,or\,19}$).

¹³C NMR (75 MHz, CDCl₃): δ= 165.5, 183.1, 148.4, 139.0, 137.0, 136.4, 131.9, 131.0, 129.5, 128.7, 128.5, 127.78, 127.3, 126.8, 126.5, 61.7, 61.6, 44.3, 19.7, 14.3.

HRMS (APCI): Calculated for C₂₄H₂₇O₄: 379.19039, found: 379.19030

9.4.7.4.3. 1,3-Diethyl 2-[(3E)-2-(3-methoxyphenyl)-4-phenylbut-3-en-1-ylidene]propanedioate (**181ca**)

Chemical Formula: $C_{24}H_{26}O_5$
Molecular Weight: 394.47

Procedure A
Eq. of TiCl$_4$: 1 eq.
Reaction time: 15 min
Eluent for purification: 9/1 *n*-hexane/AcOEt
Yield: 28%
Aspect: Yellow oil

^{1}H NMR (300 MHz, CDCl$_3$): δ= 7.42 – 7.22 (m, 6H, H^{arom}), 7.14 (d, *J* = 10.5 Hz, 1H, H^2), 6.94 – 6.78 (m, 3H, H^{arom}), 6.50 (d, *J* = 16.1 Hz, 1H, H^5), 6.35 (dd, *J* = 16.0, 6.6 Hz, 1H, H^4), 4.66 (dd, J = 10.3, 6.8 Hz, 1H, H^1), 4.34 (q, *J* = 7.1 Hz, 2H, H$^{17 \text{ or } 14}$), 4.26 (q, *J* = 7.1 Hz, 2H, H$^{14 \text{ or } 17}$), 3.81 (s, 3H, H^{23}), 1.34 (t, *J* = 7.1 Hz, 3H, H$^{16 \text{ or } 13}$), 1.30 (t, *J* = 7.1 Hz, 4H, H$^{13 \text{ or } 16}$).

^{13}C NMR (75 MHz, CDCl$_3$): δ= 165.3, 182.9, 179.0, 147.6, 142.0, 136.7, 132.4, 129.9, 128.6, 128.0, 127.7, 126.0, 120.2, 113.8, 112.5, 61.5, 55.3, 48.0, 29.7, 14.2, 14.1.

HRMS (APCI): Calculated for $C_{23}H_{27}O_5$: 395.18530, found: 395.18527

9.4.7.4.4. 1,3-Diethyl 2-[(3*E*)-4-(4-bromophenyl)-2-(4-fluorophenyl)but-3-en-1-ylidene]propanedioate (**181ae**)
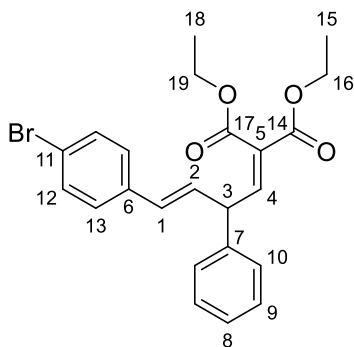
Chemical Formula: $C_{23}H_{23}BrO_4$
Molecular Weight: 442.33

Procedure A
Eq. of TiCl₄: 1 eq.
Reaction time: 15 min
Eluent for purification: Not required
Yield: 79%
Aspect: Yellow oil

¹H NMR (300 MHz, CDCl₃) δ 7.46 − 7.16 (m, 9H, H^{arom}), 7.12 (d, *J* = 10.5 Hz, 1H, H^4), 6.43 (d, *J* = 16.1 Hz, 1H, H^1), 6.34 (dd, *J* = 16.0, 6.0 Hz, 1H, H^2), 4.67 (dd, *J* = 10.5, 5.8 Hz, 1H, H^3), 4.32 (q, *J* = 7.1 Hz, 2H, H$^{19\ or\ 16}$), 4.25 (q, *J* =, 7.2 Hz, 2H, H$^{16\ or\ 19}$), 1.36 − 1.26 (m, 6H, H$^{18\ and\ 15}$).

¹³C NMR (75 MHz, CDCl₃): δ= 165.4, 183.0, 147.6, 140.3, 135.8, 131.8, 131.3 ; 129.8, 129.1, 128.3, 128.0, 127.5, 121.6, 61.7, 61.7, 48.1, 31.7, 22.8, 14.3, 14.3.

HRMS (APCI): Calculated for $C_{23}H_{24}O_4{}^{79}Br$: 443.08580, found: 443.08562

9.4.7.4.5. 1,3-Diethyl 2-[(3*E*)-5-methyl-2-phenylhex-3-en-1-ylidene]propanedioate (**181ac**)
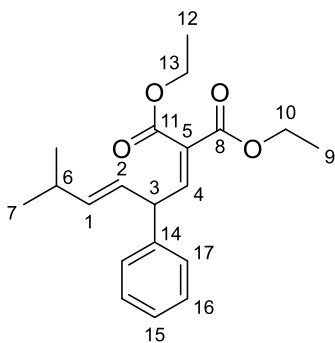
Chemical Formula: $C_{20}H_{26}O_4$
Molecular Weight: 330.42

Procedure A
Eq. of TiCl₄: 1 eq.
Reaction time: 15 min
Eluent for purification: *n*-hexane/AcOEt (8/2)
Yield: 33%
Aspect: Yellow oil

¹H NMR (300 MHz, CDCl₃): δ= 7.21 to 7.37 (m, 5H, H^{arom}), 7.05 (d, 1H, *J = 1*0.7 Hz, H⁴), 5.56 (d, 2H, *J*= 3.6, 1.6 Hz, H^{2,3}), 4.45 (dd, 1H, *J = 1*0.8, 3.5 Hz, H³), 4.33 (q, 2H, *J = 7*.1 Hz, H$^{10 \text{ or } 13}$), 4.24 (q, 2H, *J = 7*.1 Hz, H$^{13 \text{ or } 10}$), 2.32 (m, 1H, H⁶), 1.35 (t, 3H, *J = 7*.1 Hz, H$^{9 \text{ or } 12}$), 1.29 (t, 3H, *J = 7*.1 Hz, H$^{12 \text{ or } 9}$), 1.01 (dd, 6H, *J = 6*.7, 0.9 Hz, H⁷)

¹³C NMR (75 MHz, CDCl₃): δ = 166.6, 183.2, 148.9, 141.1, 140.8, 128.9, 127.9, 127.4, 127.1, 126.0, 61.5, 61.5, 47.9, 31.3, 22.5, 22.4, 14.3, 14.2

HRMS (APCI): Calculated for $C_{20}H_{27}O_4$: 331.19039, found: 331.19012

IR (cm⁻¹): 2924, 1722, 1234, 1207

9.4.7.4.6. 1,3-Diethyl 2-(4-methyl-2-phenylpent-3-en-1-ylidene)propanedioate (**181ab**)
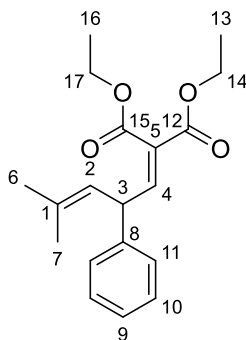
Chemical Formula: $C_{19}H_{24}O_4$
Molecular Weight: 316.40

Procedure A
Eq. of TiCl$_4$: 1 eq.
Reaction time: 15 min
Eluent for purification: *n*-hexane/AcOEt (82/18)
Yield: 25%
Aspect: Colorless oil

**^{1}H NMR (300 MHz, CDCl$_3$):** δ= 7.35 to 7.18 (m, 5H, H^{arom}), 6.99 (d, 1H, *J* = 10.6 Hz, H^4), 5.35 (m, 1H, H^2), 4.73 (m, 1H, H^3), 4.32 (dq, 2H, *J* = 7.1, 2.6 Hz, H$^{14 \text{ or } 17}$), 4.23 (q, 2H, 7.1 Hz, H$^{17 \text{ or } 14}$), 1.78 (d, 3H, *J* = 1.4 Hz, H$^{6 \text{ or } 7}$), 1.68 (d, 3H, *J* = 1.4 Hz, H$^{7 \text{ or } 6}$), 1.33 (t, 3H, *J* = 7.1 Hz, H$^{13 \text{ or } 16}$), 1.28 (t, 3H, *J* = 7.1 Hz, H$^{16 \text{ or } 13}$)

^{13}C NMR (75 MHz, CDCl$_3$): δ= 165.9, 183.5, 149.3, 141.7, 135.8, 129.1127.8, 127.2, 127.07, 123.1, 61.7, 44.2, 26.4, 18.5, 14.5, 14.5

HRMS (ESI): Calculated for $C_{19}H_{25}O_4$: 317.17474, found: 317.17478

IR (cm^{-1}): 2986, 1721, 1232, 1213, 698

9.4.7.4.7. Diethyl 2-(2,4,4-triphenylbut-3-en-1-ylidene)malonate (**181af**)
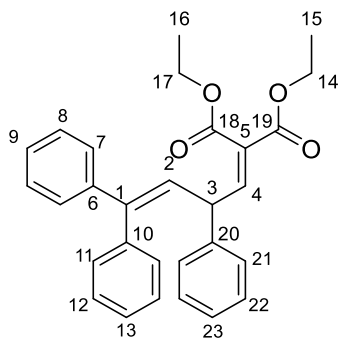
Chemical Formula: $C_{29}H_{28}O_4$
Molecular Weight: 440.54

Procedure A
Eq. of TiCl$_4$: 1 eq.
Reaction time: 15 min
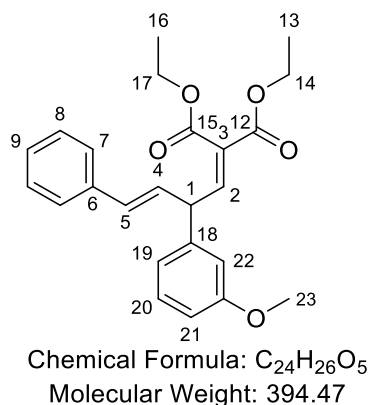**Eluent for purification:** *n*-hexane/AcOEt (82/18)
Yield: 81%
Aspect: Colorless oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.51 − 7.17 (m, 15H, H^{arom}), 7.14 (d, *J* = 10.5 Hz, 1H, H^4), 6.29 (d, *J* = 10.1 Hz, 1H, H^2), 4.70 (t, *J* = 10.3 Hz, 1H, H^3), 4.34 − 4.19 (m, 2H, H$^{17 \, or \, 14}$), 4.07 − 3.89 (m, 2H, H$^{14 \, or \, 17}$), 1.32 (t, *J* = 7.1 Hz, 3H, H$^{16 \, or \, 15}$), 1.11 (t, *J* = 7.1 Hz, 3H, H$^{15 \, or \, 16}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 165.1, 183.2, 147.9, 144.3, 141.9, 141.1, 139.3, 129.7, 129.0, 128.8, 128.5, 128.3, 128.1, 127.8, 127.6, 127.4, 127.2, 126.5, 61.6, 61.4, 45.5, 14.2, 14.0.

HRMS (ESI): Calculated for $C_{29}H_{29}O_4$: 441.20604, found: 441.20604

9.4.7.4.8. Diethyl (E)-2-(2-(tert-butyl)-4-phenylbut-3-en-1-ylidene)malonate (**181da**)
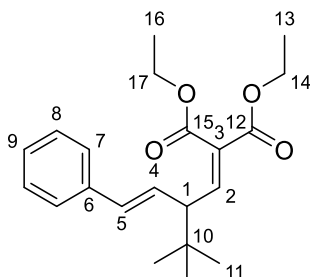
Chemical Formula: $C_{21}H_{28}O_4$
Molecular Weight: 344.45

Procedure A
Eq. of TiCl$_4$: 5 eq.
Reaction time: 24h
Eluent for purification: No purification required
Yield: quant.
Aspect: Orange oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.40 – 7.15 (m, 5H, H^{arom}), 7.06 (d, J = 11.3 Hz, 1H, H^2), 6.40 (d, J = 15.8 Hz, 1H, H^5), 6.13 (dd, J = 15.8; 8.5 Hz, 1H, H^4), 4.32 (q, 7.2 Hz, 2H, H$^{14\,or\,17}$), 4.24 (q, 7.2 Hz, 2H, H$^{17\,or\,14}$), 3.11 (dd, J = 11.3; 8.6, 1H, H^1), 1.33 (t, J = 7.1 Hz, 3H, H$^{13\,or\,16}$), 1.29 (t, J = 7.1 Hz, 3H, H$^{16\,or\,13}$), 0.97 (s, 9H, H^{11}).

^{13}C NMR (75 MHz, CDCl$_3$) δ 165.7, 183.0, 147.5, 137.1, 133.0, 128.7, 128.5, 127.5, 126.8, 126.3, 61.3, 61.2, 54.0, 28.5, 27.6, 14.2, 14.1.

HRMS (APCI) calculated for $C_{21}H_{29}O_4$: 345.20604, found : 345.20562.

9.4.7.4.9. Diethyl (*E*)-2-(2-cyclopropyl-4-phenylbut-3-en-1-ylidene)malonate (**181ea**)
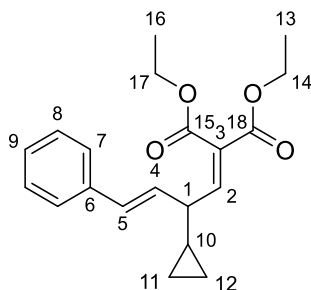
Chemical Formula: $C_{21}H_{28}O_4$
Molecular Weight: 328.41

Procedure A
Eq. of TiCl₄: 1 eq.
Reaction time: 1h at -78°C then 1h at RT
Eluent for purification: *n*-hexane/AcOEt (90/10)
Yield: 50%
Aspect: Yellow oil

¹H NMR(300 MHz, CDCl₃) δ 7.40-7.18 (m, 5H, H^{arom}), 6.98 (d, *J* = 10.6 Hz, 1H, H^2), 6.46 (d, *J* = 16.0 Hz, 1H, H^5), 6.16 (dd, *J* = 16.0; 6.6 Hz, 1H, H^4), 4.36 – 4.15 (m, 4H, H$^{17 \text{ and } 14}$), 2.74 – 2.63 (m, 1H, H^1), 1.37 – 1.24 (m, 6H, H$^{16 \text{ and } 13}$), 1.02 – 0.89 (m, 1H, H^{10}), 0.65 – 0.43 (m, 2H, H$^{11a \text{ and } 12a}$), 0.33 – 0.25 (m, 2H, H$^{11b \text{ and } 12b}$).

¹³C NMR (75 MHz, CDCl₃) δ 165.5, 183.1, 148.9, 137.0, 131.3, 128.7, 128.5, 127.7, 127.5, 126.2, 61.4, 61.3, 47.1, 15.1, 14.1, 14.1, 3.7, 3.5.

HRMS (APCI) calculated for $C_{20}H_{24}O_4$: 329.17474, found : 329.17484.

9.4.7.4.10. Diethyl (*E*)-2-(2-(tert-butyl)-4-(4-(methoxycarbonyl)phenyl)but-3-en-1-ylidene)malonate (**181dh**)
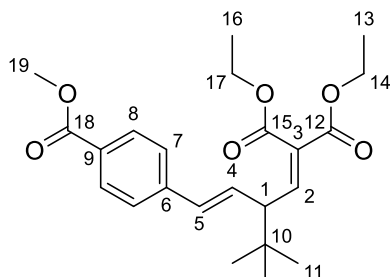
Chemical Formula: $C_{23}H_{30}O_6$
Molecular Weight: 402.49

Procedure B
Eluent for purification: Not isolated
Yield: 33% calculated by an NMR standard (dimethylterephtalate) on the crude mixture
Aspect: colorless oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.96 (d, *J* = 8.4 Hz, 2H, H^8), 7.39 (d, *J* = 8.4 Hz, 2H, H^7), 7.04 (d, *J* = 11.3 Hz, 1H, H^2), 6.44 (d, *J* = 15.9 Hz, 1H, H^5), 6.26 (dd, *J* = 15.8; 8.4 Hz, 1H, H^4), 4.37 − 4.18 (m, 4H, H$^{17 \text{ and } 14}$), 3.90 (s, 3H, H^{19}), 3.13 (dd, *J* = 10.9; 8.5 Hz, 1H, H^1), 1.38 − 1.18 (m, 6H, H$^{16 \text{ and } 13}$), 0.98 (s, 9H, H^{11}).

HRMS (APCI) calculated for $C_{23}H_{31}O_6$: 403.21152, found : 403.21202.

9.4.7.4.11. Diethyl (*E*)-2-(6-(4-(methoxycarbonyl)phenyl)-2-methylhex-5-en-3-ylidene)malonate (**204gh**)
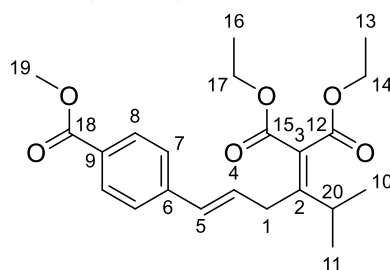
Chemical Formula: $C_{22}H_{28}O_6$
Molecular Weight: 388.46

Procedure B
Eluent for purification: Not isolated
Yield: 23% calculated by an NMR standard (dimethylterephtalate) on the crude mixture
Aspect: colorless oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 8.01 – 7.91 (m, 2H, H^8), 7.44 – 7.34 (m, 2H, H^7), 6.49 (d, J = 16.0 Hz, 1H, H^5), 6.32 (dt, J = 15.9, 6.5 Hz, 1H, H^4), 4.28 (q, J = 7.1 Hz, 2H, H$^{17\ or\ 14}$), 4.19 (q, J = 7.2 Hz, 2H, H$^{14\ or\ 17}$), 3.91 (s, 3H, H^{19}), 3.41 (dd, J = 6.5, 1.4 Hz, 2H, H^1), 3.05 (sept, J = 6.8 Hz, 1H, H^{20}), 1.32 (t, J = 7.1 Hz, 3H, H$^{16\ or\ 13}$), 1.25 (t, J = 7.1 Hz, 3H, H$^{13\ or\ 16}$), 1.13 (d, J = 6.8 Hz, 6H, H$^{10\ and\ 11}$).

HRMS (APCI): calculated for C$_{22}$H$_{29}$O$_6$: 389.19587 found: 389.19602

9.4.7.4.12. Diethyl (*E*)-2-(2-(tert-butyl)-5-methylhex-3-en-1-ylidene)malonate (**181dc**)
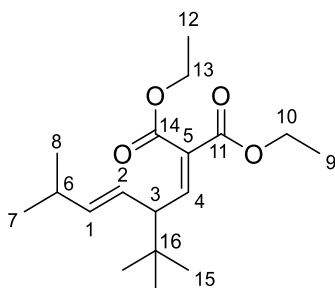
Chemical Formula: C$_{18}$H$_{30}$O$_4$
Molecular Weight: 310.43

Procedure B
Eluent for purification: *n*-hexane/AcOEt (8/2)
Yield: 57%
Aspect: Yellow oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 6.98 (d, J = 11.4 Hz, 1H, H^4), 5.42 (dd, J = 15.4; 6.3 Hz, 1H, H^1), 5.28 (dd, J = 15.7; 7.6 Hz, 1H, H^2), 4.35 – 4.11 (m, 4H, H$^{13\ and\ 10}$), 2.84 (dd, J = 11.2; 8.3 Hz, 1H, H^3), 2.32 – 2.16 (m, 1H, H^6), 1.37 – 1.21 (m, 6H, H$^{12\ and\ 9}$), 0.97 (d, J = 2.7 Hz, 3H, H$^{8\ or\ 7}$), 0.95 (d, J = 2.8 Hz, 3H, H$^{7\ or\ 8}$), 0.88 (s, 9H, H^{15}).

^{13}C NMR (75 MHz, CDCl$_3$) δ 165.8, 183.1, 148.7, 141.2, 128.0, 123.5, 61.2, 61.0, 53.6, 31.3, 27.8, 27.5, 22.4, 22.4, 14.2, 14.1.

HRMS (APCI) calculated for $C_{18}H_{30}O_4$: 311.22169, found: 311.22182.

9.4.7.4.13. Diethyl (*E*)-2-(2-cyclopropyl-5-methylhex-3-en-1-ylidene)malonate (**181ec**)
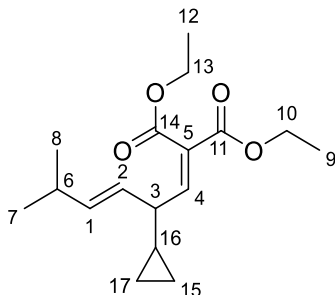
Chemical Formula: $C_{17}H_{26}O_4$
Molecular Weight: 294.39

Procedure B
Eluent for purification: *n*-hexane/AcOEt (8/2)
Yield: 54%
Aspect: Yellow oil

¹H NMR (300 MHz, CDCl₃) δ 6.90 (d, *J* = 10.8 Hz, 1H, H⁴), 5.47 (ddd, *J* = 15.6; 6.4; 1.1 Hz, 1H, H¹), 5.29 (ddd, *J* = 15.6; 6.3; 1.1 Hz, 1H, H²), 4.26 (q, *J* = 7.3 Hz, 2H, H¹³ ᵒʳ ¹⁰), 4.24 (q, *J* = 7.2 Hz, 2H, H¹⁰ ᵒʳ ¹³), 2.55 – 2.39 (m, 1H, H³), 2.28 – 2.22 (m, 1H, H⁶), 1.30 (t, *J* = 7.1 Hz, 3H, H¹² ᵒʳ ⁹), 1.30 (t, *J* = 7.1 Hz, 3H, H⁹ ᵒʳ ¹²), 0.96 (d, *J* = 6.7 Hz, 6H, H⁷ ᵃⁿᵈ ⁸), 0.55 – 0.38 (m, 2H, H¹⁵ᵃ ᵃⁿᵈ ¹⁷ᵃ), 0.30 – 0.14 (m, 2H, H¹⁵ᵇ ᵃⁿᵈ ¹⁷ᵇ), *H⁷ is hidden by H¹² ᵒʳ ⁹ signal.*

¹³C NMR (75 MHz, CDCl₃) δ 165.6, 183.2, 150.0, 139.7, 127.0, 125.4, 61.3, 61.2, 46.6, 31.1, 22.3, 15.1, 14.1, 14.1, 3.3, 3.2.

HRMS (APCI) calculated for $C_{17}H_{26}O_4$: 295.19041, found: 295.19097.

9.4.7.4.14. Diethyl (*E*)-2-(2,7-dimethyloct-5-en-3-ylidene)malonate (**204gc**)

Chemical Formula: $C_{17}H_{28}O_4$
Molecular Weight: 296.41

Procedure B
Eluent for purification: *n*-hexane/AcOEt (95/5)
Yield: 26%
Aspect: Yellow oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 5.46 (dd, *J* = 15.4; 6.5 Hz, 1H, H^1), 5.34 (dt, *J* = 15.4; 5.7 Hz, 1H, H^2), 4.35 – 4.07 (m, 4H, H$^{13 \text{ and } 10}$), 3.14 (d *J* = 6.1 Hz, 2H, H^3), 3.10 – 2.99 (m, 1H, H^{14}), 2.30 – 2.17 (m, 1H, H^6), 1.35 – 1.21 (m, 6H, H$^{12 \text{ and } 9}$), 1.07 (d, *J* = 6.9 Hz, 6H, H$^{15 \text{ and } 16}$), 0.94 (d, *J* = 6.7 Hz, 6H, H$^{7 \text{ and } 8}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 183.9, 183.0, 139.8, 130.5, 124.3, 124.0, 61.0, 60.8, 33.8, 31.9, 31.1, 22.4, 20.7, 14.1.

HRMS (APCI) calculated for $C_{17}H_{28}O_4$: 297.20604, found: 297.20650.

9.4.7.4.15. Diethyl (*E*)-2-(6-methylhept-4-en-2-ylidene)malonate (**204hc**)
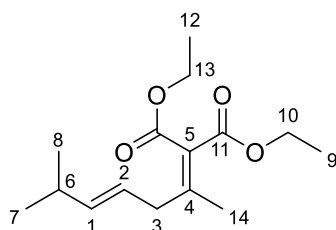
Chemical Formula: $C_{15}H_{24}O_4$
Molecular Weight: 268.35

Procedure B
Eluent for purification: *n*-hexane/AcOEt (8/2)
Yield: 39%
Aspect: Yellow oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 5.51 (dd, *J* = 15.3; 6.5 Hz, 1H, H^1), 5.31 (dt, *J* = 15.4; 5.7 Hz, 1H, H^2), 4.24 (q, *J* = 7.1 Hz, 2H, H$^{10 \text{ or } 13}$), 4.12 (q, *J* = 7.1 Hz, 2H, H $^{13 \text{ or } 10}$), 3.01 (d, *J* = 6.7 Hz, 2H, H^3), 2.34-2.19 (m, 1H, H^6), 2.0 (s, 3H, H^{14}) 1.35 – 1.20 (m, 6H, H$^{9 \text{ and } 12}$), 0.96 (d, *J* = 6.8 Hz, 6H, H$^{7 \text{ and } 8}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 165.7, 165.5, 156.8, 141.4, 124.7, 121.9, 60.9, 60.8, 39.8, 31.0, 22.4, 20.3, 14.1.

HRMS (APCI) calculated for C$_{15}$H$_{24}$O$_4$: 269.17474, found: 269.17510.

9.4.7.4.16. Diethyl (*E*)-2-(2,8-dimethylnon-6-en-4-ylidene)malonate (204ic)
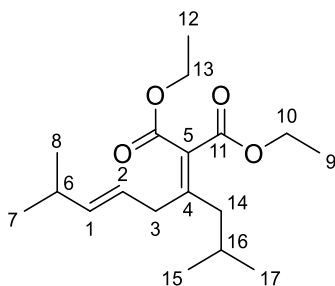
Chemical Formula: C$_{18}$H$_{30}$O$_4$
Molecular Weight: 310.43

Procedure B
Eluent for purification: *n*-hexane/AcOEt (7/3)
Yield: 49%
Aspect: Yellow oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 5.49 (dd, *J* = 15.3, 6.6 Hz, 1H, H^1), 5.37 – 5.25 (m, 1H), 4.23 (q, *J* = 7.1, 4H, H$^{10 \text{ and } 13}$), 3.09 (d, *J* = 6.7 Hz, 2H), 2.31 (d, *J* = 7.4 Hz, 2H, H^{14}), 2.29 – 2.19 (m, 1H, H^6), 2.02 – 1.86 (m, 1H, H^{16}), 1.29 (t, *J* = 7.1 Hz, 6H, H$^{9 \text{ and } 12}$), 0.98 – 0.89 (m, 12H, H$^{8, 7, 15 \text{ and } 17}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 165.9, 165.7, 159.7, 141.0, 125.7, 122.7, 61.0, 42.0, 37.3, 31.2, 27.3, 22.8, 22.5, 14.2.

HRMS (APCI) calculated for C$_{18}$H$_{31}$O$_4$: 311.22169, found: 311.22172.

9.4.7.4.17. Diethyl (*E*)-2-(2-(4-(methoxycarbonyl)phenyl)-5-methylhex-3-en-1-ylidene)malonate (**181fc**)
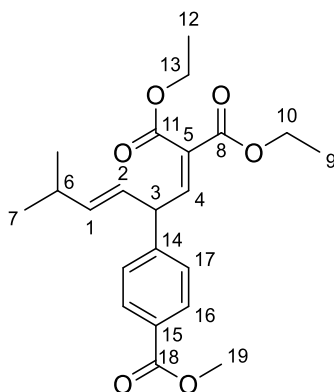
Chemical Formula: $C_{22}H_{28}O_6$
Molecular Weight: 388.46

Procedure B
Eluent for purification: *n*-hexane/AcOEt (85/15)
Yield: 12%
Aspect: Yellow oil

¹H NMR (300 MHz, CDCl₃): δ= 8.01 − 7.97 (m, 2H, H^{16}), 7.34 − 7.29 (m, 2H, H^{17}), 7.02 (d, *J* = 10.6 Hz, 1H, H^4), 5.62 − 5.48 (m, 2H, H$^{1 \text{ and } 2}$), 4.50 (dd, *J* = 10.7, 5.1 Hz, 1H, H^3), 4.32 (q, *J* = 7.1 Hz, 2H, H$^{13 \text{ or } 10}$), 4.24 (q, *J* = 7.1 Hz, 2H, H$^{10 \text{ or } 13}$), 3.91 (s, 3H, H^{19}), 2.39 − 2.26 (m, 1H, H^6), 1.33 (t, *J* = 7.1 Hz, 3H, H$^{12 \text{ or } 9}$), 1.29 (t, J = 7.1 Hz, 3H, H$^{9 \text{ or } 12}$), 1.00 (m, 6H, H^7)

¹³C NMR (75 MHz, CDCl₃): δ 165.4, 183.0, 147.9, 146.4, 141.4, 130.2, 129.4, 129.0, 127.9, 127.5, 125.4, 120.8, 61.7, 61.6, 52.2, 47.8, 39.0, 31.3, 29.8, 22.4, 22.3, 14.3, 14.2.

HRMS (APCI): calculated for $C_{22}H_{29}O_6$: 389.19587 found: 389.19602

A small amount (5%) of the following regioisomer (**204fc**) was also obtained.
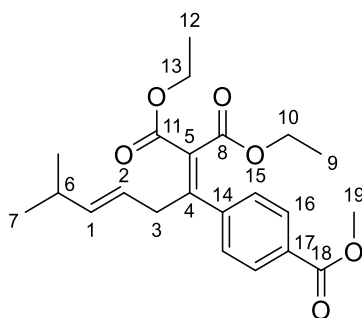
Chemical Formula: $C_{22}H_{28}O_6$
Molecular Weight: 388.46

Some of its NMR signals are given below

^{1}H NMR (300 MHz, CDCl$_3$): δ = 5.37 − 5.17 (m, 2H, H$^{1 \text{ and } 2}$), 3.92 (s, 3H, H^{19}), 3.41 (d, J = 6.2 Hz, 2H, H^3), 2.16 (m, 1H, H^6), 0.96 (t, J = 7.1 Hz, 3H), 0.86 (d, J = 6.7 Hz, 6H). *The esters and aromatic signals are hidden by those of the main product.*

9.4.7.4.18. Diethyl 2-(2-(4-(methoxycarbonyl)phenyl)-4-methylpent-3-en-1-ylidene)malonate (**181fb**)
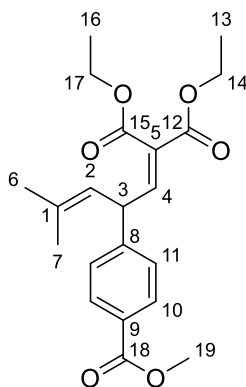
Chemical Formula: $C_{21}H_{26}O_6$
Molecular Weight: 374.43

Procedure B
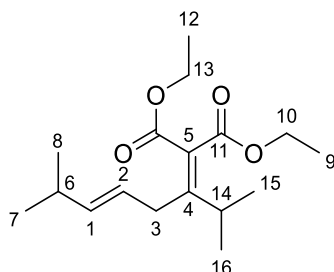**Eluent for purification:** *n*-hexane/AcOEt (85/15)
Yield: 30%
Aspect: Colorless oil

^{1}H NMR (300 MHz, CDCl$_3$): δ 7.98 (8.03 − 7.93 (m, 2H, H^{10}), 7.35 − 7.29 (m, 2H, H^{11}), 6.96 (d, J = 10.6 Hz, 1H), 5.36 − 5.29 (m, 1H, H^2), 4.83 − 4.72 (m, 1H, H^3), 4.38 − 4.28 (m, 2H, H$^{17\,or\,14}$), 4.24 (q, J = 7.1 Hz, 2H, H$^{14\,or\,17}$), 3.90 (s, 3H, H^{19}), 1.78 (d, J = 1.4 Hz, 3H, H$^{7\,or\,6}$), 1.68 (d, J = 1.4 Hz, 3H, H$^{6\,or\,7}$), 1.33 (t, J = 7.1 Hz, 3H, H$^{16\,or\,13}$), 1.29 (t, J = 7.1 Hz, 3H, H$^{13\,or\,16}$).

^{13}C NMR (75 MHz, CDCl$_3$): δ 167.0, 165.5, 183.2, 148.1, 146.8, 136.4, 130.2, 127.7, 122.3, 61.6, 52.23, 44.0, 14.3, 14.2.

HRMS (APCI): calculated for C$_{20}$H$_{27}$O$_4$: 375.18022 found: 375.18007

A small amount (4%) of the following regioisomer (**204fb**) was also obtained.
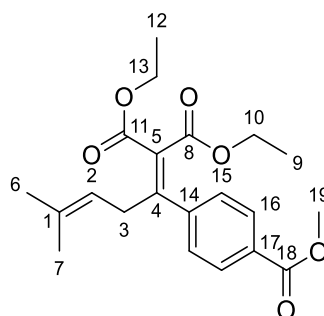
Chemical Formula: C$_{22}$H$_{28}$O$_6$
Molecular Weight: 388.46

Some of its NMR signals are given below

^{1}H NMR (300 MHz, CDCl$_3$)δ 5.03 (t, J = 7.4 Hz, 1H, H^2), 3.92 (s, 3H, H^{19}), 3.45 (d, J = 7.3 Hz, 2H, H^3), 1.57 (s, 6H, H$^{6\,and\,7}$). *The esters and aromatic signals are hidden by those of the main product.*

9.4.8. Synthesis of cyclopentenes

9.4.8.1. General procedure
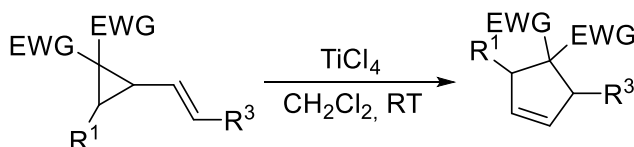
Starting vinylcyclopropane (1 eq.) and dry dichloromethane (1 mL/10 mg of vinylcyclopropane) are introduced in a dry round-bottom flask under argon. Then, titanium tetrachloride 1M in dichloromethane *(see product description for number of eq.)* is added and the mixture is stirred at room temperature for a defined time *(see description of the compound)*. Then, water is added to stop the reaction. An aqueous solution of hydrochloric acid (1M) is added. The two layers are separated and the aqueous one is extracted two times with dichloromethane. The combined organic layers are washed with brine, dried over $MgSO_4$ and concentrated under reduced pressure. The cyclopentene is obtained.

Number of $TiCl_4$ equivalents, reaction depend on the nature of the compound and are reported in the description of each product.

9.4.8.2. Product descriptions

9.4.8.2.1. Diethyl (2*S*,5*R*)-2-(*tert*-butyl)-5-phenylcyclopent-3-ene-1,1-dicarboxylate (**180da**)
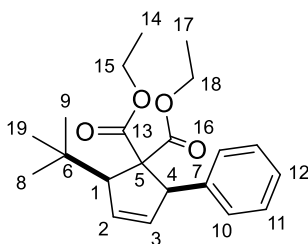
Chemical Formula: $C_{21}H_{28}O_4$
Molecular Weight: 344.45

Eq. of TiCl₄: 1 eq.
Reaction time: 15 min
No purification required
Yield: 93%
d.r.: 1/0 (*cis/trans*)
Aspect: Yellow oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.38 – 7.18 (m, 5H, H^{arom}), 5.91 (ddd, J = 6.0; 2.7; 1.9 Hz, 1H, H$^{3\ ou\ 4}$), 5.83 (ddd, J = 6.1; 2.9; 2.0 Hz, 1H, H$^{4\ ou\ 3}$), 4.71 (m, 1H, H^5), 4.37 – 4.27 (m, 2H, $^{H17\ ou\ 15}$), 3.70 – 3.53 (m, 3H, H$^{17\ ou\ 15\ et\ 7}$), 1.34 (t, J = 7.1 Hz, 3H, H$^{14\ ou\ 16}$), 1.05 (s, 9H, H^{11}), 0.93 (t, J = 7.2 Hz, 3H, H$^{16\ ou\ 14}$).

^{13}C NMR (75 MHz, CDCl$_3$): δ = 173.1, 168.7, 139.8, 132.1, 130.3, 130.2, 127.5, 127.0, 69.9, 63.9, 61.7, 60.6, 59.2, 33.7, 29.4, 14.2, 13.5.

HRMS (ESI) calculated for C$_{21}$H$_{28}$O$_4$: 345.20604, found: 345.20597.

9.4.8.2.2. 2,5-Diphenylcyclopent-3-ene-1,1-dicarbonitrile (**180aa-CN**)
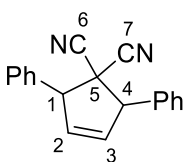
Chemical Formula: C$_{19}$H$_{14}$N$_2$
Molecular Weight: 270.34

Eq. of TiCl$_4$: 2 eq.
Reaction time: 24h
No purification required
Yield: 90%
d.r.: 2/1 (*cis/trans*)
Aspect: brown oil

^{1}H NMR (300 MHz, CDCl$_3$) δ = 7.50 – 7.34 (m, 20H, H^{arom}), 6.26 (d, J = 0.7 Hz, 2H, H$^{2\ and\ 3}_{trans}$), 6.25 (d, J = 1.2 Hz, 1H, H$^{2\ and\ 3}_{cis}$), 4.75 – 4.71 (m, 4H, H$^{1\ and\ 4}_{cis\ and\ trans}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ = 135.3, 134.3, 133.2, 133.1, 129.6, 129.4, 129.3, 128.6, 128.5, 115.8, 114.8, 112.1, 110.1, 60.8, 60.5.

HRMS (APCI): calculated for C$_{19}$H$_{15}$N$_2$: 271.12298 found: 271.12292

9.4.9. Synthesis of vinylepoxides
9.4.9.1. General procedure A: using benzylic sulfonium salts
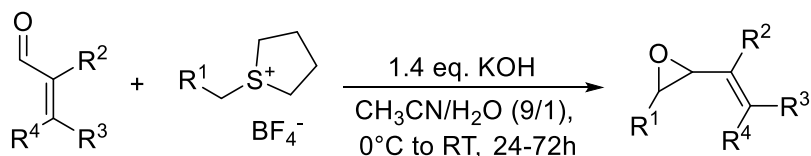
Benzylic sulfonium salt (1.4 eq.) is dissolved in a 9/1 mixture of MeCN/H$_2$O (8 mL/100 mg of α,β-unsaturated aldehyde) in a round-bottom flask at 0°C. Then, aldehyde (1 eq.) and KOH (1.4 eq) are added and the reaction mixture is stirred and allowed to warm up to room temperature for 24-72h. Then, the reaction mixture is evaporated and dissolved in dichloromethane and water. The two layers are separated and the aqueous one is extracted twice with dichloromethane. The combined organic layers are washed with brine, dried over MgSO$_4$ and concentrated under reduced pressure.

9.4.9.2. General procedure B: using allylic sulfonium salts
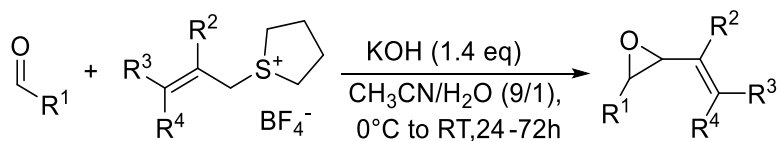
Allylic sulfonium salt (1.4 eq.) is dissolved in a 9/1 mixture of MeCN/H$_2$O (8 mL/100 mg of aldehyde) in a round-bottom flask at 0°C. Then, 1,3-diene (1 eq.) and KOH (1.4 eq) are added and the reaction mixture is stirred and allowed to warm up to room temperature for 24-72h. Then, the reaction mixture is evaporated and dissolved in dichloromethane and water. The two layers are separated and the aqueous one is extracted twice with dichloromethane. The combined organic layers are washed with brine, dried over MgSO$_4$ and concentrated under reduced pressure.

9.4.9.3. General procedure C: using chiral benzylic sulfonium salts
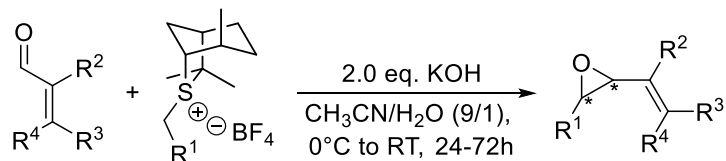
Chiral benzylic sulfonium salt (2 eq.) is dissolved in a 9/1 mixture of MeCN/H$_2$O (8 mL/100 mg of α,β-unsaturated aldehyde) in a round-bottom flask at 0°C. Then, aldehyde (1 eq.) and KOH (2 eq) are added and the mixture is stirred and allowed to warm up to room temperature for 24-72h. Then, the reaction mixture is evaporated and dissolved in dichloromethane and water. The two layers are separated and the aqueous one is extracted twice with dichloromethane. The combined organic layers are washed with brine, dried over MgSO$_4$ and concentrated under reduced pressure. The epoxide is purified by flash chromatography (95/5 n-hexane/AcOEt) to remove the chiral auxiliary.

9.4.9.4. Product descriptions

9.4.9.4.1. (*E*)-2-Phenyl-3-styryloxirane (**187aa**)
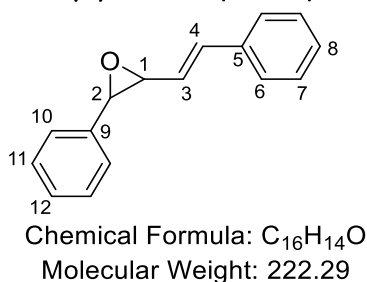
Chemical Formula: C$_{16}$H$_{14}$O
Molecular Weight: 222.29

The characterisation of this compound was made on a mixture of cis and trans diastereomers. The ^{13}C NMR signals corresponding to the cis isomer were lost in the background noise.

Procedure: A
Yield: 88%
d.r. (*cis/trans*): 1/5
Aspect: white solid

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.50 – 7.13 (m, 20H, H^{arom}), 6.83 (m, 2H, H$^4_{cis}$ and trans), 6.07 (dd, J = 16.0, 7.7 Hz, 1H, H$^3_{trans}$), 5.73 (dd, J = 16.0, 8.7 Hz, 1H, H$^3_{cis}$), 4.33 (d, J = 4.2 Hz, 1H, H$^2_{cis}$), 3.89 (d, J = 1.9 Hz, 1H, H$^2_{trans}$), 3.84 (dd, J = 8.7, 4.3 Hz, 1H, H$^1_{cis}$), 3.53 (dd, J = 7.7, 1.9 Hz, 1H, H$^1_{trans}$).

^{13}C NMR (*trans* isomer, 75 MHz, CDCl$_3$): δ = 137.0, 136.0, 134.4, 128.7, 128.5, 128.2, 128.1, 126.5, 126.2, 125.5, 63.1, 60.7.

HRMS (APCI) calculated for C$_{16}$H$_{15}$O: 223.11174, found: 223.11169.

9.4.9.4.2. (*E*)-2-Styryl-3-(p-tolyl)oxirane (187la)
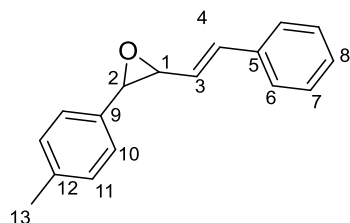
Chemical Formula: C$_{17}$H$_{16}$O
Molecular Weight: 236.31

The characterisation of this compound was made on a mixture of *cis* and *trans* diastereomers.

Procedure: A
Yield: 82%
d.r. (*cis/trans*): 3/7
Aspect: white solid

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.47 − 7.07 (m, 18H, H^{arom}), 6.84 (d, *J* = 16.0 Hz, 1H, H$^4_{cis}$), 6.80 (d, *J* = 16.0 Hz, 1H, H$^4_{trans}$), 6.06 (dd, *J* = 16.0, 7.7 Hz, 1H, H$^3_{trans}$), 5.75 (dd, *J* = 16.0, 8.7 Hz, 1H, H$^3_{cis}$), 4.29 (d, *J* = 4.2 Hz, 1H, H$^2_{cis}$), 3.85 (d, *J* = 2.0 Hz, 1H, H$^2_{trans}$), 3.84 − 3.78 (m, 1H, H$^1_{cis}$), 3.51 (dd, *J* = 7.6, 2.0, 1H, H$^1_{trans}$), 2.35 (s, 6H, H$^{13}_{cis,trans}$).

^{13}C NMR (75 MHz, CDCl$_3$): δ = 138.1, 136.8, 136.1, 134.3, 134.0, 129.3, 129.0, 128.7, 128.5, 128.1, 128.0, 126.5, 126.4, 126.3, 125.5, 123.3, 63.1, 60.8, 60.0, 59.4, 21.2. *Quaternary carbons from the cis isomer are missing*

HRMS (APCI) calculated for C$_{17}$H$_{17}$O: 237.12739, found: 237.12726.

IR (cm^{-1}): 3024, 1515, 1494, 1452.

9.4.9.4.3. (*E*)-2-(4-Methoxyphenyl)-3-styryloxirane (**187ka**)
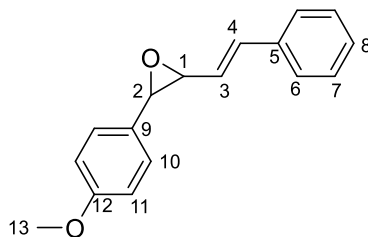
Chemical Formula: $C_{17}H_{16}O_2$
Molecular Weight: 252.31

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Procedure: A
Eluent for purification: Not required
Yield: 81%
d.r. (*cis/trans*): 4/6
Aspect: white solid

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.42 − 7.23 (m, 10H, H$^{6,7,8}_{cis,trans}$), 7.23 (d, *J* = 8.7 Hz, 4H, H$^{10}_{cis,trans}$), 6.91 (d, *J* = 8.8 Hz, 2H, H$^{11}_{cis}$), 6.90 (d, J = 8.8 Hz, 2H, H$^{11}_{trans}$), 6.84 (d, *J* = 15.9 Hz, 1H, H$^4_{cis}$), 6.80 (d, *J* = 16.0 Hz, 1H, H$^4_{trans}$), 6.06 (dd, *J* = 16.0, 7.6 Hz, 1H, H$^3_{trans}$), 5.74 (dd, *J* = 16.0, 8.7 Hz, 1H, H$^3_{cis}$), 4.27 (d, *J* = 4.1 Hz, 1H, H$^2_{cis}$), 3.83 (d, *J* = 1.9 Hz, 1H, H$^2_{trans}$), 3.81 (s, 3H, H$^{13}_{cis}$), 3.80 (s, 3H, H$^{13}_{trans}$), 3.80 − 3.77 (m, 1H, H$^1_{cis}$), 3.51 (dd, *J* = 7.6, 1.7 Hz, 1H, H$^1_{trans}$).

^{13}C NMR (75 MHz, CDCl$_3$): δ = 159.8, 159.3, 136.8, 136.2, 136.1, 134.3, 128.7, 128.6, 128.2, 128.1, 127.7, 126.8, 126.5, 126.3, 123.3, 114.1, 113.7, 61.0, 60.6, 60.1, 59.2, 55.4, 55.3.

HRMS (APCI) calculated for $C_{17}H_{17}O_2$: 253.12200, found: 253.12231.

IR (cm^{-1}): 2967, 1717, 1798, 1511, 1449, 1246, 1172, 1029.

9.4.9.4.4. (*E*)-2-Styryl-3-(o-tolyl)oxirane (**187ba**)
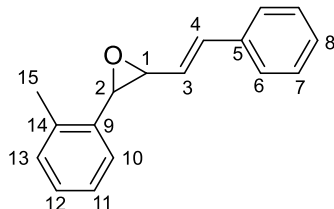
Chemical Formula: $C_{17}H_{16}O$
Molecular Weight: 236.31

The characterisation of this compound was made on a mixture of cis and trans diastereomers. The ^{13}C NMR signals corresponding to the cis isomer were lost in the background noise.

Procedure: A
Yield: 78%
d.r. (*cis/trans*): 1/9
Aspect: colorless oil

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.52 – 7.08 (m, 18H, H^{arom}), 6.83 (d, *J* = 16.0 Hz, 1H, H$^4_{cis}$), 6.82 (d, *J* = 16.0 Hz, 1H, H$^4_{trans}$), 6.12 (dd, *J* = 16.0, 7.8 Hz, 1H, H$^3_{trans}$), 5.55 (dd, *J* = 16.0, 8.8 Hz, 1H, H$^3_{cis}$), 4.31 (d, *J* = 4.2 Hz, 1H, H$^2_{cis}$), 4.02 (d, *J* = 2.0 Hz, 1H, H$^2_{trans}$), 3.90 (dd, *J* = 8.8, 4.2 Hz, 1H, H$^1_{cis}$), 3.41 (dd, *J* = 7.8, 1.6 Hz, 1H, H$^1_{trans}$), 2.39 (s, 3H, H$^{15}_{trans}$), 2.31 (s, 3H, H$^{15}_{cis}$).

^{13}C NMR (*trans* isomer, 75 MHz, CDCl$_3$): δ = 136.1, 135.9, 135.5, 134.5, 129.9, 128.8, 128.3, 127.8, 126.6, 126.3, 124.1, 62.3, 58.9, 19.0. *One aromatic ^{13}C NMR signal is missing, probably due to the overlap of two peaks*

HRMS (APCI) calculated for $C_{17}H_{17}O$: 237.12739, found: 237.12726.

IR (cm^{-1}): 3027, 1493, 1449.

9.4.9.4.5. Methyl (*E*)-4-(3-styryloxiran-2-yl)benzoate (**187fa**)
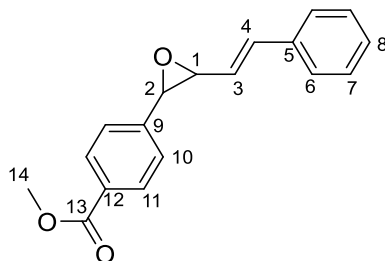
Chemical Formula: $C_{18}H_{16}O_3$
Molecular Weight: 280.32

The characterisation of this compound was made on the trans diasteresomer.

Procedure: A
Yield: 69%
d.r. (*cis/trans*): 0/1
Aspect: white solid

^{1}H NMR (300 MHz, CDCl₃): δ = 8.04 (d, *J* = 8.4 Hz, 1H, H^{11}), 7.48 – 7.21 (m, 7H, H^{10,6,7,8}), 6.83 (d, *J* = 16.0 Hz, 1H, H^4), 6.06 (dd, *J* = 16.0, 7.7 Hz, 1H, H^3), 3.93 (d, *J* = 1.9 Hz, 1H, H^2), 3.92 (s, 3H, H^{14}), 3.52 (dd, *J* = 7.7, 1.5 Hz, 1H, H^1).

^{13}C NMR (75 MHz, CDCl₃): δ = 166.8, 142.2, 135.9, 134.9, 130.0, 129.9, 128.7, 128.3, 126.6, 125.7, 125.4, 63.4, 60.2, 52.2.

HRMS (APCI) calculated for $C_{18}H_{17}O_3$: 281.11722, found: 281.11803.

IR (cm⁻¹): 2951, 1714, 1805, 1437, 1277, 1109.

9.4.9.4.6. (*E*)-2-(4-Fluorophenyl)-3-styryloxirane (**187pa**)

Chemical Formula: $C_{16}H_{13}OF$
Molecular Weight: 240.28

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Procedure: A
Yield: 87%
d.r. (cis/trans): 2/8
Aspect: white solid

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.48 − 7.17 (m, 14H, H^{10,6,7,8}$_{trans,cis}$), 7.14 − 6.98 (m, 4H, H^{11}$_{trans,cis}$), 6.85 (d, J = 15.9 Hz, 1H, H^4$_{cis}$), 6.82 (d, J = 16.0 Hz, 1H, H^4$_{trans}$), 6.05 (dd, J = 16.0, 7.7 Hz, 1H, H^3$_{trans}$), 5.67 (dd, J = 15.9, 8.6 Hz, 1H, H^3$_{cis}$), 4.30 (d, J = 4.2 Hz, 1H, H^2$_{cis}$), 3.87 (d, J = 1.9 Hz, 1H, H^2$_{trans}$), 3.83 (dd, J = 8.6, 4.2 Hz, 1H, H^1$_{cis}$), 3.48 (dd, J = 7.7, 1.9 Hz, 1H, H^1$_{trans}$).

^{13}C NMR (75 MHz, CDCl$_3$): δ = 181.8 (d, J = 246.5 Hz), 181.4 (d, J = 246.0 Hz), , 137.1, 136.0, 134.7, 132.9, 128.7, 128.6, 128.3, 128.1, 127.2 (d, J = 8.3 Hz), 126.6, 126.0, 122.7, 115.6 (d, J = 21.6 Hz), 115.1, 63.1, 60.2, 60.0, 58.9. *Quaternary carbons from the cis isomer are missing*

HRMS (APCI) calculated for $C_{16}H_{13}OF$: 241.10232, found: 241.10212.

IR (cm^{-1}): 3027, 1585, 1491, 1456, 1237.

9.4.9.4.7. (*E*)-2-(2-fluorophenyl)-3-styryloxirane (**187ta**)
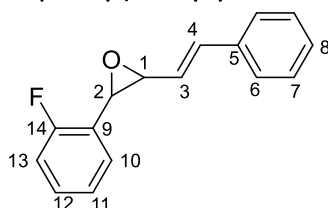
Chemical Formula: $C_{16}H_{13}OF$
Molecular Weight: 240.28

The characterisation of this compound was made on the trans diastereomer.

Procedure: A
Yield: 91%
d.r. (*cis/trans*): 0/1
Aspect: beige solid

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.49 − 7.03 (m, 9H, H^{arom}), 6.86 (d, J = 16.0 Hz, 1H, H^4), 6.11 (dd, J = 16.0, 7.7 Hz, 1H, H^3), 4.21 (d, J = 1.7 Hz, 1H, H^2), 3.55 (dd, J = 7.6, 1.6 Hz, 1H, H^1).

¹³C NMR (75 MHz, CDCl₃): δ = 180.5 (d, *J* = 247.0 Hz), 136.0, 134.9, 129.5 (d, *J* = 8.1 Hz), 128.7, 128.3, 126.6, 126.0 (d, *J* = 3.6 Hz), 125.8, 124.4 (d, *J* = 3.2 Hz), 115.3 (d, J = 20.8 Hz), 62.5, 55.1 (d, *J* = 20.8 Hz)

HRMS (APCI) calculated for $C_{16}H_{13}OF$: 241.10232, found: 241.10212.

IR (cm⁻¹): 3031, 1798, 1510, 1220, 1157, 1036.

9.4.9.4.8. (*E*)-2-(3-Methoxyphenyl)-3-styryloxirane (**187ca**)
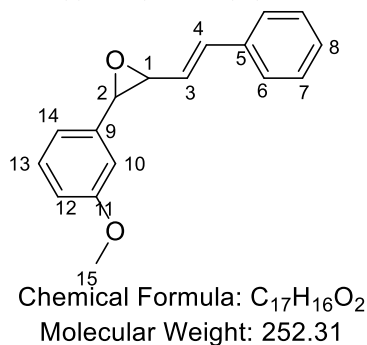
Chemical Formula: $C_{17}H_{16}O_2$
Molecular Weight: 252.31

The characterisation of this compound was made on a mixture of cis and trans diastereomers. The ¹³C NMR signals of the cis diastereomer were lost in the background noise

Procedure: A
Yield: 75%
d.r. (*cis/trans*): 1/9
Aspect: yellow oil

¹H NMR (300 MHz, CDCl₃): δ = 7.44 − 7.23 (m, 14H, H⁵,⁶,⁷,⁸,¹³,¹⁴ cis,trans), 6.96 − 6.85 (m, 4H, H¹⁰,¹² cis,trans), 6.84 − 6.76 (m, 2H, H⁴cis,trans), 6.06 (dd, *J* = 16.0, 7.7 Hz, 1H, H³trans), 5.74 (dd, *J* = 16.0, 8.7 Hz, 1H, H³cis), 4.31 (d, *J* = 4.2 Hz, 1H, H²cis), 3.87 (d, *J* = 1.9 Hz, 1H, H²trans), 3.86 − 3.82 (m, 1H, H¹cis), 3.82 (s, 6H, H¹⁵cis,trans), 3.51 (dd, *J* = 7.7, 1.9 Hz, 1H, H¹trans).

¹³C NMR (*trans* isomer, 75 MHz, CDCl₃): δ = 179.0, 138.8, 136.1, 134.5, 129.7, 128.7, 128.2, 126.6, 126.2, 118.0, 114.1, 110.5, 63.1, 60.7, 55.3.

HRMS (APCI) calculated for $C_{17}H_{17}O_2$: 253.12200, found: 253.12231.

IR (cm⁻¹): 2955, 1596, 1494, 1464, 1260, 1157, 1036.

9.4.9.4.9. (*E*)-2-(3-Methoxyphenyl)-3-styryloxirane (**187sa**)
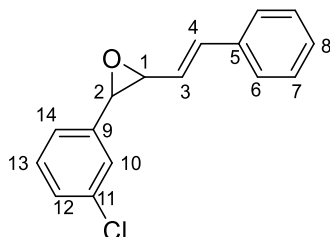
Chemical Formula: $C_{16}H_{13}OCl$
Molecular Weight: 256.73

The characterisation of this compound was made on the trans diastereomer.

Procedure: A
Yield: 75%
d.r. (*cis/trans*): 0/1
Aspect: brown solid

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.48 – 7.15 (m, 9H, H^{arom}), 6.81 (d, *J* = 16.0 Hz, 1H, H^4), 6.04 (dd, *J* = 16.0, 7.7 Hz, 1H, H^3), 3.85 (d, *J* = 1.9 Hz, 1H, H^2), 3.48 (dd, *J* = 7.7, 1.4 Hz, 1H, H^1).

^{13}C NMR (75 MHz, CDCl$_3$): δ = 139.2, 136.9, 134.9, 134.7, 129.8, 128.7, 128.4, 128.3, 126.5, 125.7, 125.5, 123.7, 63.2, 60.0.

HRMS (APCI) calculated for $C_{16}H_{14}O^{35}Cl$: 257.07277, found: 257.07183.

IR (cm^{-1}): 3023, 1790, 1479, 1191, 1065, 686.

9.4.9.4.10. (*E*)-2-(4-bromophenyl)-3-styryloxirane (**187qa**)
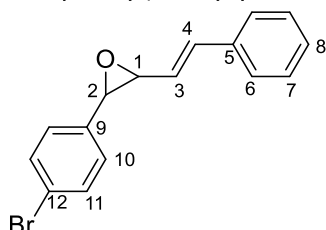
Chemical Formula: $C_{16}H_{13}OBr$
Molecular Weight: 301.18

The characterisation of this compound was made on a mixture of cis and trans diastereomers. Some ^{13}C NMR signals corresponding to the cis isomer are missing.

Procedure: A
Eluent for purification: Not required
Yield: quant.
d.r. (*cis/trans*): 1/9
Aspect: white solid

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.55 − 7.15 (m, 18H, H^{arom}), 6.85 (d, *J* = 15.9 Hz, 1H, H$^4_{cis}$), 6.82 (d, *J* = 15.9 Hz, 1H, H$^4_{trans}$), 6.04 (dd, *J* = 16.0, 7.7 Hz, 1H, H$^3_{trans}$), 5.66 (dd, *J* = 15.9, 8.6 Hz, 1H, H$^3_{cis}$), 4.27 (d, *J* = 4.2 Hz, 1H, H$^2_{cis}$), 3.89 − 3.80 (m, 2H, H$^2_{trans}$ + H$^1_{cis}$), 3.47 (ddd, *J* = 7.7, 2.0, 0.7 Hz, 1H, H$^1_{trans}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 136.3, 136.1, 136.1, 135.0, 134.9, 134.5, 131.9, 131.6, 128.8, 128.4, 128.3, 127.3, 126.7, 122.3, 121.9, 63.3, 60.3, 60.3, 60.1. *The quaternary and tertiary aromatic signals of the cis isomer are missing*

HRMS (APCI) calculated for C$_{16}$H$_{14}$O^{79}Br: 301.02225, found: 301.02223.

9.4.9.4.11. Methyl (*E*)-3-(3-styryloxiran-2-yl)benzoate (**187ra**)
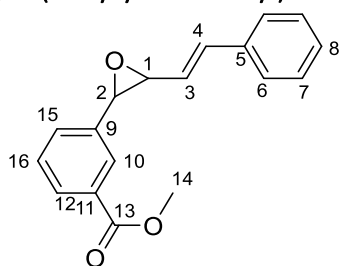
Chemical Formula: C$_{18}$H$_{16}$O$_3$
Molecular Weight: 301.18

The characterisation of this compound was made on the trans diastereomer.

Procedure: A
Eluent for purification: Not required
Yield: 90%
d.r. (*cis/trans*): 0/1
Aspect: white solid

^{1}H NMR (300 MHz, CDCl$_3$): δ = 8.02 − 7.98 (m, 2H, H$^{10\ and\ 12}$), 7.53 − 7.27 (m, 7H, H^{arom}), 6.83 (d, *J* = 16.0 Hz, 1H, H^4), 6.07 (dd, *J* = 16.0, 7.7 Hz, 1H, H^3), 3.95 (d, *J* = 1.9 Hz, 1H, H^2), 3.93 (s, 3H, H^{14}), 3.54 (dd, *J* = 7.7, 1.5 Hz, 1H, H^1).

¹³C NMR (75 MHz, CDCl₃) δ 166.9, 137.8, 136.1, 135.0, 130.7, 130.0, 129.6, 128.8, 128.4, 126.9, 126.7, 125.9, 63.3, 60.4, 52.4. *One aromatic ¹³C NMR signal is missing, probably due to the overlap of two peaks*

HRMS (APCI) calculated for $C_{18}H_{17}O_3$: 281.11722, found: 281.11803.

9.4.9.4.12. (*E*)-2-Phenyl-3-styryloxirane (**187ua**)
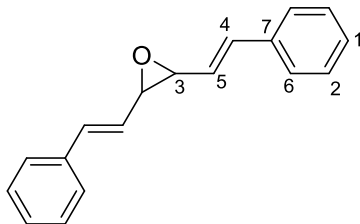
Chemical Formula: $C_{18}H_{16}O$
Molecular Weight: 248.33

The characterisation of this compound was made on a mixture of *cis* and *trans* diastereomers.

Procedure: A
Eluent for purification: Not required
Yield: 90%
d.r. (*cis/trans*): 1/1
Aspect: white solid

¹H NMR (300 MHz, CDCl₃): δ = 7.49 – 7.12 (m, 20H, H^{arom}), 6.84 (t, *J* = 15.9 Hz, 4H, $H^4_{cis,trans}$), 6.19 – 6.07 (m, 2H, H^5_{cis}), 6.00 (dd, *J* = 16.0, 7.2 Hz, 2H, H^5_{trans}), 3.86 – 3.78 (m, 2H, H^3_{cis}), 3.54 (d, *J* = 7.2 Hz, 2H, H^3_{trans}).

¹³C NMR (75 MHz, CDCl₃): δ = 136.1, 136.0, 135.8, 134.3, 128.7, 128.1, 126.6, 126.5, 126.0, 123.4, 61.0, 59.6.

HRMS (APCI) calculated for $C_{18}H_{16}O$: 249.12739, found: 249.12723.

9.4.9.4.13. (*E*)-2-(4-Methoxystyryl)-3-phenyloxirane (**187ai**)
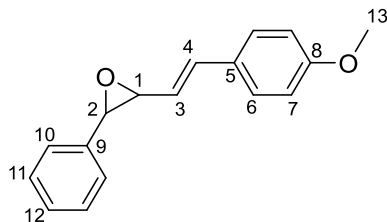
Chemical Formula: $C_{17}H_{16}O_2$
Molecular Weight: 252.31

The characterisation of this compound was made on the trans diastereomer.

Procedure: A
Yield: 82%
d.r. (*cis/trans*): 0/1
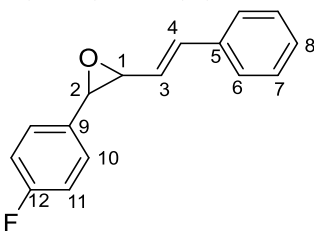**Aspect:** white solid

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.40 – 7.27 (m, 7H, H^{arom}), 6.86 (d, *J* = 8.8 Hz, 2H, H^7), 6.75 (d, *J* = 16.0 Hz, 1H, H^4), 5.92 (dd, *J* = 15.9, 7.8 Hz, 1H, H^3), 3.87 (d, *J* = 1.9 Hz, 1H, H^2), 3.80 (s, 3H, H^{13}), 3.50 (dd, *J* = 7.8, 1.6 Hz, 1H, H^1).

^{13}C NMR (75 MHz, CDCl$_3$): δ = 159.6, 137.2, 134.1, 128.9, 128.5, 128.2, 127.8, 125.5, 123.8, 114.1, 63.4, 60.7, 55.3.

HRMS (APCI) calculated for $C_{17}H_{17}O_2$: 253.12200, found: 253.12231.

9.4.9.4.14. (*E*)-2-(4-bromostyryl)-3-phenyloxirane (**187ae**)
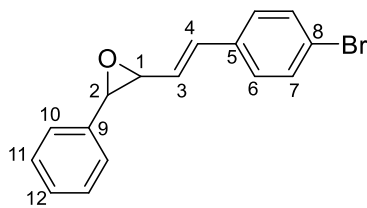
Chemical Formula: $C_{16}H_{13}OBr$
Molecular Weight: 301.18

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Procedure: A
Yield: 84%
d.r. (*cis/trans*): 2/8
Aspect: white solid

**^{1}H NMR (300 MHz, CDCl$_3$):** δ = 7.48 (d, *J* = 8.5 Hz, 4H, H$^{10,11}_{trans}$), 7.45 − 7.25 (m, 10H, H$^{1,2,3}_{trans,cis}$), 7.11 (d, *J* = 8.5 Hz, 4H, H$^{10,11}_{cis}$), 6.80 (d, *J* = 16.0 Hz, 1H, H$^{8}_{cis}$), 6.77 (d, *J* = 16.0 Hz, 1H, H$^{8}_{trans}$), 6.09 (dd, *J* = 16.0, 7.6 Hz, 1H, H$^{7}_{trans}$), 5.74 (dd, *J* = 16.0, 8.6 Hz, 1H, H$^{7}_{cis}$), 4.36 (d, *J* = 4.2 Hz, 1H, H$^{5}_{cis}$), 3.90 (d, *J* = 1.9 Hz, 1H, H$^{5}_{trans}$), 3.85 (dd, *J* = 8.7, 4.4 Hz, 1H, H$^{6}_{cis}$), 3.53 (dd, *J* = 7.5, 1.5 Hz, 1H, H$^{6}_{trans}$).

^{13}C NMR (75 MHz, CDCl$_3$): δ = 136.8, 136.6, 136.0, 133.1, 131.8, 131.7, 128.6, 128.4, 128.3, 128.0, 127.9, 127.1, 126.5, 125.5, 123.9, 122.0, 62.9, 60.8, 59.8, 59.4. *Four aromatic ^{13}C NMR signals from the cis isomer are missing including the quaternary carbons*

IR (cm^{-1}): 3042, 1585, 1487, 1456, 1066.

HRMS (APCI) calculated for C$_{16}$H$_{14}$O^{79}Br: 301.02225, found: 301.02223.

9.4.9.4.15. (*E*)-2-(4-Methylstyryl)-3-phenyloxirane (**187am**)
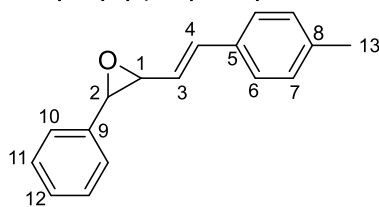
Chemical Formula: C$_{17}$H$_{16}$O
Molecular Weight: 236.31

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Procedure: A
Yield: 88%
d.r. (*cis/trans*): 1/5
Aspect: white solid

¹H NMR (300 MHz, CDCl₃): δ = 7.41 – 7.26 (m, 14H, H^{arom}), 7.15 (m, 4H, H^7 $_{cis}$ $_{and\ trans}$), 6.82 (d, *J* = 16.0 Hz, 1H, H^4 $_{cis}$), 6.78 (d, *J* = 16.0 Hz, 1H, H^4 $_{trans}$), 6.01 (dd, *J* = 16.0, 7.8 Hz, 1H, H^3 $_{trans}$), 5.67 (dd, *J* = 15.9, 8.7 Hz, 1H, H^3 $_{cis}$), 4.32 (d, *J* = 4.2 Hz, 1H, H^2 $_{cis}$), 3.88 (d, *J* = 1.9 Hz, 1H, H^2 $_{trans}$), 3.83 (dd, *J* = 8.7, 4.3 Hz, 1H, H^1 $_{cis}$), 3.51 (d, J = 7.8, 1.9 Hz, 1H, H^1 $_{trans}$), 2.34 (s, 3H, H^{13} $_{trans}$), 2.29 (s, 3H, H^{13} $_{cis}$).

HRMS (APCI) calculated for C₁₇H₁₇O: 237.12739, found: 237.12726.

9.4.9.4.16. (*E*)-2-Phenyl-3-(1-phenylprop-1-en-2-yl)oxirane (**187ad**)

Chemical Formula: C₁₇H₁₆O
Molecular Weight: 236.31

The characterisation of this compound was made on a mixture of cis and trans diastereomers. The ¹³C NMR signals corresponding to the cis isomer were lost in the background noise.

Procedure: A
Yield: 80%
d.r. (*cis/trans*): 1/12
Aspect: white solid

¹H NMR (300 MHz, CDCl₃): δ = 7.50 – 7.27 (m, 20H, H^{arom}), 6.75 (s, 1H, H^4$_{trans}$), 6.67 (s, 1H, H^4$_{cis}$), 4.33 (d, *J* = 4.4 Hz, 1H, H^2$_{cis}$), 3.97 (d, *J* = 2.0 Hz, 1H, H^2$_{trans}$), 3.89 (d, *J* = 4.4 Hz, 1H, H^1$_{cis}$), 3.56 (dd, *J* = 2.0, 0.5 Hz, 1H, H^1$_{trans}$), 2.16 (d, *J* = 1.4 Hz, 3H, H^{13}$_{cis}$), 1.95 (d, *J* = 1.4 Hz, 3H, H^{13}$_{trans}$).

¹³C NMR (*trans* isomer, 75 MHz, CDCl₃): δ = 137.4, 137.1, 133.7, 129.0, 128.8, 128.6, 128.3, 126.9, 125.6, 66.8, 58.4, 12.8.

HRMS (APCI) calculated for C₁₇H₁₇O: 237.12739, found: 237.12726.

9.4.9.4.17. 2-(2,2-Diphenylvinyl)-3-phenyloxirane (187af)
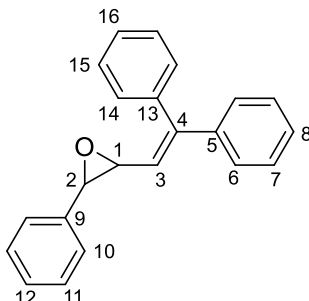
Chemical Formula: $C_{22}H_{18}O$
Molecular Weight: 298.39

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Procedure: A
Yield: 93%
d.r. (*cis/trans*): 2/8
Aspect: white solid

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.48 – 7.06 (m, 30H, H^{arom}), 5.87 (d, *J* = 8.7 Hz, 1H, H$^3_{trans}$), 5.64 (d, *J* = 8.9 Hz, 1H, H$^3_{cis}$), 4.27 (d, *J* = 4.3 Hz, 1H, H$^2_{cis}$), 3.98 (d, *J* = 1.9 Hz, 1H, H$^2_{trans}$), 3.75 (dd, *J* = 8.9, 4.3 Hz, 1H, H$^1_{cis}$), 3.49 (dd, *J* = 8.7, 2.0 Hz, 1H, H$^1_{trans}$).

RMN ^{13}C (75 MHz, CDCl$_3$): δ 148.1, 141.1, 136.7, 136.9, 130.2, 128.5, 128.3, 128.2, 128.1, 127.9, 127.7, 126.5, 125.7, 125.6, 122.1, 60.9, 60.7, 60.1, 57.5. *The aromatic signals of the cis isomers are not showing which is probably due to the low proportion of the diastereomer in the mixture and potential overlapping with the aromatic of the main trans diastereomer*

HRMS (APCI) calculated for $C_{22}H_{19}O$: 299.14034, found : 297.14293.

IR (cm^{-1}): 3027, 1680, 1790, 1494, 1460.

9.4.9.4.18. 2-(2-Methylprop-1-en-1-yl)-3-phenyloxirane (**187ab**)
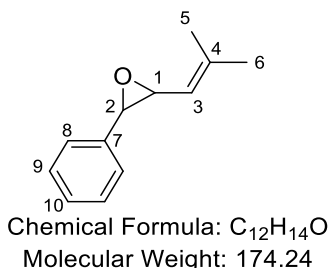
Chemical Formula: $C_{12}H_{14}O$
Molecular Weight: 174.24

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Procedure: A
**Yield:** 79%
d.r. (*cis/trans*): 2/8
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.52 – 7.12 (m, 10H, H^{arom}), 5.00 (d, J = 8.7 Hz, 1H, H$^3_{trans}$), 4.74 (d, J = 8.8 Hz, 1H, H$^3_{cis}$), 4.22 (d, J = 4.3 Hz, 1H, H$^2_{cis}$), 3.87 (dd, J = 8.8, 4.3 Hz, 1H, H$^1_{cis}$), 3.75 (d, J = 1.9 Hz, 1H, H$^2_{trans}$), 3.52 (dd, J = 8.7, 2.0 Hz, 1H, H$^1_{trans}$), 1.80 (s, 3H, H$^{6\ or\ 5}_{cis}$), 1.79 (s, 6H, H$^{5\ and\ 6}{}_{trans}$), 1.65 (s, 3H, H$^{5\ or\ 6}{}_{cis}$).

RMN ^{13}C (75 MHz, CDCl$_3$): δ 142.3, 140.6, 137.7, 136.8, 128.5, 128.1, 127.6, 126.6, 125.5, 122.0, 117.8, 60.1, 60.0, 59.0, 56.0, 26.2, 25.9, 18.5, 18.4. *The signal of the quaternary carbon from the cis diastereoisomer is missing*

HRMS (APCI) calculated for $C_{12}H_{14}O$: 175.11174, found: 175.11121.

IR (cm^{-1}): 2974, 1672, 1494, 1453.

9.4.9.4.19. (*E*)-2-(3-Methylbut-1-en-1-yl)-3-phenyloxirane (**187ac**)
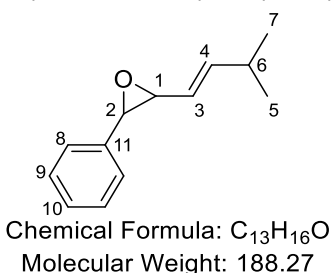
Chemical Formula: $C_{13}H_{16}O$
Molecular Weight: 188.27

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Procedure: A
Yield: 77%
d.r. (*cis/trans*): 2/8
Aspect: colorless oil

^{1}H NMR (300 MHz, CDCl$_3$): δ =7.62 − 7.12 (m, 1H, 10H, H^{arom}), 5.94 (m, 2H, H^4$_{cis,trans}$), 5.27 (ddd, *J* = 15.6, 8.0, 1.4 Hz, 1H, H^3$_{trans}$), 4.97 (ddd, *J* = 15.6, 8.6, 1.2 Hz, 1H, H^3$_{cis}$), 4.20 (d, *J* = 4.3 Hz, 1H, H^2$_{cis}$), 3.76 (d, *J* = 2.0 Hz, 1H, H^2$_{trans}$), 3.63 (dd, *J* = 8.6, 4.3 Hz, 1H, H^1$_{cis}$), 3.32 (dd, *J* = 8.0, 2.0 Hz, 1H, H^1$_{trans}$), 2.42 − 2.29 (m, 1H, H^6$_{trans}$), 2.28 − 2.14 (m, 1H, H^6$_{cis}$), 1.03 (d, *J* = 1.1 Hz, 3H, H$^{7\ ou\ 6}$$_{trans}$), 1.01 (d, *J* = 1.1 Hz, 3H, H$^{6\ ou\ 7}$$_{trans}$), 0.89 (dd, *J* = 6.7, 5.7 Hz, 6H, H^{6,7}$_{cis}$).

RMN ^{13}C (75 MHz, CDCl$_3$): δ 146.5, 144.2, 137.4, 136.5, 128.5, 128.1, 127.6, 126.5, 125.5, 124.1, 120.5, 63.3, 60.2, 59.9, 59.0, 31.2, 30.9, 22.1, 22.0. *Two aromatic ^{13}C NMR signals from the cis isomer are missing including the quaternary carbon*

HRMS (APCI) calculated for C$_{13}$H$_{17}$O: 189.12739, found : 189.12744.

IR (cm^{-1}): 2959, 1796, 1497, 1460.

9.4.9.4.20. 2-((1*E*,3*E*)-Penta-1,3-dien-1-yl)-3-phenyloxirane (**187aj**)
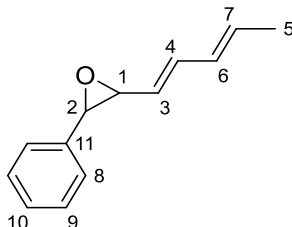
Chemical Formula: C$_{13}$H$_{14}$O
Molecular Weight: 186.25

The characterisation of this compound was made on a mixture of cis and trans diastereomers. The ^{13}C NMR signals corresponding to the cis isomer were lost in the background noise.

Procedure: A
Yield: 90%
d.r. (*cis/trans*): 3/17
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.41 – 7.23 (m, 10H, H^{arom}), 6.77 (dd, J = 15.3, 11.1 Hz, 1H, H$^8_{cis}$), 6.41 (dd, J = 15.3, 10.5 Hz, 1H, H$^8_{trans}$), 6.10 (dd, J = 14.0, 11.5 Hz, 1H, H$^9_{trans}$), 5.77 (dd, J = 15.0, 6.8 Hz, 1H, H$^9_{cis}$), 5.51 (dd, J = 15.0, 7.6 Hz, 1H, H$^{10}_{trans}$), 5.40 (dd, J = 15.3, 7.9 Hz, 1H, H$^7_{trans}$), 5.06 (dd, J = 15.4, 9.0 Hz, 1H, H$^7_{cis}$), 4.24 (d, J = 4.2 Hz, 1H, H$^5_{cis}$), 3.77 (d, J = 1.9 Hz, 1H, H$^5_{trans}$), 3.66 (dd, J = 9.0, 4.2 Hz, 1H, H$^6_{cis}$), 3.34 (dd, J = 7.9, 1.8 Hz, 1H, H$^6_{trans}$), 1.77 (d, *J* = 6.7 Hz, 3H, H$^{11}_{trans}$), 1.70 (d, *J* = 6.5 Hz, 3H, H$^{11}_{cis}$).

RMN ^{13}C (*trans* isomer, 75 MHz, CDCl$_3$): δ 137.2, 136.1, 131.4, 130.4, 128.5, 128.1, 126.7, 125.4, 63.0, 60.7, 18.2.

IR (cm^{-1}): 3019, 1658, 1498, 1456.

9.4.9.4.21. 2-(Cyclohex-1-en-1-yl)-3-phenyloxirane (187ak)
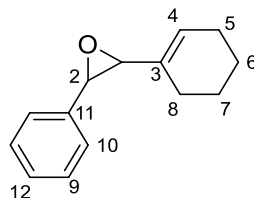
Chemical Formula: C$_{14}$H$_{16}$O
Molecular Weight: 200.28

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Procedure: A
Yield: quant.
d.r. (*cis/trans*): 1/12
Aspect: white solid

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.40 – 7.25 (m, 10H, H^{arom} $_{cis and trans}$), 5.92 (m, 1H, H$^4_{trans}$), 5.73 (m, 1H, H^4 $_{cis}$), 4.14 (d, *J* = 4.4 Hz, 1H, H$^2_{cis}$), 3.87 (d, *J* = 2.0 Hz, 1H, H$^2_{trans}$), 3.63 (bs, 1H, H$^1_{cis}$), 3.31 (d, *J* = 1.8 Hz, 1H, H$^1_{trans}$), 2.13 – 1.53 (m, 16H, H$^{5-8}$ $_{cis and trans}$).

HRMS (APCI) calculated for C$_{14}$H$_{17}$O: 201.12739, found: 201.12740.

9.4.9.4.22. (*E*)-2-Isopropyl-3-styryloxirane (**187ga**)

Chemical Formula: $C_{13}H_{16}O$
Molecular Weight: 188.12

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Procedure: B
Yield: quant.
d.r. (*cis/trans*): 3/2
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl₃): δ = 7.45 − 7.19 (m, 10H, H^{arom}), 6.79 (d, J = 16.0 Hz, 1H, H$^5_{trans}$), 6.75 (d, J = 16.0 Hz, 1H, H$^5_{cis}$), 6.07 (dd, J = 16.0, 7.7 Hz, 1H, H$^4_{trans}$), 5.93 (dd, J = 16.0, 7.8 Hz, 1H, H$^4_{cis}$), 3.60 (ddd, J = 7.7, 4.3, 0.8 Hz, 1H, H$^2_{cis}$), 3.32 (ddd, J = 7.8, 2.3, 0.6 Hz, 1H, H$^2_{trans}$), 2.83 (dd, J = 9.3, 4.3 Hz, 1H, H$^1_{cis}$), 2.74 (dd, J = 6.8, 2.2 Hz, 1H, H$^1_{trans}$), 1.69 − 1.53 (m, 2H, H$^3_{cis\ and\ trans}$), 1.15 (d, J = 6.6 Hz, 3H, H$^{8\ or\ 7}_{cis}$), 1.06 (d, J = 6.7 Hz, 3H, H$^{8\ or\ 7}_{trans}$), 1.00 (d, J = 6.9 Hz, 3H, H$^{7\ or\ 8}_{trans}$), 0.93 (d, J = 6.8 Hz, 3H, H$^{7\ or\ 8}_{cis}$).

^{13}C NMR (75 MHz, CDCl₃): δ = 136.5, 136.4, 135.5, 133.8, 128.8, 128.1, 128.1, 127.3, 126.6, 126.5, 123.9, 77.2, 66.4, 65.3, 57.9, 30.8, 27.6, 20.4, 19.2, 18.6, 18.5.

HRMS (APCI) calculated for $C_{13}H_{17}O$: 189.12739, found : 189.12744.

9.4.9.4.23. (*E*)-2-Cyclopropyl-3-styryloxirane (**187ea**)

Chemical Formula: $C_{13}H_{14}O$
Molecular Weight: 186.25

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Procedure: B
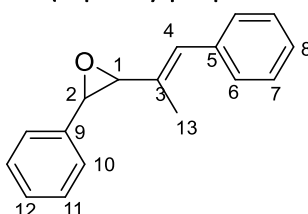**Yield:** quant.
d.r. (*cis/trans*): 2/3
Aspect: pale yellow oil

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.44 − 7.21 (m, 10H, H^{arom}), 6.83 (d, *J* = 16.0 Hz, 1H, H^5$_{trans}$), 6.76 (d, *J* = 16.0 Hz, 1H, H^5$_{cis}$), 6.19 (dd, *J* = 16.0, 7.7 Hz, 1H, H^4$_{trans}$), 5.91 (dd, *J* = 16.0, 7.8 Hz, 2H, H^4$_{cis}$), 3.61 (ddd, *J* = 7.7, 4.2, 0.8 Hz, 1H, H^2$_{cis}$), 3.35 (ddd, *J* = 7.8, 2.1, 0.6 Hz, 1H, H^2$_{trans}$), 2.74 (dd, *J* = 5.7, 2.1 Hz, 2H, H^2$_{trans}$), 2.68 (dd, *J* = 7.5, 4.2 Hz, 1H, H^2$_{cis}$), 1.00 − 0.79 (m, 2H, H^3$_{cis\ and\ trans}$), 0.74 − 0.33 (m, 8H, H$^{7\ and\ 8}$$_{cis\ and\ trans}$).

^{13}C NMR (75 MHz, CDCl$_3$): δ = 136.5, 136.3, 135.5, 134.1, 128.8, 128.1, 128.1, 126.9, 126.6, 126.5, 124.3, 77.2, 63.1, 58.7, 58.2, 11.5, 8.5, 3.6, 2.6, 2.2, 2.2.

9.4.9.4.24. (*E*)-2-Tertbutyl-3-styryloxirane (**187da**)
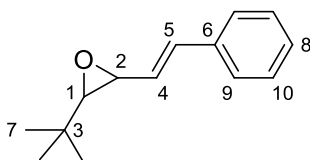
Chemical Formula: C$_{14}$H$_{18}$O
Molecular Weight: 202.30

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Procedure: B
Yield: 73%
d.r. (*cis/trans*): 3:2
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.44 − 7.26 (m, 10H, H^{arom}), 6.81 (d, *J* = 16.0 Hz, 1H, H^5 $_{trans}$), 6.75 (d, *J* = 16.2 Hz, 1H, H^5 $_{cis}$), 6.28 (dd, *J* = 16.1, 8.0 Hz, 1H, H^4 $_{cis}$), 5.95 (dd, *J* = 16.0, 7.8 Hz, 1H, H^4 $_{trans}$), 3.57 (ddd, *J* = 8.0, 4.4, 0.9 Hz, 1H, H^2 $_{cis}$), 3.38 (dd, *J* = 7.6, 2.1 Hz, 1H, H^2 $_{trans}$), 2.91 (d, *J* = 4.5 Hz, 1H, H^1 $_{cis}$), 2.75 (d, *J* = 2.3 Hz, 1H, H^1 $_{trans}$), 1.06 (s, 9H, H^7 $_{cis}$), 0.98 (d, *J* = 3.0 Hz, 9H, H^7 $_{trans}$).

9.4.9.4.25. (*E*)-2-Methyl-3-styryloxirane (**187ha**)
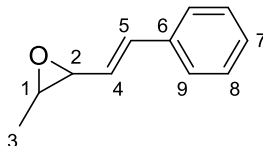
Chemical Formula: $C_{11}H_{12}O$
Molecular Weight: 160.22

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Procedure: B
Yield: quant.
d.r. (*cis/trans*): 3/2
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.43 – 7.23 (m, 10H, H^{arom}), 6.78 (d, *J* = 15.9, 1H, H$^5_{cis}$), 6.76 (d, *J* = 15.9 Hz, 1H, H$^5_{trans}$), 6.06 (dd, *J* = 16.0, 7.5 Hz, 1H, H$^4_{cis}$), 5.91 (dd, *J* = 16.0, 7.9 Hz, 1H, H$^4_{trans}$), 3.57 (ddd, *J* = 7.6, 4.3, 0.8 Hz, 1H, H$^2_{cis}$), 3.30 (qd, *J* = 5.5, 4.3 Hz, 1H, H$^1_{cis}$), 3.23 (dd, *J* = 7.9, 2.2 Hz, 1H, H$^2_{trans}$), 3.03 (qd, *J* = 5.2, 2.1 Hz, 1H, H$^1_{trans}$), 1.39 (d, *J* = 5.2 Hz, 3H, H$^3_{trans}$), 1.35 (d, *J* = 5.5 Hz, 3H, H$^3_{cis}$).

^{13}C NMR (75 MHz, CDCl$_3$): δ = 136.3, 136.2, 135.5, 135.4, 134.1, 134.0, 128.7, 128.0, 126.4, 59.8, 57.4, 57.3, 57.0, 56.8, 55.1, 17.7, 13.6, 13.5.

9.4.9.4.26. (*E*)-2-(3-styryloxiran-2-yl)pyridine (**187va**)
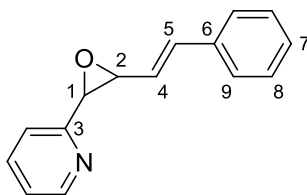
Chemical Formula: $C_{15}H_{13}ON$
Molecular Weight: 223.28

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Procedure: B
Eluent for purification: Not required
Yield: quant.
d.r. (*cis/trans*): 1/1
Aspect: red oil

^{1}H NMR (300 MHz, CDCl$_3$): δ = 8.62 − 8.56 (m, 2H, H^9 $_{cis\ and\ trans}$), 7.76 − 7.66 (m, 2H, H^{11} $_{cis\ and\ trans}$), 7.44 − 7.19 (m, 16H, H^{arom} + H$^{10,\ 12}$), 6.90 − 6.80 (m, 2H, H^5 $_{cis\ and\ trans}$), 6.07 (dd, *J* = 16.0, 7.8 Hz, 1H, H^4 $_{trans}$), 5.80 (dd, *J* = 15.9, 8.4 Hz, 1H, H^4 $_{cis}$), 4.42 (d, *J* = 4.4 Hz, 1H, H^1 $_{cis}$), 4.05 (d, *J* = 1.9 Hz, 1H, H^1 $_{trans}$), 3.94 (ddd, *J* = 8.4, 4.4, 0.4 Hz, 1H, H^2 $_{cis}$), 3.70 (dd, *J* = 7.8, 1.5 Hz, 1H, H^2 $_{trans}$).

^{13}C NMR (75 MHz, CDCl$_3$): δ = 156.7, 155.5, 149.6, 149.5, 137.3, 136.9, 136.4, 136.2, 136.1, 135.2, 128.8, 128.6, 128.3, 128.3, 126.7, 126.6, 125.8, 123.3, 122.9, 122.4, 121.2, 120.0, 62.4, 61.1, 60.1, 60.0.

HRMS (APCI) calculated for C$_{15}$H$_{14}$ON: 224.10699, found: 224.10615.

9.4.9.4.27. (*E*)-2-(naphthalen-2-yl)-3-styryloxirane (187oa)
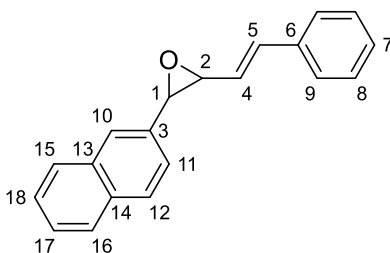
Chemical Formula: C$_{20}$H$_{16}$O
Molecular Weight: 272.35

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Procedure: B
Yield: 95%
d.r. (*cis/trans*): 2/3
Aspect: white solid

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.90 − 7.79 (m, 8H, H^{arom}), 7.54 − 7.26 (m, 13H, H^{arom}), 7.22 − 7.15 (m, 4H, H^{arom}), 6.92 − 6.79 (m, 2H, H^5 $_{cis\ and\ trans}$), 6.12 (dd, *J* = 16.0, 7.7 Hz, 1H, H^4 $_{trans}$), 5.75 (dd, *J* = 15.9, 8.8 Hz, 1H, H^4 $_{cis}$), 4.49 (d, *J* = 4.2 Hz, 1H, H^1 cis), 4.05 (d, *J* = 1.9 Hz, 1H, H^1 $_{trans}$), 3.91 (dd, *J* = 8.8, 4.2 Hz, 1H, H^2 $_{cis}$), 3.62 (dd, *J* = 7.7, 1.9 Hz, 1H, H^2 $_{trans}$).

13C NMR (75 MHz, CDCl₃): δ = 137.3, 136.2, 136.2, 134.7, 134.7, 133.5, 133.4, 133.2, 133.2, 133.0, 128.8, 128.6, 128.6, 128.3, 128.2, 128.2, 128.1, 127.9, 126.7, 126.7, 126.6, 126.5, 126.3, 126.3, 126.2, 125.61, 125.1, 124.4, 123.1, 123.0, 63.4, 61.1, 60.5, 59.7. *Two aromatic 13C NMR signals are missing, probably due to the overlap of two peaks*

HRMS (APCI) calculated for $C_{20}H_{17}O$: 273.12739, found: 273.12681.

9.4.9.4.28. (*E*)-2-(4-methoxyphenyl)-3-(4-methoxystyryl)oxirane (**187ki**)
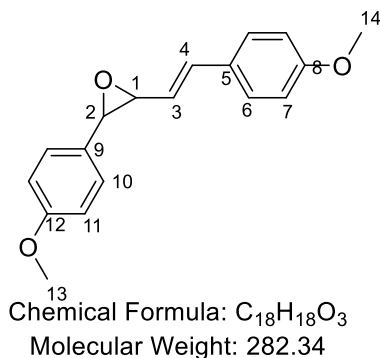
Chemical Formula: $C_{18}H_{18}O_3$
Molecular Weight: 282.34

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Procedure: A
Yield: 98%
d.r. (*cis/trans*): 0/1
Aspect: yellow solid

1H NMR (300 MHz, CDCl₃): δ = 7.37 − 7.30 (m, 2H,H$^{10\ or\ 6}$), 7.25 − 7.21 (m, 2H, H$^{6\ or\ 10}$), 6.95 − 6.84 (m, 4H, H$^{7\ and\ 11}$), 6.75 (d, *J* = 15.8 Hz, 1H, Hc), 5.91 (dd, *J* = 15.9, 7.8 Hz, 1H, Hd), 3.84 − 3.78 (m, 9H, H^1 + H$^{13\ and\ 14}$), 3.49 (dd, *J* = 7.8, 1.7 Hz, 1H, H^2).

HRMS (APCI): calculated for $C_{18}H_{19}O_3$: 283.13287, found: 283.13274.

9.4.9.4.29. (*E*)-2-Styryloxirane (**187ja**)
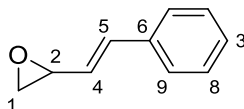
Chemical Formula: $C_{10}H_{10}O$
Molecular Weight: 146.19

Special procedure:
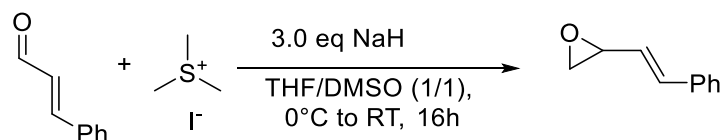
NaH (38wt% in mineral oil) (165 mg, 2.38 mmol, 3 eq) is added in a dry round bottom flask at 0°C. The mineral oil is removed by washing NaH three times with *n*-hexane. Then, trimethylsulfonium iodide (496 mg, 2.38 mmol, 3 eq.) and 3 mL of dry THF are introduced. Aldehyde (0.1 mL, 0.79 mmol, 1 eq.) in a mixture of 5 mL of dry DSMO and 2 mL of dry THF is added by small portions over 10 minutes and the mixture is stirred and allowed to warm up to room temperature for 16h. Then, the reaction mixture is dissolved in diethylether and water. The phases are separated and the aqueous phase is extracted twice with diethylether. The combined organic phases are washed with brine, dried on MgSO$_4$ and concentrated under reduced pressure to give the desired epoxide.

Yield: quant.
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.42 – 7.26 (m, 5H, H^{arom}), 6.81 (d, *J* = 16.0 Hz, 1H, H^5), 5.88 (dd, *J* = 16.0, 8.0 Hz, 1H, H^4), 3.57 – 3.48 (m, 1H, H^2), 3.06 (dd, *J* = 5.2, 4.1 Hz, 1H, H^{1a}), 2.77 (dd, *J* = 5.2, 2.6 Hz, 1H, H^{1b}).

^{13}C NMR (75 MHz, CDCl$_3$) δ 136.3, 134.7, 128.8, 128.2, 127.1, 126.6, 52.8, 49.4.

9.4.9.4.30. (*E*)-2-Phenyl-3-styryloxirane-2-d (**187aa-D**)
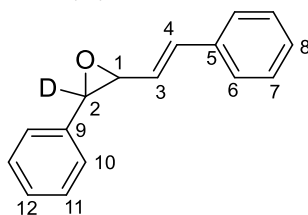
Chemical Formula: C$_{16}$H$_{13}$DO
Molecular Weight: 223.29

The characterisation of this compound was made on a mixture of cis and trans diastereoisomer.
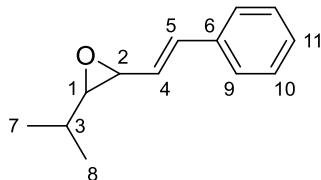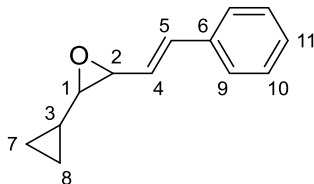
Procedure: B
Yield: 88%
d.r. (*cis/trans*): 2/3
Aspect: white solid

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.50 – 7.13 (m, 20H, H^{arom}), 6.83 (m, 2H, H$^4_{cis}$ $_{and\ trans}$), 6.07 (dd, *J* = 16.0, 7.7 Hz, 1H, H$^3_{trans}$), 5.73 (dd, *J* = 16.0, 8.7 Hz, 1H, H$^3_{cis}$) , 3.84 (d, *J* = 8.7 Hz, 1H, H^1 $_{cis}$), 3.53 (dd, *J* = 7.7, 0.5 Hz, 2H, H$^1_{trans}$).

9.4.8.4.31. (2*R*,3*R*)-2-Phenyl-3-((*E*)-styryl)oxirane (**187aa-(*R,R*)**)
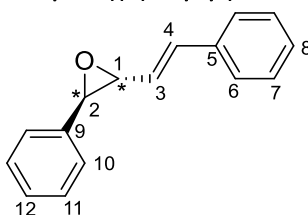
Chemical Formula: C$_{16}$H$_{14}$O
Molecular Weight: 222.29

Procedure: C
Yield: 49%
Aspect: white solid
d.r. (*cis/trans*): 0/1
e.r.: 98/2.
For full details on the HPLC method and the chromatograms, see 9.5.1.

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.50 – 7.13 (m, 10H, H^{arom}), 6.83 (d, *J* = 16.0 Hz, 1H, H^4), 6.07 (dd, *J* = 16.0, 7.7 Hz, 1H, H^3), 3.89 (d, *J* = 1.9 Hz, 1H, H^2), 3.53 (dd, *J* = 7.7, 1.9 Hz, 1H, H^1).

^{13}C NMR (75 MHz, CDCl$_3$): δ = 137.0, 136.0, 134.4, 128.7, 128.5, 128.2, 128.1, 126.5, 126.2, 125.5, 63.1, 60.7.

HRMS (APCI) calculated for C$_{16}$H$_{15}$O: 223.11174, found: 223.11169.

9.4.8.4.32. (2*R*,3*R*)-2-(2,2-Diphenylvinyl)-3-phenyloxirane (**187af-(*R,R*)**)
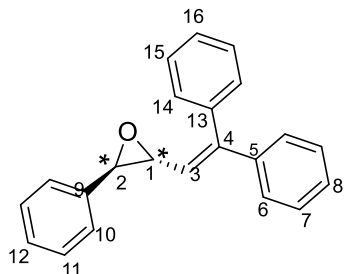
Chemical Formula: $C_{22}H_{18}O$
Molecular Weight: 298.39

Procedure: C
Yield: 30%
Aspect: white solid
d.r. (*cis/trans*): 0/1
Because of the lack of time, the e.r. of this epoxide was not measured by chiral HPLC

^{1}H NMR (300 MHz, CDCl₃): δ = 7.48 – 7.06 (m, 15H, H^{arom}), 5.87 (d, *J* = 8.7 Hz, 1H, H^3), 3.98 (d, *J* = 1.9 Hz, 1H, H^2), , 3.49 (dd, *J* = 8.7, 2.0 Hz, 1H, H^1).

9.4.10. Synthesis β,γ-unsaturated aldehydes/ketones

9.4.10.1. General procedure A
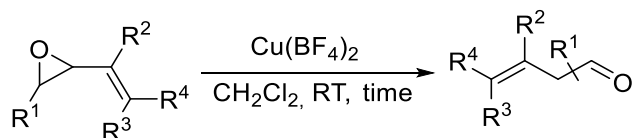
Epoxide (1 eq.) and dry dichloromethane (6 mL/100mg of epoxide) are introduced in a dry round-bottom flask under argon. Then, Cu(BF₄)₂ is added and the mixture is stirred at room temperature for a defined time. Water is added to stop the reaction. The two layers are separated and the aqueous one is extracted twice with dichloromethane. The combined organic layers are washed with brine, dried over MgSO₄ and concentrated under reduced pressure.

Number of Cu(BF₄)₂ equivalents and the reaction time depend on the nature of the compound and are reported in the description of each product.

9.4.10.2. General procedure B
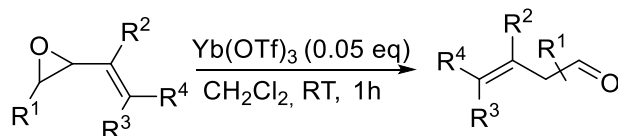
Epoxide (1 eq.) and dry dichloromethane (6 mL/100mg of epoxide) are introduced in a dry round-bottom flask under argon. Then, $Yb(OTf)_3$ (0.05 eq) is added and the mixture is stirred at room temperature for 1 hour. Water is added to stop the reaction. The two layers are separated and the aqueous one is extracted twice with dichloromethane. The combined organic layers are washed with brine, dried over $MgSO_4$ and concentrated under reduced pressure.

9.4.9.4. Product descriptions

9.4.9.4.1. (E)-2,4-Diphenylbut-3-enal (188aa)
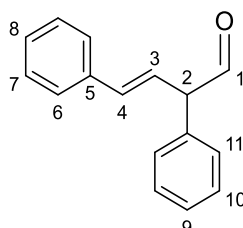
Chemical Formula: $C_{16}H_{14}O$
Molecular Weight: 222.29

Procedure: A
Eq of (CuBF$_4$)$_2$: 0.05 eq.
Time: 1h
Yield: 86%
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$): δ = 9.76 (d, J = 2.1 Hz, 1H, H^1), 7.48 – 7.17 (m, 10H, H^{arom}), 6.54 – 6.49 (m, 2H, H$^{3\ and\ 4}$), 4.43 (dd, J = 5.5, 2.0 Hz, 1H, H^2).

^{13}C NMR (75 MHz, CDCl$_3$): δ = 198.3, 136.5, 135.6, 134.3, 129.2, 129.0, 128.6, 128.0, 127.8, 126.5, 124.5, 61.9.

HRMS (ESI) calculated for $C_{16}H_{15}O$: 223.11174, found: 223.11169.

IR (cm^{-1}): 3031, 1722, 1690, 1596, 1494, 1453.

9.4.9.4.2. (*E*)-2-(4-Methoxyphenyl)-4-phenylbut-3-enal (**188ka**)
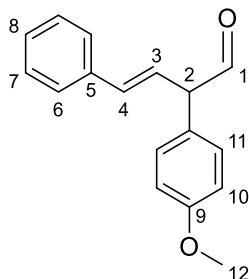
Chemical Formula: $C_{17}H_{16}O_2$
Molecular Weight: 252.31

Procedure: A
Eq of Cu(BF₄)₂: 0.05 eq.
Time: 1h
Yield: 97%
Aspect: yellow oil

¹H NMR (300 MHz, CDCl₃): δ = 9.72 (d, J = 2.1 Hz, 1H, H¹), 7.43 – 7.23 (m, 5H, H⁶,⁷,⁸), 7.20 (d, J = 8.7 Hz, 2H, H¹¹), 6.94 (d, J = 8.8 Hz, 2H, H¹⁰), 6.52 – 6.46 (m, 2H, H³,⁴), 4.38 (dd, J = 5.7, 2.0 Hz, 1H, H²), 3.81 (s, 3H, H¹²).

¹³C NMR (75 MHz, CDCl₃): δ = 198.4, 159.2, 136.6, 134.0, 130.0, 128.6, 127.9, 127.4, 126.4, 124.8, 114.7, 61.1, 55.3.

HRMS (ESI) calculated for $C_{17}H_{17}O_2$: 253.12200, found: 253.12231.

IR (cm⁻¹): 2836, 1687, 1796, 1510, 1247.

9.4.9.4.4. (*E*)-4-Phenyl-2-(*p*-tolyl)but-3-enal (**188la**)
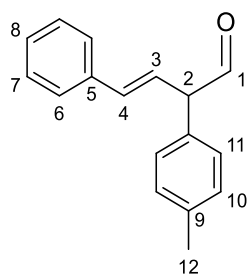
Chemical Formula: $C_{17}H_{16}O$
Molecular Weight: 236.31

Procedure: A
Eq of Cu(BF₄)₂: 0.05 eq.
Time: 1h
Yield: 84%
Aspect: yellow oil

¹H NMR (300 MHz, CDCl₃): δ = 9.73 (d, J = 2.1 Hz, 1H, H¹), 7.42 – 7.13 (m, 9H, Hᵃʳᵒᵐ), 6.53 – 6.47 (m, 2H, H³·⁴), 4.39 (dd, J = 5.6, 2.0 Hz, 1H, H²), 2.36 (s, 3H, H¹²).

¹³C NMR (75 MHz, CDCl₃): δ = 198.5, 137.6, 136.6, 134.1, 132.5, 129.9, 128.2, 128.6, 127.9, 126.5, 124.8, 61.6, 21.2.

HRMS (ESI) calculated for $C_{17}H_{17}O$: 237.12739, found: 237.12726.

IR (cm⁻¹): 3031, 2952, 1721, 1689, 1513, 1453.

9.4.9.4.5. (*E*)-4-phenyl-2-(o-tolyl)but-3-enal (**188ba**)
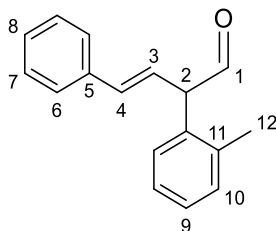
Chemical Formula: $C_{17}H_{16}O$
Molecular Weight: 236.31

Procedure: A
Eq of Cu(BF₄)₂: 0.05 eq.
Time: 1h
Yield: 70%
Aspect: yellow oil

¹H NMR (300 MHz, CDCl₃): δ = 9.75 (d, J = 1.4 Hz, 1, H¹), 7.42 – 7.15 (m, 9H, Hᵃʳᵒᵐ), 6.55 (dd, J = 16.1, 6.4 Hz, 1H, H³), 6.37 (d, J = 16.2 Hz, 1H, H⁴), 4.61 (dt, J = 6.4, 1.3 Hz, 1H, H²), 2.36 (s, 2H, H¹²).

¹³C NMR (75 MHz, CDCl₃) δ = 198.9, 137.2, 136.7, 134.1, 133.8, 131.3, 129.2, 128.7, 128.0, 127.9, 126.8, 126.5, 124.8, 58.7, 19.9.

HRMS (ESI) calculated for $C_{17}H_{17}O$: 237.12739, found: 237.12726.

IR (cm⁻¹): 3027, 1721, 1689, 1494, 1453.

9.4.9.4.6. (*E*)-2-(4-fluorophenyl)-4-phenylbut-3-enal (**188pa**)
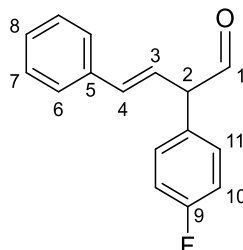
Chemical Formula: $C_{16}H_{13}OF$
Molecular Weight: 240.28

Procedure: A
Eq of Cu(BF$_4$)$_2$: 0.05 eq.
Time: 1h
Yield: 82%
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$): δ = 9.70 (d, *J* = 1.9 Hz, 1H, H^5), 7.42 – 7.15 (m, 7H, H^{3,10,11,12}), 7.13 – 7.01 (m, 2H, H^2), 6.49 – 6.45 (m, 2H, H^{7,8}), 4.39 (dd, *J* = 5.2, 2.6 Hz, 1H, H^6).

^{13}C NMR (75 MHz, CDCl$_3$): δ = 198.2, 135.5, 135.3, 134.6, 133.3, 132.5, 129.0, 128.7, 128.6, 128.1, 127.1, 126.5, 124.2, 61.0.

HRMS (ESI): calculated for $C_{16}H_{13}OF$: 241.10232, found: 241.10212.

IR (cm^{-1}): 3035, 1721, 1691, 1790, 1507, 1222.

9.4.9.4.7. (*E*)-4-(4-Bromophenyl)-2-phenylbut-3-enal (**188ae**)
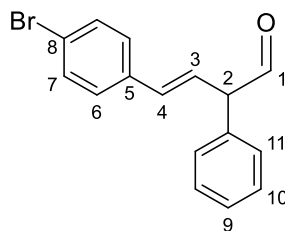
Chemical Formula: $C_{16}H_{13}OBr$
Molecular Weight: 301.18

Procedure: A
Eq of Cu(BF$_4$)$_2$: 0.05 eq.
Time: 1h
Yield: 90%
Aspect: yellow oil

¹H NMR (300 MHz, CDCl₃): δ = 9.75 (d, *J* = 1.9 Hz, 1H, H^1), 7.47 – 7.21 (m, 9H, H^{arom}), 6.54 (dd, *J* = 16.1, 7.0 Hz, 1H, H^3), 6.41 (d, *J* = 16.1 Hz, 1H, H^4), 4.41 (d, *J* = 7.0 Hz, 1H, H^2).

¹³C NMR (75 MHz, CDCl₃): δ = 198.2, 135.5, 135.3, 133.3, 131.7, 129.3, 129.0, 128.0, 125.5, 121.7, 61.9.

HRMS (ESI) calculated for $C_{16}H_{14}O^{79}Br$: 301.02225, found: 301.02223.

IR (cm⁻¹): 3027, 1722, 1486, 1453, 1400.

9.4.9.4.8. (*E*)-2,4,4-Triphenylbut-3-enal (**188af**)

Chemical Formula: $C_{22}H_{18}O$
Molecular Weight: 298.39
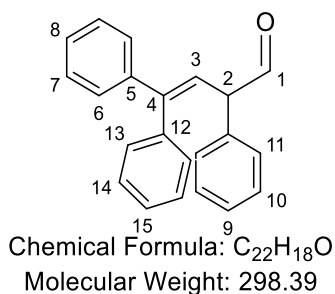
Procedure: A
Eq of Cu(BF₄)₂: 0.05 eq.
Time: 1h
Yield: 80%
Aspect: yellow oil

¹H NMR (300 MHz, CDCl₃): δ = 9.70 (d, *J* = 1.7 Hz, 1H, H^1), 7.46 – 7.02 (m, 15H, H^{arom}), 6.49 (d, *J* = 10.1 Hz, 2H, H^3), 4.43 (dd, *J* = 10.1, 1.5 Hz, 1H, H^2).

¹³C NMR (75 MHz, CDCl₃) δ 198.5, 146.0, 141.7, 139.2, 136.5, 129.8, 129.4, 128.8, 128.6, 128.4, 127.9, 127.8, 127.8, 127.6, 122.8, 59.5.

HRMS (ESI): calculated for $C_{22}H_{19}O$: 299.14034, found : 297.14293.

IR (cm⁻¹): 3023, 1723, 1790, 1493, 1445.

9.4.9.4.9. (*E*)-3-Methyl-2,4-diphenylbut-3-enal (**188ad**)
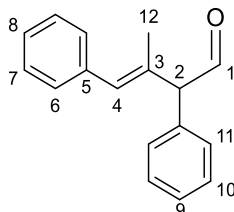
Chemical Formula: $C_{17}H_{16}O$
Molecular Weight: 236.31

Procedure: A
Eq of Cu(BF$_4$)$_2$: 0.05 eq.
Time: 1h
Yield: 85%
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$): δ = 9.90 (d, *J* = 2.3 Hz, 1H, H^1), 7.46 – 7.12 (m, 10H, H^{arom}), 6.38 (s, 1H, H^4), 4.31 (d, *J* = 1.2 Hz, 1H, H^2), 1.86 (s, 3H, H^{12}).

^{13}C NMR (75 MHz, CDCl$_3$): δ = 199.6, 137.3, 136.2, 1347, 129.9, 129.3, 129.1, 129.0, 128.9, 128.2, 128.1, 67.4, 17.9.

HRMS (ESI) calculated for $C_{17}H_{17}O$: 237.12739, found: 237.12726.

IR (cm^{-1}): 3027, 1721, 1790, 1492, 1449.

9.4.9.4.9. (*E*)-2,4-Bis(4-methoxyphenyl)but-3-enal (**188ki**)
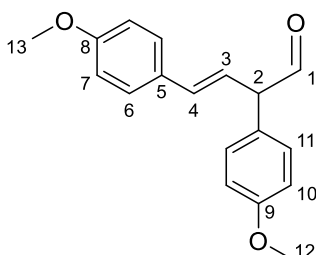
Chemical Formula: $C_{18}H_{18}O_3$
Molecular Weight: 282.34

Procedure: A
Eq of Cu(BF$_4$)$_2$: 0.05 eq.
Time: 1h
Eluent for purification: not required
Yield: 77%
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$): δ = 9.70 (d, *J* = 2.2 Hz, 1H, H^1), 7.34 – 7.28 (m, 1H, H$^{6 \text{ or } 11}$), 7.23 – 7.16 (m, 1H, H$^{11 \text{ or } 6}$), 6.96 – 6.91 (m, 1H, H$^{10 \text{ or } 7}$), 6.87 – 6.81 (m, 1H, H$^{7 \text{ or } 10}$), 6.46 – 6.29 (m, 1H, H$^{3 \text{ and } 4}$), 4.34 (dd, *J* = 6.2, 2.2 Hz, 1H, H^2), 3.81 (s, 3H, H$^{13 \text{ or } 12}$), 3.79 (s, 3H, H$^{12 \text{ or } 13}$).

^{13}C NMR (75 MHz, CDCl$_3$): δ = 198.5, 159.4, 159.2, 133.5, 130.7, 130.0, 129.4, 127.6, 122.4, 114.6, 114.0, 61.1, 55.3. *C^{13} and C^{12} are overlapping*

HRMS (ESI): calculated for C$_{18}$H$_{19}$O$_3$: 283.13287, found: 283.13274.

9.4.9.4.10. 4-Methyl-2-phenylpent-3-enal (**188ab**)
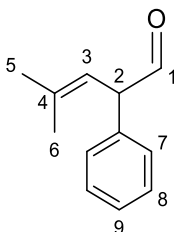
Chemical Formula: C$_{12}$H$_{14}$O
Molecular Weight: 174.24

Procedure: A
Eq of Cu(BF$_4$)$_2$: 0.05 eq.
Time: 1h
Yield: 78%
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$): δ = 9.56 (d, *J* = 2.5 Hz, 1H, H^1), 7.47 – 7.11 (m, 5H, H^{arom}), 5.52 (dd, *J* = 8.9, 1.1 Hz, 1H, H^3), 4.43 – 4.36 (m, 1H, H^2), 1.81 (s, 3H, H$^{6 \text{ or } 5}$), 1.68 (s, 3H, H$^{5 \text{ or } 6}$).

^{13}C NMR (75 MHz, CDCl$_3$): δ = 198.4, 138.0, 136.8, 129.1, 128.5, 127.4, 118.5, 58.0, 26.1, 18.5.

HRMS (ESI): calculated for C$_{12}$H$_{14}$O: 175.11174, found: 175.11121.

IR (cm^{-1}): 2978, 1721, 1494, 1450, 1377.

9.4.9.4.11. (*E*)-5-Methyl-2-phenylhex-3-enal (**188ac**)
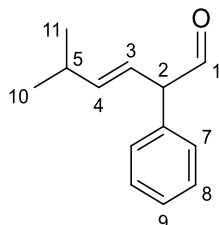
Chemical Formula: $C_{13}H_{16}O$
Molecular Weight: 188.27

Procedure: B
Yield: 78%
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$): δ = 9.60 (d, *J* = 2.4 Hz, 1H, H^1), 7.38 − 7.15 (m, 5H, H^{arom}), 5.67 (dd, *J* = 15.6, 6.9 Hz, 1H, H^3), 5.56 (dd, *J* = 15.7, 6.0 Hz, 1H, H^4), 4.16 (dd, *J* = 6.9, 2.4 Hz, 1H, H^2), 2.33 (m, 1H, H^5), 1.03 − 0.93 (m, 6H, H$^{10 \text{ and } 11}$).

HRMS (ESI): calculated for $C_{13}H_{17}O$: 189.12739, found : 189.12744.

9.4.9.4.12. 2-(Cyclohex-1-en-1-yl)-2-phenylacetaldehyde (**188ak**)
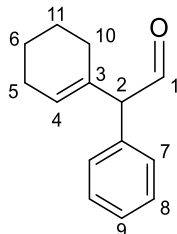
Chemical Formula: $C_{14}H_{16}O$
Molecular Weight: 200.28

Procedure: A
Eq of (CuBF$_4$)$_2$: 0.05 eq.
Time: 3h
Yield: 92%
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$): δ = 9.79 (d, *J* = 2.6 Hz, 1H, H^1), 7.43 − 7.16 (m, 5H, H^{arom}), 5.64 − 5.53 (m, 1H, H^4), 4.07 (d, *J* = 2.6 Hz, 1H, H^2), 2.20 − 2.01 (m, 2H), 2.00 − 1.85 (m, 1H, H$^{5, 6, 10 \text{ or } 11}$), 1.71 − 1.49 (m, 5H, H$^{5, 6, 10, 11}$), 1.26 (bs, 1H, H$^{5, 6, 10 \text{ or } 11}$).

13C NMR (75 MHz, CDCl₃): δ = 200.0, 135.7, 134.3, 129.3, 128.8, 127.5, 126.9, 65.9, 28.3, 25.6, 22.9, 22.2.

HRMS (ESI): calculated for $C_{14}H_{17}O$: 201.12739, found : 201.12740.

9.4.9.4.14. (*E*)-2-(naphthalen-2-yl)-4-phenylbut-3-enal (188oa)
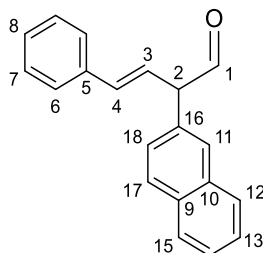
Chemical Formula: $C_{20}H_{16}O$
Molecular Weight: 272.35

Procedure: A
Eq of (CuBF₄)₂: 0.05 eq.
Time: 1h
Yield: 83%
Aspect: yellow oil

1H NMR (300 MHz, CDCl₃): δ = 9.81 (d, J = 2.0 Hz, 1H, H¹), 7.95 – 7.17 (m, 15H, H^arom), 6.63 (dd, J = 16.1, 6.8 Hz, 1H, H³), 6.51 (d, J = 16.2 Hz, 1H, H⁴), 4.57 (d, J = 6.7 Hz, 1H, H²).

HRMS (ESI) calculated for $C_{20}H_{17}O$: 273.12739, found: 273.12681.

9.4.9.4.15. (*E*)-2,4-diphenylbut-3-enal-1-d (188aa-D)
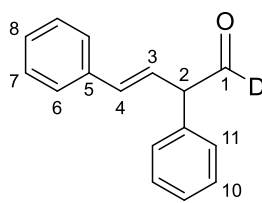
Chemical Formula: $C_{16}H_{13}DO$
Molecular Weight: 223.29

Procedure: A
Eq of (CuBF₄)₂: 0.1 eq.
Time: 1h
Yield: 80%
Aspect: yellow oil

¹H NMR (300 MHz, CDCl₃): δ = 7.48 − 7.17 (m, 10H, H^{arom}), 6.54 − 6.49 (m, 2H, H$^{3 \text{ and } 4}$), 4.43 (d, *J* = 5.5, 1H, H²).

9.4.9.4.16. (*E*)-4-Phenylbut-3-enal (**188ja**)

Chemical Formula: $C_{10}H_{10}O$
Molecular Weight: 146.19
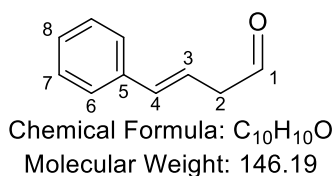
Procedure: B
Yield: 77%
Aspect: yellow oil

¹H NMR (300 MHz, CDCl₃) δ 9.75 (t, *J* = 1.9 Hz, 1H, H¹), 7.44 − 7.21 (m, 5H), 6.54 (d, *J* = 16.0 Hz, 1H, H⁴), 6.28 (dt, *J* = 16.0, 7.0 Hz, 1H, H³), 3.37 − 3.32 (m, 2H, H²).

¹³C NMR (75 MHz, CDCl₃) δ 199.6, 135.3, 128.7, 127.9, 126.7, 126.4, 119.3, 47.6.

9.4.9.4.17. (*E*)-2,4-Diphenylbut-3-enal (**188aa***)
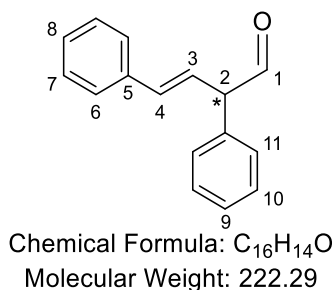
Chemical Formula: $C_{16}H_{14}O$
Molecular Weight: 222.29

Procedure: A
Eq of (CuBF₄)₂: 0.1 eq.
Time: 1h
Yield: 83%
Aspect: yellow oil

¹H NMR (300 MHz, CDCl₃): δ = 9.76 (d, *J* = 2.1 Hz, 1H, H¹), 7.48 − 7.17 (m, 10H, H^{arom}), 6.54 − 6.49 (m, 2H, H$^{3 \text{ and } 4}$), 4.43 (dd, *J* = 5.5, 2.0 Hz, 1H, H²).

^{13}C NMR (75 MHz, CDCl$_3$): δ = 198.3, 136.5, 135.6, 134.3, 129.2, 129.0, 128.6, 128.0, 127.8, 126.5, 124.5, 61.9.

9.4.9.4.18. (*E*)-2,4,4-Triphenylbut-3-enal (**188af***)
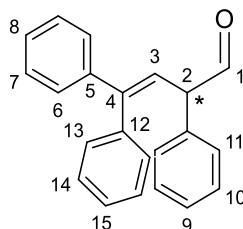
Chemical Formula: C$_{22}$H$_{18}$O
Molecular Weight: 298.39

Procedure: A
Eq of Cu(BF$_4$)$_2$: 0.1 eq.
Time: 1h
Yield: 40%
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$): δ = 9.70 (d, *J* = 1.7 Hz, 1H, H^1), 7.46 – 7.02 (m, 15H, H^{arom}), 6.49 (d, *J* = 10.1 Hz, 2H, H^3), 4.43 (dd, *J* = 10.1, 1.5 Hz, 1H, H^2).

^{13}C NMR (75 MHz, CDCl$_3$) δ 198.5, 146.0, 141.7, 139.2, 136.5, 129.8, 129.4, 128.8, 128.6, 128.4, 127.9, 127.8, 127.8, 127.6, 122.8, 59.5.

9.4.9.4.18. (*E*)-5-Phenylpent-4-en-2-one (**222ha**)
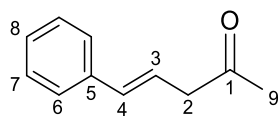
Chemical Formula: C$_{11}$H$_{12}$O
Molecular Weight: 160.22

Eq of (CuBF$_4$)$_2$: 0.15 eq.
Time: 5h
Yield: 51%
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$): 7.46 – 7.17 (m, 5H, H^{arom}), 6.46 (d, J = 16.0 Hz, 1H, H^4), 6.30 (dt, J = 15.9, 7.0 Hz, 1H, H^3), 3.32 (dd, J = 7.0, 1.2 Hz, 2H, H^2), 2.19 (s, 3H, H^9).

9.4.9.4.19. (*E*)-2-Methyl-6-phenylhex-5-en-3-one (**222ga**)
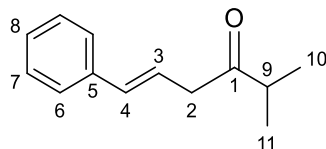
Chemical Formula: $C_{13}H_{16}O$
Molecular Weight: 188.27

Eq of (CuBF$_4$)$_2$: 0.25 eq.
Time: 16h
Yield: 42%
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.56 − 7.02 (m, 5H, H^{arom}), 6.46 (d, J = 15.9 Hz, 1H, H^4), 6.32 (dt, *J* = 15.9, 6.8 Hz, 1H, H^3), 3.37 (dd, *J* = 6.8, 1.2 Hz, 2H, H^2), 2.79 − 2.62 (m, 1H, H^9), 1.13 (d, *J* = 6.9 Hz, 6H, H$^{10 \text{ and } 11}$).

9.4.9.4.20. (*E*)-2,2-dimethyl-6-phenylhex-5-en-3-one (**222da**)
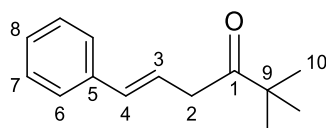
Chemical Formula: $C_{14}H_{18}O$
Molecular Weight: 202.30

Eq of (CuBF$_4$)$_2$: 0.15 eq.
Time: 5h
Yield: 72%
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$): δ = 7.46 − 7.16 (m, 5H, H^5), 6.45 (d, *J* = 16.3 Hz, 1H, H^4), 6.41 − 6.28 (m, 1H, H^3), 3.44 (dd, *J* = 6.4, 0.9 Hz, 2H, H^2), 1.19 (s, 9H, H^{10}).

9.4.11. Synthesis of α-aryl α,β-unsaturated aldehydes

9.4.11.1. (E)-2,4-Diphenylbut-2-enal (*191aa*)
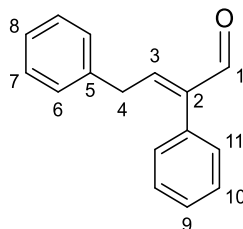
Chemical Formula: $C_{16}H_{14}O$
Molecular Weight: 222.29

Procedure:
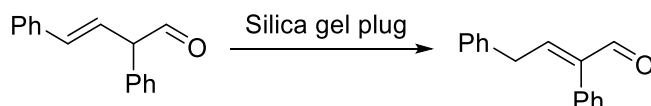
A plug of silica gel is washed with a mixture of 80mL/20mL/0.5mL (*n*-hexane/AcOEt/NEt₃). The plug is then washed five times with an 8/2 n-hexane/AcOEt eluent to remove the amine. The β,γ-unsaturated aldehyde is then added and purified on the silica plug with the same eluent. The product is concentrated under reduced pressure to give the α,β-unsaturated aldehyde with a yield of 60%.

Yield: 60%
Aspect: yellow oil

¹H NMR (300 MHz, CDCl₃): δ = δ 9.66 (s, 1H, H¹), 7.48 − 7.12 (m, 10H, Hᵃʳᵒᵐ), 6.87 (t, *J* = 7.6 Hz, 1H, H³), 3.70 (d, *J* = 7.6 Hz, 2H, H⁴).

¹³C NMR (75 MHz, CDCl₃) δ 193.7, 153.6, 144.3, 138.2, 132.3, 129.6, 129.0, 128.6, 128.6, 128.4, 127.0, 36.0.

HRMS (ESI) calculated for $C_{16}H_{15}O$: 223.11174, found: 223.11169.

9.4.12. Synthesis of primary homoallylic alcohols

9.4.12.1. General procedure
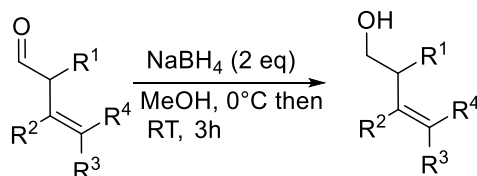
Aldehyde (1 eq) and MeOH (2 mL/100mg of aldehyde) are introduced in a round-bottom flask at 0°C. Then, $NaBH_4$ (2 eq) is added and the mixture is stirred at room temperature for 3h. Then, the reaction mixture is evaporated and then dissolved with diethylether and water. The two layers are separated and the aqueous one is extracted twice with diethylehter. The combined organic layers are washed with brine, dried over $MgSO_4$ and concentrated under reduced pressure. The alcohol is then purified by flash chromatography.

The eluent used for the chromatography column depends on the product and is given for each synthesised alcohol in the next section.

9.4.12.2. Product descriptions

9.4.12.2.1. (*E*)-2,4-Diphenylbut-3-en-1-ol (**204aa**)
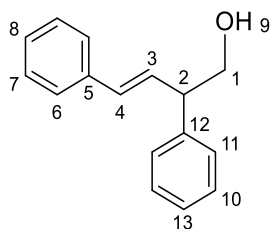
Chemical Formula: $C_{16}H_{16}O$
Molecular Weight: 224.30

Eluent for purification: 73/27 (*n*-hexane/AcOEt)
Yield: 54%
Aspect: colorless oil

¹H NMR (300 MHz, CDCl₃) δ 7.41 – 7.19 (m, 10H, H^{arom}), 6.54 (d, *J* = 16.0 Hz, 1H, H⁴), 6.38 (dd, *J* = 15.9, 7.7 Hz, 1H, H³), 3.96 – 3.89 (m, 2H, H¹), 3.71 (q, *J* = 7.2 Hz, 1H, H²), 1.50 (t, *J* = 6.4 Hz, 1H, H⁹).

¹³C NMR (75 MHz, CDCl₃) δ 140.9, 137.1, 132.3, 129.8, 129.0, 128.7, 128.1, 127.6, 127.2, 126.4, 66.5, 52.0.

9.4.12.2.2. 2,4,4-Triphenylbut-3-en-1-ol (204af)

Chemical Formula: $C_{22}H_{20}O$
Molecular Weight: 300.40
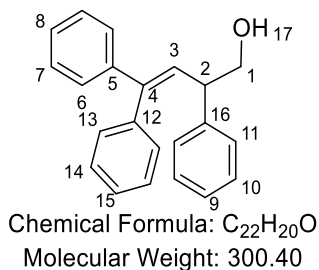
Eluent for purification: Not required
Yield: 27%
Aspect: colorless oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.41 − 7.11 (m, 15H, H^{arom}), 6.30 (d, J = 10.3 Hz, 1H, H^3), 3.83 (d, J = 6.7 Hz, 2H, H^1), 3,70 (dt, J = 10,2, 6,8 Hz, 1H, H^2), 1,34 (m, 1H, H^{17}).

^{13}C NMR (75 MHz, CDCl$_3$) δ 144.2, 142.2, 141.6, 139.7, 129.8, 128.9, 128.4, 128.4, 128.2, 127.8, 127.4, 127.4, 127.4, 126.9, 67.2, 48.4.

HRMS (APCI): found for $C_{22}H_{19}O_{23}Na$ [M+Na]$^+$: 323.14066 (calculated 323.14064)

9.4.12.2.3. 4-Methyl-2-phenylpent-3-en-1-ol (204ab)

Chemical Formula: $C_{12}H_{16}O$
Molecular Weight: 176.26
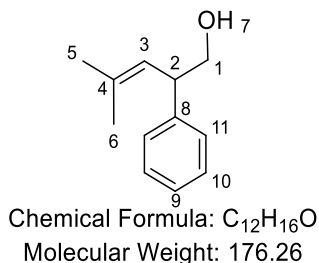
Eluent for purification: 8/2 *n*-hexane/AcOEt
Yield: 12%
Aspect: colorless oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.39 − 7.17 (m, 5H, H^{arom}), 5.34 (d, J = 7.6, 1H, H^3), 3.73 (m, 3H, H$^{2\ and\ 1}$), 1.76 (d, J = 1.0 Hz, 3H, H$^{6\ or\ 5}$), 1.70 (d, J = 1.1 Hz, 3H, H$^{5\ or\ 6}$), 1.43 (m, 1H, H^7).

^{13}C NMR (75 MHz, CDCl$_3$) δ 142.2, 135.7, 128.8, 127.9, 126.8, 124.3, 67.4, 47.5, 26.2, 18.5.

9.4.12.2.4. (*E*)-5-Methyl-2-phenylhex-3-en-1-ol (**204ac**)
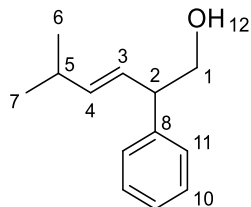
Chemical Formula: $C_{13}H_{18}O$
Molecular Weight: 190.29

Eluent for purification: 85/15 *n*-hexane/AcOEt
Yield: 16%
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.41 – 7.15 (m, 5H, H^{arom}), 5.61 (dd, *J* = 15.4, 5.7 Hz, 1H, H^4), 5.53 (dd, *J* = 15,7, 7,0 Hz, 1H, H^3), 3.85 – 3.65 (m, 2H, H7), 3.45 (m, 1H, H^2), 2.40 – 2.23 (m, 1H, H^5), 1.01 (d, *J* = 3.7 Hz, 3H, H$^{7\,or\,6}$), 1,46 (t, *J* = 6.6 Hz, 1H, H^{12}), 0.99 (d, *J* = 3,7 Hz, 3H, H$^{6\,or\,7}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 141.6, 141.0, 128.9, 128.0, 126.9, 126.6, 66.7, 51.6, 31.3, 22.7, 22.6.

9.4.12.2.5. (*E*)-4-(4-bromophenyl)-2-phenylbut-3-en-1-ol (**204ae**)
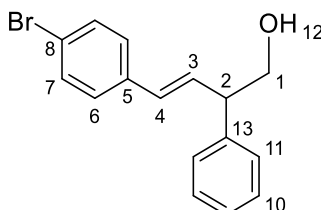
Chemical Formula: $C_{16}H_{15}OBr$
Molecular Weight: 303.1990

Eluent for purification: Not required
Yield: 63%
Aspect: colorless oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.50 – 7.17 (m, 9H, H^{arom}), 6.53 – 6.33 (m, 2H, H$^{3-4}$), 3.92 (m, 2H, H^1), 3.69 (m, 1H, H^2), 1.46 (t, *J* = 6.4 Hz, 1H, H^{12}).

^{13}C NMR (75 MHz, CDCl$_3$) δ 140.7, 136.1, 131.8, 131.1, 130.8, 129.1, 128.2, 128.0, 127.3, 121.4, 66.5, 51.9.

9.4.12.2.6. (*E*)-4-phenyl-2-(p-tolyl)but-3-en-1-ol (**204la**)
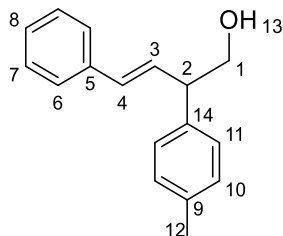
Chemical Formula: $C_{17}H_{18}O$
Molecular Weight: 238.33

Eluent for purification: Not required
Yield: 75%
Aspect: colorless oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.43 – 7.12 (m, 9H, H^{arom}), 6.57 – 6.31 (m, 2H, H$^{4-3}$), 3.90 (m, 2H, H^1), 3.67 (m, 1H, H^2), 2.34 (s, 3H, H^{12}), 1,49 (t, *J* = 6,3 Hz, 1H, H^{13}).

^{13}C NMR (75 MHz, CDCl$_3$) δ 138.0, 137.3, 136.8, 132.1, 130.2, 129.7, 128.7, 128.1, 127.6, 126.5, 66.6, 51.6, 21.3.

9.4.12.2.7. (*E*)-2,4-diphenylbut-3-en-1-ol (**204pa**)
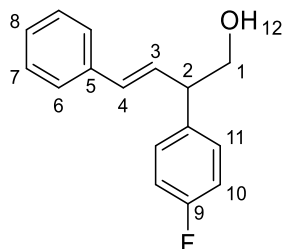
Chemical Formula: $C_{16}H_{15}OF$
Molecular Weight: 242.29

Eluent for purification: Not required
Yield: 72%
Aspect: colorless oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.51 – 6.92 (m, 9H, H^{arom}), 6.55 – 6.46 (m, 1H, H^4), 6.33 (dd, *J* = 15.9, 7.6 Hz, 1H, H^3), 3.88 (d, 2H, H^1), 3.67 (dt, *J* = 7.7, 6.1 Hz, 1H, H^2), 1.57 (bs, 1H, H^{12}).

^{13}C NMR (75 MHz, CDCl$_3$) δ 137.0, 136.8, 136.8, 129.7, 129.6, 128.8, 127.8, 126.5, 115.9, 115.6, 66.5, 51.1.

9.4.12.2.8. (*E*)-3-methyl-2,4-diphenylbut-3-en-1-ol (**204da**)
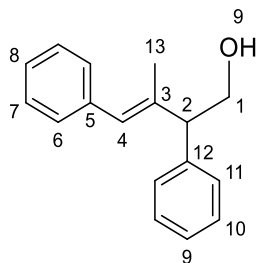
Chemical Formula: $C_{17}H_{18}O$
Molecular Weight: 238.33

Eluent for purification: Not required
Yield: 62%
Aspect: white solid

^{1}H NMR (300 MHz, CDCl₃) δ 7.49 – 7.15 (m, 10H, H^{arom}), 6.53 (s, 1H, H^4), 4.06 (m, 2H, H^1), 3.65 (t, *J* = 7.2 Hz, 1H, H^2), 1,77 (s, 3H, H^{13}), 1.51 (t, *J* = 6.3 Hz, 1H, H^9).

9.4.12.2.9. (E)-2,4-diphenylbut-3-en-1-ol (**204aa***)
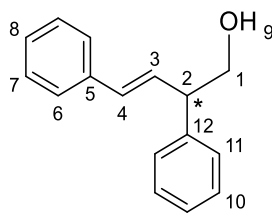
Chemical Formula: $C_{16}H_{16}O$
Molecular Weight: 224.30

Eluent for purification: 73/27 (*n*-hexane/AcOEt)
Yield: 54%
Aspect: colorless oil
e.r.: 74/26
For full details on the HPLC method and the chromatograms, see 9.5.2.

^{1}H NMR (300 MHz, CDCl₃) δ 7.41 – 7.19 (m, 10H, H^{arom}), 6.54 (d, *J* = 16.0 Hz, 1H, H^4), 6.38 (dd, *J* = 15.9, 7.7 Hz, 1H, H^3), 3.96 – 3.89 (m, 2H, H^1), 3.71 (q, *J* = 7.2 Hz, 1H, H^2), 1.50 (t, *J* = 6.4 Hz, 1H, H^9).

9.4.12.2.10. 2,4,4-triphenylbut-3-en-1-ol (**204af***)
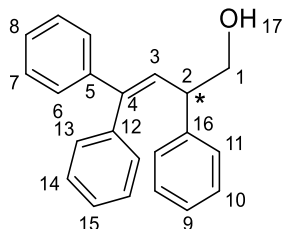
Chemical Formula: $C_{22}H_{20}O$
Molecular Weight: 300.40

Eluent for purification: 73/27 (*n*-hexane/AcOEt)
Yield: 8%
Aspect: colorless oil
e.r.: 71/29
For full details on the HPLC method and the chromatograms, see 9.5.3.

^{1}H NMR (300 MHz, CDCl[3]) δ 7.41 − 7.11 (m, 15H, H[arom]), 6.30 (d, *J* = 10.3 Hz, 1H, H[3]), 3.83 (d, *J* = 6.7 Hz, 2H, H[1]), 3,70 (dt, *J* = 10,2, 6,8 Hz, 1H, H[2]), 1,34 (m, 1H, H[17]).

9.4.13. Synthesis of secondary homoallylic alcohols

9.4.13.1. (E)-1,3-diphenylhepta-1,6-dien-4-ol (190aad)
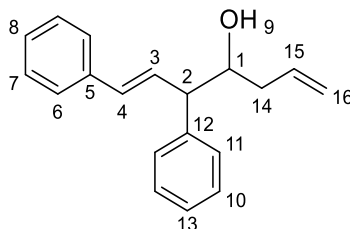
Chemical Formula: $C_{19}H_{16}O$
Molecular Weight: 264.37

The characterisation of this compound was made on a mixture of cis and trans diastereomers. The analysis of the recorded data were not sufficient to attribute a set of signals to the cis or trans isomer.

Procedure
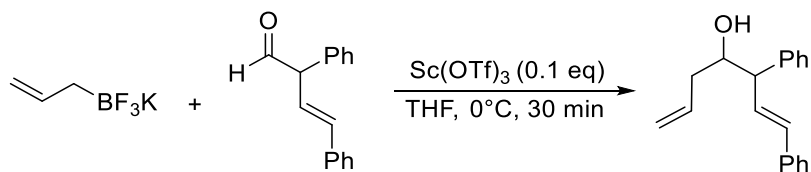
Aldehyde (0.71 mmol, 158mg) and potassium allyltrifluoroborate (1.1 mmol, 158mg) in THF (10 mL) are added to a dry round-bottom flask under inert atmosphere at 0°C. Sc(OTf)$_3$ (0.071 mmol, 35 mg) is then added and the reaction mixture is stirred for 30 min at 0°C. The reaction is stopped by the addition of water. The layers are separated and the aqueous layer extracted with duethylether. The combined organic extracts are washed with brine, dried over MgSO$_4$ and concentrated under reduced pressure. The secondary homoallylic alcohol is purified by flash chromatography on silica gel (n-hexane/AcOEt 8/2) to afford the alcohol as a yellow oil.

Yield: 40%
d.r.: 3/5
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.43 − 7.14 (m, 20H, H^{arom}), 6.60 − 6.34 (m, 4H, H$^{3 \text{ and } 4}$ $_{maj \text{ and } min}$), 6.01 − 5.74 (m, 2H, H^{15} $_{maj \text{ and } min}$), 5.21 − 5.02 (m, 4H, H^{16} $_{maj \text{ and } min}$), 4.09 − 3.93 (m, 2H, H^1 $_{maj \text{ and } min}$), 3.56 − 3.42 (m, 2H, H^2 $_{maj \text{ and } min}$), 1.91 (d, J = 3.1 Hz, 1H, H^9 $_{maj}$), 1.61 (d, J = 3.8 Hz, 1H, H^9 $_{min}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 141.8, 141.0, 137.3, 137.1, 135.0, 134.8, 133.0, 132.0, 130.1, 129.5, 128.9, 128.9, 128.6, 128.3, 127.6, 127.5, 127.1, 126.9, 126.4, 126.4, 118.0, 73.7, 56.0, 55.7, 39.4, 39.3. *Four signal are missing due to overlapping between signals of the two diastereomers.*

9.4.14. Synthesis of donor-acceptor cyclopropanes

9.4.14.1. General procedure
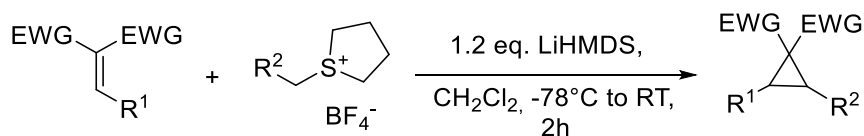
In a dry round-bottomed flask, under an inert atmosphere, sulfonium salt (1.2 equiv.) is dissolved in dichloromethane (1 mL/20mg of sulfonium salt). LiHMDS (1.0M in THF, 1.2 equiv.) is added dropwise at -78°C. The olefin is then added dropwise. The mixture is stirred at -78°C for 1 h and 1h at room temperature. Water is added to stop the reaction. An aqueous solution of hydrochloric acid (1M) is added. The two layers are separated and the aqueous one is extracted two times with dichloromethane. The combined organic layers are washed with brine, dried over $MgSO_4$ and concentrated under reduced pressure. The cyclopropane is then purified by flash column chromatography to yield a mixture of *trans* and *cis* isomers.

The eluent used for the chromatography column depends on the product and is given for each synthesised cyclopropane in the next section.

9.4.14.2. Product descriptions

9.4.14.2.1. Diethyl 2,3-diphenylcyclopropane-1,1-dicarboxylate (193aa)
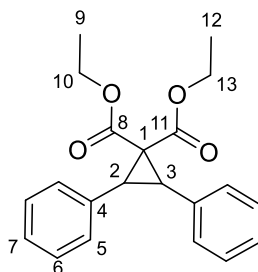
Chemical Formula: $C_{21}H_{22}O_4$
Molecular Weight: 338.40

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Eluent for purification: 95/5 *n*-Hexane/AcOEt
Yield: 47%
d.r. (*cis/trans*): 3/4
Aspect: white solid

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.38 – 7.07 (m, 20H, H^{arom}), 4.30 (q, J = 7.1 Hz, 2H, H$^{10 \text{ or } 13}$ $_{cis}$), 3.95 (q, J = 7.1 Hz, 4H, H$^{10 \text{ and } 13}$ $_{trans}$), 3.93 (q, J = 7.1 Hz, 2H, H$^{13 \text{ or } 10}$ $_{cis}$), 3.83 (s, 2H, H$^{2 \text{ and } 3}$ $_{trans}$), 3.31 (s, 2H, H$^{2 \text{ et } 3}$ $_{cis}$), 1.30 (t, J = 7.1 Hz, 6H, H$^{9 \text{ and } 12}$ $_{trans}$), 0.95 (t, J = 7.1 Hz, 3H, H$^{9 \text{ or } 12}$ $_{cis}$), 0.93 (t, J = 7.1 Hz, 3H, H$^{12 \text{ or } 9}$ $_{cis}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 170.6, 166.6, 165.8, 134.7 132.9, 130.7, 126.8, 62.2, 61.4, 61.0, 45.4, 41.1, 35.5, 34.5, 14.1, 13.8, 13.6.

HRMS (APCI) calculated for C$_{21}$H$_{22}$O$_4$: 339.15909. Measured: 339.15935.

9.4.14.2.2. Diethyl 2,3-bis(4-methoxyphenyl)cyclopropane-1,1-dicarboxylate (**193kk**)
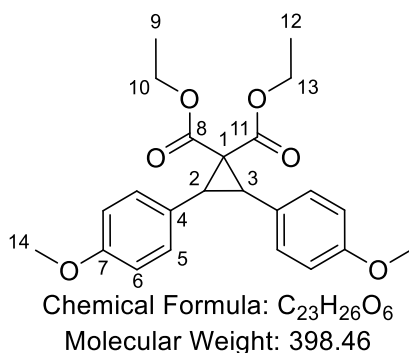
Chemical Formula: C$_{23}$H$_{26}$O$_6$
Molecular Weight: 398.46

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Eluent for purification: Not necessary
Yield: quant.
d.r. (*cis/trans*): 2/1
Aspect: orange oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.24 (d, J = 8.8 Hz, 4H, H^5 $_{trans}$), 6.98 (d, J = 8.8 Hz, 4H, H^5 $_{cis}$), 6.83 (d, J = 8.8 Hz, 4H,H^6 $_{trans}$), 6.72 (d, J = 8.9 Hz, 4H, H^6 $_{cis}$), 4.28 (q, J = 7.1 Hz, 2H, H$^{10 \text{ or } 13}$ $_{cis}$), 3.96 (m, 4H, H$^{10 \text{ and } 13}$ $_{trans}$), 3.95 (q, J = 7.1 Hz, 2H, H$^{13 \text{ or } 10}$ $_{cis}$), 3.79 (s, 6H, H^{14} $_{trans}$), 3.77 (s, 6H, H^{14} $_{cis}$), 3.72 (s, 2H, H$^{2 \text{ and } 3}$ $_{trans}$), 3.22 (s, 2H, H$^{2 \text{ and } 3}$ $_{cis}$), 1.32 (t, J = 7.1 Hz, 6H, H$^{9 \text{ or } 12}$ $_{cis}$), 0.99 (t, J = 7.2 Hz, 3H, H$^{9 \text{ and } 12}$ $_{trans}$), 0.98 (t, J = 7.2 Hz, 3H, H$^{12 \text{ or } 9}$ $_{cis}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 170.7, 158.4, 131.8, 129.9, 126.7, 124.8, 113.6, 112.9, 62.1, 60.9, 55.3, 55.1, 45.3, 40.8, 34.9, 34.1, 31.8, 31.1, 14.1, 13.6.

HRMS (APCI) calculated for C$_{23}$H$_{27}$O$_6$: 399.18022. Measured: 399.18070.

9.4.14.2.3. Diethyl 2-(4-methoxyphenyl)-3-phenylcyclopropane-1,1-dicarboxylate (**193ka**)

Chemical Formula: $C_{22}H_{24}O_5$
Molecular Weight: 368.43

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Eluent for purification: Not necessary
Yield: quant.
d.r. (*cis/trans*): 2/1
Aspect: orange oil

¹H NMR (300 MHz, CDCl₃) δ 7.31 – 7.03 (m, 10H, H$^{9, 10 \text{ and } 11}$ $_{cis \text{ and } trans}$), 7.25 (d, J = 8.9 Hz, 2H, H^5$_{trans}$), 7.00 (d, J = 8.8 Hz, 2H, H^5$_{cis}$), 6.84 (d, J = 8.8 Hz, 2H, H^6$_{trans}$), 6.72 (d, J = 8.9 Hz, 2H, H^6$_{cis}$), 4.29 (q, J = 7.1 Hz, 2H, H$^{15 \text{ or } 18}$ $_{cis}$), 4.01 – 3.94 (m, 4H, H$^{15 \text{ and } 18}$$_{trans}$), 3.94 (q, J = 7.1 Hz, 2H, $^{H18 \text{ or } 15}$$_{cis}$), 3.79 (s, 3H, H^{12} $_{trans}$), 3.78 (s, 2H, H$^{2 \text{ and } 3}$ $_{trans}$), 3.76 (s, 3H, H^{12} $_{cis}$), 3.27 (s, 2H, H$^{2 \text{ and } 3}$ $_{cis}$), 1.32 (t, J = 7.1 Hz, 3H, H$^{14 \text{ or } 17}$ $_{cis}$), 1.00 (t, J = 7.1 Hz, 3H, H$^{14 \text{ or } 17}$ $_{trans}$), 0.95 (t, J = 7.1 Hz, 3H, H$^{17 \text{ or } 14}$ $_{cis}$), 0.94 (t, J = 7.1 Hz, 3H, H$^{17 \text{ or } 14}$ $_{trans}$).

¹³C NMR (75 MHz, CDCl₃) δ 170.8, 166.8, 159.0, 134.9, 133.2, 132.0, 130.8, 129.0, 128.4, 127.6, 126.9, 124.7, 113.8, 113.0, 62.3, 61.2, 55.4, 45.5, 35.1, 34.8, 14.1, 13.9.

HRMS (APCI) calculated for $C_{22}H_{25}O_5$: 369.16965. Measured: 369.16955.

9.4.14.2.4. Diethyl 2-(4-(methoxycarbonyl)phenyl)-3-phenylcyclopropane-1,1-dicarboxylate (**193fa**)
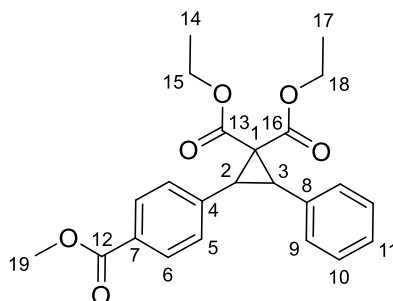
Chemical Formula: $C_{23}H_{24}O_6$
Molecular Weight: 396.44

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Eluent for purification: 95/5 *n*-Hexane/AcOEt
Yield: 23%
d.r. (*cis/trans*): 2/1
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.98 (d, *J* = 8.4 Hz, 2H, H^6 *trans*), 7.84 (d, *J* = 8.4 Hz, 2H, H^6*cis*), 7.52 − 7.00 (m, 14H, H$^{9-11}$*cis and trans*+ H^5*cis and trans*), 4.30 (q, *J* = 7.1 Hz, 2H, H$^{18\ or\ 15}$ *cis*), 4.00 − 3.90 (m, 6H, H$^{18\ or\ 15}$ *cis* + H$^{18\ and\ 15}$ *trans*), 3.91 (s, 3H, H^{19} *trans*), 3.88 (s, 3H, H^{19} *cis*), 3.85 (s, 2H, H$^{2\ and\ 3}$ *trans*), 3.37 (d, *J* = 10.5 Hz, 1H, H$^{2\ or\ 3}$ *cis*), 3.31 (d, *J* = 10.5 Hz, 1H, H$^{2\ or\ 3}$ *cis*), 1.33 (t, *J* = 7.1 Hz, 3H, H17 or 14 *cis*), 0.97 (t, *J* = 7.1 Hz, 9H, H$^{14\ or\ 17}$ *cis* + H$^{14\ and\ 17}$ *trans*).

^{13}C NMR (75 MHz, CDCl$_3$) δ 174.6 ; 173.9, 170.4, 165.7, 138.6, 138.4, 132.4, 130.8, 130.7, 129.6, 129.3, 129.1, 129.0, 128.8, 128.7, 128.6, 128.4, 128.3, 128.2, 127.7, 127.1, 126.6, 62.5, 61.7, 61.7, 61.3, 52.2, 52.2, 45.7, 41.5, 35.7, 35.2, 34.7, 34.3, 14.2, 14.0, 13.9, 13.7.

HRMS (APCI) calculated for $C_{22}H_{25}O_5$: 397.18371. Measured: 397.18356.

9.4.14.2.5. Diethyl 2-(4-methylphenyl)-3-phenylcyclopropane-1,1-dicarboxylate (193Ia)
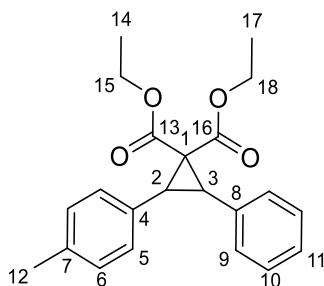
Chemical Formula: $C_{22}H_{24}O_4$
Molecular Weight: 352.43

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Eluent for purification: Not necessary
Yield: quant.
d.r. (*cis/trans*): 3/2
Aspect: clear yellow oil

^{1}H NMR (300 MHz, CDCl₃) δ 7.34 - 6.94 (m, 18H, H^{arom}), 4.29 (q, *J* = 7.1 Hz, 2H, H$^{15\ or\ 18}_{cis}$), 3.95 (q, *J* = 7.1 Hz, 4H, H$^{15\ and\ 18}_{trans}$), 3.93 (q, *J* = 7.1 Hz, 2H, H$^{15\ or\ 18}$ *cis*), 3.83 (s, 2H, H$^{2\ and\ 3}_{trans}$), 3.31 (s, 2H, H$^{2\ and\ 3}_{cis}$), 2.32 (s, 3H, H$^{18}_{trans}$), 2.29 (s, 3H, H$^{18}_{cis}$), 1.32 (t, *J* = 7.1 Hz, 6H, H$^{8\ and\ 13}_{trans}$), 0.99 (t, *J* = 7.1 Hz, 3H, H$^{8\ or\ 13}_{cis}$), 0.94 (t, *J* = 7.1 Hz, 3H, H$^{13\ or\ 8}_{cis}$)

^{13}C NMR (75 MHz, CDCl₃) δ 170.7, 166.7, 165.9, 137.0, 136.4, 134.8, 133.1, 130.7, 130.6, 129.0, 128.9, 128.7, 128.2, 128.2, 127.4, 127.4, 126.7, 62.1, 61.4, 61.3, 60.9, 21.1, 14.1, 13.9, 13.8, 13.6.
One of the carbonyl of the minor diastereoisomer is missing

9.4.14.2.6. Diethyl 2-(4-fluorophenyl)-3-phenylcyclopropane-1,1-dicarboxylate (**193ap**)
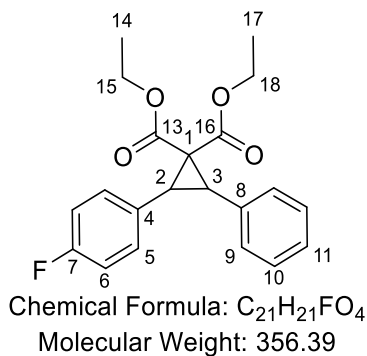
Chemical Formula: $C_{21}H_{21}FO_4$
Molecular Weight: 356.39

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Eluent for purification: 95/5 *n*-hexane/AcOEt
Yield: 34%
d.r. (*cis/trans*): 1/1
Aspect: white solid

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.34 - 6.83 (m, 18H, H^{arom}), 4.29 (q, *J* = 7.1 Hz, 2H, H$^{15 \text{ or } 18}$ $_{cis}$), 4.01 - 3.89 (m, 6H, H$^{15 \text{ and } 18}$ $_{trans}$ + H$^{18 \text{ or } 15}$ $_{cis}$), 3.78 (s, 2H, H$^{2 \text{ and } 3}$ $_{trans}$), 3.28 (s, 2H, H$^{2 \text{ and } 3}$ $_{cis}$), 1.32 (t, *J* = 7.1 Hz, 3H, H$^{14 \text{ or } 17}$ $_{trans}$), 0.99 (t, *J* = 7.1 Hz, 3H, H$^{14 \text{ or } 17}$ $_{cis}$) 0.95 (t, *J* = 7.1 Hz, 3H, H$^{17 \text{ or } 14}$ $_{trans}$), 0.94 (t, *J* = 7.1 Hz, 3H, H$^{17 \text{ or } 14}$ $_{cis}$)

^{13}C NMR (75 MHz, CDCl$_3$) δ 170.5, 166.5, 166.5, 165.8, 134.4, 132.8, 132.5, 132.4, 130.5, 130.4, 128.79, 128.3, 127.5, 126.9, 115.3, 115.0, 114.5, 114.3, 62.3, 61.5, 61.5, 61.1, 45.4, 41.1, 35.3, 34.7, 33.7, 14.08, 13.9, 13.8, 13.6.

HRMS (APCI) calculated for $C_{21}H_{22}FO_4$: 357.14981. Measured: 357.14996.

9.4.14.2.7. Diethyl 2-(2-methylphenyl)-3-phenylcyclopropane-1,1-dicarboxylate (**193ab**)
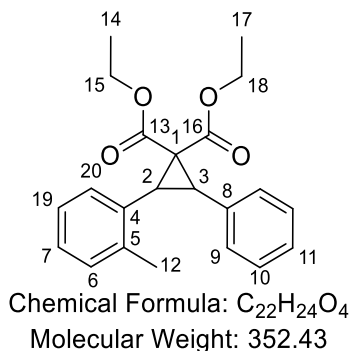
Chemical Formula: $C_{22}H_{24}O_4$
Molecular Weight: 352.43

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Eluent for purification: 95/5 *n*-hexane/AcOEt then 80/20 *n*-hexane/AcOEt
Yield: 60%
d.r. (*cis/trans*): 3/1
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.34 - 6.94 (m, 18H, H^{arom}), 4.30 (q, *J* = 7.1 Hz, 2H, H$^{15\ or\ 18}$ *cis*), 4.01 - 3.75 (m, 8H, H$^{15\ and\ 18}$ *trans* + H$^{18\ or\ 15}$ *cis* + H$^{2\ and\ 3}$ *trans*), 3.33 (d, *J* = 10.3 Hz, 2H, H$^{2\ or\ 3}$ *cis*), 3.19 (d, *J* = 10.3 Hz, 1H, H$^{3\ or\ 2}$ *cis*), 2.43 (s, 3H, H^{12} *trans*), 2.27 (s, 3H, H^{12} *cis*), 1.32 (t, *J* = 7.1 Hz, 6H, H$^{14\ and\ 17}$ *trans*), 0.95 (t, *J* = 7.1 Hz, 3H, H$^{14\ or\ 17}$ *cis*), 0.88 (t, *J* = 7.1 Hz, 3H, H$^{17\ or\ 14}$ *cis*)

^{13}C NMR (75 MHz, CDCl$_3$) δ 170.7, 166.7, 165.9, 139.5, 139.3, 138.8, 134.8, 134.4, 132.9, 131.1, 130.3, 129.8, 129.4, 128.9, 128.3, 128.1, 127.5, 127.4, 127.2, 126.8, 125.6, 124.8, 62.1, 61.4, 61.3, 60.9, 53.4, 41.2, 35.4, 34.9, 34.2, 33.8, 20.2, 19.4, 14.2, 13.8, 13.7, 13.5. *One of the carbonyl of the minor diastereomer is missing*

9.4.14.2.8. Diethyl 2-(2-fluorophenyl)-3-phenylcyclopropane-1,1-dicarboxylate (**193at**)
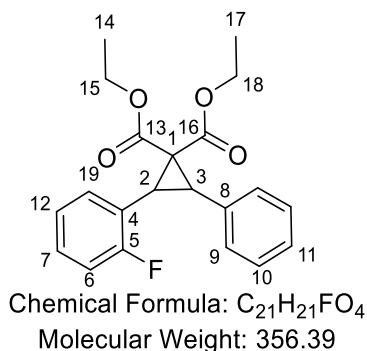
Chemical Formula: $C_{21}H_{21}FO_4$
Molecular Weight: 356.39

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Eluent for purification: 98/2 *n*-Hexane/AcOEt
Yield: 60%
d.r. (*cis/trans*): 8/2
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.39 − 6.84 (m, 18H, H^{arom}), 4.31 (q, *J* = 7.1 Hz, 4H, H$^{18 \text{ and } 15}$$_{trans}$), 4.01 − 3.86 (m, 4H, H$^{18 \text{ and } 15}$ $_{cis}$), 3.82 (d, *J* = 8.1 Hz, 1H, H$^{2 \text{ or } 3}$ $_{trans}$), 3.80 (d, *J* = 8.1 Hz, 1H, H$^{2 \text{ or } 3}$ $_{trans}$), 3.39 (d, *J* = 10.2 Hz, 1H, H$^{2 \text{ or } 3}$ $_{cis}$), 3.28 (d, *J* = 10.2 Hz, 1H, H2 or ^{3} $_{cis}$), 1.34 (t, *J* = 7.1 Hz, 3H, H$^{14 \text{ or } 17}$ $_{cis}$), 0.98 (t, *J* = 7.1 Hz, 3H, H$^{14 \text{ or } 17}$ $_{trans}$), 0.94 (t, *J* = 7.1 Hz, 3H, H$^{14 \text{ or } 17}$ $_{trans}$), 0.93 (t, *J* = 7.1 Hz, 3H, H$^{14 \text{ or } 17}$ $_{cis}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 170.4, 183.2 (d, *J* = 247.8 Hz), 133.4, 131.7 (d, *J* = 3.1 Hz), 129.9, 129.0, 128.9 (d, *J* = 8.6 Hz), 128.8, 128.4, 127.7, 127.0, 122.9, 120.6 (d, *J* = 13.6 Hz), 115.2 (d, *J* = 22.0 Hz), 62.4, 61.1, 40.7, 34.8, 29.5 (d, *J* = 4.0 Hz), 14.2, 13.7.

HRMS (APCI) calculated for $C_{21}H_{22}FO_4$: 357.14981. Measured: 357.14996.

9.4.14.2.9. Diethyl 2-(3-methoxyphenyl)-3-phenylcyclopropane-1,1-dicarboxylate (**193ca**)

Chemical Formula: $C_{22}H_{24}O_5$
Molecular Weight: 368.43

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Eluent for purification: Not necessary
Yield: 78%
d.r. (*cis/trans*): 2/1
Aspect: orange oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.38 – 6.54 (m, 18H, H^{arom}), 4.30 (q, *J* = 7.1 Hz, 2H, H$^{18 \, or \, 15}$ $_{cis}$), 4.03 – 3.87 (m, 6H, H$^{18 \, or \, 15}$ $_{cis}$ + H$^{18 \, and \, 15}$ $_{trans}$)), 3.80 (s, 3H, H^{12} $_{trans}$), 3.79 (s, 2H, H$^{2 \, and \, 3}$ $_{cis}$)*,* 3.59 (s, 3H, H^{12} $_{cis}$), 3.30 (s, 2H, H$^{2 \, and \, 3}$ $_{trans}$), 1.33 (t, *J* = 7.1 Hz, 3H, H$^{14 \, or \, 17}$ $_{cis}$), 0.99 (t, *J* = 7.1 Hz, 3H, H$^{14 \, or \, 17}$ $_{trans}$) 0.94 (t, *J* = 7.1 Hz, 3H, H$^{14 \, or \, 17}$ $_{trans}$), 0.94 (t, *J* = 7.1 Hz, 3H, H$^{14 \, or \, 17}$ $_{cis}$).

^{13}C NMR (*cis* isomer, 75 MHz, CDCl$_3$) δ 170.7, 158.7, 136.3, 134.7, 132.9, 128.9, 128.5, 127.5, 123.2, 113.4, 113.1, 62.3, 61.5, 55.3, 45.5, 41.2, 34.7, 34.5, 13.9, 13.7.

HRMS (APCI) calculated for $C_{22}H_{25}O_5$: 369.16965. Measured: 369.16955.

9.4.14.2.10. Diethyl 2-(3-chlorophenyl)-3-phenylcyclopropane-1,1-dicarboxylate (**193as**)


Chemical Formula: $C_{21}H_{21}ClO_4$
Molecular Weight: 372.85

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Eluent for purification: 95/5 *n*-hexane/AcOEt
Yield: 77%
d.r. (*cis/trans*): 3/1
Aspect: clear yellow oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.36 - 6.84 (m, 18H, H^{arom}), 4.30 (q, 2H, J = 7.1 Hz, H$^{15 \text{ or } 18}$ $_{cis}$), 4.02 (d, J = 7.1 Hz, 1H ; H$^{2 \text{ or } 3}$ $_{trans}$), 4.00 - 3.90 (q, J = 7.1 Hz, 8H, H$^{15 \text{ and } 18}$ $_{trans}$ + H$^{15 \text{ or } 18}$ $_{cis}$), 3.79 (d, J = 7.1 Hz, 1H, H$^{3 \text{ or } 2}$ $_{trans}$), 3.32 (d, J = 10.3 Hz, 1H, H$^{2 \text{ or } 3}$ $_{cis}$), 3.25 (d, J = 10.3 Hz, 1H, H$^{3 \text{ or } 2}$ $_{cis}$), 1.33 (t, J = 7.1 Hz, 3H, H$^{14 \text{ or } 17}$ $_{cis}$), 1.01 (t, J = 7.1 Hz, 3H, H$^{14 \text{ or } 17}$ $_{trans}$), 0.96 (t, J = 7.1 Hz, 3H, H$^{17 \text{ or } 14}$ $_{cis}$), 0.94 (t, J = 7.1 Hz, 3H, H$^{17 \text{ or } 14}$ $_{trans}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 170.3, 166.4, 166.3, 165.6, 136.9, 134.9, 134.2, 134.1, 133.3, 132.4, 131.1, 129.5, 129.2, 128.8, 128.8, 128.6, 128.3, 127.7, 127.6, 127.0, 62.4, 61.6, 61.5, 61.2, 45.4, 41.1, 35.3, 34.8, 34.5, 33.8, 14.1, 13.9, 13.8, 13.6.

HRMS (ESI): Calculated for $C_{21}H_{22}ClO_4$: 373.12022, found: 373.12011.

9.4.14.2.11. Diethyl 2-(naphthalen-2-yl)-3-phenylcyclopropane-1,1-dicarboxylate (193oa)

Chemical Formula: $C_{25}H_{24}O_4$
Molecular Weight: 388.46

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Eluent for purification: Not necessary
Yield: 86%
d.r. (*cis/trans*): 1/1
Aspect: orange oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.85 − 7.02 (m, 12H, H^{arom}), 4.32 (q, *J* = 7.1 Hz, 2H, H$^{13\ or\ 10}$ $_{cis}$), 4.04 − 3.84 (m, 6H, H$^{13\ and\ 10}$ $_{trans}$ + H$^{13\ or\ 10}$ $_{cis}$), 3.92 (d, *J* = 7.1 Hz, 1H, H$^{2\ or\ 3}$ $_{trans}$), 3.89 (d, *J* = 7.1 Hz, 1H, H$^{2\ or\ 3}$ $_{trans}$), 3.48 (d, *J* = 10.8 Hz, 1H, H$^{2\ or\ 3}$ $_{cis}$), 3.38 (d, *J* = 11.0 Hz, 1H, H$^{2\ or\ 3}$ $_{cis}$), 1.34 (t, *J* = 7.1 Hz, 3H, H$^{9\ or\ 12}$ $_{cis}$), 0.96 (t, *J* = 7.1 Hz, 3H, H$^{9\ or\ 12}$ $_{trans}$), 0.90 (t, *J* = 7.1 Hz, 3H, H$^{9\ or\ 12}$ $_{cis}$), 0.88 (t, *J* = 7.1 Hz, 3H, H$^{9\ or\ 12}$ $_{trans}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 170.7, 166.0, 134.8, 133.1, 133.0, 132.4, 130.8, 130.1, 129.0, 128.4, 127.7, 127.7, 127.6, 127.1, 127.0, 126.8, 126.3, 62.4, 61.2, 45.7, 41.4, 35.8, 35.6, 14.2, 14.0.

HRMS (ESI) calculated for $C_{21}H_{22}O_4$: 389.17474. Measured: 389.17474.

9.4.14.2.12. Diethyl 2-(furan-2-yl)-3-phenylcyclopropane-1,1-dicarboxylate (**193na**)

Chemical Formula: $C_{19}H_{20}O_5$
Molecular Weight: 328.36

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Eluent for purification: 95/5 *n*-Hexane/AcOEt
**Yield:** 51%
d.r. (*cis/trans*): 1/2
Aspect: colorless oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.37 − 7.12 (m, 12H, H^{arom} + H^{16} $_{trans\ and\ cis}$), 6.32 (dd, *J* = 3.3 Hz, 1H, H^{15} *trans*), 6.25 (dd, *J* = 3.3, 1.9 Hz, 1H, H^{15} $_{cis}$), 6.23 (d, *J* = 3.3 Hz, 1H, H^{14} $_{trans}$), 5.98 (d, *J* = 3.3 Hz, 1H, H^{14} *cis*), 4.28 (q, *J* = 7.2 Hz, 2H, H$^{13\ or\ 10}$ $_{cis}$), 4.09 (q, *J* = 7.1 Hz, 2H, H$^{13\ or\ 10}$ $_{trans}$), 4.03 (q, *J* = 7.2 Hz, 2H, H$^{13\ or\ 10}$ $_{cis}$), 3.93), 4.09 (q, *J* = 7.1 Hz, 2H, H$^{13\ or\ 10}$ $_{trans}$), 3.76 (d, *J* = 8.2 Hz, 1H, H$^{2\ or\ 3}$ $_{trans}$), 3.70 (d, *J* = 8.1 Hz, 1H, H$^{2\ or\ 3}$ $_{trans}$), 3.28 (d, *J* = 10.7 Hz, 1H, H$^{2\ or\ 3}$ $_{cis}$), 3.28 (d, *J* = 10.7 Hz, 1H, H$^{2\ or\ 3}$ $_{cis}$), 1.32 (t, *J* = 7.1 Hz, 3H, H$^{9\ or\ 11}$ $_{cis}$), 1.10 (t, *J* = 7.1 Hz, 3H, H$^{9\ or\ 12}$ $_{trans}$), 1.03 (t, *J* = 7.1 Hz, 3H, H$^{9\ or\ 12}$ $_{trans}$), 0.93 (t, *J* = 7.1 Hz, 3H, H$^{9\ or\ 12}$ $_{cis}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 170.0, 166.6, 166.2, 149.5, 147.9, 142.3, 141.8, 134.0, 132.7, 130.4, 128.9, 128.4, 127.7, 127.2, 110.6, 110.5, 109.8, 108.0, 62.5, 61.8, 61.6, 61.3, 44.9, 40.1, 34.7, 34.6, 28.6, 27.7, 14.2, 14.1, 13.9, 13.8.

HRMS (APCI) calculated for $C_{19}H_{21}O_5$: 329.13841. Measured: 329.13835.

9.4.14.2.13. Diethyl 2,3-diphenylcyclopropane-1,1-dicarboxylate (193va)

Chemical Formula: $C_{20}H_{21}NO_4$
Molecular Weight: 339.39

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Eluent for purification: 90/10 *n*-hexane/AcOEt
Yield: 31%
d.r. (*cis/trans*): 1/2
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 8.51 (ddd, *J* = 4.9, 1.8, 0.9, 1H, H^{18} *trans*), 8.29 (ddd, *J* = 4.9, 1.9, 0.9, 1H, H^{18} *cis*), 7.64 (td, *J* = 7.7, 1.8 Hz, 1H, H^{16} *trans*), 7.52 (td, *J* = 7.7, 1.8 Hz, 1H, H16 *cis*), 7.44 − 7.10 (m, 14H, H$^{5-7}$ *cis and trans* + H$^{17 and 15}$ *cis and trans*), 4.36 − 4.22 (m, 2H, H$^{13 or 10}$ *cis*), 4.06 − 3.89 (m, 6H, H$^{13 and 10}$ *trans* + H$^{13 or 10}$ *cis*), 3.86 (d, *J* = 8.1 Hz, 1H, H$^{2 or 3}$ *trans*), 3.84 (d, *J* = 8.1 Hz, 1H, H$^{2 or 3}$ *trans*), 3.45 (d, *J* = 10.2 Hz, 1H, H$^{2 or 3}$ *cis*), 3.35 (d, *J* = 10.2 Hz, 1H, H$^{2 or 3}$ *cis*), 1.33 (t, *J* = 7.1 Hz, 3H, H$^{9 or 12}$ *cis*), 1.02 (t, *J* = 7.1 Hz, 3H, H$^{9 or 12}$ *trans*), 0.99 (t, *J* = 7.1 Hz, 3H, H$^{9 or 12}$ *cis*), 0.95 (t, *J* = 7.1 Hz, 3H, H$^{9 or 12}$ *trans*).

^{13}C NMR (75 MHz, CDCl$_3$) δ 166.8, 166.4, 155.2, 149.2, 148.1, 136.3, 135.4, 134.6, 131.2, 128.9, 128.2, 127.4, 126.7, 124.8, 123.9, 122.1, 121.4, 62.3, 61.6, 61.5, 60.8, 53.5, 45.8, 36.6, 35.6, 14.2, 13.9, 13.9, 13.7.

HRMS (APCI) calculated for $C_{20}H_{22}NO_4$: 340.15425. Measured: 340.15433.

9.4.14.2.14. Diethyl 2-phenylcyclopropane-1,1-dicarboxylate (**193aj**)

Chemical Formula: $C_{15}H_{18}O_4$
Molecular Weight: 262.31

Special procedure:

In a dry round-bottomed flask, under an inert atmosphere, NaH (38 wt% in mineral oil, 0.086 g, 1.36 mmol, 1.1 equiv.) is washed with 3 portions of *n*-hexane, 5 ml of dry DMSO is then added. The sulfoxonium salt (0.300 g, 1.36 mmol, 1.1 eq) is added, 6 ml of dry DMSO are added. The reaction was stirred for 1h and the round bottomed flask was placed in an ice bath (0°C). The olefin (0.308 g, 1.24 mmol, 1.0 equiv.) dissolved in 3 ml of dry DMSO was added. The mixture was stirred overnight and allowed to warm up to room temperature. Water is added to stop the reaction. The two layers are separated and the aqueous one is extracted three times with DCM. The combined organic layers are washed with brine, dried over $MgSO_4$ and concentrated under reduced pressure to give the desired product as a colorless oil (0.205 g).

Yield: 63%
Aspect: colorless oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.28 – 7.18 (m, 5H, H^{arom}), 4.38 – 4.15 (m, 2H, H^{10} $^{or\ 13}$), 3.84 (q, *J* = 7.1 Hz, 2H, H$^{10\ or\ 13}$), 3.22 (t, *J* = 8.5 Hz, 1H, H^2), 2.18 (dd, *J* = 8.0, 5.0 Hz, 1H, H^{3a}), 1.70 (dd, *J* = 9.2, 5.2 Hz, 1H, H^{3b}), 1.30 (t, J = 7.1 Hz, 3H, H$^{12\ or\ 9}$), 0.86 (t, *J* = 7.1 Hz, 3H, H$^{9\ or\ 12}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 170.0, 166.8, 134.8, 128.7, 128.2, 127.4, 61.8, 61.2, 37.5, 32,3, 18,8 ; 14.2, 13.8.

HRMS (APCI) calculated for $C_{15}H_{19}O_4$: 263.12771. Measured: 263.12779.

9.4.14.2.15. Diethyl 2-methyl-3-phenylcyclopropane-1,1-dicarboxylate (**193ha**)

Chemical Formula: $C_{16}H_{20}O_4$
Molecular Weight: 276.33

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Procedure note: A delay of 15 min was applied between the addition of the base and the olefin
Eluent for purification: 98/2 *n*-hexane/AcOEt then 95/5 *n*-hexane/AcOEt then 90/10 *n*-hexane/AcOEt
Yield: 80%
d.r. (*cis*/*trans*): 3/2
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.32 - 7.16 (m, 10H, H^{arom}), 4.35 - 4.17 (m, 4H, H$^{10\ or\ 13}$ $_{cis\ and\ trans}$), 4.10 (q, *J* = 7.1 Hz, 2H, H$^{13\ or\ 10}$ $_{trans}$), 3.85 (q, *J* = 7.1 Hz, 2H, H$^{13\ or\ 10}$ $_{cis}$), 3.08 (d, *J* = 9.9 Hz, 1H, H^2 $_{cis}$), 3.04 (d, *J* = 8.0 Hz, 1H, H^2 $_{trans}$), 2.54 (dq, *J* = 8.0, 6.3 Hz, 1H, H^3 $_{trans}$), 2.06 (dq, *J* = 9.9, 6.7 Hz, 1H, H^3 $_{cis}$), 1.37 - 1.25 (m, 12H, H^{14} $_{cis\ and\ trans}$ + H$^{9\ or12}$ $_{cis\ and\ trans}$), 1.15 (t, *J* = 7.1 Hz, 3H, H$^{12\ or\ 9}$ $_{trans}$), 0.88 (t, *J* = 7.1 Hz, 3H, H$^{12\ or\ 9}$ $_{cis}$)

^{13}C NMR (75 MHz, CDCl$_3$) δ 170.9, 168.0, 167.1, 166.8, 135.2, 133.8, 130.3, 128.6, 128.0, 127.9, 127.06, 126.8, 61.7, 61.5, 61.0, 60.8, 43.4, 37.8, 37.5, 34.6, 26.7, 24.7, 14.3, 14.1, 13.9, 13.7, 12.4, 10.9.

HRMS (APCI) calculated for $C_{16}H_{20}O_4$: 277.14344, found: 277.14310.

9.4.14.2.16. Diethyl 3-phenyl-[1,1'-bi(cyclopropane)]-2,2-dicarboxylate (**193ea**)

Chemical Formula: $C_{18}H_{22}O_4$
Molecular Weight: 302.37

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Procedure note: A delay of 15 min was applied between the addition of the base and the olefin
Eluent for purification: 95/5 *n*-Hexane/AcOEt
Yield: 47%
d.r. (*cis/trans*): 2/3
Aspect: brown oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.51 − 7.13 (m, 10H, H^{arom}), 4.36 − 3.97 (m, 4H, H$^{13 \text{ and } 10}$ $_{trans}$), 3.86 (q, *J* = 7.1, 4H, H$^{13 \text{ and } 10}$ $_{cis}$), 3.21 (d, *J* = 8.0 Hz, 1H, H^2 $_{trans}$), 3.10 (d, J = 9.8 Hz, 1H, H^2 $_{cis}$) 2.21 (dd, *J* = 7.9; 7.0 Hz, 1H, H^3 $_{trans}$), 1.43 − 1.04 (m, 7H, H$^{12 \text{ and } 9}$ $_{trans}$ + H^3$_{cis}$), 0.89 (t, *J* = 7.1 Hz, 6H, H$^{12 \text{ and } 9}$ $_{cis}$), 0.77 − 0.64 (m, 1H, H^{14}), 0.56 (ddd, *J* = 5.4; 3.4;1.5 Hz, 2H, H$^{16a \text{ and } 15a}$), 0.44 (ddd, *J* = 6.3; 4.9; 1.4 Hz, 2H, H$^{16b \text{ and } 15b}$).

^{13}C NMR (75 MHz, CDCl$_3$) 170.7, 166.7, 135.0, 133.9, 130.3, 126.8 , 61.6, 60.7, 43.2, 41.6, 37.7, 34.1, 14.2, 13.7, 8.4, 7.4, 5.8, 5.6, 4.4, 4.1.

HRMS (APCI) calculated for $C_{18}H_{23}O_4$: 303.15891. Measured: 3030.15909.

9.4.14.2.17. Diethyl 2-(*tert*-butyl)-3-phenylcyclopropane-1,1-dicarboxylate (**193da**)

Chemical Formula: $C_{19}H_{26}O_4$
Molecular Weight: 318.41

The characterisation of this compound was made on the trans diastereomer.

Eluent for purification: 95/5 *n*-hexane/AcOEt
Yield: 65%
Aspect: yellow oil
d.r. (*cis/trans*): 0/1

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.27 − 7.18 (m, 5H, H^{arom}), 4.34 − 4.19 (m, 2H, H$^{13 \text{ or } 10}$), 3.88 (m, 2H, H$^{10 \text{ or } 13}$), 3.23 (d, *J* = 9.4 Hz, 1H, H^2), 2.48 (d, *J* = 9.4 Hz, 1H, H^3), 1.32 (t, *J* = 7.1 Hz, 3H, H$^{12 \text{ or } 9}$), 1.05 (s, 9H, H^{15}), 0.92 (t, *J* = 7.1 Hz, 3H, H$^{9 \text{ or } 12}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 168.6, 167.5, 135.9, 128.9, 128.0, 127.0, 61.5, 61.2, 42.4, 42.1, 32.7, 30.6, 28.7, 14.0, 13.8.

HRMS (APCI) calculated for $C_{19}H_{27}O_4$: 319.19039. Measured: 319.19032.

9.4.14.2.18. 2,3-diphenylcyclopropane-1,1-dicarbonitrile (**193aa-CN**)

Chemical Formula: $C_{17}H_{12}N_2$
Molecular Weight: 244.30

Eluent for purification: 90/10 *n*-Hexane/AcOEt
Yield: 38%
d.r. (*cis/trans*): 2/1
Aspect: yellow oil

¹H NMR (300 MHz, CDCl₃) δ 7.54 − 7.22 (m, 16H, H^{arom}), 7.14 − 7.00 (m, 4H, H^{7}$_{cis\ and\ trans}$), 3.68 (s, 2H, H$^{2\ and\ 3}$$_{cis}$), 3.60 (s, 2H, H$^{2\ and\ 3}$$_{trans}$).

¹³C NMR (75 MHz, CDCl₃) δ 134.8, 134.3, 130.8, 130.0, 129.7, 129.4, 129.2, 129.0, 128.9, 128.8, 127.9, 113.2, 39.0, 38.9, 15.5.

9.4.14.2.19. 2-(4-Methoxyphenyl)-3-phenylcyclopropane-1,1-dicarbonitrile (**193**ak-CN)

Chemical Formula: C$_{18}$H$_{14}$N$_2$O
Molecular Weight: 274.32

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Eluent for purification: Not necessary
Yield: quant.
d.r. (*cis/trans*): 3/2
Aspect: yellow oil

¹H NMR (300 MHz, CDCl₃) δ 7.50 - 6.89 (m, 18H, H^{arom} *cis* and *trans*), 3.83 (s, 2H, H$^{2\ and\ 3}$ *trans*), 3.79 (s, 3H, H^{13} *trans*), 3.63 (s, 2H, H$^{2\ and\ 3}$ *cis*), 3.55 (s, 3H, H^{13} *cis*)

¹³C NMR (75 MHz, CDCl₃) δ 179.5, 179.0, 131.3, 130.0, 129.7, 129.6, 129.3, 128.9, 128.7, 128.6, 128.5, 122.5, 120.2, 116.0, 114.7, 114.1, 111.9, 55.4, 55.3, 38.9, 38.8, 38.7, 15.5, 12.7.

9.4.14.2.20. Diethyl 2-(4-methoxyphenyl)-3-phenylcyclopropane-1,1-dicarboxylate (**193ka***)

Chemical Formula: $C_{22}H_{24}O_5$
Molecular Weight: 368.43

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Procedure:

In a dry round-bottomed flask, under an inert atmosphere, the olefin (0.11 mL, 0.51 mmol, 1.0 equiv.) and the chiral sulfonium salt (0.3 g, 1.01 mmol, 2.0 eq.) were dissolved in dichloromethane (1 mL/20mg of sulfonium salt). LiHMDS (1.0M in THF, 1 mL, 1.01 mmol, 2.0 equiv.) was then added dropwise at -78°C. The mixture was stirred at -78°C for 1 h and then 1h at room temperature overnight. Water is added to stop the reaction. An aqueous solution of hydrochloric acid (1M) is added. The two layers are separated and the aqueous one is extracted twice with dichloromethane. The combined organic layers are washed with brine, dried over $MgSO_4$ and concentrated under reduced pressure. The cyclopropane is isolated by flash chromatography (95/5 n-hexane/AcOEt) (0.135 g).

Yield: 51%
d.r. (*cis/trans*): 2/1
Aspect: brown oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.31 – 7.03 (m, 10H, H$^{9, 10 \text{ and } 11}$ $_{\text{cis and trans}}$), 7.25 (d, J = 8.9 Hz, 2H, H^5$_{\text{trans}}$), 7.00 (d, J = 8.8 Hz, 2H, H^5$_{\text{cis}}$), 6.84 (d, J = 8.8 Hz, 2H, H^6$_{\text{trans}}$), 6.72 (d, J = 8.9 Hz, 2H, H^6$_{\text{cis}}$), 4.29 (q, J = 7.1 Hz, 2H, H$^{15 \text{ or } 18}$ $_{\text{cis}}$), 4.01 – 3.94 (m, 4H, H$^{15 \text{ and } 18}$$_{\text{trans}}$), 3.94 (q, J = 7.1 Hz, 2H, $^{\text{H18 or } 15}$$_{\text{cis}}$), 3.79 (s, 3H, H^{12} $_{\text{trans}}$), 3.78 (s, 2H, H^2 $_{\text{and } 3}$ $_{\text{trans}}$), 3.76 (s, 3H, H^{12} $_{\text{cis}}$), 3.27 (s, 2H, H$^{2 \text{ and } 3}$ $_{\text{cis}}$), 1.32 (t, J = 7.1 Hz, 3H, H$^{14 \text{ or } 17}$ $_{\text{cis}}$), 1.00 (t, J = 7.1 Hz, 3H, H$^{14 \text{ or } 17}$ $_{\text{trans}}$), 0.95 (t, J = 7.1 Hz, 3H, H$^{17 \text{ or } 14}$ $_{\text{cis}}$), 0.94 (t, J = 7.1 Hz, 3H, H$^{17 \text{ or } 14}$ $_{\text{trans}}$).

9.4.14.2.21. Diethyl 2-(4-methoxyphenyl)-3-phenylcyclopropane-1,1-dicarboxylate-3-d (**193ak-D**)

Chemical Formula: C$_{22}$H$_{23}$DO$_5$
Molecular Weight: 369.44

The characterisation of this compound was made on a mixture of cis and trans diastereomers.

Eluent for purification: Not necessary
Yield: 95%
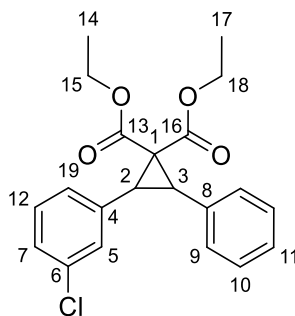**d.r. (*cis/trans*):** 2/1
Aspect: orange oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.31 – 7.03 (m, 10H, H$^{9, 10 \text{ and } 11}$ $_{\text{cis and trans}}$), 7.25 (d, J = 8.9 Hz, 2H, H^5$_{\text{trans}}$), 7.00 (d, J = 8.8 Hz, 2H, H^5$_{\text{cis}}$), 6.84 (d, J = 8.8 Hz, 2H, H^6$_{\text{trans}}$), 6.72 (d, J = 8.9 Hz, 2H, H^6$_{\text{cis}}$), 4.29 (q, J = 7.1 Hz, 2H, H$^{15 \text{ or } 18}$ $_{\text{cis}}$), 4.01 – 3.94 (m, 4H, H$^{15 \text{ and } 18}$$_{\text{trans}}$), 3.94 (q, J = 7.1 Hz, 2H, H$^{18 \text{ or } 15}$$_{\text{cis}}$), 3.79 (s, 3H, H^{12} $_{\text{trans}}$), 3.78 (s, 1H, H^2 $_{\text{trans}}$), 3.76 (s, 3H, H^{12} $_{\text{cis}}$), 3.27 (s, 1H, H^2 $_{\text{cis}}$), 1.32 (t, J = 7.1 Hz, 3H, H$^{14 \text{ or } 17}$ $_{\text{cis}}$), 1.00 (t, J = 7.1 Hz, 3H, H$^{14 \text{ or } 17}$ $_{\text{trans}}$), 0.95 (t, J = 7.1 Hz, 3H, H$^{17 \text{ or } 14}$ $_{\text{cis}}$), 0.94 (t, J = 7.1 Hz, 3H, H$^{17 \text{ or } 14}$ $_{\text{trans}}$).
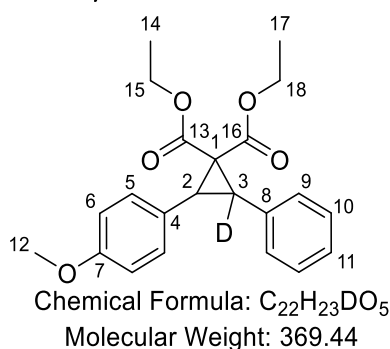
HRMS (APCI) calculated for C$_{22}$H$_{24}$DO$_5$: 370.17593. Measured: 370.17576.

9.4.15. Synthesis of homologated olefins

9.4.15.1. General procedure A: TiCl₄ promoted rearrangement
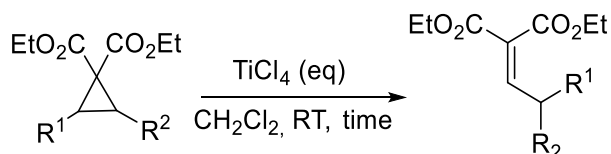
Cyclopropane (1 eq.) and dry dichloromethane (1 mL/10mg of cyclopropane) are introduced in a dry round-bottom flask under argon. Then, titanium tetrachloride 1M in dichloromethane *(see product description for number of eq.)* is added and the mixture is stirred at room temperature for a defined time *(see description of the compound)*. Water is added to stop the reaction. An aqueous solution of hydrochloric acid (1M) is added. The two layers are separated and the aqueous one is extracted twice with dichloromethane. The combined organic layers are washed with brine, dried over MgSO₄ and concentrated under reduced pressure.

Number of TiCl₄ equivalents, reaction time and eluent for purification depend on the nature of the compound and are reported in the description of each product.

9.4.15.2 General procedure B: FeCl₃ promoted rearrangement
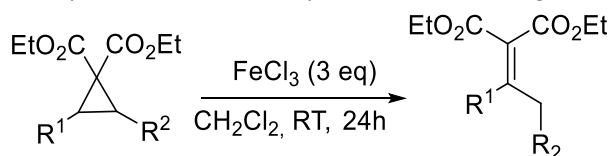
Cyclopropane (1 eq.) and dry dichloromethane (1 mL/10mg of cyclopropane) are introduced in a dry round-bottom flask under argon. Then, 3 equivalents of FeCl₃ are added and the mixture is stirred at room temperature for 24h. Water is added to stop the reaction. An aqueous solution of hydrochloric acid (1M) is added. The two layers are separated and the aqueous one is extracted twice with dichloromethane. The combined organic layers are washed with brine, dried over MgSO₄ and concentrated under reduced pressure.

Eluent for purification depends on the nature of the compound and are reported in the description of each product.

9.4.15.3. Product descriptions

9.4.15.3.1. Diethyl 2-(2,2-diphenylethylidene)malonate (194aa)
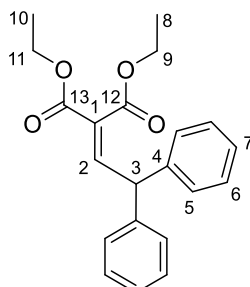
Chemical Formula: $C_{21}H_{22}O_4$
Molecular Weight: 338.40

Procedure: A
Time: 24h
Eq. TiCl$_4$: 3
Eluent for purification: Not necessary
Yield: 91%
Aspect: brown oil

^{1}H NMR (300 MHz, CDCl$_3$): δ= 7.40 (d, J = 10.9 Hz, 1H, H^2), 7.29 (m, 10H, H^{arom}), 5.18 (d, J = 11.0 Hz, 1H, H^3), 4.30 (q, J = 7.2 Hz, 2H, H$^{9\ or\ 11}$), 4.24 (q, J = 7.2 Hz, 2H, H$^{11\ or\ 9}$), 1.30 (t, J = 7.1 Hz, 3H, H$^{8\ or\ 10}$), 1.29 (t, J = 7.1 Hz, 3H, H$^{10\ or\ 8}$).

^{13}C NMR (75 MHz, CDCl$_3$): δ= 165.2, 182.9, 148.4, 141.2, 128.7, 128.4, 128.2, 127.0, 61.5, 61.4, 50.1, 14.1.

HRMS (APCI): Calculated for $C_{21}H_{22}O_4$: 339.15909, found: 339.15900

9.4.15.3.2. Diethyl 2-(2,2-bis(4-methoxyphenyl)ethylidene)malonate (194kk)
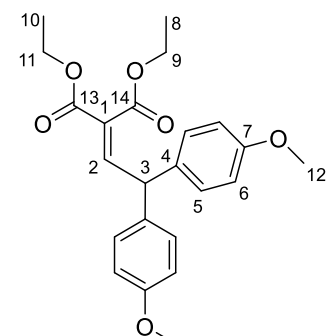
Chemical Formula: $C_{23}H_{26}O_6$
Molecular Weight: 398.46

Procedure: A
Time: 1h
Eq. TiCl$_4$: 0.4
Eluent for purification: Not necessary
Yield: 90%
Aspect: brown oil

^{1}H NMR (300 MHz, CDCl$_3$): δ= 7.30 (d, *J* = 11.1 Hz, 1H, H^2), 7.13 – 7.06 (m, 4H, H^5), 6.89 – 6.81 (m, 4H, H^6), 5.03 (d, *J* = 11.1 Hz, 1H, H^3), 4.30 (q, *J* = 7.1 Hz, 2H, H$^{9 \text{ or } 11}$), 4.24 (q, *J* = 7.1 Hz, 2H, H$^{9 \text{ or } 11}$), 3.79 (s, 6H, H^{12}), 1.31 (t, *J* = 7.2 Hz, 3H, H$^{8 \text{ or } 10}$), 1.28 (t, *J* = 7.2 Hz, 3H, H$^{10 \text{ or } 8}$).

^{13}C NMR (75 MHz, CDCl$_3$): δ= 165.3, 183.0, 158.5, 148.8, 133.4, 129.3, 127.4, 114.1, 61.4, 55.2, 48.4, 14.1, 14.1.

HRMS (APCI): Calculated for C$_{21}$H$_{22}$O$_4$: 399.18022, found: 399.18005.

9.4.15.3.3. Diethyl 2-(2-(4-methoxyphenyl)-2-phenylethylidene)malonate (**194ka**)

Chemical Formula: C$_{22}$H$_{24}$O$_5$
Molecular Weight: 368.43

Procedure: A
Time: 2h
Eq. TiCl$_4$: 0.4
Eluent for purification: Not necessary
Yield: 88%
Aspect: brown oil

^{1}H NMR (300 MHz, CDCl$_3$): δ= 7.34 (d, *J* = 11.0 Hz, 1H, H^2), 7.36 – 6.67 (m, 9H, H^{arom}), 5.10 (d, *J* = 11.0 Hz, 1H, H^3), 4.30 (q, *J* = 7.1 Hz, 2H, H$^{11 \text{ or } 9}$), 4.24 (q, *J* = 7.1 Hz, 2H, H$^{9 \text{ or } 11}$), 3.79 (s, 3H, H^{12}), 1.31 (t, *J* = 7.1 Hz, 3H, H$^{10 \text{ or } 8}$), 1.29 (t, *J* = 7.1 Hz, 3H, H$^{8 \text{ or } 10}$).

13C NMR (75 MHz, CDCl₃): δ= 165.3, 183.0, 158.6, 148.7, 133.2, 129.4, 128.7, 128.3, 127.8, 127.5, 127.0, 114.2, 61.5, 61.4, 55.3, 49.4, 14.1, 14.1.

HRMS (APCI): Calculated for $C_{22}H_{25}O_5$: 369.16965, found: 369.16957.

9.4.15.3.4. Diethyl 2-(2-(4-(methoxycarbonyl)phenyl)-2-phenylethylidene)malonate (**194fa**)
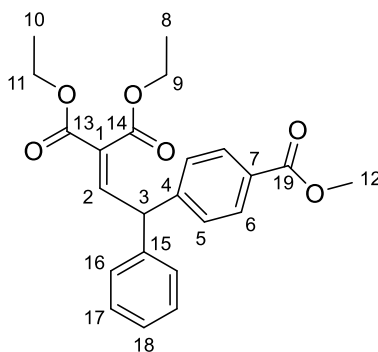
Chemical Formula: $C_{23}H_{24}O_6$
Molecular Weight: 396.44

Procedure: A
Time: 24h
Eq. TiCl₄: 3
Eluent for purification: Not necessary
Yield: 21%
Aspect: brown oil

¹H NMR (300 MHz, CDCl₃): δ= 7.41 (d, J = 8.4 Hz, 1H, H²), 7.39 – 6.94 (m, 9H, H^arom), 5.22 (d, J = 10.9 Hz, 1H, H³), 4.29 (q, J = 7.1 Hz, 2H, H^{11 or 9}), 4.25 (q, J = 7.1 Hz, 2H, H^{9 or 11}), 3.91 (s, 3H, H¹²), 1.29 (t, J = 7.1 Hz, 3H, H^{10 or 8}), 0.97 (t, J = 7.1 Hz, 3H, H^{10 or 8}).

The recorded ¹³C NMR spectrum is not exploitable

HRMS (APCI): Calculated for $C_{22}H_{24}O_6Na$: 419.14670, found: 419.14651.

9.4.15.3.5. Diethyl 2-(2-phenyl-2-(*p*-tolyl)ethylidene)malonate (**194la**)
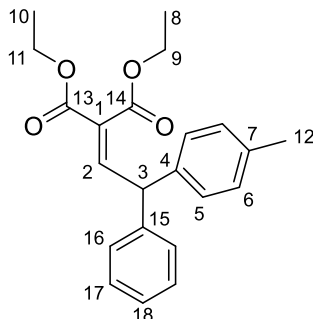
Chemical Formula: $C_{22}H_{24}O_4$
Molecular Weight: 352.43

Procedure: A
Time: 24h
Eq. TiCl$_4$: 3
Eluent for purification: Not necessary
Yield: 68%
Aspect: brown oil

^{1}H NMR (300 MHz, CDCl$_3$): δ= 7.36 (d, *J* = 11.0 Hz, 1H, H^2), 7.34 - 7.05 (m, 9H, H^{arom}), 5.11 (d, *J* = 11.0 Hz, 1H, H^3), 4.29 (q, *J* = 7.1 Hz, 2H, H$^{11 \text{ or } 9}$), 4.24 (q, *J* = 7.1 Hz, 2H, H$^{9 \text{ or } 11}$), 2.32 (s, 3H, H^{12}), 1.30 (t, *J* = 7.1 Hz, 3H, H$^{10 \text{ or } 8}$), 1.28 (t, *J* = 7.1 Hz, 3H, H$^{8 \text{ or } 10}$).

^{13}C NMR (75 MHz, CDCl$_3$): δ= 165.3, 183.0, 148.6, 141.4, 138.2, 136.8, 129.5, 128.7, 128.4, 128.3, 128.0, 127.0, 61.5, 61.4, 49.8, 21.0, 14.1.

9.4.15.3.6. Diethyl 2-(2-(4-fluorophenyl)-2-phenylethylidene)malonate (**194ap**)
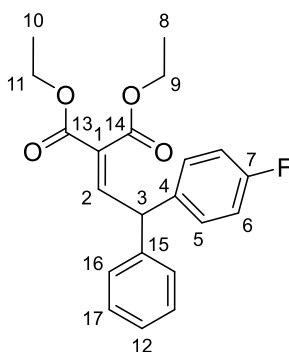
Chemical Formula: $C_{21}H_{21}FO_4$
Molecular Weight: 356.39

Procedure: A
Time: 24h
Eq. TiCl₄: 3
Eluent for purification: Not necessary
Yield: 88%
Aspect: brown oil

¹H NMR (300 MHz, CDCl₃): δ= 7.32 (d, *J* = 10.9 Hz, 1H, H²), 7.37 - 6.95 (m, 9H, H^{arom}), 5.14 (d, *J* = 10.9 Hz, 1H, H³), 4.30 (q, *J* = 7.1 Hz, 2H, H$^{11\ or\ 9}$), 4.25 (q, *J* = 7.1 Hz, 2H, H$^{9\ or\ 11}$), 1.30 (t, *J* = 7.1 Hz, 3H, H$^{10\ or\ 8}$), 1.29 (t, *J* = 7.1 Hz, 3H, H$^{8\ or\ 10}$).

¹³C NMR (75 MHz, CDCl₃): δ= 165.2, 182.9, 148.1, 141.0, 137.0, 137.0, 130.0, 129.9, 128.9, 128.3, 127.2, 115.8, 115.5, 61.6, 61.5, 49.4, 14.1, 14.1.

HRMS (APCI): Calculated for $C_{21}H_{22}FO_4$: 357.14967, found: 357.14966.

9.4.15.3.7. Diethyl 2-(2-phenyl-2-(o-tolyl)ethylidene)malonate (**194ab**)
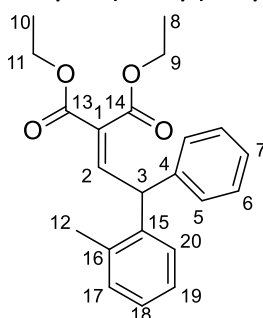
Chemical Formula: $C_{22}H_{24}O_4$
Molecular Weight: 352.43

Procedure: A
Time: 24h
Eq. TiCl₄: 3
Eluent for purification: Not necessary
Yield: 98%
Aspect: brown oil

¹H NMR (300 MHz, CDCl₃): δ= 7.39 (d, *J* = 10.5 Hz, 1H, H²), 7.32 - 7.10 (m, 9H, H^{arom}), 5.37 (d, *J* = 10.5 Hz, 1H, H³), 4.24 (q, *J* = 7.1 Hz, 4H, H$^{11\ and\ 9}$), 2.22 (s, 3H, H¹²), 1.29 (t, *J* = 7.1 Hz, 3H, H$^{10\ or\ 8}$), 1.25 (t, *J* = 7.1 Hz, 3H, H$^{8\ or\ 10}$).

13C NMR (75 MHz, CDCl₃): δ= 165.4, 183.1, 149.2, 141.4, 139.5, 136.6, 131.0, 128.8, 128.3, 128.3, 128.2, 127.2, 127.0, 126.5, 61.6, 61.5, 46.8, 19.9, 14.2, 14.2.

9.4.15.3.8. Diethyl 2-(2-(2-fluorophenyl)-2-phenylethylidene)malonate (**194at**)
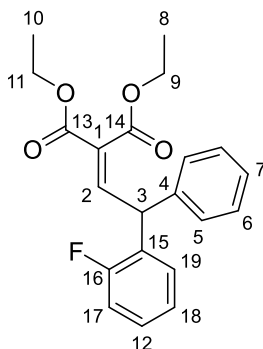
Chemical Formula: $C_{21}H_{21}FO_4$
Molecular Weight: 356.39

Procedure: A
Time: 48h
Eq. TiCl₄: 3
Eluent for purification: Not necessary
Yield: 94%
Aspect: brown oil

1H NMR (300 MHz, CDCl₃): δ= 7.42 (d, J = 10.5, 1H, H²), 7.30 (d, J = 7.4 Hz, 9H, H^arom), 5.43 (d, J = 10.5 Hz, 1H, H³), 4.26 (d, J = 7.1, 2H, H⁹ ᵒʳ ¹¹), 4.20 (q, J = 7.1, 2H, H¹¹ ᵒʳ ⁹), 1.29 (t, J = 7.1, 3H, H¹⁰ ᵒʳ ⁸), 1.25 (t, J = 7.1, 3H, H¹⁰ ᵒʳ ⁸).

13C NMR (75 MHz, CDCl₃): δ= 165.1, 183.0, 159.1 ;147.3, 140.5, 129.9, 129.6, 129.1, 129.0, 128.9, 128.0, 127.2, 124.6, 116.2, 115.9, 61.7, 61.7, 44.1, 14.2, 14.2.

HRMS (APCI): Calculated for $C_{21}H_{22}FO_4$: 357.14967, found: 357.14966.

9.4.15.3.9. Diethyl 2-(2-(3-methoxyphenyl)-2-phenylethylidene)malonate (**194ca**)
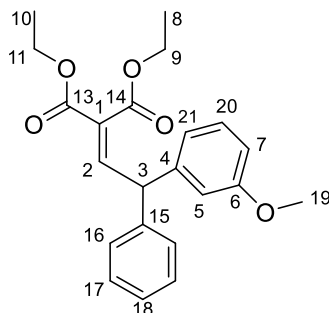
Chemical Formula: $C_{22}H_{24}O_5$
Molecular Weight: 368.43

Procedure: A
Time: 24h
Eq. TiCl$_4$: 3
Eluent for purification: Not necessary
Yield: 63%
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$): δ= 7.36 (d, J = 11.0 Hz, 1H, H^1), 7.41 – 7.28 (m, 5H, H$^{16-18}$), 6.84 – 6.70 (m, 4H, H$^{5, 7, 20, 21}$), 5.12 (d, J = 11.0 Hz, 1H, H^3), 4.30 (q, J = 7.1 Hz, 2H, H$^{9 \, or \, 11}$), 4.24 (q, J = 7.1 Hz, 2H, H$^{11 \, or \, 9}$), 3.77 (s, 3H, H^{19}), 1.30 (t, J = 7.1 Hz, 3H, H$^{10 \, or \, 8}$), 1.29 (t, J = 7.1 Hz, 3H, H$^{10 \, or \, 8}$).

The recorded ^{13}C NMR spectrum is not analysable

HRMS (APCI): Calculated for $C_{22}H_{25}O_5$: 369.16965, found: 369.16957.

9.4.15.3.10. Diethyl 2-(2-(3-chlorophenyl)-2-phenylethylidene)malonate (**194as**)
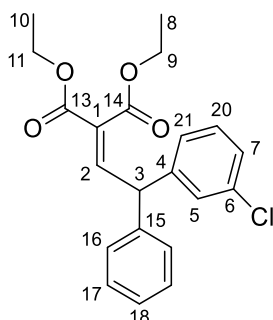
Chemical Formula: $C_{21}H_{21}ClO_5$
Molecular Weight: 372.85

Procedure: A
Time: 72h
Eq. TiCl$_4$: 6
Eluent for purification: 90/10 *n*-hexane/AcOEt
Yield: 58%
Aspect: yellow oil

^{1}H NMR (300 MHz, CDCl$_3$): δ= 7.31 (d, *J* = 10.9 Hz, 1H, H^2), 7.32 – 7.04 (m, 9H, H^{arom}), 5.13 (d, *J* = 10.9 Hz, 1H, H^3), 4.28 (q, *J* = 7.1 Hz, 4H, H$^{9\,and\,11}$), 1.30 (t, *J* = 7.1 Hz, 6H, H$^{10\,and\,8}$).

^{13}C NMR (75 MHz, CDCl$_3$): δ= 165.2, 182.9, 147.6, 143.4, 140.6, 134.8, 130.1, 129.7, 129.1, 128.8, 128.6, 127.8, 127.5, 126.7, 61.8, 61.7, 49.9, 14.2, 14.2.

HRMS (ESI): Calculated for C$_{21}$H$_{22}$ClO$_5$: 373.12022, found: 373.12011.

9.4.15.3.11. Diethyl 2-(2-(naphthalen-2-yl)-2-phenylethylidene)malonate (**194oa**)
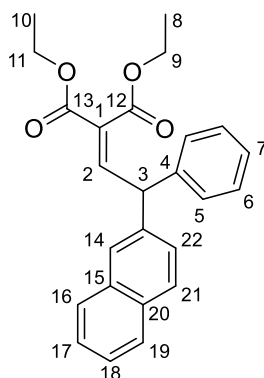
Chemical Formula: C$_{25}$H$_{24}$O$_4$
Molecular Weight: 388.46

Procedure: A
Time: 24h
Eq. TiCl$_4$: 3
Eluent for purification: 95/5 *n*-hexane/AcOEt
Yield: 36%
Aspect: brown oil

^{1}H NMR (300 MHz, CDCl$_3$): δ= 7.80 (d, *J* = 8.9 Hz, 1H, H^{22}), 7.79 (d, *J* = 8.4 Hz, 2H, H$^{16\,and\,19}$), 7.66 (s, 1H, H^{14}), 7.50 – 7.43 (m, 2H, H$^{17\,and\,18}$), 7.47 (d, *J* = 11.0 Hz, 1H, H^2), 7.37 – 7.21 (m, 6H, H$^{5-7}$ + H^{21}), 5.33 (d, *J* = 11 Hz, 1H, H^3), 4.28 (q, *J* = 7.1 Hz, 4H, H$^{9\,and\,11}$), 1.30 (t, *J* = 7.1 Hz, 6H, H$^{10\,and\,8}$).

¹³C NMR (75 MHz, CDCl₃): δ= 165.4, 183.1, 148.4, 141.3, 138.7, 133.6, 132.6, 129.4, 129.0, 128.7, 128.6, 128.5, 128.0, 127.8, 127.3, 127.1, 126.7, 126.4, 126.1, 61.7, 61.6, 50.4, 14.3.

HRMS (APCI): Calculated for $C_{21}H_{22}O_4$: 389.16746, found: 389.17475

9.4.15.3.12. Diethyl 2-(2-phenylethylidene)malonate (**194aj**)
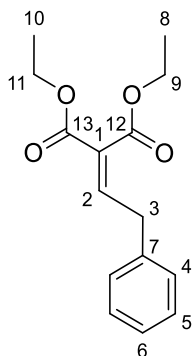
Chemical Formula: $C_{15}H_{18}O_4$
Molecular Weight: 262.31

Procedure: B
Eluent for purification: Not necessary
Yield: 62%
Aspect: orange oil

¹H NMR (300 MHz, CDCl₃): δ= 7.49 − 7.17 (m, 5H, H^{arom}), 7.08 (t, J = 8.0 Hz, 1H, H^2), 4.35 (q, J = 7.1 Hz, 2H, H$^{9\,or\,11}$), 4.24 (q, J = 7.1 Hz, 2H, H$^{11\,or\,9}$), 3.63 (d, J = 8.0 Hz, 2H, H^3), 1.36 (t, J = 7.1 Hz, 3H, H$^{10\,or\,8}$), 1.29 (t, J = 7.1 Hz, 3H, H$^{10\,or\,8}$).

¹³C NMR (75 MHz, CDCl₃): δ= 165.5, 183.0, 146.9, 129.6, 129.1, 129.1, 128.9, 127.0, 61.6, 61.5, 36.0, 14.3, 14.2.

HRMS (APCI): Calculated for $C_{15}H_{18}O_4Na$: 285.10965, found: 285.10973

9.4.15.3.13. Diethyl 2-(1-phenylpropan-2-ylidene)malonate (235ha)
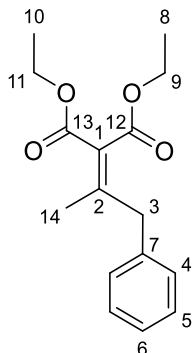
Chemical Formula: $C_{16}H_{20}O_4$
Molecular Weight: 276.33

Procedure: B
Eluent for purification: Not necessary
Yield: 77%
Aspect: brown oil

¹H NMR (300 MHz, CDCl₃): δ= 7.37 – 7.17 (m, 5H, H^{arom}), 4.36 – 4.18 (m, 4H, $H^{10\,and\,8}$), 3.71 (s, 2H, H^3), 1.96 (s, 3H, H^{14}), 1.35 – 1.24 (m, 6H, $H^{11\,and\,9}$).

¹³C NMR (75 MHz, CDCl₃): δ= 166.0, 165.5, 155.9, 137.6, 129.3, 128.7, 126.8, 125.8, 61.3, 61.1, 42.1, 20.4, 14.2.

HRMS (APCI) calculated for $C_{16}H_{20}O_4$: 277.14344, found: 277.14310.

9.4.15.3.14. diethyl 2-(2-cyclopropyl-2-phenylethylidene)malonate (194ea)
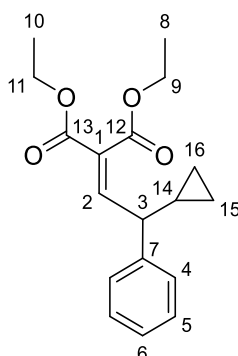
Chemical Formula: $C_{18}H_{22}O_4$
Molecular Weight: 302.37

Procedure: A
Time: 30 min
Eq. TiCl$_4$: 1
Eluent for purification: Not necessary
Yield: 95%
Aspect: brown oil

^{1}H NMR (300 MHz, CDCl$_3$): δ= 7.37 − 7.22 (m, 5H, H^{arom}), 7.07 (d, J = 11.1 Hz, 1H, H^2), 4.35 − 4.18 (m, 4H, H$^{11 \text{ and } 9}$), 3.01 (dd, J = 11.1; 9.2 Hz, 1H, H^3), 1.32 (t, J = 7.1 Hz, 3H, H$^{10 \text{ or } 8}$), 1.29 (t, J = 7.1 Hz, 3H, H$^{8 \text{ or } 10}$), 0.94 − 0.80 (m, 1H, H^{14}), 0.67 − 0.56 (m, 2H, H$^{16 \text{ or } 15}$), 0.41 − 0.22 (m, 2H, H $^{15 \text{ or } 16}$).

^{13}C NMR (75 MHz, CDCl$_3$): δ= 165.6, 183.1, 149.5, 141.1, 128.7, 127.7, 127.3, 127.0, 61.4, 61.3, 49.7, 15.2, 14.2, 14.1, 4.6, 4.2.

HRMS (APCI): Calculated for C$_{18}$H$_{23}$O$_4$: 303.15909, found: 303.15822

9.4.15.3.15. Diethyl 2-(3,3-dimethyl-2-phenylbutylidene)malonate (194da)
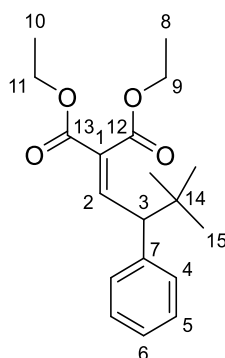
Chemical Formula: C$_{19}$H$_{26}$O$_4$
Molecular Weight: 318.41

Procedure: A
Time: 24h
Eq. TiCl$_4$: 1
Eluent for purification: Not necessary
Yield: 74%
Aspect: orange oil

^{1}H NMR (300 MHz, CDCl$_3$): δ= 7.46 (d, J = 11.6 Hz, 1H, H^2), 7.30 − 7.10 (m, 5H, H^{arom}), 4.29 − 4.18 (m, 4H, H$^{11 \text{ and } 9}$), 3.49 (d, J = 11.6 Hz, 1H, H^3), 1.28 (t, J = 7.1 Hz, 3H, H$^{10 \text{ or } 8}$), 1.27 (t, J = 7.2 Hz, 3H, H$^{8 \text{ or } 10}$), 0.93 (s, 9H, H^{15}).

^{13}C NMR (75 MHz, CDCl₃): δ= 165.5, 183.0, 148.5, 139.9, 129.2, 129.0, 128.1, 126.8, 61.3, 61.1, 55.9, 34.8, 27.8, 14.1, 14.1.

HRMS (APCI): Calculated for $C_{19}H_{26}O_4$: 319.19039, found: 319.19032

9.4.15.3.16. 2-(2,2-diphenylethylidene)malononitrile (**194aa-CN**)
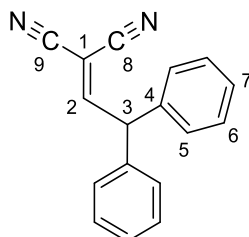
Chemical Formula: $C_{17}H_{12}N_2$
Molecular Weight: 244.30

Procedure: A
Time: 24h
Eq. TiCl₄: 6
Eluent for purification: Not necessary
Yield: 87%
Aspect: orange oil

^{1}H NMR (300 MHz, CDCl₃): δ= 7.70 (d, J = 11.1 Hz, 1H, H²), 7.52 − 7.12 (m, 10H, H^arom), 5.34 (d, J = 11.1 Hz, 1H, H³).

^{13}C NMR (75 MHz, CDCl₃): δ= 167.9, 138.4, 129.6, 128.4, 128.2, 112.1, 89.2, 54.1.

HRMS (APCI): Calculated for $C_{17}H_{12}N_2$: 245.10745, found: 245.10732

9.4.15.3.17. 2-(2-(4-methoxyphenyl)-2-phenylethylidene)malononitrile (**194ka-CN**)
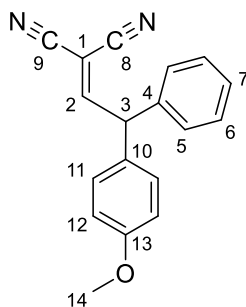
Chemical Formula: $C_{18}H_{14}N_2O$
Molecular Weight: 244.30

Procedure: A
Time: 24h
Eq. TiCl₄: 6
Eluent for purification: Not necessary
Yield: 87%
Aspect: orange oil

¹H NMR (300 MHz, CDCl₃): δ= 7.65 (d, J = 11.1 Hz, 1H, H²), 7.50 - 6.82 (m, 9H, H^{arom}), 5.28 (d, J = 11.1 Hz, 1H, H³), 3.80 (s, 3H, H¹⁴).

9.4.15.3.18. Diethyl 2-(2-(4-methoxyphenyl)-2-phenylethylidene)malonate (**194ka-(S)**)
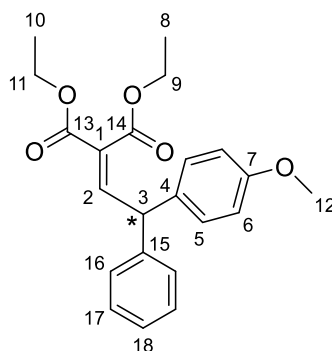
Chemical Formula: $C_{22}H_{24}O_5$
Molecular Weight: 368.43

Procedure: A
Time: 2h
Eq. TiCl₄: 0.4

Eluent for purification: 95/5 *n*-hexane/AcOEt
Yield: 51%
Aspect: brown oil
e.r.: 98/2
For full details on the HPLC method and the chromatograms, see 9.5.4.

^{1}H NMR (300 MHz, CDCl$_3$): δ= 7.34 (d, *J* = 11.0 Hz, 1H, H^2), 7.36 − 6.67 (m, 9H, H^{arom}), 5.10 (d, *J* = 11.0 Hz, 1H, H^3), 4.30 (q, *J* = 7.1 Hz, 2H, H$^{11\ or\ 9}$), 4.24 (q, *J* = 7.1 Hz, 2H, H$^{9\ or\ 11}$), 3.79 (s, 3H, H^{12}), 1.31 (t, *J* = 7.1 Hz, 3H, H$^{10\ or\ 8}$), 1.29 (t, *J* = 7.1 Hz, 3H, H$^{8\ or\ 10}$).

9.4.15.3.19. Diethyl 2-(2-(4-methoxyphenyl)-2-phenylethylidene-1-d)malonate (**194ak-D**)
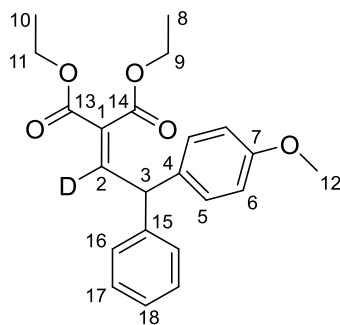
Chemical Formula: C$_{22}$H$_{23}$DO$_5$
Molecular Weight: 369.44

Procedure: A
Time: 2h
Eq. TiCl$_4$: 0.4
Eluent for purification: Not necessary
Yield: 55%
Aspect: brown oil

^{1}H NMR (300 MHz, CDCl$_3$): δ= 7.36 − 6.67 (m, 9H, H^{arom}), 5.10 (d, *J* = 11.0 Hz, 1H, H^3), 4.30 (q, *J* = 7.1 Hz, 2H, H$^{11\ or\ 9}$), 4.24 (q, *J* = 7.1 Hz, 2H, H$^{9\ or\ 11}$), 3.79 (s, 3H, H^{12}), 1.31 (t, *J* = 7.1 Hz, 3H, H$^{10\ or\ 8}$), 1.29 (t, *J* = 7.1 Hz, 3H, H$^{8\ or\ 10}$).

HRMS (APCI) calculated for C$_{22}$H$_{24}$DO$_5$: 370.17593. Measured: 370.17576.

9.4.16. Synthesis of divinylcyclopropanes

9.4.16.1. General procedure
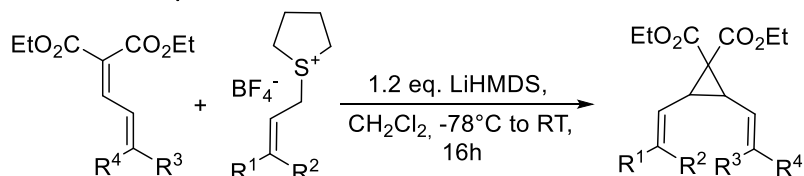
In a dry round-bottomed flask, under an inert atmosphere, sulfonium salt (1.2 equiv.) is dissolved in dichloromethane (1 mL/20mg of sulfonium salt). LiHMDS (1.0M in THF, 1.2 equiv.) is then added dropwise at -78°C. The diene is then added dropwise. The mixture is stirred at -78°C for 1 h and allowed to warm up to room temperature overnight. Water is added to stop the reaction. An aqueous solution of hydrochloric acid (1M) is added. The two layers are separated and the aqueous one is extracted two times with dichloromethane. The combined organic layers are washed with brine, dried over MgSO₄ and concentrated under reduced pressure. The divinylcyclopropane is then purified by flash column chromatography.

The eluent used for the chromatography column depends on the product and is given for each synthesised divinylcyclopropane in the next section.

9.4.16.2. Product descriptions

9.4.16.2.1. 1,1-Diethyl 2,3-bis[(*E*)-2-phenylethenyl]cyclopropane-1,1-dicarboxylate (**195aa**)

Chemical Formula: $C_{25}H_{26}O_4$
Molecular Weight: 390.48
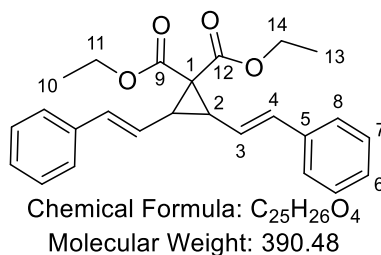
The characterisation of this compound was made on a 7/3 mixture of cis and trans diastereomers

Eluent for purification: *n*-hexane/AcOEt (8/2)
Yield: 90%
Aspect: Yellow oil

^{1}H NMR (500 MHz, CDCl$_3$) : δ= 7.29 to 7.05 (m, 16H, H^{arom}), 6.74 (m, 4H, H$^{arom}_{cis}$), 6.64 (d, *J* = *1*5.8 Hz, 2H, H$^4_{trans}$), 6.09 (d, 2H, *J* = 11.7 Hz, H$^4_{cis}$), 5.95 (dd, 2H, *J* = 11.7, 6.1 Hz, H$^3_{cis}$) 5.83 (ddd, 2H, *J* = 15.8, 6.6, 2.2 Hz, H$^3_{trans}$), 4.30 to 4.05 (m, 8H, H^{11,14}), 4.06 to 3.98 (m, 2H, H$^2_{cis}$), 2.91 (m, 2H, H$^2_{trans}$), 1.28 (t, 3H, *J* = 7.1 Hz, H$^{10\,or\,13}_{cis}$), 1.19 (m, 6H, H$^{10,13}_{trans}$), 0.85 (t, 3H, *J* = 7.4 Hz, H$^{13\,or\,10}_{cis}$)

^{13}C NMR (125 MHz, CDCl$_3$): δ= 167.6, 137.0, 136.4, 134.2, 130.0, 128.9, 127.9, 127.9, 127.0, 126.5, 124.0, 62.6, 62.5, 62.1, 44.0, 14.6

HRMS (APCI): Calculated for C$_{25}$H$_{27}$O$_4$: 391.19039, found: 391.19019.

9.4.16.2.2. 1,1-Diethyl 2,3-bis[(*E*)-2-phenylethenyl]cyclopropane-1,1-dicarboxylate (**195ba**)

Chemical Formula: C$_{21}$H$_{26}$O$_4$
Molecular Weight: 342.44
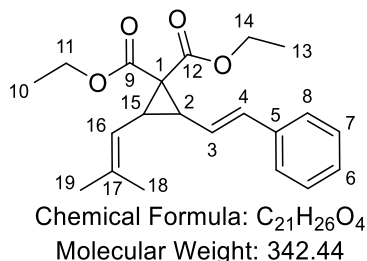
This description corresponds to only one diastereomer

Procedure note: A 15-minute delay was observed between the addition of the base used to deprotonate the sulfonium salt and the 1,3-diene.
Eluent for purification: *n*-hexane/AcOEt (9/1)
Yield: 25%
d.r. (*cis/trans*): 4/6
Aspect: Yellow oil

^{1}H NMR (500 MHz, CDCl$_3$) δ 7.35 − 7.17 (m, 5H, H^{arom}), 6.66 (d, *J* = 15.8 Hz, 1H, H^4), 5.90 (dd, *J* = 15.8, 8.9 Hz, 1H, H^3), 4.85 (m, , 1H, H^{16}), 4.33 − 4.11 (m, 4H, H$^{14\,and\,11}$), 2.88 (t, *J* = 7.8 Hz, 1H, H^{15}), 2.78 (m, 1H, H^2), 1.78 (d, *J* = 1.3 Hz, 3H, H$^{19\,or\,18}$), 1.74 − 1.69 (s, 3H, H$^{18\,or\,19}$), 1.25 (dt, *J* = 8.5, 7.1 Hz, 1H).

^{13}C NMR (125 MHz, CDCl$_3$): δ 167.9, 167.6, 138.2, 137.0, 133.3, 128.7, 127.5, 126.2, 124.7, 118.5, 61.7, 61.6, 53.6, 43.6, 36.4, 32.2, 25.7, 18.8, 14.3.

9.4.17. Synthesis of 1,4,4'-trienes

9.4.17.1. General procedure
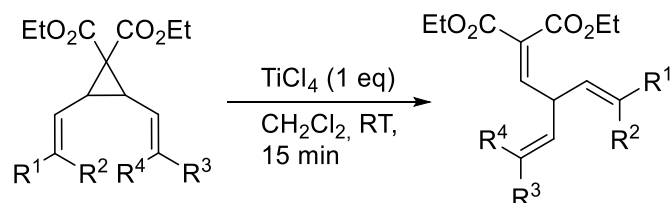
Divinylcyclopropane (1 eq.) and dry dichloromethane (1 mL/10mg of vinylcyclopropane) are introduced in a dry round-bottom flask under argon. Then, 1 eq of titanium tetrachloride 1M in dichloromethane is added and the mixture is stirred at room temperature for 15 minutes. Water is added to stop the reaction. An aqueous solution of hydrochloric acid (1M) is added. The two layers are separated and the aqueous one is extracted twice with dichloromethane. The combined organic layers are washed with brine, dried over $MgSO_4$ and concentrated under reduced pressure.
The product crude product obtained is purified by flash chromatography over silica gel.

Eluent for purification depends on the nature of the compound and are reported in the description of each product.

9.4.17.2. Product descriptions

9.4.17.2.1. 1,3-Diethyl 2-[(3E)-4-phenyl-2-[(*E*)-2-phenylethenyl]but-3-en-1-ylidene]propanedioate (**196aa**)
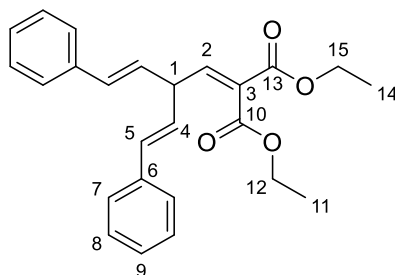
Chemical Formula: $C_{25}H_{26}O_4$
Molecular Weight: 390.48

Eluent for purification: *n*-hexane/AcOEt (82/18)
Yield: 80%
Aspect: Yellow oil

[1H](^{1}H) NMR (300 MHz, CDCl$_3$): δ= 7.43 to 7.13 (m, 10H, H^{arom}), 7.03 (d, 1H, *J = 1*0.1 Hz, H^2), 6.94 (m, 1H, H^1), 6.53 (dd, 2H, *J = 1*6.0, 1.3 Hz, H^5), 6.24 (dd, 2H, *J = 1*6.0, 6.7 Hz, H^4), 4.31 (m, 4H, H^{12,15}), 1.34 (m, 6H, H^{11,14}),

^{13}C NMR (75 MHz, CDCl$_3$): δ= 165.6, 183.3, 147.4, 137.1, 136.4, 132.5, 130.0, 128.9, 128.4, 128.3, 128.1, 127.9, 127.0, 126.7, 61.9, 61.8, 45.9, 14.5, 14.5

HRMS (APCI): Calculated for C$_{25}$H$_{27}$O$_4$: 391.19039, found: 391.19035.

9.4.17.2.2. Diethyl *(E)*-2-(4-methyl-2-styrylpent-3-en-1-ylidene)malonate (**196ba**)
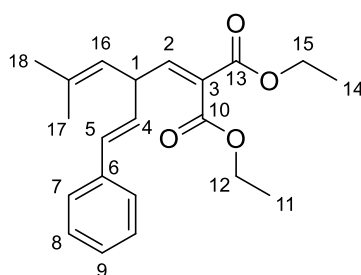
Chemical Formula: C$_{21}$H$_{26}$O$_4$
Molecular Weight: 342.44

Eluent for purification: *n*-hexane/AcOEt (82/18)
Yield: 54%
Aspect: Yellow oil

^{1}H NMR (300 MHz, CDCl$_3$) δ 7.41 − 7.18 (m, 5H, H^{arom}), 6.88 (d, *J* = 10.2 Hz, 1H, H^2) 6.43 (dd, *J* = 16.0, 1.3 Hz, 1H, H^5), 6.10 (dd, *J* = 16.0, 6.1 Hz, 1H, H^4), 5.21 − 5.13 (m, 1H, H^{16}), 4.39 − 4.20 (m, 4Hh $^{H12 \, and \, 15}$), 1.77 (d, *J* = 1.2 Hz, 3H, H$^{18 \, or \, 17}$), 1.68 (d, *J* = 1.2 Hz, 3H, H$^{17 \, or \, 18}$), 1.35 (t, *J* = 7.1 Hz, 3H, H$^{14 \, or \, 11),}$ 1.31 (t, *J* = 7.1 Hz, 3H, H$^{11 \, or \, 14}$), *H^1 is hidden by the H$^{12 \, and \, 15}$ signal.*

^{13}C NMR (75 MHz, CDCl$_3$) δ 165.7, 183.3, 148.5, 137.2, 135.6, 130.9, 129.2, 128.7, 127.6, 126.9, 126.4, 122.2, 61.5, 42.1, 26.1, 18.35, 14.35, 14.28.

9.4.18. Synthesis of cycloheptadienes

9.4.18.1. Diethyl 4,5-diphenylcyclohepta-2,6-diene-1,1-dicarboxylate (197aa)
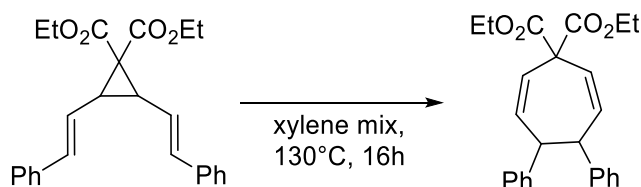
Divinylcyclopropane (1 eq.) and xylene mix (1 mL/10mg of vinylcyclopropane) are introduced in a round-bottom flask with a condenser. Then, the reaction mixture is heated up to 130°C (reflux) and the agitation is maintained overnight. Then, the solvent is removed under vaccum and the product crude product obtained is purified by flash chromatography over silica gel.
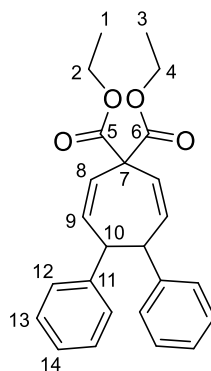
Chemical Formula : $C_{25}H_{26}O_4$
Molecular Weight : 390.48

Eluent for purification: *n*-hexane/AcOEt (90/10)
Yield: 22%
Aspect: Yellow oil

^{1}H NMR (300 MHz, CDCl$_3$): δ= 7.23 − 7.09 (m, 6H, H^{arom}), 6.88 − 6.76 (m, 4H, H^{arom}), 6.15 (d, J = 11.7 Hz, 1H, H^8), 6.02 (dd, J = 11.7, 6.2 Hz, 1H, H^9), 4.34 (q, J = 7.1 Hz, 2H, H$^{4\,or\,2}$), 4.25 (q, J = 7.1 Hz, 2H, H$^{2\,or\,4}$), 4.10 (bs, 2H, H^{10}), 1.35 (t, J = 7.1 Hz, 3H, H$^{3\,or\,1}$), 1.27 (t, J = 7.1 Hz, 3H, H$^{1\,or\,3}$).

^{13}C NMR (75 MHz, CDCl$_3$) δ 170.9, 168.8, 140.0, 136.2, 129.8, 127.7, 126.8, 126.4, 62.4, 62.2, 61.2, 49.5, 14.2, 14.2.

HRMS (APCI): Calculated for $C_{25}H_{27}O_4$: 391.19039, found: 391.19035

9.5. HPLC analysis

9.5.1. Separation and analysis of **187aa**

An analytical method has been developed from a mixture of the four possible isomers of **187aa**.
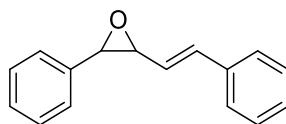
187aa

Column: CHIRALKPAK IA
Flow rate: 1 mL/min
Eluent: isohexane/ethanol (95/5)
Mode: isocratic
Injected volume: 5 μL

Observed chromatogram
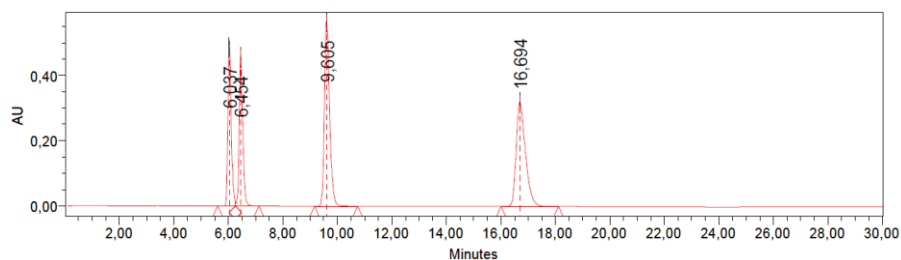
	RT	Area	% Area	Height
1	6,037	4221845	17,86	487472
2	6,454	4262399	18,04	458263
3	9,605	7576616	32,06	565921
4	16,694	7572963	32,04	318574

The analytical method was then used to determine the e.r. of **187aa-*trans*** obtained with the chiral sulfonium salt.

Observed chromatogram
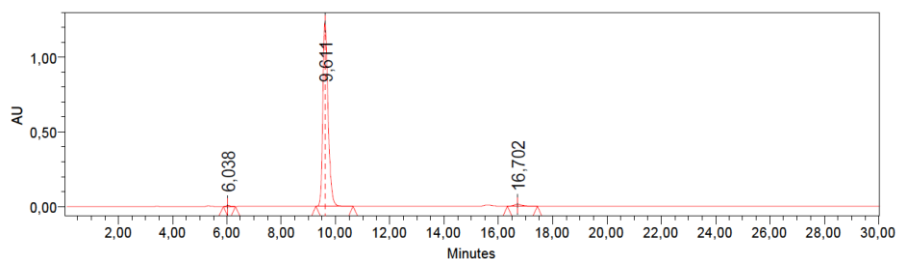
	RT	Area	% Area	Height
1	6,038	63788	0,37	7312
2	9,611	16814681	97,92	1236655
3	16,702	293279	1,71	13035

9.5.2. Separation and analysis of **192aa**

An analytical method has been developed from a racemic mixture of **192aa**.
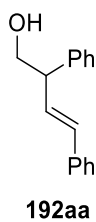
192aa

Column: CHIRALKPAK IB
Flow rate: 1 mL/min
Eluent: isohexane/isopropanol (95/5)
Mode: isocratic
Injected volume: 5 µL
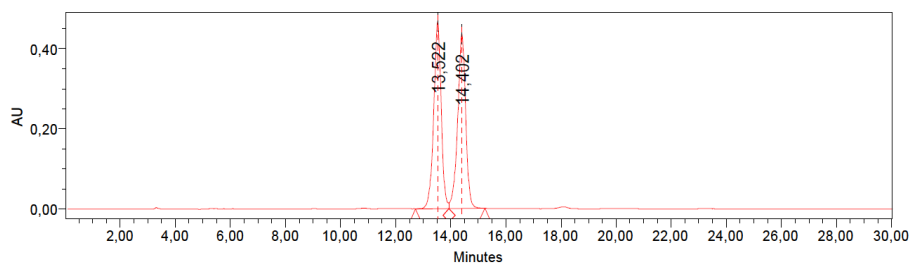
Observed chromatogram

	RT	Area	% Area	Height
1	13,522	8819106	49,94	466467
2	14,402	8841949	50,06	435872

The analytical method was then used to determine the e.r. of **192aa**

Observed chromatogram
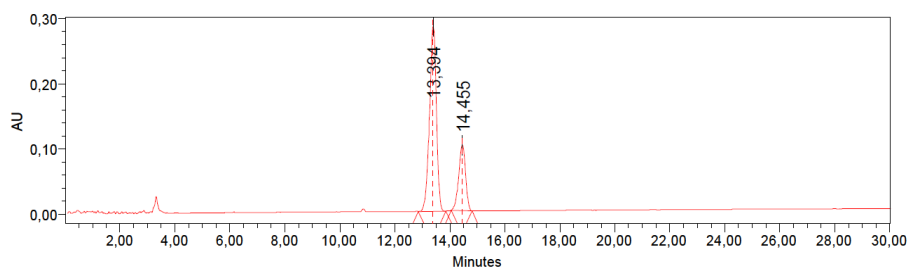
	RT	Area	% Area	Height
1	13,394	4943030	73,75	284141
2	14,455	1759278	26,25	100557

9.5.3. Separation and analysis of **192af**

An analytical method has been developed from a racemic mixture of **192af**.
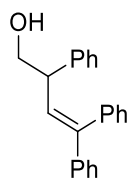
192af

Column: CHIRALKPAK IB
Flow rate: 1 mL/min
Eluent: isohexane/ethanol (95/5)
Mode: isocratic
Injected volume: 5 µL

Observed chromatogram
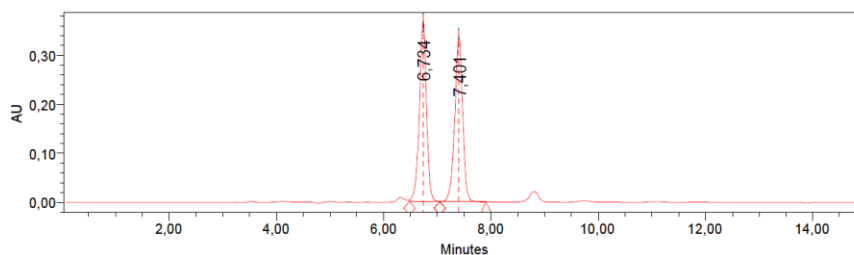
	RT	Area	% Area	Height
1	6,734	3459906	50,10	368452
2	7,401	3446773	49,90	336885

The analytical method was then used to determine the e.r. of **192af**

Observed chromatogram
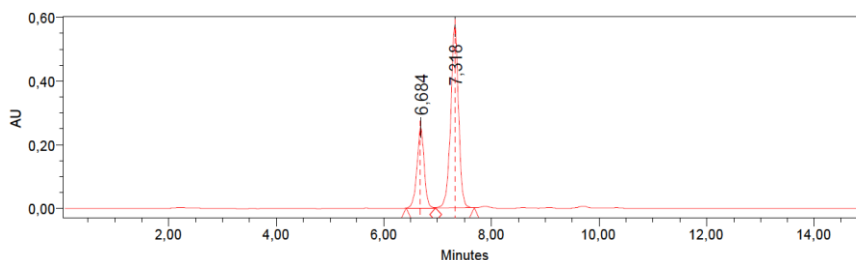
	RT	Area	% Area	Height
1	6,684	2352869	28,88	253631
2	7,318	5793348	71,12	572682

9.5.4. Separation and analysis of **194ka**

An analytical method has been developed from a racemic mixture of **194ka**.
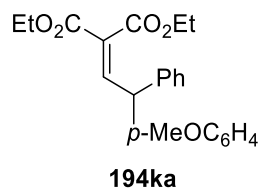
194ka

Column: CHIRALKPAK IA
Flow rate: 1 mL/min
Eluent: isohexane/isopropanol (95/5)
Mode: isocratic
Injected volume: 5 µL

Observed chromatogram
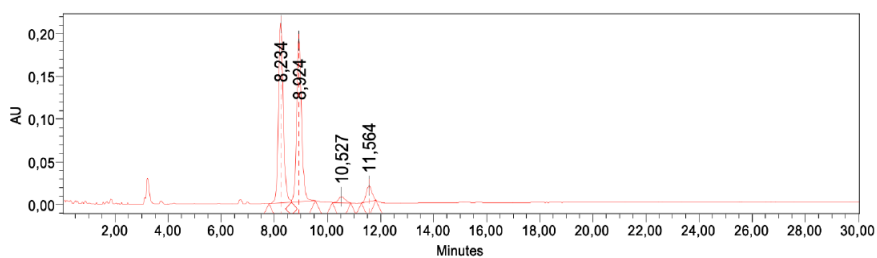
	RT	Area	% Area	Height
1	8,234	2635571	47,59	211368
2	8,924	2509877	45,32	188858
3	10,527	120243	2,17	7020
4	11,564	272665	4,92	18665

The analytical method was then used to determine the e.r. of **194ka**

Observed chromatogram
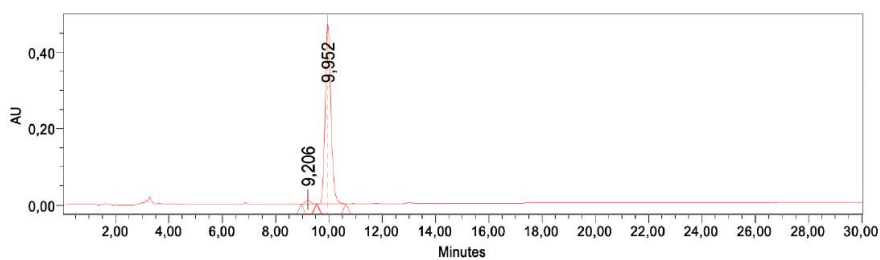
	RT	Area	% Area	Height
1	9,206	131216	1,82	10748
2	9,952	7077793	98,18	472494

Chapter 10: Computational details

10.1. Methods

Calculations were carried out using the Jaguar 8.5 program package.[122] Geometry optimisations were performed at the M06-2X/6-31+G(d) level of theory. The basis set was used for every atoms except for Ti for which LACV3P was used. Solvent effects were modelled by using the polarizable continuum-Poisson method as incorporated in Jaguar, using the parameters for dichloromethane, i.e. a dielectric constant of 2.33 and a solvent probe radius of 8.93 Å.

The stationary points were characterised by full calculation of vibrational frequencies at the M06-2X/6-31+G(d)(CH_2Cl_2) level using ultrafine grids. These frequency calculations provided also thermal and entropic contributions to free energy. In Jaguar, the translational partition function is computed for ideal gas standard conditions, corresponding to a pressure of 1 atm at 298.15 K. For solution reactions, the standard condition is instead 1 mol/L. Accordingly, the free energy value computed in Jaguar was corrected by a concentration term, equal to RT ln (V_mol_gas_1 atm/V_mol_1M), i.e. 1.89 kcal/mol at 298.15 K.

In order to determine the most suitable method for describing the studied system, benchmark calculations were performed (see 11.2). According to these results, gas phase electronic energies were obtained after corresponding fully analytical single point calculations, at the M06-2X/6-311+G(d,p) level of theory.

We have made a systematic attempt to locate all possible local minima (at the M06-2X/6- 31+G(d) level), with the data presented referring to the lowest energy form.

10.2. Benchmark calculations

Experimental observations show 95% conversion of VCP **179aa** into skipped diene **1 8 1 aa** in less than 15 min at room temperature (see Chapter 2). According to Eyring equation, this indicates that

$\Delta G_{mig}^{\ddagger} < 21$ kcal/mol. The total kinetic selectivity for skipped diene at room temperature indicates also that $\Delta G_{cycl}^{\ddagger} - \Delta G_{mig}^{\ddagger} > 2$ kcal/mol. The slow conversion of skipped diene **181aa** into cyclopentene **180aa** (full conversion after 24 h at room temperature) suggests that $\Delta G_{cycl}^{\ddagger}$ ~ 23-24 kcal/mol.

Table 10.1: Benchmark calculations (Free energies relative to **179aa-co-*trans*-TiCl₄** in kcal/mol)

| Method[a] | Ring-opening 182aa-co-*trans-E*-TiCl₄ | Ph migration | | Cyclisation | | $\Delta G_{cycl}^{\ddagger} - \Delta G_{mig}^{\ddagger}$ |
		TS$_{mig}$aa-co-*trans-E*	181aa-co-TiCl₄	TS$_{cycl}$aa-co-*trans-Z*	180aa-co-cis-TiCl₄	
B3LYP-D3/6-311+G**	3.8	15.8	-1.6	13.4	-5.0	-2.4
B3LYP-D3/6-311+G**[b]	3.9	14.4	-2.5	13.2	-5.8	-2.2
B3LYP-D3/Def2-TZVPP[c]	4.2	16.0	-2.7	13.1	-5.5	-2.9
B3LYP/6-311+G**	4.7	14.9	-3.6	21.2	-3.6	6.3
BP86-D3/6-311+G**	3.8	13.3	0.1	13.3	-7.5	0.0
B-97-D3/6-311+G**	2.6	13.3	-2.2	11	-2.0	-2.3
M06-2X/6-31+G*	13.4	19.7	3.8	24	-4.3	4.3
M06-2X/6-311+G**	**13.4**	**20.0**	**3.4**	**22.8**	**-5.2**	**2.8**
M06-2X/6-311+G**[d]	13.6	20.0	4.2	23	-5.2	3.0
M06-2X/cc-pVTZ[b]	13.8	20.1	2.6	24.4	-3.1	4.3
SC5-MP2/6-311+G**[c]	17.5	23.6	2.6	21.6	-13.4	-2.0

[a] Geometry optimisations and frequency calculations were performed at the M06-2X/6-31+G* level, unless mentioned otherwise. All free energies include solvation energy obtained at this level. [b] Optimisation at the B3LYP-D3/6-31+G* level. [c] Obtained using ORCA 4.1.0. [d] 6-311+G** on Ti

10.3. Carthesian coordinates and energy values

10.3.1. Rearrangement of VCPs

10.3.1.1. R^1 = Ph, R^3 = Ph

10.3.1.1.1. 179aa-co-trans-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -3011.685903
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3012.11223
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3011.801008

C -0.95900 -0.40000 -0.19710
C 0.48060 -0.50930 0.08510
C -0.18060 0.92330 0.06430
H 1.12410 -0.61350 -0.78640
C 0.16820 1.78430 -1.09600
O 0.60420 1.14470 -2.14260
O 0.06190 3.01660 -1.11830
C 0.90470 1.92080 -3.33120
C -0.45400 1.62820 1.33760
O -0.75220 0.85440 2.34320
O -0.41500 2.85600 1.48570
C -1.06630 1.49460 3.60830
C 2.33930 -1.35210 1.45740
C 1.02770 -1.10360 1.32770
H 0.31910 -1.35650 2.11150
H 3.00440 -1.07220 0.63720
C 4.38800 -3.06290 4.80920
C 5.09630 -2.54460 3.72500
C 4.40940 -2.00030 2.63970
C 3.00700 -1.96020 2.62120
C 2.30460 -2.49400 3.71510
C 2.98960 -3.03750 4.79810
H 4.91880 -3.48800 5.65720
H 6.18330 -2.56340 3.72260
H 4.96510 -1.59540 1.79550
H 1.21730 -2.49680 3.72230
H 2.43230 -3.44680 5.63700
H -1.32930 0.67870 4.27870

H -0.18900 2.03570 3.96620
H -1.90720 2.17550 3.46810
H 1.23640 1.18890 -4.06490
H 0.00260 2.43590 -3.66570
H 1.69510 2.63790 -3.10500
H -1.61170 -0.62280 0.64790
C -2.77340 -1.19090 -4.00600
C -3.28650 -0.19130 -3.17580
C -2.68820 0.06700 -1.94320
C -1.56740 -0.66580 -1.53920
C -1.05750 -1.66740 -2.36820
C -1.66140 -1.93020 -3.59910
H -3.24180 -1.39480 -4.96570
H -4.15410 0.38500 -3.48670
H -3.09070 0.84130 -1.29200
H -0.20420 -2.24720 -2.05260
H -1.26350 -2.71320 -4.23970
Ti -0.54210 4.50390 0.21400
Cl -0.60720 5.98920 -1.46900
Cl -1.20580 5.79120 1.93360
Cl 1.70220 4.74520 0.63210
Cl -2.67580 3.66480 -0.20940

10.3.1.1.2. 179aa-co-cis-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -3011.68344
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3012.10969
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3011.797506

C -0.97240 -0.58179 0.30830
C 0.49890 -0.52570 0.45770
C -0.31720 0.80830 0.18320
H -1.30030 -0.93620 -0.66710
H 1.07300 -0.81890 -0.41970
C -3.80930 -1.67740 3.34350
C -2.62960 -2.40600 3.19150
C -1.69500 -2.03140 2.22360
C -1.93400 -0.92360 1.40660
C -3.12680 -0.20720 1.54960
C -4.05850 -0.57850 2.51650
H -4.53690 -1.96790 4.09720
H -2.43590 -3.27020 3.82230
H -0.78320 -2.61190 2.09650
H -3.32770 0.64680 0.90370

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H -4.98070 -0.01270 2.62380
C -0.17960 1.33179 -1.21720
O -0.29910 0.43450 -2.15450
O 0.10190 2.50420 -1.51010
C -0.08810 0.86140 -3.52680
C -0.38410 1.83170 1.23530
O -0.71130 1.39190 2.41520
O -0.14510 3.03440 1.06230
C -0.76490 2.35410 3.50190
C 2.50520 -1.04320 1.78800
C 1.20850 -0.70140 1.74220
H 0.63470 -0.56830 2.65400
H 3.05620 -1.14120 0.85040
C 4.86200 -1.75180 5.29890
C 5.46630 -1.59900 4.05020
C 4.68340 -1.37760 2.91670
C 3.28580 -1.29600 3.01220
C 2.68900 -1.46320 4.27400
C 3.46910 -1.68600 5.40520
H 5.46850 -1.92810 6.18370
H 6.54800 -1.65410 3.95690
H 5.15970 -1.26010 1.94440
H 1.60690 -1.43590 4.37770
H 2.98960 -1.81650 6.37280
H -1.06630 1.77490 4.37240
H 0.22220 2.79750 3.64240
H -1.50230 3.12330 3.26840
H -0.24940 -0.03360 -4.12400
H -0.81010 1.63960 -3.77650
H 0.93220 1.23310 -3.63560
Ti 0.78170 4.15430 -0.43150
Cl 1.69990 5.01460 -2.29390
Cl 1.37630 5.70400 1.08280
Cl 2.60220 2.76140 0.02090
Cl -1.31320 5.00750 -0.80770

10.3.1.1.3. 181aa-co-TiCl₄

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3011.681851
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3012.109104
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3011.798809

C -0.76990 1.09510 -0.61070
C -0.00740 0.10640 -0.08820

C 1.48760 -0.04260 -0.03179
C 1.80950 -1.19300 -0.95940
C 2.57240 -1.04650 -2.05000
C 2.93100 -2.09640 -3.02100
C -2.24190 1.02750 -0.42850
C -0.25470 2.31870 -1.27070
O 0.90620 2.20340 -1.85220
O -0.87220 3.38980 -1.30260
C 1.45510 3.39250 -2.48250
O -2.98420 2.01780 -0.43030
O -2.72370 -0.16870 -0.24500
C -4.14340 -0.28300 0.03870
C 2.31000 -3.35640 -3.04570
C 2.69170 -4.31410 -3.98140
C 3.69610 -4.03130 -4.91260
C 4.31460 -2.78090 -4.90280
C 3.93179 -1.82180 -3.96510
C 1.91500 -0.27580 1.41860
C 2.83140 -1.27270 1.76320
C 3.24330 -1.42440 3.08910
C 2.74260 -0.58210 4.08230
C 1.82800 0.41780 3.74480
C 1.41860 0.56890 2.42030
H -0.54800 -0.71250 0.39000
H 1.98810 0.85440 -0.40270
H 1.37920 -2.15870 -0.69050
H 3.00460 -0.06350 -2.24730
H 2.43770 3.09170 -2.84090
H 0.80850 3.69290 -3.30850
H 1.53410 4.19300 -1.74510
H -4.31560 -1.34940 0.17000
H -4.37430 0.26930 0.95120
H -4.71330 0.10990 -0.80450
H 1.51540 -3.59040 -2.34100
H 2.20030 -5.28370 -3.99040
H 3.98850 -4.78090 -5.64370
H 5.09330 -2.55020 -5.62540
H 4.41690 -0.84730 -3.96010
H 3.23470 -1.92980 0.99670
H 3.95910 -2.20200 3.34430
H 3.06480 -0.70200 5.11360
H 1.43660 1.08190 4.51150
H 0.71450 1.35960 2.18270
Ti -2.61730 4.08100 -0.35740
Cl -1.82760 6.18090 -0.43360
Cl -4.57210 4.40140 0.69670

Cl -1.45740 3.55320 1.60280
Cl -3.49210 4.09980 -2.46730

10.3.1.1.4. 180aa-co-*cis*-TiCl₄

E(M06-2X/6-31+G(d)(CH₂Cl₂)) =
-3011.696955
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-3012.124818
G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-3011.812499

C 0.96790 -0.00760 1.15660
C -0.33010 0.00940 1.44280
C -1.22120 0.25780 0.25310
C -0.17880 0.20390 -0.97400
C 1.28200 0.22480 -0.29900
H -1.91810 -0.58300 0.12360
H -0.75950 -0.13170 2.43220
H 1.76950 -0.16590 1.87480
C -3.61880 3.85250 0.40300
C -3.96580 2.80280 -0.44960
C -3.20010 1.63630 -0.46550
C -2.07210 1.51280 0.35290
C -1.73640 2.56410 1.21080
C -2.50750 3.72650 1.23870
H -4.21510 4.76140 0.42100
H -4.83500 2.88820 -1.09690
H -3.47720 0.81790 -1.12780
H -0.86060 2.48410 1.85040
H -2.23670 4.53720 1.91070
C -0.35020 -1.15530 -1.63680
O -0.16890 -2.14430 -0.80850
O -0.63530 -1.37710 -2.81510
C -0.31800 -3.49260 -1.32560
C -0.38090 1.34260 -1.96040
O -0.24640 2.51360 -1.42850
O -0.64680 1.22740 -3.18140
C -0.41590 3.67330 -2.27600
H -0.25980 4.52410 -1.61830
H 0.32890 3.64870 -3.07390
H -1.42550 3.67350 -2.69130
H -0.13070 -4.14080 -0.47179
H -1.32930 -3.62460 -1.70860
H 0.41810 -3.65940 -2.11560
H 1.83700 -0.63220 -0.70380
C 3.61200 3.75740 -1.18820

C 3.52930 2.71080 -2.10880
C 2.79800 1.56450 -1.79610
C 2.12670 1.45840 -0.57280
C 2.22120 2.50630 0.34740
C 2.96340 3.64830 0.04320
H 4.18480 4.65020 -1.42680
H 4.03900 2.78300 -3.06620
H 2.74120 0.74810 -2.51450
H 1.70340 2.43990 1.30130
H 3.03110 4.45610 0.76790
Ti -0.99330 -0.27380 -4.55960
Cl -1.29640 -2.17440 -5.72540
Cl -1.30920 1.25790 -6.16740
Cl 1.30700 -0.31760 -4.76790
Cl -3.16660 -0.20680 -3.78390

10.3.1.1.5. 180aa-co-*trans*-TiCl₄

E(M06-2X/6-31+G(d)(CH₂Cl₂)) =
-3011.701571
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-3012.12909
G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-3011.816648

C 0.88580 -0.17060 1.09030
C -0.43950 -0.07730 1.17740
C -1.08620 0.28550 -0.14179
C 0.08410 0.03030 -1.18350
C 1.40030 0.10680 -0.30540
H -1.91820 -0.38790 -0.37890
H 1.75710 1.14420 -0.36480
H -1.02540 -0.17530 2.08820
H 1.56280 -0.37360 1.91660
C 4.60860 -2.42680 -1.71050
C 4.53090 -1.09290 -2.11730
C 3.50100 -0.27800 -1.64830
C 2.53440 -0.78390 -0.77220
C 2.62340 -2.11910 -0.36300
C 3.65390 -2.93740 -0.82990
H 5.41460 -3.06130 -2.07150
H 5.27660 -0.68580 -2.79610
H 3.43800 0.76110 -1.96630
H 1.88290 -2.52380 0.32540
H 3.71310 -3.97190 -0.49960
C -2.62730 4.33570 -0.19820
C -3.39530 3.27940 -0.69100

C -2.89120 1.97840 -0.66730
C -1.62030 1.71170 -0.14650
C -0.85920 2.77780 0.34950
C -1.35600 4.08150 0.32010
H -3.01870 5.35010 -0.21300
H -4.38880 3.46650 -1.09180
H -3.48980 1.15710 -1.05740
H 0.12700 2.59030 0.76990
H -0.75210 4.89800 0.70890
C -0.05230 -1.38120 -1.74420
O 0.59030 -1.50180 -2.90240
O -0.62770 -2.29540 -1.19350
C 0.64530 -2.82179 -3.46770
C 0.07270 1.04940 -2.29960
O -1.02580 0.91540 -3.04250
O 0.91400 1.90060 -2.48700
C -1.22280 1.89810 -4.07180
H -2.18220 1.63360 -4.55410
H -1.28540 2.89330 -3.62390
H -0.39890 1.86380 -4.78830
H 1.20090 -2.71890 -4.39870
H 1.18270 -3.49390 -2.77950
H -0.36460 -3.19090 -3.65890

10.3.1.1.6. 182aa-co-*trans-E*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3011.665887
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3012.092816
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3011.784089

C -0.36920 -1.17730 -0.28710
C 0.99179 -1.70900 0.02830
C -0.39840 0.27300 -0.72340
H 1.04620 -2.77570 0.25880
C 0.15420 0.67270 -1.95530
O 0.71410 -0.28090 -2.68430
O 0.18340 1.85450 -2.42080
C 1.24130 0.09020 -3.97310
C -1.05000 1.25990 0.04060
O -1.69630 0.85790 1.12890
O -1.07740 2.50070 -0.22800
C -2.36090 1.86740 1.91460

C 3.34540 -1.57010 0.46580
C 2.13179 -0.95700 0.10950
H 2.08510 0.10840 -0.10320
H 3.32520 -2.64180 0.68060
C 7.12230 0.26560 0.76430
C 6.98360 -1.10200 1.03380
C 5.73430 -1.69530 0.93400
C 4.60430 -0.92080 0.56280
C 4.76490 0.46570 0.29550
C 6.01790 1.04710 0.39630
H 8.10250 0.73140 0.84040
H 7.85120 -1.69070 1.31770
H 5.60810 -2.75690 1.13860
H 3.91350 1.07850 0.01220
H 6.14340 2.10620 0.19110
H -2.77690 1.33350 2.76800
H -1.64340 2.62180 2.24040
H -3.15360 2.33460 1.32730
H 1.66800 -0.82600 -4.37980
H 0.43680 0.45720 -4.61370
H 2.00710 0.85960 -3.85820
Ti -0.05440 3.61370 -1.52370
Cl 1.26360 4.59980 -3.13470
Cl -0.36910 5.46150 -0.18510
Cl 1.88580 2.97820 -0.25630
Cl -2.00010 3.97010 -2.71480
H -0.86670 -1.21940 0.69960
C -2.73330 -3.76450 -2.83770
C -3.34750 -2.91460 -1.91400
C -2.57120 -2.09800 -1.09350
C -1.17470 -2.11480 -1.18870
C -0.56720 -2.96290 -2.11790
C -1.34220 -3.78730 -2.93630
H -4.43130 -2.89000 -1.83070
H -3.05300 -1.43770 -0.37390
H 0.51790 -2.96980 -2.22300
H -0.85590 -4.44070 -3.65680
H -3.33700 -4.40310 -3.47760

10.3.1.1.7. 182aa-co-*trans-Z*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3011.656945
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3012.082955

G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-3011.773708

C -1.68570 -1.44420 0.50110
C -0.21760 -1.42120 0.25130
C -2.39760 -0.15000 0.17320
H 0.07330 -1.05950 -0.73500
C -1.75140 1.09720 0.15620
O -0.45950 1.10970 0.47550
O -2.29480 2.21179 -0.11230
C 0.22730 2.37650 0.43710
C -3.80560 -0.14340 0.05190
O -4.42490 -1.28100 0.32000
O -4.51560 0.85580 -0.26880
C -5.85230 -1.32550 0.12240
C 0.56870 -2.35860 2.35450
C 0.78850 -1.95870 1.04000
H 1.77690 -2.04230 0.59580
H -6.13930 -2.34790 0.36300
H -6.34640 -0.61700 0.78950
H -6.09220 -1.09070 -0.91820
H 1.26600 2.14130 0.66520
H 0.13920 2.82179 -0.55560
H -0.19110 3.04780 1.18950
Ti -4.05330 2.68000 -0.92650
Cl -3.19900 4.70930 -1.60600
Cl -6.16610 2.88570 -1.81940
Cl -4.71550 3.52660 1.13980
Cl -3.25220 1.60640 -2.87360
H -1.92230 -1.77350 1.51880
C -2.65050 -4.74010 -2.15640
C -2.51170 -3.44980 -2.67179
C -2.20290 -2.38630 -1.82410
C -2.04190 -2.60940 -0.45270
C -2.17940 -3.90480 0.05840
C -2.47480 -4.96610 -0.78870
H -2.89320 -5.56790 -2.81800
H -2.64630 -3.26850 -3.73490
H -2.11060 -1.37860 -2.22530
H -2.02890 -4.08310 1.12470
H -2.58360 -5.96870 -0.38250
H -0.40910 -2.18260 2.79690
C 3.22920 -4.29390 4.99870
C 1.94270 -3.94250 5.42170
C 1.08680 -3.29520 4.54150
C 1.50940 -2.99230 3.22420

C 2.81690 -3.35300 2.81250
C 3.66480 -3.99820 3.69770
H 3.90110 -4.80360 5.68560
H 1.61820 -4.17650 6.43100
H 0.08220 -3.01720 4.85600
H 3.17960 -3.13430 1.80530
H 4.66660 -4.27860 3.38470

10.3.1.1.8. 182aa-co-*cis*-*E*-TiCl₄

E(M06-2X/6-31+G(d)(CH₂Cl₂)) =
-3011.663934
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-3012.089969
G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-3011.779569

C -0.55760 -0.92380 0.36690
C 0.74170 -1.52450 0.79610
C -0.34630 0.40080 -0.34230
H 1.42050 -0.85580 1.33230
C 0.67910 0.59680 -1.28270
O 1.48040 -0.44130 -1.50960
O 0.89750 1.65680 -1.94179
C 2.53960 -0.27010 -2.47100
C -1.30400 1.42860 -0.19830
O -2.33270 1.16920 0.59350
O -1.27130 2.55440 -0.77850
C -3.34530 2.18760 0.72290
C 2.35450 -3.27020 1.07600
C 1.11170 -2.83370 0.60840
H 0.45020 -3.49930 0.06320
H 2.95810 -2.55480 1.64030
C 4.13960 -7.04780 0.49800
C 4.80240 -6.06020 1.23550
C 4.20060 -4.82350 1.42220
C 2.92140 -4.56190 0.87180
C 2.26360 -5.57670 0.12830
C 2.87220 -6.80610 -0.05460
H 4.61220 -8.01790 0.34920
H 5.78310 -6.26150 1.65640
H 4.70550 -4.04470 1.99100
H 1.28490 -5.40200 -0.30850
H 2.37060 -7.58179 -0.62690
H -4.08980 1.76090 1.39330
H -2.91179 3.09430 1.14880
H -3.78300 2.40420 -0.25320

H 3.05900 -1.22730 -2.49320
H 2.12179 -0.03770 -3.45260
H 3.21090 0.52930 -2.15180
Ti 0.11940 3.49100 -1.86240
Cl 1.90110 4.27940 -3.09130
Cl -0.98220 5.48710 -1.55460
Cl 1.30630 3.74350 0.18220
Cl -1.11800 2.97210 -3.76830
H -1.02310 -0.66770 1.33890
C -3.19590 -3.75600 -1.57770
C -3.21280 -3.60830 -0.18980
C -2.36520 -2.68410 0.42430
C -1.49640 -1.89660 -0.33850
C -1.48630 -2.04910 -1.72850
C -2.33060 -2.97380 -2.34500
H -3.89080 -4.20530 0.41510
H -2.38820 -2.56640 1.50710
H -0.82490 -1.44010 -2.33940
H -2.31670 -3.07780 -3.42720
H -3.85850 -4.47040 -2.06000

10.3.1.1.9. 182aa-co-*cis-Z*-TiCl₄

$E(\text{M06-2X/6-31+G(d)(CH}_2\text{Cl}_2)) =$
-3011.654119
$E(\text{M06-2X/6-311+G(d,p)(CH}_2\text{Cl}_2)) =$
-3012.080808
$G(\text{M06-2X/6-311+G(d,p)(CH}_2\text{Cl}_2)) =$
-3011.770513

C -1.51780 -1.40860 0.37020
C -0.10590 -1.55110 -0.10880
C -2.32830 -0.16700 0.05950
H 0.47240 -2.21710 0.53530
C -1.76570 1.12290 0.03960
O -0.47550 1.22330 0.33660
O -2.38450 2.19950 -0.23060
C 0.10990 2.54100 0.31750
C -3.74460 -0.20870 0.10780
O -4.30090 -1.33360 0.51810
O -4.51780 0.75560 -0.17830
C -5.74080 -1.41090 0.50820
C 0.02900 -0.30730 -2.22910
C 0.56520 -1.14030 -1.24790
H 1.57430 -1.52650 -1.36480
H -5.97110 -2.42180 0.84130
H -6.15930 -0.67240 1.19420

H -6.11710 -1.23930 -0.50230
H 1.16620 2.38510 0.53220
H -0.02740 2.99950 -0.66400
H -0.35150 3.18340 1.08570
Ti -4.19080 2.53450 -1.00070
Cl -3.42690 4.48790 -1.94810
H 2.24850 -2.79980 5.60430
H -3.68520 -0.93070 3.38790
H -2.50260 0.38620 3.70010
H -4.03390 0.74600 2.84850
H 0.73700 1.51370 -3.71020
H -0.35179 2.78310 -3.05980
H 1.20020 2.43650 -2.23960
Ti -0.78810 3.33550 1.30910
Cl 0.69350 4.96300 0.65440
Cl -1.02440 3.94890 3.50810
Cl 0.98280 1.84110 1.83820
Cl -2.63420 4.53970 0.62150
H -1.90490 -1.78200 0.15130
C -2.78850 -2.34930 -4.47790
C -3.22690 -1.15530 -3.90250
C -2.74570 -0.75860 -2.65500
C -1.82620 -1.55400 -1.96790
C -1.39330 -2.75200 -2.54500
C -1.86850 -3.14820 -3.79570
H -3.18130 -2.65580 -5.45140
H -3.94280 -0.52700 -4.42780
H -3.08880 0.17540 -2.21570
H -0.68600 -3.38780 -2.01170
H -1.52400 -4.08190 -4.23350

10.3.1.1.10. TS_{open}aa-co-*trans-E*

$E(\text{M06-2X/6-31+G(d)(CH}_2\text{Cl}_2)) =$
-3011.6624154
$E(\text{M06-2X/6-311+G(d,p)(CH}_2\text{Cl}_2)) =$
-3012.089112
$G(\text{M06-2X/6-311+G(d,p)(CH}_2\text{Cl}_2)) =$
-3011.779676

C -1.33410 -1.19590 -0.57710
C 0.12040 -1.39530 -0.32260
C -1.41450 0.26030 -0.14090
H 0.80780 -1.06910 -1.10490
C -0.78800 1.29930 -0.87670
O -0.26480 0.96460 -2.04400

O -0.70870 2.50880 -0.51530
C 0.37410 2.00720 -2.81000
C -2.01050 0.60800 1.10120
O -2.64240 -0.35400 1.75370
O -1.99700 1.76020 1.61910
C -3.25650 -0.00250 3.01280
C 2.00040 -1.65620 1.11680
C 0.63790 -1.82130 0.88440
H -0.03650 -2.17440 1.66140
H 2.60660 -1.29810 0.28110
C 4.09410 -2.05740 4.75780
C 4.74910 -1.58480 3.61580
C 4.05280 -1.48470 2.41840
C 2.68770 -1.85000 2.35540
C 2.03980 -2.33040 3.52030
C 2.74330 -2.43360 4.70890
H 4.63740 -2.13310 5.69700
H 5.79490 -1.29530 3.66710
H 4.54660 -1.11130 1.52270
H 0.99460 -2.62620 3.49170
H 2.24850 -2.79980 5.60430
H -3.68520 -0.93070 3.38790
H -2.50260 0.38620 3.70010
H -4.03390 0.74600 2.84850
H 0.73700 1.51370 -3.71020
H -0.35179 2.78310 -3.05980
H 1.20020 2.43650 -2.23960
Ti -0.78810 3.33550 1.30910
Cl 0.69350 4.96300 0.65440
Cl -1.02440 3.94890 3.50810
Cl 0.98280 1.84110 1.83820
Cl -2.63420 4.53970 0.62150
H -1.90490 -1.78200 0.15130
C -2.78850 -2.34930 -4.47790
C -3.22690 -1.15530 -3.90250
C -2.74570 -0.75860 -2.65500
C -1.82620 -1.55400 -1.96790
C -1.39330 -2.75200 -2.54500
C -1.86850 -3.14820 -3.79570
H -3.18130 -2.65580 -5.45140
H -3.94280 -0.52700 -4.42780
H -3.08880 0.17540 -2.21570
H -0.68600 -3.38780 -2.01170
H -1.52400 -4.08190 -4.23350

10.3.1.1.11. TS$_{open}$aa-co-*trans-Z*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3011.6560786
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3012.081895
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3011.77284

C -1.36990 -1.22450 0.52990
C 0.08970 -1.37620 0.26090
C -1.92820 0.09920 0.04740
H 0.41010 -1.04600 -0.72880
C -1.16810 1.27680 0.15100
O 0.04950 1.14910 0.67600
O -1.54100 2.44340 -0.17700
C 0.86670 2.33320 0.76310
C -3.28910 0.25200 -0.30520
O -4.08170 -0.78790 -0.11480
O -3.81070 1.31210 -0.76530
C -5.45490 -0.66780 -0.53610
C 0.78820 -2.44560 2.33470
C 1.03760 -2.03460 1.02830
H 2.00530 -2.21790 0.56820
H -5.89350 -1.64700 -0.34970
H -5.96080 0.10110 0.05060
H -5.50110 -0.42040 -1.59820
H 1.80390 1.99820 1.20710
H 1.03360 2.74540 -0.23460
H 0.37980 3.07430 1.40030
Ti -3.06210 3.07920 -1.29670
Cl -1.90010 5.01420 -1.76440
Cl -4.93850 3.49260 -2.56830
Cl -4.01850 3.98910 0.62300
Cl -2.01800 1.93080 -3.08000
H -1.60380 -1.38520 1.58950
C -2.76410 -4.71070 -1.64230
C -2.31410 -3.58990 -2.34230
C -1.86910 -2.46390 -1.64960
C -1.88120 -2.45320 -0.25050
C -2.31490 -3.58210 0.44910
C -2.76540 -4.70380 -0.24470
H -3.11410 -5.58690 -2.18240
H -2.31120 -3.58830 -3.42940
H -1.53840 -1.58450 -2.20030
H -2.32870 -3.57580 1.53770
H -3.12200 -5.57170 0.30470

H -0.15600 -2.15390 2.79730
C 3.24670 -4.76460 4.86290
C 2.02230 -4.27210 5.32700
C 1.23150 -3.50230 4.48490
C 1.65890 -3.21830 3.16530
C 2.90220 -3.72360 2.71100
C 3.68450 -4.49120 3.55780
H 3.86700 -5.37010 5.51980
H 1.69260 -4.49270 6.33820
H 0.27620 -3.11260 4.83240
H 3.24500 -3.52480 1.69940
H 4.63560 -4.88510 3.21120

10.3.1.1.12. TS$_{open}$aa-co-*cis-E*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3011.655870
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3012.082028
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3011.772476

C -1.09810 -1.00040 0.08980
C 0.03890 -1.60330 0.84340
C -0.38180 0.19750 -0.54930
H 0.33620 -1.02950 1.72450
C 0.59130 0.08530 -1.56980
O 0.86740 -1.12920 -2.01870
O 1.21800 1.05000 -2.09810
C 1.82010 -1.23640 -3.09730
C -0.68230 1.51240 -0.09270
O -1.65230 1.62850 0.79870
O -0.11100 2.57180 -0.47550
C -1.97060 2.95740 1.26360
C 1.94130 -2.97300 1.26670
C 0.79910 -2.70530 0.51250
H 0.52840 -3.32380 -0.33520
H 2.14700 -2.30640 2.10820
C 4.89910 -5.90350 0.58530
C 5.06470 -4.95600 1.60070
C 4.07020 -4.01420 1.82840
C 2.90050 -4.00390 1.03030
C 2.74560 -4.97730 0.01050
C 3.73860 -5.91770 -0.20410
H 5.67810 -6.64090 0.40500
H 5.96680 -4.95710 2.20570
H 4.18790 -3.26940 2.61380

H 1.84780 -5.00450 -0.60120
H 3.62179 -6.66500 -0.98390
H -2.77510 2.81870 1.98420
H -1.09480 3.40440 1.73780
H -2.30090 3.57380 0.42570
H 1.88180 -2.30200 -3.31710
H 1.45960 -0.68590 -3.96810
H 2.79000 -0.84790 -2.78150
Ti 1.58610 2.91380 -1.48920
Cl 3.54060 2.93970 -2.69210
Cl 1.75010 4.97980 -0.50850
Cl 2.67500 1.87970 0.36470
Cl 0.32420 3.69140 -3.25720
H -1.73450 -0.54810 0.85530
C -3.94730 -3.31440 -2.23650
C -4.34770 -2.47640 -1.19600
C -3.39390 -1.76340 -0.46930
C -2.02510 -1.85890 -0.76470
C -1.63770 -2.70450 -1.81410
C -2.58960 -3.42570 -2.53770
H -5.40140 -2.37540 -0.94710
H -3.72240 -1.11560 0.34179
H -0.59720 -2.79070 -2.09800
H -2.26450 -4.07180 -3.34990
H -4.68430 -3.87220 -2.80890

10.3.1.1.13. TS$_{open}$aa-co-*cis-Z*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3011.649856
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3012.075977
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3011.765278

C -1.32890 -1.67900 0.00710
C -0.00620 -2.15260 -0.53170
C -1.93820 -0.36610 -0.46960
H 0.54750 -2.75630 0.19140
C -3.02860 -0.24960 -1.35660
O -3.30910 -1.30930 -2.10470
O -3.73660 0.78780 -1.53230
C -4.52450 -1.27960 -2.87990
C -1.48610 0.83050 0.13130
O -0.41470 0.73010 0.90800
O -1.99430 1.98260 -0.01960
C 0.02450 1.92570 1.58570

C -0.02480 -1.36650 -2.84010
C 0.60490 -1.99360 -1.75240
H 1.59610 -2.42310 -1.87190
H 0.87670 1.61240 2.18740
H 0.32030 2.68210 0.85590
H -0.77750 2.31130 2.21900
H -4.56800 -2.25050 -3.37150
H -5.38330 -1.14280 -2.21950
H -4.48690 -0.47290 -3.61380
Ti -3.80140 2.56860 -0.63170
Cl -5.91700 2.90400 -1.47020
Cl -3.58900 4.52630 0.55930
Cl -2.78700 3.49550 -2.52280
Cl -4.63510 1.42000 1.24740
H -1.09470 -1.50400 1.06660
C -4.16960 -4.95360 0.17680
C -4.12940 -3.98270 1.18030
C -3.19330 -2.95230 1.11730
C -2.30260 -2.86900 0.04140
C -2.34370 -3.84590 -0.95680
C -3.27260 -4.88500 -0.88880
H -4.89570 -5.76090 0.22730
H -4.82510 -4.02820 2.01430
H -3.16500 -2.19630 1.90020
H -1.66710 -3.79510 -1.80610
H -3.29700 -5.63870 -1.67210
H -1.03190 -0.99150 -2.67850
C 1.38700 -0.79140 -6.76240
C 0.10520 -0.35690 -6.40330
C -0.33930 -0.55710 -5.10620
C 0.49200 -1.20000 -4.15070
C 1.79060 -1.63179 -4.53440
C 2.22650 -1.42510 -5.83110
H 1.74050 -0.63590 -7.77940
H -0.53190 0.13370 -7.13330
H -1.33080 -0.22040 -4.81140
H 2.44530 -2.12270 -3.81960
H 3.21780 -1.75180 -6.13220

10.3.1.1.14. TS$_{mig}$aa-co-*trans-E*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3011.655134
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3012.081435
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3011.772351

C 0.42260 -1.18960 0.61690
C 1.54000 -1.64700 1.38330
C -0.05840 0.18930 0.62330
H 2.11200 -0.88620 1.91030
C -0.64200 0.71550 -0.55940
O -0.71040 -0.11770 -1.58330
O -1.07620 1.88920 -0.70960
C -1.24860 0.39960 -2.82040
C -0.05140 1.00320 1.78460
O 0.34480 0.44380 2.91800
O -0.42930 2.20710 1.81850
C 0.32350 1.26440 4.10380
C 2.61880 -3.26220 2.85240
C 1.67770 -3.00800 1.92740
H 0.97790 -3.76680 1.58120
H 3.27010 -2.43940 3.15620
C 3.49270 -6.92430 4.88390
C 4.17790 -5.74990 5.19770
C 3.87550 -4.56770 4.52290
C 2.88470 -4.54000 3.52840
C 2.20060 -5.72900 3.22130
C 2.50420 -6.90920 3.89370
H 4.94740 -5.75330 5.96590
H 4.41190 -3.65220 4.76730
H 1.42990 -5.73980 2.45370
H 1.97040 -7.82310 3.64560
H 0.68760 0.61680 4.90030
H 0.97780 2.12800 3.97310
H -0.69690 1.59270 4.30750
H -1.20030 -0.43310 -3.51850
H -2.28010 0.72320 -2.67179
H -0.63900 1.23590 -3.16560
Ti -0.78470 3.56400 0.37500
Cl -1.15610 4.83110 -1.49450
Cl -0.30810 5.24960 1.84630
Cl 1.50730 3.27750 -0.17870
Cl -3.01870 3.47990 0.95090
H -0.24870 -1.95250 0.22180
C 3.48040 -1.47460 -2.51900
C 3.50100 -0.35850 -1.67260
C 2.70150 -0.34220 -0.54200
C 1.89610 -1.46120 -0.23480
C 1.87770 -2.58060 -1.09670
C 2.66610 -2.57920 -2.23660
H 4.09980 -1.47970 -3.41290

405

H 4.13390 0.49350 -1.90500
H 2.68610 0.53040 0.10770
H 1.24150 -3.43560 -0.87540
H 2.65200 -3.43240 -2.90850
H 3.72650 -7.84880 5.40600

10.3.1.1.15. TS$_{mig}$aa-co-*trans-Z*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3011.65380
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3012.080048
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3011.770766

C 0.68610 -1.19020 0.23170
C 1.72430 -1.66730 1.09360
C 0.09770 0.15690 0.36960
H 2.27610 -0.92320 1.66430
C -0.42910 0.78380 -0.78470
O -0.35380 0.08020 -1.90290
O -0.95270 1.93150 -0.83280
C -0.87500 0.68630 -3.10420
C -0.08110 0.79780 1.61800
O 0.25280 0.11970 2.70410
O -0.56350 1.95700 1.76850
C 0.04290 0.76460 3.97790
C 0.95440 -3.98920 1.43960
C 1.92330 -3.05550 1.50560
H 2.90340 -3.27930 1.92040
H -0.03390 -3.70270 1.07510
C 1.18110 -8.08040 2.65370
C -0.03580 -7.51800 2.26890
C -0.08740 -6.18020 1.87350
C 1.07320 -5.38990 1.86060
C 2.29490 -5.97170 2.24310
C 2.34550 -7.30470 2.63730
H 1.22640 -9.12220 2.96110
H -0.94260 -8.11530 2.27520
H -1.03630 -5.73870 1.57410
H 3.21240 -5.38860 2.22760
H 3.29570 -7.74430 2.92990
H 0.38210 0.04179 4.71830
H 0.62960 1.68350 4.03360
H -1.01710 0.98700 4.11230
H -0.71770 -0.05520 -3.88580
H -1.93810 0.90120 -2.98310

H -0.32920 1.60550 -3.32420
Ti -0.94770 3.44820 0.48500
Cl -1.32190 4.92070 -1.23330
Cl -0.80320 4.96370 2.19990
Cl 1.39530 3.49350 0.13040
Cl -3.20570 3.05690 0.82760
H 0.04560 -1.94580 -0.22600
C 4.01660 -1.11960 -2.59340
C 3.86250 -0.04830 -1.70550
C 2.90580 -0.11840 -0.70450
C 2.10650 -1.27630 -0.57830
C 2.28280 -2.35980 -1.46880
C 3.22410 -2.27090 -2.48020
H 4.76270 -1.05890 -3.38240
H 4.48240 0.83820 -1.80460
H 2.75250 0.72040 -0.02800
H 1.67660 -3.25700 -1.35980
H 3.35390 -3.09400 -3.17700

10.3.1.1.16. TS$_{mig}$aa-co-*cis-E*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3011.652428
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3012.079432
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3011.76868

C 0.38510 -1.36500 0.12260
C 1.50550 -2.24870 0.35320
C 0.37500 0.04179 0.47040
H 1.56680 -3.11990 -0.29980
C 1.42890 0.91860 0.08210
O 2.32360 0.42770 -0.75360
O 1.53190 2.12380 0.43190
C 3.42330 1.28110 -1.13530
C -0.76240 0.61650 1.10450
O -1.78850 -0.19120 1.28830
O -0.83760 1.80080 1.52560
C -2.92860 0.34070 1.99900
C 3.96520 -2.39460 0.64000
C 2.80380 -1.77580 0.89010
H 2.77910 -0.89060 1.52250
H 3.96620 -3.29790 0.02640
C 7.82600 -1.20900 2.08570
C 7.63780 -2.45700 1.49179
C 6.37750 -2.82380 1.01820

C 5.28290 -1.95490 1.13840
C 5.48890 -0.69710 1.73100
C 6.74600 -0.32860 2.20100
H 8.80760 -0.92040 2.45230
H 8.47340 -3.14570 1.39510
H 6.23580 -3.79880 0.55550
H 4.66710 0.00840 1.82360
H 6.88610 0.65020 2.65330
H -3.63930 -0.48230 2.04990
H -2.62420 0.65730 2.99850
H -3.34930 1.18470 1.45000
H 4.09550 0.63930 -1.70300
H 3.05480 2.10190 -1.75380
H 3.91820 1.67820 -0.24720
Ti 0.58790 3.19940 1.86300
Cl 2.42040 4.55140 2.03760
Cl -0.68560 4.10630 3.52010
Cl 1.53180 1.60190 3.36150
Cl -0.37540 4.44570 0.18980
H -0.45210 -1.76850 -0.44410
C -1.04650 -3.63350 3.62650
C -0.23270 -2.51380 3.83460
C 0.48520 -1.97490 2.77770
C 0.40730 -2.57020 1.50250
C -0.43620 -3.68220 1.29370
C -1.14990 -4.21590 2.35730
H -1.61290 -4.04800 4.45730
H -0.16910 -2.05800 4.81890
H 1.08490 -1.08220 2.93510
H -0.51180 -4.12620 0.30170
H -1.78870 -5.08090 2.20380

10.3.1.1.17. TS$_{mig}$aa-co-*cis-Z*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3011.647347
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3012.074754
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3011.764734

C 0.57690 -1.29150 0.15710
C 1.73920 -2.10870 0.43180
C 0.40530 0.11090 0.48760
H 1.81460 -2.97080 -0.23000
C 1.38150 1.08970 0.13930
O 2.30650 0.71120 -0.71930

O 1.39480 2.27610 0.55920
C 3.37420 1.64050 -0.99820
C -0.82179 0.57290 1.02980
O -1.76270 -0.33720 1.19520
O -1.05840 1.76260 1.37890
C -2.99580 0.09240 1.81280
C 3.39130 -0.63390 1.70330
C 3.08100 -1.69860 0.94820
H 3.86510 -2.39210 0.64950
H 2.61700 0.07190 2.00320
C 7.23250 0.63580 3.10370
C 6.12880 1.48730 3.15570
C 4.88710 1.04250 2.70390
C 4.73040 -0.25310 2.18490
C 5.84630 -1.10500 2.14600
C 7.08550 -0.66140 2.60140
H 8.20180 0.97540 3.46040
H 6.23210 2.49410 3.55270
H 4.02200 1.70280 2.75460
H 5.74700 -2.12260 1.77560
H 7.94150 -1.33100 2.57320
H -3.61020 -0.80440 1.87120
H -2.79010 0.49000 2.80860
H -3.47710 0.85340 1.19610
H 4.04760 1.10620 -1.66670
H 2.97380 2.53410 -1.48030
H 3.88179 1.91140 -0.06950
Ti 0.18060 3.28180 1.84320
Cl 1.86990 4.77070 2.21310
Cl -1.37040 4.13610 3.28210
Cl 1.02050 1.80040 3.50730
Cl -0.65290 4.41820 0.02360
H -0.18200 -1.75730 -0.46990
C -0.92960 -3.64100 3.54960
C -0.18340 -2.48610 3.81180
C 0.57250 -1.90760 2.80400
C 0.59790 -2.49090 1.52179
C -0.17710 -3.64330 1.26000
C -0.92730 -4.21900 2.27440
H -1.52410 -4.08870 4.34260
H -0.19950 -2.03570 4.80050
H 1.12560 -0.99600 3.00770
H -0.17530 -4.08080 0.26230
H -1.51310 -5.11240 2.07800

10.3.1.1.18. TS_{cycl}aa-co-*trans-Z*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3011.650976
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3012.079488
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3011.767838

C -2.33090 -0.34200 8.76060
C -1.35700 -1.25330 9.49570
C -2.49220 -0.82480 7.32660
H -3.30690 -0.48270 9.25580
H -0.65180 -0.82830 10.20650
C -1.35820 -0.81270 6.45260
O -0.20520 -0.55100 7.03340
O -1.36980 -1.04500 5.21500
C -3.76500 -1.03510 6.72330
O -4.81110 -0.99700 7.53410
C -1.39900 3.86430 9.32410
C -1.64820 3.37790 8.04190
C -1.94179 2.02620 7.84450
C -1.98360 1.14080 8.92340
C -1.74250 1.64020 10.21070
C -1.45260 2.98920 10.41140
H -1.17220 4.91820 9.47790
H -1.61870 4.04910 7.18680
H -2.14960 1.67760 6.83610
H -1.79780 0.97690 11.07280
H -1.27320 3.35800 11.41840
C -2.33480 -3.09850 8.29410
C -1.33450 -2.56290 9.19740
H -0.55930 -3.22190 9.58380
H -3.37670 -2.85520 8.51510
C -1.76430 -6.29380 5.62050
C -3.06090 -5.92610 5.99670
C -3.24260 -4.85520 6.85800
C -2.12070 -4.16740 7.38130
C -0.81330 -4.55300 6.99140
C -0.64290 -5.60530 6.10890
H -1.62210 -7.12440 4.93290
H -3.91690 -6.46670 5.60300
H -4.24360 -4.55110 7.15940
H 0.05090 -4.01960 7.38240
H 0.35440 -5.90140 5.79600
C 0.96280 -0.45720 6.19000
H 1.78500 -0.23330 6.86770

H 1.12900 -1.40230 5.67030
H 0.82570 0.34850 5.46560
C -6.11690 -1.15040 6.93450
H -6.81830 -1.09070 7.76520
H -6.28860 -0.34190 6.22110
H -6.18850 -2.11500 6.42950
O -3.96560 -1.30560 5.50890
Ti -2.84490 -1.09420 3.83210
Cl -3.05950 1.22750 4.23720
Cl -1.31950 -0.70770 2.17080
Cl -2.57610 -3.36430 3.74150
Cl -4.76190 -1.12860 2.57900

10.3.1.1.19. TS_{cycl}aa-co-*cis-Z*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3011.645689
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3012.073581
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3011.761467

C -2.45750 -0.63190 8.81730
C -1.53310 -1.58610 9.54970
C -2.61330 -1.02660 7.33780
H -0.94500 -1.19020 10.37750
C -1.48840 -0.73290 6.50220
O -0.38480 -0.39910 7.14870
O -1.44620 -0.76460 5.24430
C -3.82560 -1.34630 6.66380
O -4.85700 -1.69120 7.41550
C -2.30240 -3.39050 8.15190
C -1.38950 -2.86000 9.13990
H -0.60660 -3.50220 9.53990
H -3.35800 -3.18160 8.29530
C -1.59090 -6.48560 5.40140
C -2.90420 -6.11780 5.71480
C -3.12280 -5.08450 6.61140
C -2.02660 -4.42960 7.22700
C -0.70210 -4.81750 6.90200
C -0.49290 -5.83460 5.98750
H -1.41800 -7.28760 4.68770
H -3.74180 -6.62900 5.24860
H -4.13670 -4.78070 6.86600
H 0.14370 -4.31040 7.36190
H 0.51760 -6.13270 5.72210
C 0.77520 -0.06390 6.35720

H 1.55960 0.14750 7.08210
H 1.04830 -0.90590 5.72040
H 0.56210 0.81450 5.74510
C -6.11840 -1.93040 6.75720
H -6.79580 -2.23230 7.55430
H -6.46470 -1.01100 6.28040
H -6.01460 -2.72060 6.01179
O -3.97990 -1.38550 5.41110
Ti -2.83090 -1.01730 3.80490
Cl -3.36230 1.25150 4.15760
Cl -1.27700 -0.46440 2.20640
Cl -2.23450 -3.24540 3.77990
Cl -4.64900 -1.33960 2.44670
H -1.93600 0.33400 8.81750
C -6.17150 0.14520 10.91260
C -5.63250 1.08590 10.03050
C -4.42850 0.82270 9.38070
C -3.75550 -0.38730 9.58870
C -4.29260 -1.31850 10.48030
C -5.49570 -1.05330 11.13960
H -7.10780 0.35140 11.42530
H -6.14750 2.02740 9.85410
H -4.00920 1.56010 8.69720
H -3.78090 -2.26040 10.67030
H -5.90170 -1.78570 11.83320

10.3.1.1.20. TS$_{isom}$aa-co-E

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3011.659399
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3012.084908
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3011.774877

C 0.15190 -1.64230 0.01980
C 1.50450 -2.00560 0.55870
C 0.23550 -1.15070 -1.41090
H 2.38480 -1.61300 0.04750
C -0.45360 -1.79620 -2.45490
O -1.23240 -2.81980 -2.12570
O -0.40230 -1.47190 -3.68100
C -1.93100 -3.49000 -3.19390
C 0.95790 0.01340 -1.73120
O 1.55220 0.62420 -0.71400
O 1.09330 0.52090 -2.88570
C 2.29080 1.82830 -0.99840

C 3.00830 -3.10360 2.04820
C 1.69220 -2.82300 1.64030
H 0.83310 -3.22970 2.17020
H 3.81280 -2.65920 1.45610
C 4.30990 -5.42660 5.30370
C 5.24310 -4.80250 4.46700
C 4.79710 -4.04300 3.39640
C 3.40590 -3.89930 3.15320
C 2.47320 -4.54070 4.01290
C 2.92980 -5.29680 5.07750
H 4.65810 -6.02300 6.14410
H 6.30660 -4.91380 4.65730
H 5.50660 -3.54940 2.73440
H 1.40380 -4.44610 3.84390
H 2.22370 -5.78980 5.73960
H 2.67850 2.15820 -0.03510
H 3.10600 1.61230 -1.69180
H 1.62580 2.58180 -1.42470
H -2.47640 -4.29970 -2.71090
H -2.61910 -2.79760 -3.68230
H -1.21690 -3.88140 -3.92070
Ti 0.75430 -0.21470 -4.70360
Cl 0.23890 -1.32850 -6.65500
Cl 2.21880 1.33200 -5.58830
Cl 2.52750 -1.72220 -4.23670
Cl -1.06030 1.21970 -4.89940
H -0.41650 -2.58290 0.00480
C -2.18540 0.98680 2.56350
C -2.80110 0.15510 1.62490
C -2.02890 -0.68780 0.82760
C -0.63490 -0.70730 0.95330
C -0.02430 0.13020 1.88980
C -0.79680 0.97170 2.69380
H -2.78580 1.64320 3.18850
H -3.88290 0.15950 1.51650
H -2.51150 -1.33600 0.09800
H 1.05830 0.14250 1.99030
H -0.30980 1.62030 3.41790

10.3.1.1.21. TS$_{isom}$aa-co-Z

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3011.653538
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3012.079436
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3011.768585

C 0.08740 -1.54840 0.07070
C 1.42640 -1.95140 0.64300
C 0.21660 -1.11590 -1.37760
H 2.31500 -1.57460 0.13730
C -0.47040 -1.78460 -2.40850
O -1.26560 -2.79000 -2.05830
O -0.40780 -1.49440 -3.64200
C -1.96380 -3.47850 -3.11790
C 0.95720 0.03000 -1.72670
O 1.54620 0.66480 -0.72230
O 1.10280 0.50410 -2.89350
C 2.30530 1.84910 -1.03590
C 0.54960 -3.29380 2.45220
C 1.63520 -2.78510 1.71320
H 2.65800 -3.03130 1.98550
H -0.44920 -3.00200 2.12590
C 0.52600 -5.80400 5.82150
C -0.68110 -5.36320 5.26370
C -0.65310 -4.53380 4.15510
C 0.58900 -4.13480 3.58830
C 1.80390 -4.59550 4.16690
C 1.76310 -5.42190 5.27480
H 0.50630 -6.45340 6.69390
H -1.62850 -5.66840 5.69870
H -1.58280 -4.18480 3.70910
H 2.76260 -4.29950 3.74950
H 2.68520 -5.77640 5.72590
H 2.69310 2.19850 -0.07990
H 3.12000 1.60060 -1.71890
H 1.65450 2.60030 -1.48720
H -2.53000 -4.26400 -2.61730
H -2.63310 -2.78810 -3.63270
H -1.24840 -3.90410 -3.82190
Ti 0.75010 -0.26580 -4.69730
Cl 0.20900 -1.41060 -6.62390
Cl 2.21650 1.25410 -5.62020
Cl 2.51280 -1.77500 -4.21750
Cl -1.05850 1.17710 -4.90740
H -0.53080 -2.45300 0.05380
C -2.19400 1.29860 2.42530
C -2.80900 0.50660 1.45260
C -2.05340 -0.40290 0.71460
C -0.67720 -0.53270 0.93680
C -0.06720 0.26330 1.90870
C -0.82320 1.17470 2.65050

H -2.78100 2.00860 3.00260
H -3.87730 0.59520 1.26990
H -2.53560 -1.01650 -0.04510
H 1.00300 0.18760 2.08760
H -0.33560 1.79230 3.40090

10.3.1.1.22. 179aa-co-*trans*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -1112.747794
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -1113.021808
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -1112.709527

C -0.57770 -0.31080 -0.13100
C 0.83920 0.02520 0.19820
C -0.21750 1.13790 0.15510
H 1.51950 0.10230 -0.64910
C -0.15170 2.05300 -1.03740
O -1.24080 2.81190 -1.13170
O 0.74380 2.05620 -1.85530
C -1.29980 3.69190 -2.26890
C -0.67620 1.71030 1.46270
O -0.34210 2.99260 1.59190
O -1.23210 1.06890 2.33200
C -0.72600 3.63140 2.82410
C 2.77800 -0.64240 1.57040
C 1.46130 -0.41030 1.46790
H 0.79230 -0.56380 2.31420
H 3.40050 -0.48210 0.68730
C 4.99810 -1.97860 4.99020
C 5.63520 -1.71760 3.77740
C 4.89320 -1.28530 2.67810
C 3.50420 -1.10570 2.76740
C 2.87430 -1.37600 3.99420
C 3.61410 -1.80600 5.09220
H 5.57220 -2.31480 5.85000
H 6.71040 -1.85030 3.68490
H 5.39580 -1.08250 1.73360
H 1.79870 -1.25400 4.09780
H 3.10950 -2.00910 6.03370
H -0.38440 4.66210 2.73800
H -1.81100 3.59170 2.93980
H -0.24390 3.13340 3.66790
H -2.25410 4.21050 -2.18780
H -0.46910 4.40040 -2.23440

H -1.25230 3.10920 -3.19150
H -1.14580 -0.74860 0.69040
C -1.92180 -1.60430 -4.00450
C -2.75320 -0.83570 -3.18600
C -2.30180 -0.40730 -1.93880
C -1.01450 -0.73950 -1.49740
C -0.18650 -1.50610 -2.32120
C -0.63880 -1.93770 -3.57000
H -2.27490 -1.94440 -4.97490
H -3.75520 -0.57410 -3.51760
H -2.95150 0.18660 -1.29760
H 0.81150 -1.77760 -1.98330
H 0.01120 -2.53960 -4.20050

10.3.1.1.23. 181aa-co

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -1112.7428799
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -1113.017467
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -1112.704122

C -0.33360 1.40270 2.06840
C 0.39570 0.23960 2.69680
H -0.50940 2.17070 2.83060
C 0.78310 0.20480 3.97690
C 2.93150 -2.92770 5.97500
C 2.75790 -1.68150 6.57640
C 2.04860 -0.67950 5.91380
C 1.50570 -0.90010 4.63940
C 1.67870 -2.18230 4.04910
C 2.38610 -3.18310 4.70950
H 3.48260 -3.71220 6.48760
H 3.17390 -1.48760 7.56210
H 1.91820 0.29210 6.38720
H 1.25180 -2.37550 3.07170
H 2.50870 -4.13600 4.23780
C -2.88630 1.29050 1.84050
C -1.64520 0.86770 1.55240
H -1.56490 0.00350 0.89020
H 0.58240 1.07430 4.60730
H 0.60330 -0.59810 2.02810
C -3.12770 2.48370 2.71800
O -4.00840 2.23990 3.68360
O -2.55390 3.54590 2.58180
C -4.31790 3.34320 4.55460

C -4.03470 0.54750 1.23340
O -5.18360 1.21140 1.33240
O -3.92820 -0.52860 0.67790
C -6.33670 0.57060 0.75820
C 1.86980 3.30590 -1.15540
C 0.51550 3.58430 -0.95780
C -0.18610 2.95760 0.07100
C 0.45460 2.04590 0.92030
C 1.81170 1.77560 0.71900
C 2.51520 2.40179 -0.31320
H 2.41700 3.79250 -1.95900
H 0.00320 4.29210 -1.60500
H -1.23750 3.18930 0.22630
H 2.33280 1.08130 1.37320
H 3.57040 2.18060 -0.45480
H -7.16940 1.24790 0.94280
H -6.18610 0.42430 -0.31370
H -6.50490 -0.39310 1.24380
H -5.06690 2.96670 5.24800
H -3.41790 3.65730 5.09179
H -4.71030 4.17850 3.97200

10.3.1.1.24. 180aa-co-*cis*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -1112.7599488
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -1113.035467
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -1112.718516

C 0.98410 -0.00030 1.03840
C -0.32570 0.03610 1.27480
C -1.14530 0.33940 0.04620
C -0.07740 0.22230 -1.11550
C 1.34340 0.26760 -0.40290
H -1.88179 -0.45260 -0.12460
H -0.79610 -0.11760 2.24360
H 1.75430 -0.19150 1.78260
C -3.34340 4.06940 0.13870
C -3.74540 3.02530 -0.69650
C -3.03760 1.82310 -0.70040
C -1.91430 1.64960 0.11790
C -1.52560 2.69770 0.95720
C -2.23480 3.89950 0.96930
H -3.89580 5.00600 0.14890
H -4.61480 3.14310 -1.33900

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H -3.35950 1.00780 -1.34740
H -0.66000 2.57890 1.60380
H -1.92010 4.70440 1.62960
C -0.22250 -1.15090 -1.80080
O 0.76290 -1.36110 -2.67150
O -1.10530 -1.95380 -1.59010
C 0.70380 -2.58750 -3.41970
C -0.36360 1.24920 -2.21290
O -0.03470 2.48060 -1.86940
O -0.91350 0.96060 -3.25990
C -0.40580 3.52630 -2.77830
H -0.07010 4.44870 -2.30670
H 0.08920 3.38110 -3.74140
H -1.49060 3.53120 -2.91240
H 1.57390 -2.57190 -4.07520
H 0.74750 -3.44280 -2.74130
H -0.22040 -2.62220 -4.00320
H 1.93120 -0.56860 -0.79800
C 3.79300 3.77540 -1.06990
C 3.73920 2.75070 -2.01850
C 2.95500 1.62320 -1.78220
C 2.20250 1.50630 -0.60730
C 2.27220 2.52930 0.34080
C 3.06190 3.65800 0.11190
H 4.40870 4.65390 -1.24770
H 4.31490 2.82830 -2.93800
H 2.91830 0.82410 -2.52190
H 1.70550 2.45080 1.26530
H 3.10650 4.44530 0.86110

10.3.1.1.25. 182aa-co-*trans-E*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-1112.6804442
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-1112.953809
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-1112.643314

C -1.55640 -1.10460 0.67070
C -0.12860 -1.06310 0.29810
C -2.34170 0.12220 0.25870
H 0.10990 -0.67930 -0.69510
C -1.70480 1.39790 0.26650
O -2.50220 2.45790 -0.04570
O -0.50970 1.62250 0.55460

C -1.88660 3.74230 0.01900
C -3.76070 -0.11800 0.20460
O -4.53140 0.85180 -0.35340
O -4.29090 -1.15950 0.61540
C -5.93490 0.59480 -0.36590
C 2.18730 -1.59179 0.57950
C 0.90500 -1.57480 1.08330
H 0.67450 -1.93530 2.08330
H -6.39260 1.47850 -0.81290
H -6.18240 -0.29120 -0.96450
H -6.31540 0.44660 0.64820
H -2.66660 4.45480 -0.25390
H -1.52260 3.95320 1.02820
H -1.05090 3.81330 -0.68220
H -1.66970 -1.37770 1.72870
C -2.30090 -4.69990 -1.66190
C -2.28880 -3.45330 -2.29100
C -2.05930 -2.29620 -1.54860
C -1.84940 -2.37650 -0.16650
C -1.84230 -3.62990 0.45720
C -2.07980 -4.78490 -0.28460
H -2.48310 -5.60190 -2.24120
H -2.46110 -3.38060 -3.36220
H -2.06650 -1.32240 -2.03370
H -1.67580 -3.69580 1.53120
H -2.09480 -5.75280 0.21050
H 2.33510 -1.20620 -0.43280
C 5.71430 -3.01680 2.44400
C 5.75780 -2.50510 1.14440
C 4.59180 -2.03430 0.55080
C 3.36820 -2.07310 1.25180
C 3.33930 -2.58940 2.56710
C 4.50640 -3.05680 3.15370
H 6.62480 -3.38640 2.90990
H 6.69770 -2.47550 0.60020
H 4.61380 -1.63470 -0.46179
H 2.41040 -2.62300 3.13070
H 4.48350 -3.45430 4.18370

10.3.1.1.26. 182aa-co-*trans-Z*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-1112.6753102
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-1112.948614
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-1112.638326

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C -1.60050 -1.24150 0.60950
C -0.14990 -1.20410 0.32450
C -2.33590 0.03470 0.25760
H 0.11870 -0.85400 -0.67170
C -1.67110 1.29710 0.25530
O -2.47740 2.37540 0.04600
O -0.45400 1.50060 0.44840
C -1.84340 3.65130 0.09860
C -3.76370 -0.17270 0.25730
O -4.54180 0.82410 -0.23520
O -4.29190 -1.21960 0.65800
C -5.94850 0.58550 -0.19680
C 0.67300 -1.96080 2.47270
C 0.88200 -1.69770 1.13450
H 1.86380 -1.82190 0.68420
H -6.41140 1.48420 -0.60690
H -6.21240 -0.28480 -0.80350
H -6.28980 0.42179 0.82880
H -2.63500 4.37900 -0.08690
H -1.39610 3.82770 1.08060
H -1.06760 3.73650 -0.66680
H -1.82480 -1.59450 1.62130
C -2.40760 -4.61280 -2.02500
C -2.36700 -3.31770 -2.54590
C -2.10650 -2.23350 -1.70960
C -1.89530 -2.43640 -0.34179
C -1.91110 -3.73660 0.17180
C -2.18020 -4.82020 -0.66220
H -2.61400 -5.45740 -2.67780
H -2.54200 -3.14920 -3.60590
H -2.09170 -1.22130 -2.10840
H -1.73220 -3.90000 1.23380
H -2.21080 -5.82620 -0.25110
H -0.30240 -1.71950 2.89480
C 3.32950 -3.58020 5.34420
C 2.04210 -3.18100 5.71330
C 1.19090 -2.64110 4.75630
C 1.61850 -2.49570 3.41880
C 2.92280 -2.90250 3.05960
C 3.76810 -3.43990 4.01990
H 3.99720 -4.00480 6.09030
H 1.70750 -3.29300 6.74090
H 0.18530 -2.32770 5.03200
H 3.26890 -2.80330 2.03390
H 4.77090 -3.75520 3.74530

10.3.1.1.27. TS$_{mig}$aa-co-*trans-E*-NoTiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -1112.6804455
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -1112.95364
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -1112.643566

C 0.27690 -1.09380 0.58310
C 1.36990 -1.46700 1.43090
C -0.29490 0.26500 0.58150
H 2.02280 -0.67840 1.79340
C -1.00820 0.56780 -0.62950
O -1.53290 1.81320 -0.74140
O -1.14210 -0.24690 -1.55330
C -2.23890 2.07870 -1.95430
C -0.19330 1.03820 1.78410
O -0.79430 2.25480 1.75320
O 0.37030 0.66280 2.82630
C -0.75580 2.99920 2.97150
C 2.58680 -3.01790 2.83920
C 1.57510 -2.78980 1.97240
H 0.86050 -3.56460 1.70110
H 3.25470 -2.18650 3.07540
C 3.56680 -6.64430 4.86990
C 4.30580 -5.48110 5.08920
C 3.96770 -4.30680 4.41880
C 2.88750 -4.27800 3.52120
C 2.14840 -5.45670 3.31020
C 2.48800 -6.62780 3.97890
H 5.14430 -5.48820 5.78090
H 4.54340 -3.39890 4.58890
H 1.30590 -5.46550 2.62310
H 1.91150 -7.53330 3.80720
H -0.41940 -1.90740 0.36210
C 3.33500 -1.66470 -2.52210
C 3.30050 -0.46220 -1.80950
C 2.39620 -0.30190 -0.76670
C 1.52940 -1.35410 -0.42400
C 1.57460 -2.56570 -1.13800
C 2.46610 -2.71170 -2.20400
H 4.03740 -1.78590 -3.34340
H 3.97220 0.35050 -2.07340

H 2.33960 0.63960 -0.22410
H 0.89440 -3.37560 -0.88030
H 2.48780 -3.63810 -2.75960
H 3.82760 -7.56280 5.39000
H -1.26560 2.45890 3.77370
H 0.27470 3.20010 3.27540
H -1.27510 3.93480 2.75880
H -3.09120 1.40320 -2.06470
H -1.58090 1.96790 -2.82010
H -2.58480 3.11030 -1.87370

10.3.1.1.28. TS$_{cycl}$aa-co-*trans-Z-*NoTiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -1112.6826606
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -1112.958077
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -1112.646193

C 1.22690 0.11930 0.68110
C -0.04980 0.18110 1.07179
C -1.20100 0.24210 0.15740
C 0.46970 0.24390 -1.71480
C 1.65620 0.22540 -0.77250
H -1.62820 -0.70450 -0.17950
H -0.27610 0.14240 2.14120
H 2.02450 0.02190 1.41750
C -3.78510 3.60560 -0.03520
C -4.13570 2.41200 -0.67430
C -3.29380 1.30880 -0.59360
C -2.08190 1.38780 0.11940
C -1.74250 2.59470 0.76010
C -2.59030 3.69280 0.68720
H -4.44590 4.46700 -0.09590
H -5.06720 2.34650 -1.23050
H -3.56190 0.37690 -1.08810
H -0.80960 2.66179 1.31450
H -2.32360 4.61970 1.18890
C -0.00550 -1.03950 -2.20960
O -0.91280 -0.90920 -3.20120
O 0.32770 -2.13680 -1.77030
C -1.45550 -2.12470 -3.72730
C 0.23500 1.46290 -2.56179
O 0.99150 1.42770 -3.67020

O -0.48750 2.39630 -2.29080
C 0.95020 2.60410 -4.49170
H 1.63810 2.41560 -5.31530
H -0.06260 2.77020 -4.86560
H 1.27330 3.47210 -3.91130
H -2.15970 -1.82350 -4.50290
H -0.66190 -2.74310 -4.15440
H -1.96940 -2.68520 -2.94230
H 2.22170 -0.69440 -0.98700
C 4.33620 3.57570 -1.36030
C 4.70130 2.30040 -1.79420
C 3.83730 1.22140 -1.60030
C 2.60350 1.40210 -0.96820
C 2.24620 2.68380 -0.53500
C 3.10460 3.76580 -0.73130
H 5.00960 4.41660 -1.50760
H 5.66080 2.14450 -2.28180
H 4.12240 0.22860 -1.94430
H 1.28610 2.83320 -0.04480
H 2.81390 4.75610 -0.38900

10.3.1.1.29. 183aa-co-*trans-*TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -3011.64657
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3012.072135
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3011.762651

C -1.98610 -0.04260 7.84050
C -1.31800 -1.09790 8.61810
C -1.13060 0.96880 7.11080
H -2.71220 -0.45390 7.14110
H -0.51650 -0.76740 9.27640
C -0.08350 1.68090 7.72660
O 0.12940 1.42130 9.01580
O 0.66170 2.54200 7.17700
C -1.41260 1.26350 5.75820
O -2.43210 0.62240 5.20170
C 1.20030 2.13550 9.66850
H 1.21310 1.75380 10.68850
H 2.14690 1.93110 9.16520
H 0.99430 3.20740 9.65860
C -2.72840 0.91830 3.82150

H -3.57790 0.28280 3.57480
H -2.98960 1.97250 3.71260
H -1.86760 0.67880 3.19470
O -0.77980 2.09000 5.03850
Ti 0.86420 3.19320 5.29510
Cl -0.53670 4.97350 5.87020
Cl 2.75710 4.34470 5.90870
Cl 2.08130 1.22100 4.89890
Cl 0.83940 3.74280 3.06460
C -3.91890 -0.01150 9.45850
C -2.72190 0.48490 9.07780
H -2.20190 1.24910 9.64670
H -4.34300 -0.83500 8.87800
C -2.09860 -5.22590 8.77180
C -1.16660 -4.64910 9.64300
C -0.93860 -3.28300 9.58740
C -1.64110 -2.47670 8.65210
C -2.58120 -3.08100 7.77380
C -2.80230 -4.44550 7.83960
H -2.27850 -6.29790 8.81370
H -0.62790 -5.26750 10.35520
H -0.21880 -2.81660 10.25750
H -3.12270 -2.48930 7.04030
H -3.51450 -4.91800 7.16790
C -6.38540 1.19930 12.72179
C -6.72710 0.09430 11.94040
C -5.91320 -0.27820 10.87240
C -4.74330 0.44300 10.57740
C -4.41350 1.56090 11.36720
C -5.22910 1.93290 12.42990
H -7.01930 1.49390 13.55430
H -7.62650 -0.47430 12.18030
H -6.18179 -1.13720 10.26000
H -3.52650 2.15080 11.15050
H -4.96820 2.79860 13.03310

10.3.1.1.30. 183aa-co-*cis*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3011.644718
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3012.07099
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3011.761035

C -1.40520 -0.22070 8.43890

C -0.30550 -1.05280 8.98720
C -0.82090 0.80520 7.47630
H -1.94400 -0.96420 7.81360
H 0.42110 -1.33760 8.22020
C 0.23500 1.63810 7.88710
O 0.71850 1.39440 9.10660
O 0.75330 2.58179 7.22710
C -1.46430 1.10480 6.25620
O -2.53740 0.39000 5.95920
C 1.78330 2.24540 9.58030
H 2.01670 1.88060 10.57980
H 2.65050 2.17960 8.92270
H 1.44170 3.28179 9.61840
C -3.22470 0.70650 4.73010
H -4.04260 -0.01010 4.67110
H -3.60680 1.72860 4.76980
H -2.54590 0.59230 3.88290
O -1.10370 2.00460 5.44290
Ti 0.46680 3.24420 5.35090
Cl -0.90360 4.90190 6.24380
Cl 2.35480 4.53720 5.55060
Cl 1.71810 1.36070 4.68110
Cl -0.07800 3.77620 3.18810
C -3.70740 0.22450 9.31090
C -2.38660 0.43470 9.37710
H -1.95990 1.18110 10.04850
H -4.07400 -0.53130 8.61260
C 0.64100 -2.65840 12.73750
C 1.47730 -2.88190 11.63470
C 1.12910 -2.35570 10.40430
C -0.06390 -1.58140 10.25910
C -0.90270 -1.37810 11.39780
C -0.54740 -1.91810 12.61800
H 0.91490 -3.06950 13.70730
H 2.38840 -3.46150 11.74880
H 1.76520 -2.51730 9.53580
H -1.82190 -0.81370 11.29980
H -1.18130 -1.76710 13.48720
C -6.83300 2.15760 11.52250
C -7.10490 1.05710 10.70940
C -6.07290 0.44250 9.99990
C -4.75370 0.91200 10.09250
C -4.49460 2.02530 10.90950
C -5.52370 2.63910 11.61830
H -7.63500 2.64350 12.07290
H -8.12080 0.67950 10.62370

H -6.29090 -0.41300 9.36230
H -3.48870 2.43100 10.98590
H -5.30670 3.50380 12.24110

10.3.1.1.31. TS$_{migstyryl}$aa-co-*trans*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3011.646538
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3012.072438
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3011.753973

C -1.68500 -0.24320 7.91120
C -1.11270 -1.45750 8.42780
C -0.87650 0.83440 7.25040
H -2.66250 -0.35640 7.44350
H -0.07310 -1.39620 8.75810
C -0.08460 1.82130 7.86600
O 0.03730 1.79350 9.18840
O 0.53930 2.73780 7.25290
C -0.87670 0.79100 5.83620
O -1.53820 -0.22240 5.29040
C 0.82200 2.83870 9.79990
H 0.78570 2.63210 10.86890
H 1.84920 2.79870 9.43350
H 0.38220 3.81310 9.57920
C -1.56620 -0.29730 3.85040
H -2.15360 -1.18620 3.62410
H -2.03970 0.59560 3.43790
H -0.55070 -0.39620 3.46280
O -0.30100 1.60440 5.05850
Ti 0.63090 3.34580 5.35640
Cl -1.50870 4.26590 5.69360
Cl 1.66430 5.28680 6.03080
Cl 2.65530 2.19720 5.17840
Cl 0.55150 3.76640 3.09650
C -3.13410 -0.65400 10.00130
C -1.90420 -0.26010 9.54090
H -1.14920 0.20960 10.15180
H -3.81780 -1.11860 9.28700
C -2.58730 -5.44920 8.14760
C -1.47720 -5.15330 8.94240
C -1.01510 -3.84280 9.02560
C -1.66180 -2.81650 8.31800
C -2.77050 -3.12140 7.51240
C -3.22880 -4.43430 7.43150

H -2.94810 -6.47250 8.07880
H -0.97210 -5.94290 9.49230
H -0.14780 -3.60660 9.63970
H -3.26880 -2.34710 6.93310
H -4.08240 -4.66930 6.80130
C -4.73680 -0.34840 13.90630
C -5.52190 -0.82580 12.85360
C -4.97710 -0.91970 11.57790
C -3.64150 -0.52750 11.34330
C -2.85760 -0.04930 12.41710
C -3.40580 0.03610 13.68820
H -5.17940 -0.27740 14.90530
H -6.55150 -1.12460 13.03100
H -5.58080 -1.29030 10.75130
H -1.82080 0.23760 12.26100
H -2.80270 0.39880 14.51790

10.3.1.1.32. TS$_{isomPh}$aa-co

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3011.640194
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3012.066697
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3011.754773

C -1.24710 -0.25120 8.36480
C -0.14940 -1.03630 8.99120
C -1.29690 -0.15580 6.85640
H -2.19640 -0.68840 8.69460
H 0.74970 -1.20040 8.39330
C -0.19750 0.30370 6.10760
O 0.89970 0.59970 6.80450
O -0.15580 0.46780 4.85410
C -2.51730 -0.34290 6.17640
O -3.57750 -0.64040 6.91810
C 2.04020 1.08850 6.06790
H 2.81000 1.26140 6.81870
H 2.36570 0.34090 5.34220
H 1.78420 2.01820 5.55650
C -4.83670 -0.81230 6.23370
H -5.55180 -1.05740 7.01780
H -5.11760 0.11460 5.73050
H -4.76180 -1.62470 5.50880
O -2.68520 -0.22780 4.92630
Ti -1.44820 0.04990 3.38480
Cl -2.06020 2.29660 3.39580

Cl 0.22320 0.40070 1.84210
Cl -0.81670 -2.20180 3.67670
Cl -3.13680 -0.51830 1.93260
C -2.23460 1.70660 9.60730
C -1.18490 1.15470 8.98470
H -0.25780 1.69870 8.82020
H -3.13730 1.10630 9.74200
C 0.11130 -2.52360 12.88760
C 1.20610 -2.63460 12.01970
C 1.09460 -2.15280 10.72800
C -0.12110 -1.53820 10.29150
C -1.22890 -1.45200 11.19370
C -1.10520 -1.94180 12.47470
H 0.19770 -2.90010 13.90500
H 2.12890 -3.09480 12.36040
H 1.93020 -2.22970 10.03400
H -2.16770 -1.01010 10.87220
H -1.93830 -1.88330 13.16910
C -2.63010 5.68810 11.14610
C -3.63630 4.74150 11.33830
C -3.48590 3.45140 10.82900
C -2.32860 3.08390 10.12560
C -1.32350 4.04710 9.93640
C -1.47420 5.33520 10.44230
H -2.74570 6.69670 11.53480
H -4.54060 5.00740 11.87980
H -4.27730 2.71810 10.97570
H -0.42100 3.80179 9.38260
H -0.69050 6.07120 10.28110

10.3.1.1.33. TS_{backmigH}aa-co-*Z*

E(M06-2X/6-31+G(d)(CH₂Cl₂))=
-3011.645508
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-3012.070466
G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-3011.764337

C 1.73280 -0.27770 0.03560
C 2.60140 -0.85570 1.01140
C 0.89700 0.88260 0.23000
C 0.59120 1.72520 -0.87800
O 1.14920 1.38760 -2.02760

O -0.14240 2.74340 -0.83980
C 0.83090 2.20100 -3.17930
C 0.21550 1.12910 1.46460
O 0.26350 0.16940 2.36340
O -0.44450 2.18300 1.72600
C -0.35690 0.41850 3.64290
C 2.14440 -3.19380 0.45080
C 3.01370 -2.25390 0.87860
H 3.99130 -2.51130 1.27820
H 1.14100 -2.87980 0.15580
C 2.66570 -7.42920 0.47350
C 1.40680 -6.86660 0.25970
C 1.26270 -5.48040 0.23470
C 2.37170 -4.64179 0.43210
C 3.63780 -5.21890 0.63570
C 3.77990 -6.60250 0.65640
H 2.78260 -8.50990 0.49510
H 0.53940 -7.50520 0.11460
H 0.28110 -5.03900 0.07120
H 4.51570 -4.59170 0.77310
H 4.76140 -7.04170 0.81510
H -0.19480 -0.49270 4.21810
H 0.12350 1.27290 4.12420
H -1.42270 0.61040 3.50880
H 1.39370 1.75980 -4.00020
H -0.24190 2.15960 -3.37620
H 1.14250 3.23179 -3.00179
Ti -1.03210 3.78140 0.66190
Cl -1.53760 5.45110 -0.80540
Cl -1.92540 4.68800 2.55400
Cl 1.10520 4.62270 1.10310
Cl -2.95600 2.56820 0.16540
H 1.64480 -0.83480 -0.90100
H 3.02820 -0.08570 -0.01750
C 3.62760 1.18530 4.63580
C 3.67070 1.87730 3.42200
C 3.36370 1.22320 2.23210
C 3.01110 -0.13370 2.24940
C 2.99510 -0.83170 3.46370
C 3.29500 -0.16930 4.65370
H 3.86110 1.70170 5.56350
H 3.94690 2.92810 3.40280
H 3.40780 1.77220 1.29290
H 2.71800 -1.88270 3.48650
H 3.26590 -0.71410 5.59390

10.3.1.1.34. 207aa-co-*Z*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3011.679183
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3012.10576
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3011.793515

C -0.75930 -1.21480 -0.24800
C 0.69830 -1.39800 0.06880
C -0.89320 0.26330 0.07390
C -0.61900 1.25390 -0.90410
O -0.47010 0.82400 -2.14390
O -0.51950 2.49480 -0.68570
C -0.08150 1.78860 -3.14220
C -1.22670 0.70620 1.37170
O -1.58670 -0.22980 2.23990
O -1.22910 1.90850 1.76680
C -1.90910 0.20050 3.57840
C 0.34179 -2.31770 2.31980
C 1.15350 -1.77320 1.35000
H 2.21990 -1.70040 1.53890
H -0.70180 -2.51490 2.08450
C 1.39060 -3.49020 6.25750
C 0.12340 -3.77830 5.74300
C -0.19770 -3.38770 4.44760
C 0.74860 -2.71180 3.64780
C 2.02510 -2.42610 4.18210
C 2.33780 -2.81370 5.47730
H 1.64340 -3.78940 7.27200
H -0.60830 -4.30170 6.35220
H -1.18210 -3.60890 4.03790
H 2.76850 -1.89310 3.59550
H 3.31770 -2.58710 5.88840
H -2.17970 -0.71240 4.11660
H -1.04750 0.69650 4.03010
H -2.76320 0.87950 3.55490
H 0.01320 1.21730 -4.06470
H -0.85100 2.55660 -3.23940
H 0.87150 2.24510 -2.86580
Ti -0.36820 3.55360 1.01450
Cl 0.67590 5.24360 -0.13490
Cl -0.29120 4.47430 3.11860
Cl 1.67050 2.40630 1.34850
Cl -2.49170 4.38910 0.58980
H -1.42450 -1.82090 0.36640

H -0.98800 -1.40520 -1.29610
C 3.58830 -0.49360 -2.93670
C 2.39910 -1.14220 -3.28060
C 1.44330 -1.40710 -2.30610
C 1.68680 -1.06850 -0.95920
C 2.90000 -0.43270 -0.62260
C 3.83200 -0.13150 -1.60860
H 4.32480 -0.26740 -3.70410
H 2.21380 -1.43280 -4.31130
H 0.52400 -1.91200 -2.58990
H 3.09250 -0.11990 0.39920
H 4.74750 0.38960 -1.34280

10.3.1.1.35. TS$_{cyclsec}$aa-co-*Z*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3011.66449
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3012.091035
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3011.780883

C -2.13450 -0.32790 8.65880
C -1.30230 -1.28350 9.50660
C -2.41030 -0.81700 7.25560
H -3.07860 -0.11230 9.17900
C -1.33920 -0.82990 6.32080
O -0.14280 -0.60620 6.83740
O -1.42570 -1.06920 5.08430
C -3.71840 -1.00220 6.74210
O -4.70370 -0.99580 7.63000
C -2.19720 -3.14000 8.20720
C -1.25240 -2.59750 9.11850
H -0.47560 -3.26260 9.48520
H -3.23820 -2.84440 8.32510
C -1.59850 -6.45070 5.66090
C -2.89580 -6.03810 5.97860
C -3.08080 -4.94200 6.80920
C -1.96630 -4.26770 7.35680
C -0.65870 -4.69670 7.02620
C -0.48130 -5.77740 6.17770
H -1.45240 -7.30030 4.99810
H -3.75210 -6.56170 5.56340
H -4.08520 -4.60210 7.05470
H 0.20620 -4.16990 7.42350
H 0.52030 -6.10320 5.91070
C 0.97990 -0.58110 5.93020

H 1.84790 -0.39050 6.55920
H 1.07040 -1.54090 5.41910
H 0.84670 0.22000 5.20060
C -6.05150 -1.11830 7.12420
H -6.68940 -1.08470 8.00620
H -6.26990 -0.28420 6.45450
H -6.16980 -2.06380 6.59250
O -4.01180 -1.22920 5.53530
Ti -2.98100 -1.03190 3.81110
Cl -3.06320 1.29150 4.27030
Cl -1.54980 -0.69020 2.05140
Cl -2.82500 -3.32060 3.68470
Cl -4.96660 -0.95610 2.66300
H -1.59620 0.62340 8.59520
C 0.86500 0.26980 12.86190
C 0.00850 1.09700 12.13530
C -0.68390 0.59470 11.03580
C -0.54270 -0.75240 10.64510
C 0.31650 -1.57800 11.40310
C 1.01510 -1.07090 12.49080
H 1.41050 0.66330 13.71810
H -0.12280 2.13690 12.42210
H -1.35180 1.26200 10.50060
H 0.44770 -2.62580 11.14960
H 1.67660 -1.72210 13.05580

10.3.1.1.36. 206aa-co-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3011.710313
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3012.137459
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3011.822352

C 0.84090 -0.07660 0.97870
C -0.41140 0.08130 1.42470
C -1.32370 0.59640 0.32570
C -0.51540 0.33570 -0.96740
C 1.02010 0.30080 -0.46940
H -2.29320 0.08880 0.30230
H 1.70210 -0.36170 1.57750
C -0.82890 -1.04500 -1.53200
O -1.11340 -1.93400 -0.62870
O -0.79300 -1.35430 -2.72610
C -1.38270 -3.28870 -1.07690
C -0.62780 1.39300 -2.04640

O -0.96450 2.57130 -1.62360
O -0.33030 1.20370 -3.23080
C -0.90440 3.66440 -2.57730
H -1.21650 4.54480 -2.01850
H 0.12320 3.76050 -2.93380
H -1.58220 3.45960 -3.40750
H -1.60780 -3.84200 -0.16820
H -2.23590 -3.28080 -1.75650
H -0.49750 -3.68890 -1.57390
H 1.56610 -0.45960 -1.04250
C 3.02510 4.09580 -1.05310
C 3.22480 3.04690 -1.95060
C 2.58450 1.82270 -1.74910
C 1.74210 1.63180 -0.64880
C 1.55179 2.68830 0.25150
C 2.18690 3.91290 0.04900
H 3.52600 5.04840 -1.20630
H 3.88250 3.17640 -2.80610
H 2.74190 1.00810 -2.45100
H 0.90820 2.55560 1.11810
H 2.03240 4.72300 0.75730
Ti -0.50400 -0.39780 -4.56560
Cl -0.85080 -2.32890 -5.65940
Cl -0.15020 0.99550 -6.28520
Cl 1.71830 -0.81410 -4.18250
Cl -2.77630 0.07220 -4.38630
H -1.51840 1.66800 0.44580
C -1.85280 -0.56810 5.40830
C -2.56790 0.24030 4.52490
C -2.10150 0.44310 3.22500
C -0.90710 -0.15180 2.79330
C -0.20030 -0.97250 3.68840
C -0.66770 -1.17640 4.98370
H -2.21820 -0.73100 6.41900
H -3.49240 0.71410 4.84490
H -2.67020 1.07900 2.54980
H 0.71090 -1.46890 3.36290
H -0.11220 -1.81840 5.66270

10.3.1.1.37. 204aa-co-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3011.684356
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3012.112123
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3011.80135

C -1.04750 1.09420 -0.75490
C -0.70600 -0.22290 -0.85850
C 0.70390 -0.72179 -1.10880
C 1.41990 -0.71340 0.22490
C 1.68430 -1.81900 0.93210
C 2.34630 -1.86100 2.25090
C -2.44010 1.52090 -0.44930
C -0.08290 2.22040 -0.76760
O 0.95940 2.10180 -1.54179
O -0.24200 3.24100 -0.08460
C 1.92710 3.18560 -1.52440
O -2.72410 2.41560 0.35920
O -3.37230 0.91940 -1.13070
C -4.74760 1.24760 -0.81040
C 2.39010 -0.74810 3.10610
C 3.04530 -0.82220 4.33310
C 3.66240 -2.01130 4.73270
C 3.60980 -3.12940 3.89920
C 2.95210 -3.05480 2.67100
H 0.64820 -1.74700 -1.48510
H 1.69060 0.26830 0.61800
H 1.41970 -2.78910 0.50560
H 2.70320 2.87920 -2.22360
H 1.44250 4.10720 -1.85140
H 2.32710 3.30040 -0.51470
H -5.34770 0.62660 -1.47240
H -4.94020 1.00870 0.23730
H -4.92360 2.30760 -0.99820
H 1.88780 0.17380 2.82330
H 3.06530 0.04670 4.98630
H 4.17090 -2.06700 5.69210
H 4.07880 -4.06130 4.20610
H 2.91190 -3.93010 2.02480
Ti -1.54060 3.72690 1.49380
Cl 0.02730 5.06190 2.39550
Cl -3.20590 3.93550 2.98450
Cl -0.67650 1.80290 2.47690
Cl -2.33720 5.32270 0.05230
H 1.22840 -0.11010 -1.84260
C -3.43250 -3.34050 0.21830
C -2.77570 -3.38430 -1.01400
C -1.88420 -2.37380 -1.36880
C -1.67570 -1.28990 -0.50450
C -2.33490 -1.25090 0.73210
C -3.20380 -2.27800 1.09470

H -4.11220 -4.14100 0.49950
H -2.95090 -4.21250 -1.69620
H -1.37320 -2.41490 -2.32880
H -2.13170 -0.43630 1.42570
H -3.69310 -2.25179 2.06520

10.3.1.1.38. TS$_{migH}$aa-co-*trans-E*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3011.643487
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3012.068874
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3011.762922

C -0.08680 -0.93130 -0.54179
C 1.03600 -1.54910 0.07390
C -0.51150 0.42850 -0.12930
H 1.25720 -2.58030 -0.20940
C -0.56840 1.47540 -1.09050
O -0.27030 1.15890 -2.33470
O -0.85860 2.67430 -0.82850
C -0.27730 2.22270 -3.31170
C -0.86000 0.73740 1.20880
O -0.86920 -0.27940 2.06140
O -1.18130 1.87550 1.64130
C -1.24110 0.00290 3.42940
C 3.02670 -1.47960 1.47870
C 1.94390 -0.85770 0.95880
H 1.77660 0.20670 1.10430
H 3.15040 -2.55090 1.30480
C 6.19940 0.33470 3.68790
C 6.21250 -1.03490 3.41690
C 5.16540 -1.61250 2.70010
C 4.09120 -0.82910 2.24580
C 4.08910 0.55170 2.52700
C 5.13420 1.12560 3.24210
H 7.01580 0.78850 4.24420
H 7.03850 -1.65120 3.76200
H 5.17710 -2.67950 2.48420
H 3.27530 1.18630 2.18590
H 5.12270 2.20430 3.45179
H -1.13760 -0.94680 3.95140
H -0.57020 0.75490 3.84740
H -2.27240 0.35730 3.46440
H 0.02400 1.74820 -4.24420
H -1.28020 2.64550 -3.39600

H 0.43530 2.99710 -3.02179
Ti -0.89440 3.72840 0.88820
Cl -0.46570 5.65500 -0.26050
Cl -0.91870 4.57870 3.00890
Cl 1.41140 3.19410 1.03280
Cl -3.18130 3.89730 0.63180
H -0.19740 -1.69100 0.54460
C -2.03680 -2.75520 -3.87810
C -2.78240 -2.03010 -2.94390
C -2.14660 -1.44170 -1.85470
C -0.76310 -1.59240 -1.68660
C -0.01690 -2.31890 -2.62390
C -0.65630 -2.89510 -3.72000
H -2.53170 -3.20420 -4.73570
H -3.85640 -1.91930 -3.06820
H -2.72110 -0.86860 -1.13030
H 1.06400 -2.39700 -2.52560
H -0.07510 -3.44250 -4.45730

10.3.1.1.39. 182aa-co-*trans-E'*-TiCl₄

E(M06-2X/6-31+G(d)(CH₂Cl₂)) =
-3011.661496
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-3012.087494
G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-3011.778339

C -1.72460 -1.38540 0.62150
C -0.27150 -1.34450 0.30810
C -2.49610 -0.20750 0.07280
H 0.00230 -1.00610 -0.69360
C -1.91740 1.07120 0.01950
O -0.68790 1.18710 0.51930
O -2.46360 2.12200 -0.43390
C -0.06060 2.48310 0.45450
C -3.87720 -0.29330 -0.21760
O -4.48940 -1.41860 0.10770
O -4.57430 0.62620 -0.74340
C -5.87690 -1.55310 -0.25880
C 2.01720 -1.92430 0.62480
C 0.72030 -1.86020 1.12150
H 0.47050 -2.19740 2.12530

H -6.15810 -2.55400 0.06480
H -6.47620 -0.79810 0.25320
H -5.98930 -1.44930 -1.33990
H 0.93320 2.33770 0.87630
H 0.00240 2.81790 -0.58260
H -0.62960 3.20080 1.04830
Ti -4.10080 2.39230 -1.53630
Cl -3.24260 4.38530 -2.31830
Cl -6.06200 2.37360 -2.74430
Cl -5.09930 3.41690 0.29830
Cl -2.97110 1.18310 -3.21580
H -1.87090 -1.51360 1.70310
C -2.47760 -5.21390 -1.26850
C -2.36420 -4.06290 -2.05060
C -2.13030 -2.82840 -1.44700
C -2.02040 -2.74040 -0.05420
C -2.11670 -3.89620 0.72740
C -2.35530 -5.12800 0.12130
H -2.66220 -6.17620 -1.73980
H -2.46070 -4.12410 -3.13179
H -2.05760 -1.92940 -2.05660
H -2.03100 -3.82880 1.81070
H -2.45000 -6.02180 0.73290
H 2.17740 -1.56230 -0.39430
C 5.48620 -3.41550 2.51250
C 5.55170 -2.91700 1.20730
C 4.40230 -2.42460 0.60300
C 3.17270 -2.42710 1.30220
C 3.12300 -2.93190 2.62510
C 4.27440 -3.42190 3.21980
H 6.38520 -3.80340 2.98600
H 6.49580 -2.91810 0.67000
H 4.43730 -2.03590 -0.41320
H 2.18980 -2.93840 3.18240
H 4.23990 -3.81170 4.23330

10.3.1.1.40. TS_openPh aa-co-*trans*

E(M06-2X/6-31+G(d)(CH₂Cl₂)) =
-3011.645686
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-3012.071838
G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-3011.76168

C -1.96710 -0.11300 8.12950
C -1.21950 -1.27630 8.67700

C -0.96580 0.77470 7.40100
H -2.70360 -0.44270 7.39710
H -0.45480 -1.02750 9.41520
C 0.06700 1.47020 8.06910
O 0.15180 1.28450 9.38390
O 0.90850 2.24570 7.53570
C -1.06090 0.93320 5.99520
O -2.02670 0.26430 5.38110
C 1.19080 1.99720 10.09000
H 1.07410 1.70490 11.13290
H 2.17040 1.70260 9.70940
H 1.05150 3.07330 9.97180
C -2.14620 0.43900 3.95250
H -2.98340 -0.19300 3.65970
H -2.35190 1.48600 3.72220
H -1.22620 0.11950 3.46000
O -0.31040 1.66020 5.28580
Ti 1.32780 2.75900 5.64210
Cl -0.08200 4.58700 5.93730
Cl 3.17230 3.90900 6.37380
Cl 2.52010 0.72990 5.53060
Cl 1.55570 3.13270 3.39270
C -3.98320 0.24020 9.56520
C -2.70179 0.52870 9.29390
H -2.12720 1.20470 9.92010
H -4.50460 -0.48360 8.93360
C -1.62430 -5.36240 7.87360
C -0.66680 -4.92030 8.79920
C -0.54970 -3.56720 9.05580
C -1.39510 -2.63100 8.38240
C -2.36630 -3.10740 7.44760
C -2.47210 -4.46110 7.20220
H -1.71430 -6.42730 7.66910
H -0.02480 -5.63570 9.30490
H 0.18670 -3.20020 9.76900
H -3.02270 -2.41520 6.92750
H -3.20500 -4.83400 6.49260
C -6.36170 1.78840 12.77180
C -6.76890 0.65800 12.06210
C -5.98910 0.17650 11.01070
C -4.78570 0.80790 10.66240
C -4.39340 1.95430 11.37430
C -5.17410 2.43780 12.42050
H -6.96960 2.16870 13.58880
H -7.69490 0.15290 12.32440
H -6.31130 -0.70320 10.45600

H -3.48640 2.48730 11.10030
H -4.86100 3.32860 12.95940

10.3.1.1.41. TS$_{openPh}$aa-co-*trans*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3011.644821
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3012.070769
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3011.761273

C -1.24710 -0.25120 8.36480
C -0.14940 -1.03630 8.99120
C -1.29690 -0.15580 6.85640
H -2.19640 -0.68840 8.69460
H 0.74970 -1.20040 8.39330
C -0.19750 0.30370 6.10760
O 0.89970 0.59970 6.80450
O -0.15580 0.46780 4.85410
C -2.51730 -0.34290 6.17640
O -3.57750 -0.64040 6.91810
C 2.04020 1.08850 6.06790
H 2.81000 1.26140 6.81870
H 2.36570 0.34090 5.34220
H 1.78420 2.01820 5.55650
C -4.83670 -0.81230 6.23370
H -5.55180 -1.05740 7.01780
H -5.11760 0.11460 5.73050
H -4.76180 -1.62470 5.50880
O -2.68520 -0.22780 4.92630
Ti -1.44820 0.04990 3.38480
Cl -2.06020 2.29660 3.39580
Cl 0.22320 0.40070 1.84210
Cl -0.81670 -2.20180 3.67670
Cl -3.13680 -0.51830 1.93260
C -2.23460 1.70660 9.60730
C -1.18490 1.15470 8.98470
H -0.25780 1.69870 8.82020
H -3.13730 1.10630 9.74200
C 0.11130 -2.52360 12.88760
C 1.20610 -2.63460 12.01970
C 1.09460 -2.15280 10.72800
C -0.12110 -1.53820 10.29150
C -1.22890 -1.45200 11.19370
C -1.10520 -1.94180 12.47470
H 0.19770 -2.90010 13.90500

H 2.12890 -3.09480 12.36040
H 1.93020 -2.22970 10.03400
H -2.16770 -1.01010 10.87220
H -1.93830 -1.88330 13.16910
C -2.63010 5.68810 11.14610
C -3.63630 4.74150 11.33830
C -3.48590 3.45140 10.82900
C -2.32860 3.08390 10.12560
C -1.32350 4.04710 9.93640
C -1.47420 5.33520 10.44230
H -2.74570 6.69670 11.53480
H -4.54060 5.00740 11.87980
H -4.27730 2.71810 10.97570
H -0.42100 3.80179 9.38260
H -0.69050 6.07120 10.28110

10.3.1.2. R^1 = p-MeOC$_6$H$_4$, R^3 = Ph

10.3.1.2.1. 179ka-co-trans-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -3126.168684
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3126.628011
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3126.284354

C -0.85320 -0.37350 -0.20770
C 0.58140 -0.55610 0.06470
C 0.02490 0.90700 0.06000
H 1.22560 -0.69940 -0.80030
C 0.38320 1.75400 -1.10420
O 0.89530 1.11080 -2.11470
O 0.21820 2.97890 -1.18100
C 1.19880 1.87070 -3.31300
C -0.23150 1.62700 1.32530
O -0.49090 0.87020 2.35360
O -0.22120 2.86020 1.44540
C -0.80350 1.52940 3.60920
C 2.38890 -1.38780 1.52840
C 1.08170 -1.18410 1.31530
H 0.33790 -1.46900 2.05450
H 3.10260 -1.05710 0.77060
C 4.19880 -3.00740 5.05950
C 4.96280 -2.32240 4.11420
C 4.35950 -1.81940 2.96120

C 2.98400 -1.98290 2.73890
C 2.22790 -2.68770 3.69050
C 2.83020 -3.20410 4.84020
H 4.66500 -3.40179 5.95890
H 6.02860 -2.17860 4.27330
H 4.95810 -1.28280 2.22700
H 1.16590 -2.85740 3.52950
H 2.23210 -3.73640 5.56670
H -1.04250 0.72190 4.29830
H 0.06630 2.09490 3.94690
H -1.66080 2.18920 3.46550
H 1.60640 1.14150 -4.01070
H 0.28250 2.32000 -3.69940
H 1.93370 2.64150 -3.07600
H -1.49700 -0.54600 0.65500
C -2.94470 -0.89330 -3.92350
C -3.55240 -0.23800 -2.84730
C -2.84220 -0.08600 -1.65740
C -1.53740 -0.56710 -1.51940
C -0.94730 -1.23390 -2.60150
C -1.64240 -1.39670 -3.79300
O -3.54320 -1.09630 -5.12830
H -4.56220 0.15220 -2.91710
H -3.32010 0.41910 -0.82050
H 0.05830 -1.64010 -2.51570
H -1.19480 -1.91700 -4.63630
Ti -0.55860 4.42940 0.12010
Cl -0.81880 5.82880 -1.61790
Cl -1.36810 5.69620 1.79460
Cl 1.64020 4.96610 0.50700
Cl -2.57830 3.32440 -0.24440
C -4.86520 -0.59740 -5.30870
H -5.14770 -0.85850 -6.32900
H -5.55920 -1.06800 -4.60340
H -4.89280 0.49090 -5.18570

10.3.1.2.2. 182ka-co-trans-E-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -3126.148786
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3126.608176
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3126.269577

C -0.36140 -1.19750 -0.25310
C 0.99590 -1.75600 0.02990
C -0.33690 0.07640 -1.07830
H 1.04040 -2.79700 0.35930
C 0.19780 0.08560 -2.38050
O 0.68179 -1.06450 -2.82630
O 0.25570 1.09060 -3.15510
C 1.21140 -1.08690 -4.16730
C -0.94430 1.26100 -0.62320
O -1.59610 1.20370 0.53250
O -0.92970 2.37660 -1.23020
C -2.22470 2.41520 0.99820
C 3.36430 -1.61730 0.38870
C 2.15200 -1.02150 0.00810
H 2.11580 0.01790 -0.31110
H 3.33810 -2.66510 0.70040
C 7.15970 0.20870 0.46370
C 7.01110 -1.11940 0.88400
C 5.75720 -1.71120 0.85270
C 4.63170 -0.97400 0.40300
C 4.80290 0.37150 -0.01990
C 6.05860 0.95130 0.01130
H 8.14350 0.67240 0.48580
H 7.87490 -1.67920 1.23020
H 5.62440 -2.74260 1.17390
H 3.95720 0.95250 -0.37620
H 6.19310 1.97870 -0.31520
H -2.67560 2.15040 1.95350
H -1.47820 3.20120 1.12550
H -2.98750 2.73650 0.28640
H 1.59040 -2.09850 -4.30690
H 0.41680 -0.86990 -4.88410
H 2.01410 -0.35370 -4.26620
Ti 0.12020 3.03760 -2.78430
Cl 1.46070 3.47400 -4.60770
Cl -0.09980 5.19970 -2.01650
Cl 2.04950 2.70260 -1.39000
Cl -1.82300 3.13410 -4.02940
H -0.68690 -0.88640 0.75840
C -3.31230 -4.02950 -1.69010
C -3.69390 -2.94720 -0.89060
C -2.71740 -2.06430 -0.42610
C -1.36870 -2.23100 -0.74410
C -1.00410 -3.32110 -1.54530
C -1.96179 -4.21480 -2.01150
H -4.73210 -2.78020 -0.62270

H -3.02310 -1.22420 0.19500
H 0.03640 -3.47290 -1.82490
H -1.68210 -5.05990 -2.63640
O -4.18010 -4.94880 -2.19790
C -5.56610 -4.77790 -1.92220
H -6.07800 -5.59790 -2.42680
H -5.76050 -4.83150 -0.84510
H -5.92870 -3.82180 -2.31790

10.3.1.2.3. 182ka-co-*trans-E'*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -3126.145603
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3126.604209
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3126.26293

C -1.77130 -1.37600 0.64560
C -0.32910 -1.37800 0.29560
C -2.53290 -0.21010 0.06060
H -0.07650 -1.07470 -0.72350
C -1.94510 1.06810 0.04300
O -0.72890 1.18320 0.57740
O -2.46810 2.13110 -0.40750
C -0.09230 2.45760 0.55870
C -3.89840 -0.28670 -0.29120
O -4.53050 -1.41680 -0.02490
O -4.56800 0.64880 -0.82580
C -5.90070 -1.52790 -0.45910
C 1.96320 -1.96310 0.58060
C 0.68460 -1.87220 1.10460
H 0.45690 -2.16720 2.12650
H -6.20090 -2.53890 -0.18800
H -6.51900 -0.78960 0.05480
H -5.96350 -1.38070 -1.53910
H 0.88860 2.29620 1.00380
H 0.00050 2.81520 -0.46840
H -0.67280 3.16580 1.15280
Ti -4.07280 2.43580 -1.54980
Cl -3.19020 4.45000 -2.24280
Cl -5.99730 2.45870 -2.81510
Cl -5.12560 3.40600 0.28490
Cl -2.89540 1.25840 -3.23280
H -1.89720 -1.45750 1.73400

C -2.46350 -5.30320 -1.06300
C -2.37420 -4.18180 -1.90350
C -2.18340 -2.92440 -1.36150
C -2.04960 -2.75730 0.02960
C -2.12510 -3.88210 0.85570
C -2.34179 -5.15190 0.32510
O -2.66900 -6.49040 -1.68340
H -2.47660 -4.32100 -2.97710
H -2.10710 -2.06000 -2.02150
H -2.03840 -3.77020 1.93530
H -2.41770 -6.00250 0.99470
H 2.10179 -1.63730 -0.45370
C 5.47800 -3.42510 2.41970
C 5.51220 -2.95020 1.10510
C 4.34850 -2.46680 0.51940
C 3.13660 -2.45300 1.24600
C 3.11820 -2.93220 2.57750
C 4.28290 -3.41480 3.15400
H 6.38700 -3.80670 2.87900
H 6.44270 -2.96060 0.54440
H 4.36080 -2.09730 -0.50450
H 2.19850 -2.92770 3.15690
H 4.27050 -3.78630 4.17490
C -2.77020 -7.66500 -0.88420
H -2.92410 -8.48840 -1.58230
H -1.84760 -7.83070 -0.31720
H -3.62250 -7.59900 -0.19910

10.3.1.2.4. TS$_{mig}$ka-co-*trans-E*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3126.147585
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3126.606043
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3126.264125

C 0.53420 -1.15290 0.66660
C 1.65900 -1.61140 1.44530
C -0.01400 0.21460 0.68080
H 2.21700 -0.86560 2.00490
C -0.69910 0.66310 -0.47510
O -0.82410 -0.22340 -1.44990
O -1.18820 1.81490 -0.64980
C -1.52080 0.19680 -2.64150
C 0.03980 1.08240 1.79350

O 0.54640 0.60460 2.92090
O -0.37660 2.27830 1.79650
C 0.60440 1.49930 4.05190
C 2.69150 -3.29260 2.89250
C 1.77410 -2.98800 1.96020
H 1.06990 -3.72630 1.57900
H 3.35890 -2.49750 3.23220
C 3.39930 -7.03050 4.85460
C 4.15690 -5.90180 5.16750
C 3.90900 -4.69480 4.51460
C 2.90460 -4.59650 3.53920
C 2.14610 -5.73970 3.23380
C 2.39340 -6.94420 3.88610
H 4.94000 -5.95950 5.91930
H 4.50060 -3.81470 4.76070
H 1.35670 -5.69530 2.48730
H 1.79960 -7.82120 3.64130
H 1.05900 0.91520 4.85100
H 1.21660 2.36990 3.80930
H -0.40280 1.81520 4.32900
H -1.47980 -0.66179 -3.31050
H -2.55450 0.44920 -2.39790
H -1.01870 1.05920 -3.08350
Ti -0.87420 3.53980 0.32470
Cl -1.40890 4.70080 -1.58200
Cl -0.34070 5.32190 1.66760
Cl 1.38850 3.29860 -0.38240
Cl -3.06210 3.45300 1.06020
H -0.14430 -1.93370 0.32120
C 3.61800 -1.27260 -2.39370
C 3.58100 -0.16870 -1.50910
C 2.74660 -0.22350 -0.41950
C 1.94670 -1.36950 -0.14860
C 2.00360 -2.47060 -1.05810
C 2.81560 -2.42060 -2.15970
H 4.18880 0.71380 -1.67860
H 2.69710 0.63220 0.25080
H 1.38600 -3.35080 -0.88670
H 2.86390 -3.24110 -2.87080
H 3.58840 -7.97330 5.36179
O 4.37260 -1.31270 -3.48070
C 5.21140 -0.19400 -3.81250
H 5.71870 -0.47640 -4.73390
H 4.60270 0.69960 -3.97780
H 5.94440 -0.02179 -3.01930

10.3.1.3. R^1 = styryl, R^3 = Ph

10.3.1.3.1. 179ua-co-trans-TiCl₄

E(M06-2X/6-31+G(d)(CH₂Cl₂)) =
-3089.051804
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-3089.49667
G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-3089.155095

```
C -0.72200 -0.43910 -0.33450
C 0.70380 -0.44390 0.04000
C -0.03700 0.93810 0.00900
H 1.39590 -0.50400 -0.79850
C 0.32080 1.86130 -1.09590
O 0.86490 1.29110 -2.13620
O 0.14179 3.08420 -1.08360
C 1.22260 2.14290 -3.25650
C -0.46730 1.57650 1.27390
O -0.77210 0.74780 2.23360
O -0.55260 2.79730 1.45650
C -1.24320 1.31380 3.48530
C 2.53740 -1.20960 1.49070
C 1.22179 -1.03660 1.29740
H 0.49120 -1.35300 2.03680
H 3.22830 -0.85850 0.72080
C 4.48690 -2.92420 4.90010
C 5.21790 -2.23780 3.92880
C 4.56410 -1.69560 2.82090
C 3.17500 -1.82230 2.66950
C 2.45300 -2.52540 3.64860
C 3.10360 -3.06850 4.75330
H 4.99090 -3.35020 5.76400
H 6.29230 -2.12470 4.03170
H 5.13580 -1.17970 2.06440
H 1.37980 -2.66510 3.54450
H 2.53170 -3.61220 5.50110
H -1.46540 0.45510 4.11790
H -0.45760 1.93270 3.92179
H -2.14020 1.90640 3.29800
H 1.67370 1.47280 -3.98610
H 0.32290 2.61580 -3.65380
H 1.93670 2.89770 -2.92370
H -1.41520 -0.71400 0.45990
Ti -0.65690 4.48690 0.24190
Cl -0.63980 6.04140 -1.37950
```

```
Cl -1.52600 5.67330 1.94060
Cl 1.53570 4.80840 0.86490
Cl -2.69220 3.57130 -0.40130
C -2.50080 -0.93670 -1.96110
C -1.19940 -0.73800 -1.70460
H -0.44570 -0.82030 -2.48370
H -3.21540 -0.82840 -1.14220
C -4.31730 -1.88950 -5.72270
C -5.09420 -1.50180 -4.63060
C -4.48490 -1.20500 -3.41130
C -3.09150 -1.28200 -3.26580
C -2.32070 -1.68480 -4.36920
C -2.92860 -1.98290 -5.58560
H -4.78840 -2.12400 -6.67390
H -6.17480 -1.43120 -4.72620
H -5.09420 -0.90400 -2.56080
H -1.24179 -1.78330 -4.27820
H -2.31930 -2.29550 -6.43000
```

10.3.1.3.2. 182ua-co-trans-E-TiCl₄

E(M06-2X/6-31+G(d)(CH₂Cl₂)) =
-3089.031595
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-3089.477092
G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-3089.134592

```
C -0.42610 -1.11670 -0.11150
C 0.92820 -1.66520 0.19790
C -0.40380 0.12290 -0.98930
H 0.96470 -2.69070 0.57350
C 0.14710 0.08190 -2.28480
O 0.65340 -1.07780 -2.67630
O 0.20350 1.05500 -3.09950
C 1.20170 -1.14530 -4.00800
C -1.01780 1.32430 -0.58710
O -1.67770 1.31130 0.56470
O -0.99800 2.41500 -1.23660
C -2.30920 2.54070 0.97770
C 3.29640 -1.55640 0.52260
C 2.09010 -0.94179 0.15350
H 2.06830 0.08570 -0.20460
H 3.24650 -2.58790 0.88180
C 7.18140 0.10060 0.32080
```

C 6.97980 -1.19810 0.81330
C 5.70179 -1.73170 0.87830
C 4.58640 -0.96460 0.45350
C 4.79120 0.35100 -0.04190
C 6.07110 0.87260 -0.10620
H 8.16540 0.51770 0.26510
H 7.83640 -1.78120 1.13840
H 5.54170 -2.74050 1.25450
H 3.95230 0.95230 -0.38080
H 6.23240 1.87620 -0.48960
H -2.76280 2.31830 1.94200
H -1.56340 3.33180 1.07360
H -3.06980 2.83050 0.25020
H 1.61810 -2.14880 -4.09430
H 0.41030 -0.99010 -4.74420
H 1.98080 -0.39090 -4.13220
Ti 0.06730 3.01510 -2.80700
Cl 1.41890 3.38260 -4.63690
Cl -0.15670 5.20500 -2.12420
Cl 1.98490 2.73050 -1.38760
Cl -1.86750 3.06270 -4.06850
H -0.76090 -0.76260 0.88320
C -1.42060 -2.15100 -0.59500
C -1.08270 -3.27290 -1.24230
H -0.02440 -3.47100 -1.42240
H -2.46300 -1.88640 -0.42410
C -3.61590 -6.33010 -2.86620
C -2.22700 -6.42760 -2.95100
C -1.42410 -5.42040 -2.41530
C -1.99000 -4.30110 -1.78580
C -3.38990 -4.21380 -1.70780
C -4.20410 -5.21850 -2.24300
H -4.24640 -7.11179 -3.28270
H -1.76740 -7.28620 -3.43440
H -0.34050 -5.50150 -2.48510
H -3.86140 -3.35770 -1.23110
H -5.27390 -5.13460 -2.17590

10.3.1.3.3. 182ua-co-*trans-E'*-TiCl₄

E(M06-2X/6-31+G(d)(CH₂Cl₂)) =
-3089.028262
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-3089.472793

G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-3089.13366

C -1.89280 -1.38930 0.55260
C -0.45820 -1.45500 0.18140
C -2.60840 -0.17390 0.01150
H -0.20800 -1.17880 -0.84670
C -1.96120 1.07610 -0.00140
O -0.72090 1.10060 0.48179
O -2.45090 2.17190 -0.40570
C -0.02500 2.36310 0.47020
C -3.98040 -0.18730 -0.31830
O -4.64450 -1.30930 -0.08990
O -4.62780 0.79300 -0.79370
C -6.04120 -1.33910 -0.44500
C 1.80810 -2.14970 0.45110
C 0.54010 -1.98800 0.98420
H 0.30860 -2.25890 2.01200
H -6.37010 -2.35010 -0.20880
H -6.59320 -0.60610 0.14610
H -6.18130 -1.12920 -1.50940
H 0.96380 2.14270 0.86990
H 0.04420 2.74440 -0.55020
H -0.54710 3.08050 1.10610
Ti -4.10550 2.60370 -1.43370
Cl -3.18790 4.62740 -2.04730
Cl -6.09800 2.77540 -2.57410
Cl -5.01150 3.48710 0.51960
Cl -3.07230 1.50310 -3.25280
H -2.01179 -1.50630 1.63890
H 1.95170 -1.85670 -0.59210
C 5.26179 -3.73570 2.30310
C 5.30100 -3.32340 0.96760
C 4.15830 -2.79660 0.37790
C 2.96150 -2.67920 1.12060
C 2.93800 -3.09620 2.47290
C 4.08240 -3.62020 3.05380
H 6.15430 -4.14970 2.76620
H 6.22040 -3.41500 0.39430
H 4.17490 -2.47380 -0.66179
H 2.03179 -3.00820 3.06660
H 4.06660 -3.94210 4.09130
C -2.33800 -3.87290 0.51940
C -2.25360 -2.70370 -0.13700
H -2.39680 -2.63850 -1.21310
H -2.18860 -3.87490 1.60179

C -3.25120 -7.72470 -1.10310
C -3.10520 -7.54480 0.27260
C -2.80800 -6.28100 0.78170
C -2.65230 -5.17840 -0.07400
C -2.79920 -5.37400 -1.45910
C -3.09660 -6.63440 -1.96630
H -3.48340 -8.70790 -1.50430
H -3.22320 -8.38760 0.94890
H -2.69650 -6.14200 1.85560
H -2.67720 -4.54350 -2.14970
H -3.20720 -6.77070 -3.03900

10.3.1.3.4. TS$_{mig}$ua-co-*trans-E*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3089.025771
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3089.470132
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3089.12968

C -2.08179 -1.21130 1.25880
C -2.62070 0.00920 0.59820
C -1.85370 0.92950 -0.14720
O -0.55680 0.67260 -0.26910
O -2.29420 1.97670 -0.70230
C 0.23900 1.61890 -1.01530
C -4.01820 0.23760 0.67650
O -4.72230 -0.63490 1.38190
O -4.64180 1.19380 0.13550
C -6.14730 -0.42500 1.46450
H -6.51950 -1.25670 2.06100
H -6.35500 0.52830 1.95360
H -6.58470 -0.43680 0.46470
H 1.25330 1.22300 -0.98150
H -0.12140 1.67810 -2.04390
H 0.18930 2.60090 -0.54190
Ti -4.13010 2.61070 -1.18400
Cl -3.22800 4.11050 -2.66830
Cl -6.35120 3.04450 -1.55970
Cl -3.99720 4.10110 0.59300
Cl -4.10880 0.87690 -2.79130
H -2.75320 -1.58090 2.03270
C -1.70330 -2.37690 0.27690
C -0.69410 -1.53540 1.52440
H 0.07440 -1.08220 0.90670
C -2.07040 -3.67010 0.53120

H -1.35690 -2.05500 -0.69950
H -2.40940 -3.91410 1.54179
C -2.11750 -6.96670 -2.13700
C -2.58330 -7.10630 -0.82740
C -2.55910 -6.01360 0.03330
C -2.07200 -4.76640 -0.40970
C -1.60240 -4.63950 -1.73540
C -1.62570 -5.73400 -2.58770
H -2.13410 -7.82040 -2.81170
H -2.96240 -8.06390 -0.48150
H -2.92130 -6.11420 1.05500
H -1.20920 -3.69360 -2.09870
H -1.26180 -5.63400 -3.60650
C 1.06950 -2.49570 2.87590
C -0.25100 -2.27860 2.68640
H -1.00240 -2.61170 3.40080
H 1.75850 -2.13860 2.10720
C 3.02790 -4.51330 6.08870
C 3.74590 -4.07950 4.97330
C 3.08780 -3.41250 3.94150
C 1.70380 -3.17680 4.00570
C 0.99200 -3.61270 5.13810
C 1.65110 -4.27460 6.16890
H 3.53720 -5.03210 6.89710
H 4.81790 -4.25820 4.90750
H 3.64680 -3.07220 3.07150
H -0.07620 -3.42790 5.22280
H 1.09340 -4.60480 7.04140

10.3.1.4. R^1 = p-MeC$_6$H$_4$, R^3 = Ph

10.3.1.4.1. 179la-co-*trans*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3050.982605
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3051.419345
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3051.082803

C -0.95210 -0.39810 -0.19580
C 0.48750 -0.50930 0.08580
C -0.16790 0.92460 0.06770
H 1.13150 -0.61440 -0.78520
C 0.18210 1.78300 -1.09250
O 0.62340 1.14130 -2.13550
O 0.07260 3.01520 -1.11770

C 0.92350 1.91460 -3.32470
C -0.44420 1.63060 1.33930
O -0.74510 0.85910 2.34600
O -0.40530 2.85890 1.48550
C -1.06400 1.50050 3.60970
C 2.34480 -1.35260 1.46090
C 1.03320 -1.10600 1.32820
H 0.32330 -1.35990 2.11040
H 3.01250 -1.06760 0.64470
C 4.37980 -3.06360 4.82110
C 5.09300 -2.51930 3.75310
C 4.41110 -1.97640 2.66390
C 3.00860 -1.96280 2.62600
C 2.30140 -2.52360 3.70320
C 2.98150 -3.06600 4.78990
H 4.90670 -3.48790 5.67200
H 6.18000 -2.51830 3.76640
H 4.97050 -1.55120 1.83230
H 1.21440 -2.54880 3.69360
H 2.42040 -3.49640 5.61560
H -1.32390 0.68410 4.28080
H -0.18950 2.04560 3.96840
H -1.90800 2.17750 3.46850
H 1.25460 1.18120 -4.05710
H 0.02100 2.42920 -3.65910
H 1.71400 2.63240 -3.10030
H -1.60250 -0.61710 0.65230
C -2.80060 -1.18460 -4.01550
C -3.30040 -0.19630 -3.15970
C -2.69480 0.06190 -1.93060
C -1.56540 -0.65920 -1.53540
C -1.05630 -1.64750 -2.38250
C -1.67090 -1.90610 -3.60600
C -3.45810 -1.47810 -5.34150
H -4.17710 0.37700 -3.45520
H -3.10320 0.82960 -1.27520
H -0.18179 -2.22300 -2.08450
H -1.26770 -2.68320 -4.25410
Ti -0.54220 4.50090 0.20770
Cl -0.61490 5.98180 -1.47910
Cl -1.21670 5.79060 1.92170
Cl 1.70050 4.75900 0.62720
Cl -2.67050 3.64920 -0.21330
H -4.31910 -0.82490 -5.51140
H -2.75480 -1.33670 -6.17030
H -3.80650 -2.51660 -5.38440

10.3.1.4.2. 182la-co-*trans-E*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -3050.962776
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3051.399755
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3051.062864

C -0.42690 -1.17070 -0.24410
C 0.93280 -1.71110 0.06240
C -0.40250 0.10490 -1.06660
H 0.98370 -2.75250 0.38860
C 0.12880 0.11100 -2.36990
O 0.61280 -1.03960 -2.81200
O 0.18310 1.11340 -3.14860
C 1.11700 -1.07260 -4.18080
C -0.98550 1.29880 -0.60210
O -1.61800 1.25360 0.56550
O -0.96630 2.41330 -1.21180
C -2.21230 2.47700 1.04320
C 3.29340 -1.57410 0.43400
C 2.08260 -0.96790 0.06330
H 2.04700 0.07380 -0.24880
H 3.25910 -2.62350 0.73970
C 7.11690 0.18890 0.43250
C 6.95730 -1.14050 0.84450
C 5.69280 -1.70970 0.84430
C 4.56880 -0.94820 0.43290
C 4.75050 0.39870 0.01940
C 6.01650 0.95620 0.02070
H 8.10920 0.63460 0.42910
H 7.82090 -1.71910 1.15940
H 5.55030 -2.74220 1.15780
H 3.90390 0.99640 -0.30590
H 6.17930 1.98450 -0.29890
H -2.64530 2.22230 2.00940
H -1.44910 3.24990 1.15080
H -2.98590 2.81030 0.34880
H 1.48830 -2.08700 -4.30179
H 0.31000 -0.85620 -4.86480
H 1.92140 -0.34420 -4.28030
Ti 0.06560 3.06170 -2.78430
Cl 1.38000 3.48230 -4.63060

Cl -0.13180 5.22860 -2.02530
Cl 2.01410 2.72340 -1.41720
Cl -1.89640 3.18340 -3.99730
H -0.78200 -0.86200 0.75800
C -3.26470 -4.09570 -1.77580
C -3.68310 -3.00210 -1.00290
C -2.76490 -2.08170 -0.50670
C -1.39660 -2.22390 -0.77020
C -0.97500 -3.30820 -1.54100
C -1.89890 -4.23320 -2.03350
H -4.74260 -2.87300 -0.78580
H -3.11270 -1.24020 0.09060
H 0.07870 -3.43330 -1.78150
H -1.54680 -5.07000 -2.63430
C -4.26970 -5.08590 -2.31130
H -3.77750 -5.88780 -2.86960
H -4.84440 -5.54110 -1.49660
H -4.98510 -4.59510 -2.98120

10.3.1.4.3. 182la-co-*trans-E'*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -3050.958863
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3051.394965
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3051.060716

C -1.72530 -1.37690 0.63630
C -0.27420 -1.33230 0.31830
C -2.50250 -0.20280 0.08800
H -0.00370 -0.99070 -0.68360
C -1.92340 1.07560 0.02100
O -0.69120 1.19480 0.51430
O -2.46940 2.12360 -0.43940
C -0.06060 2.48810 0.42870
C -3.88450 -0.28930 -0.19330
O -4.49790 -1.40890 0.14830
O -4.58190 0.62650 -0.72540
C -5.88780 -1.54240 -0.20850
C 2.01710 -1.91210 0.63510
C 0.72120 -1.84860 1.12970
H 0.47030 -2.19140 2.13110
H -6.17180 -2.53690 0.13230
H -6.48110 -0.77690 0.29480

H -6.00570 -1.45520 -1.29050
H 0.93350 2.34650 0.85100
H 0.00130 2.80680 -0.61360
H -0.62640 3.21670 1.01200
Ti -4.10600 2.37640 -1.54930
Cl -3.23980 4.35040 -2.36820
Cl -6.06280 2.33760 -2.76300
Cl -5.10740 3.43780 0.26090
Cl -2.97490 1.11410 -3.20560
H -1.86710 -1.50550 1.71860
C -2.47770 -5.21950 -1.27840
C -2.35990 -4.04830 -2.04090
C -2.12450 -2.81880 -1.43650
C -2.01180 -2.73030 -0.04220
C -2.10780 -3.89260 0.72710
C -2.34820 -5.11950 0.11220
H -2.45920 -4.10060 -3.12440
H -2.05260 -1.91970 -2.04630
H -2.02120 -3.83730 1.81120
H -2.44250 -6.01480 0.72460
H 2.17960 -1.55130 -0.38400
C 5.48490 -3.40350 2.52960
C 5.55000 -2.91320 1.22140
C 4.40120 -2.42020 0.61580
C 3.17250 -2.41480 1.31570
C 3.12300 -2.91140 2.64140
C 4.27380 -3.40110 3.23790
H 6.38320 -3.79150 3.00440
H 6.49310 -2.91910 0.68240
H 4.43660 -2.03730 -0.40260
H 2.19070 -2.91120 3.20040
H 4.23910 -3.78420 4.25410
C -2.73910 -6.54270 -1.95110
H -2.80490 -7.35530 -1.22180
H -3.67760 -6.51520 -2.51710
H -1.93950 -6.78500 -2.66100

10.3.1.4.4. TS$_{mig}$la-co-*trans-E*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -3050.955197
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3051.391792
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3051.056603

C 0.42510 -1.15070 0.68840

C 1.53350 -1.60440 1.47470
C -0.06950 0.22980 0.67340
H 2.11540 -0.84680 1.99440
C -0.69080 0.70860 -0.50830
O -0.79180 -0.18340 -1.49660
O -1.13640 1.87470 -0.69040
C -1.39570 0.29480 -2.72430
C -0.03500 1.08590 1.80050
O 0.39950 0.57460 2.94220
O -0.41510 2.29110 1.80000
C 0.42470 1.44910 4.09060
C 2.65250 -3.26470 2.86940
C 1.66000 -2.96820 2.01340
H 0.91790 -3.70260 1.70440
H 3.35120 -2.46850 3.13650
C 3.56820 -6.99830 4.74550
C 4.35300 -5.86850 4.97740
C 4.03180 -4.66040 4.35930
C 2.92480 -4.56270 3.50180
C 2.14100 -5.70750 3.27630
C 2.46180 -6.91290 3.89350
H 5.21450 -5.92640 5.63780
H 4.64530 -3.77950 4.54020
H 1.27660 -5.66330 2.61790
H 1.84880 -7.79180 3.71090
H 0.82320 0.84020 4.90070
H 1.07110 2.30630 3.89370
H -0.58680 1.78720 4.32190
H -1.35400 -0.56010 -3.39740
H -2.42920 0.59410 -2.54120
H -0.82700 1.13510 -3.12630
Ti -0.82660 3.58670 0.32030
Cl -1.26800 4.78230 -1.58310
Cl -0.32310 5.33270 1.71430
Cl 1.44950 3.30330 -0.29300
Cl -3.04380 3.51050 0.96940
H -0.25800 -1.92110 0.32860
C 3.54030 -1.48720 -2.40260
C 3.51690 -0.35770 -1.56540
C 2.68350 -0.31670 -0.46350
C 1.86350 -1.42540 -0.15090
C 1.87980 -2.56280 -0.99710
C 2.70300 -2.58330 -2.10480
H 4.15460 0.49410 -1.79080
H 2.65440 0.57190 0.18310
H 1.23960 -3.41820 -0.78060

H 2.70960 -3.45450 -2.75680
H 3.81490 -7.94250 5.22440
C 4.43460 -1.53390 -3.60640
H 5.02880 -0.62180 -3.70230
H 5.11560 -2.39130 -3.54110
H 3.83980 -1.66300 -4.51880

10.3.1.5. R^1 = p-ClC$_6$H$_4$, R^3 = Ph

10.3.1.5.1. 179ma-co-*trans*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -3471.252272
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3471.712608
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3471.413284

C -0.88370 -0.36120 -0.13790
C 0.55790 -0.45840 0.14000
C -0.10210 0.96840 0.10150
H 1.19900 -0.57540 -0.73130
C 0.23140 1.81230 -1.07700
O 0.69820 1.18090 -2.10390
O 0.08290 3.03870 -1.12930
C 0.98179 1.91890 -3.30940
C -0.38680 1.69670 1.35980
O -0.65590 0.94060 2.38640
O -0.38190 2.92840 1.47510
C -0.99070 1.60250 3.63600
C 2.39890 -1.38660 1.47970
C 1.10330 -1.05460 1.38150
H 0.40280 -1.25080 2.18830
H 3.06100 -1.15920 0.64120
C 4.38960 -3.20920 4.80640
C 5.11590 -2.69710 3.73100
C 4.44850 -2.11560 2.65290
C 3.04840 -2.03040 2.63460
C 2.32730 -2.56040 3.71790
C 2.99280 -3.14120 4.79360
H 4.90530 -3.66460 5.64800
H 6.20179 -2.75050 3.72950
H 5.01750 -1.71680 1.81480
H 1.24020 -2.53450 3.72000
H 2.42110 -3.54830 5.62390
H -1.21300 0.79400 4.32970

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H -0.13600 2.19070 3.97320
H -1.86210 2.24140 3.48320
H 1.34179 1.18190 -4.02450
H 0.06600 2.39820 -3.66020
H 1.74770 2.66570 -3.09540
H -1.53320 -0.57110 0.71290
C -2.69070 -1.19890 -3.91240
C -3.28100 -0.26560 -3.06300
C -2.67740 -0.00080 -1.83680
C -1.49460 -0.65190 -1.47100
C -0.92550 -1.58920 -2.33560
C -1.52270 -1.87060 -3.56320
H -4.19610 0.24250 -3.35410
H -3.13250 0.72020 -1.17990
H -0.01400 -2.11400 -2.05740
H -1.08690 -2.60210 -4.23800
Ti -0.62830 4.52440 0.15280
Cl -0.80540 5.94100 -1.57880
Cl -1.39050 5.81380 1.82710
Cl 1.59000 4.93970 0.55780
Cl -2.69690 3.51370 -0.23620
Cl -3.44030 -1.54010 -5.45130

10.3.1.5.2. 182ma-co-*trans-E*-TiCl₄

E(M06-2X/6-31+G(d)(CH₂Cl₂)) = -3471.232389
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) = -3471.693286
G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) = -3471.39645

C -0.39620 -1.18000 -0.25220
C 0.96390 -1.72300 0.05070
C -0.38020 0.09180 -1.08010
H 1.01430 -2.76540 0.37460
C 0.15070 0.10100 -2.38410
O 0.63670 -1.04860 -2.82910
O 0.19800 1.10330 -3.18090
C 1.14170 -1.07750 -4.17980
C -0.99210 1.27480 -0.62390
O -1.64620 1.21330 0.52990
O -0.98060 2.39000 -1.23040
C -2.28330 2.42100 0.99520

C 3.32370 -1.58480 0.42490
C 2.11179 -0.97920 0.05240
H 2.07430 0.06330 -0.25680
H 3.29110 -2.63700 0.72070
C 7.13700 0.19320 0.48090
C 6.97990 -1.14290 0.87200
C 5.71850 -1.71740 0.85140
C 4.59500 -0.95420 0.44010
C 4.77410 0.39970 0.04680
C 6.03750 0.96220 0.06870
H 8.12700 0.64350 0.49450
H 7.84300 -1.72200 1.18710
H 5.57690 -2.75490 1.14890
H 3.92810 0.99860 -0.27830
H 6.18030 1.99550 -0.23450
H -2.73560 2.15220 1.94870
H -1.54140 3.21060 1.12580
H -3.04560 2.73860 0.28120
H 1.51670 -2.09030 -4.32200
H 0.33390 -0.86290 -4.88240
H 1.94330 -0.34580 -4.29670
Ti 0.06240 3.05280 -2.79180
Cl 1.39240 3.48940 -4.62100
Cl -0.15530 5.21180 -2.02210
Cl 2.00000 2.71710 -1.40780
Cl -1.88610 3.14270 -4.02380
H -0.75140 -0.87430 0.75010
C -3.21100 -4.06770 -1.76030
C -3.66200 -2.99770 -0.99040
C -2.73179 -2.08520 -0.49990
C -1.36720 -2.23180 -0.77390
C -0.94380 -3.31300 -1.55120
C -1.86090 -4.23940 -2.04730
H -4.72090 -2.88280 -0.77680
H -3.07600 -1.24700 0.10270
H 0.10870 -3.43850 -1.79440
H -1.52970 -5.07800 -2.65350
Cl -4.36770 -5.22060 -2.37990

10.3.1.5.3. 182ma-co-*trans-E'*-TiCl₄

E(M06-2X/6-31+G(d)(CH₂Cl₂)) = -3471.227315
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) = -3471.687102

G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3471.389407

```
C -1.71750 -1.33440  0.67990
C -0.26290 -1.27230  0.36280
C -2.50740 -0.17600  0.11790
H  0.00350 -0.93390 -0.64150
C -1.95090  1.11320  0.06230
O -0.73640  1.25420  0.59050
O -2.50330  2.14810 -0.41780
C -0.12870  2.55990  0.52680
C -3.87940 -0.29110 -0.20080
O -4.47880 -1.42290  0.12690
O -4.57950  0.60830 -0.75620
C -5.85200 -1.59250 -0.27750
C  2.02340 -1.86680  0.65750
C  0.73420 -1.77580  1.17440
H  0.49220 -2.10730  2.18200
H -6.12460 -2.59040  0.06290
H -6.48010 -0.83670  0.19700
H -5.93270 -1.51830 -1.36390
H  0.85380  2.43720  0.98060
H -0.04060  2.88130 -0.51260
H -0.72750  3.27550  1.09310
Ti -4.11280  2.36350 -1.57690
Cl -3.26200  4.34850 -2.38210
Cl -6.03290  2.28070 -2.84500
Cl -5.18460  3.41230  0.19870
Cl -2.91090  1.11130 -3.19000
H -1.85990 -1.45670  1.76290
C -2.43490 -5.14510 -1.20170
C -2.30200 -4.01200 -2.00070
C -2.08110 -2.78220 -1.38810
C -2.00310 -2.68890  0.00630
C -2.12450 -3.84130  0.78790
C -2.35080 -5.07670  0.18780
Cl -2.71510 -6.69030 -1.96000
H -2.37320 -4.08810 -3.08210
H -1.99040 -1.88870 -2.00350
H -2.06750 -3.77680  1.87300
H -2.46530 -5.97410  0.78930
H  2.17690 -1.49950 -0.36080
C  5.46470 -3.52750  2.44690
C  5.52580 -3.00350  1.15140
C  4.38650 -2.45120  0.58179
C  3.17130 -2.41850  1.30580
```

```
C  3.12670 -2.94890  2.61940
C  4.26820 -3.49870  3.17940
H  6.35550 -3.96370  2.89310
H  6.45810 -3.03100  0.59470
H  4.41670 -2.04360 -0.42730
H  2.20510 -2.93090  3.19530
H  4.23770 -3.90950  4.18460
```

10.3.1.5.4. TS$_{mig}$ma-co-*trans-E*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3471.21836
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3471.67898
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3471.380795

```
C  0.40550 -1.18530  0.67890
C  1.53300 -1.64680  1.43170
C -0.06750  0.19570  0.66720
H  2.11180 -0.88830  1.95500
C -0.64320  0.70320 -0.52830
O -0.71240 -0.14950 -1.53620
O -1.06280  1.87780 -0.70510
C -1.23480  0.34890 -2.78700
C -0.03970  1.03710  1.80870
O  0.36290  0.49850  2.94800
O -0.40070  2.24600  1.81690
C  0.36560  1.34800  4.11790
C  2.60590 -3.26070  2.90710
C  1.68760 -3.01190  1.95800
H  1.02430 -3.78410  1.57230
H  3.21810 -2.42660  3.25770
C  3.52990 -6.96360  4.83650
C  4.10450 -5.76850  5.27010
C  3.78890 -4.57210  4.62740
C  2.89310 -4.55180  3.54710
C  2.31990 -5.76179  3.11910
C  2.63780 -6.95580  3.75890
H  4.79930 -5.76710  6.10610
H  4.24120 -3.64050  4.96330
H  1.63020 -5.77820  2.27850
H  2.20400 -7.88600  3.41820
H  0.73460  0.71660  4.92290
H  1.02640  2.20180  3.95540
H -0.64880  1.69150  4.32530
H -1.17300 -0.49250 -3.47530
```

H -2.26960 0.67010 -2.65750
H -0.62370 1.18360 -3.13550
Ti -0.75290 3.57430 0.34210
Cl -1.12210 4.79920 -1.55330
Cl -0.25940 5.28900 1.77120
Cl 1.53320 3.25330 -0.21300
Cl -2.98390 3.51740 0.92900
H -0.27110 -1.94800 0.29170
C 3.42570 -1.47080 -2.46840
C 3.47330 -0.35300 -1.62640
C 2.68000 -0.34530 -0.49550
C 1.86640 -1.45840 -0.18830
C 1.83220 -2.57080 -1.05880
C 2.60810 -2.57620 -2.20330
H 4.11490 0.49020 -1.86590
H 2.68130 0.52640 0.15580
H 1.19030 -3.42420 -0.84730
H 2.58740 -3.42040 -2.88740
H 3.77610 -7.89910 5.33240
Cl 4.40090 -1.48020 -3.89060

10.3.1.6. R¹ = p-CO₂MeC₆H₄, R³ = Ph

10.3.1.6.1. 179ma-co-*trans*-TiCl₄

E(M06-2X/6-31+G(d)(CH₂Cl₂)) = -3239.490252
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) = -3239.980826
G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) = -3239.632356

C -0.88410 -0.37840 -0.23020
C 0.55300 -0.44790 0.07710
C -0.15030 0.96350 0.05590
H 1.21690 -0.52600 -0.78180
C 0.19830 1.84360 -1.09020
O 0.65680 1.22000 -2.13730
O 0.07320 3.07330 -1.09920
C 0.97030 2.01520 -3.31000
C -0.46130 1.64940 1.33310
O -0.75080 0.85760 2.32650
O -0.45310 2.87570 1.49300
C -1.08510 1.47390 3.59930
C 2.40420 -1.25280 1.48360

C 1.08900 -1.04400 1.32410
H 0.36880 -1.33210 2.08490
H 3.08100 -0.93750 0.68630
C 4.41790 -2.97380 4.85250
C 5.13640 -2.42330 3.79240
C 4.46170 -1.87500 2.70140
C 3.05960 -1.86350 2.65310
C 2.34520 -2.42840 3.72330
C 3.01790 -2.97590 4.81190
H 4.93710 -3.40230 5.70490
H 6.22330 -2.42000 3.81340
H 5.02670 -1.44500 1.87610
H 1.25820 -2.45210 3.70810
H 2.45140 -3.40940 5.63230
H -1.30840 0.64090 4.26290
H -0.22980 2.04880 3.95760
H -1.95560 2.11900 3.46980
H 1.31090 1.29490 -4.05100
H 0.07150 2.53510 -3.64560
H 1.75740 2.72900 -3.06200
H -1.54540 -0.62950 0.60050
C -2.64870 -1.26140 -4.03950
C -3.22210 -0.29260 -3.20710
C -2.63300 -0.00010 -1.98010
C -1.46660 -0.66280 -1.58060
C -0.89460 -1.62570 -2.41590
C -1.48530 -1.92560 -3.64060
H -4.12610 0.22440 -3.51360
H -3.08470 0.74310 -1.32590
H 0.00650 -2.15180 -2.10810
H -1.05090 -2.67930 -4.29110
Ti -0.60910 4.53120 0.23090
Cl -0.68860 6.02570 -1.44090
Cl -1.35480 5.78090 1.94200
Cl 1.61480 4.83850 0.69860
Cl -2.70120 3.61540 -0.24670
C -3.25280 -1.63340 -5.35500
O -4.36240 -0.94810 -5.63420
O -2.78850 -2.47720 -6.09880
C -5.00950 -1.25790 -6.88000
H -5.87120 -0.59330 -6.93360
H -4.32780 -1.07350 -7.71340
H -5.32790 -2.30300 -6.88460

10.3.1.6.2. 182ma-co-*trans-E-*TiCl₄

E(M06-2X/6-31+G(d)(CH₂Cl₂)) = -3239.471454
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) = -3239.961731
G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) = -3239.612659

C -0.54920 -1.07860 -0.22520
C 0.78310 -1.61270 0.20550
C -0.54090 0.36860 -0.67390
H 0.78400 -2.64770 0.55700
C -0.01180 0.75490 -1.92090
O 0.48730 -0.21180 -2.67550
O 0.03400 1.93940 -2.37740
C 0.97980 0.15010 -3.98100
C -1.08060 1.38720 0.13860
O -1.66560 1.01690 1.27080
O -1.05380 2.62930 -0.12190
C -2.19560 2.06120 2.11310
C 3.14179 -1.56920 0.60360
C 1.95790 -0.91560 0.20930
H 1.97170 0.12080 -0.11960
H 3.05230 -2.60190 0.95080
C 7.05980 -0.04470 0.45930
C 6.83330 -1.35870 0.89010
C 5.53700 -1.84650 0.94350
C 4.44740 -1.01960 0.56180
C 4.69760 0.31260 0.13190
C 5.99480 0.78940 0.08360
H 8.07750 0.33720 0.41420
H 7.67050 -1.98810 1.17740
H 5.34210 -2.86560 1.27260
H 3.87760 0.96440 -0.15680
H 6.19130 1.80600 -0.24520
H -2.57550 1.54760 2.99510
H -1.40400 2.76270 2.38270
H -3.00030 2.58640 1.59490
H 1.34870 -0.77930 -4.41300
H 0.16750 0.55920 -4.58550
H 1.78270 0.88420 -3.88970
Ti -0.05640 3.70250 -1.46950
Cl 1.21470 4.63190 -3.14980
Cl -0.21430 5.55630 -0.11250
Cl 1.92060 2.97560 -0.31130

Cl -2.04810 4.15030 -2.54910
H -1.14530 -1.11950 0.70290
C -2.54780 -3.84300 -2.90330
C -3.29180 -2.97610 -2.09360
C -2.63770 -2.09010 -1.24020
C -1.23970 -2.05310 -1.18680
C -0.50560 -2.91330 -2.01010
C -1.15180 -3.80490 -2.85940
H -4.37690 -2.99940 -2.12380
H -3.22179 -1.42340 -0.60790
H 0.58130 -2.87840 -2.00550
H -0.57840 -4.47380 -3.49510
C -3.18950 -4.82900 -3.82350
O -4.52270 -4.80180 -3.77540
O -2.56750 -5.58760 -4.54480
C -5.21090 -5.72480 -4.63660
H -6.27110 -5.56500 -4.44380
H -4.97150 -5.51100 -5.68070
H -4.92390 -6.74970 -4.39110

10.3.1.6.3. 182ma-co-*trans-Z-*TiCl₄

E(M06-2X/6-31+G(d)(CH₂Cl₂)) = -3239.461291
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) = -3239.951114
G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) = -3239.601518

C -1.66060 -1.50890 0.45190
C -0.18140 -1.47360 0.24400
C -2.36620 -0.20130 0.15430
H 0.13470 -1.10710 -0.73280
C -1.71770 1.04460 0.13150
O -0.41830 1.05420 0.41260
O -2.26660 2.18090 -0.10940
C 0.27590 2.31700 0.34210
C -3.77760 -0.18980 0.07920
O -4.38610 -1.33300 0.35120
O -4.49820 0.81260 -0.20179
C -5.82210 -1.36900 0.22980
C 0.56450 -2.39830 2.36780
C 0.80220 -2.02540 1.04320
H 1.80170 -2.09670 0.62230
H -6.09910 -2.39640 0.46120

H -6.27560 -0.67540 0.94020
H -6.11740 -1.10820 -0.78810
H 1.31730 2.08020 0.55650
H 0.17350 2.74350 -0.65750
H -0.12630 3.00460 1.08830
Ti -4.05420 2.64930 -0.84780
Cl -3.22100 4.68910 -1.52080
Cl -6.19720 2.87620 -1.65470
Cl -4.63250 3.45710 1.25970
Cl -3.33040 1.60580 -2.83720
H -1.91540 -1.85910 1.45910
C -2.66850 -4.69870 -2.31350
C -2.43120 -3.40520 -2.78920
C -2.11240 -2.38330 -1.90150
C -2.03180 -2.64460 -0.52910
C -2.25440 -3.94040 -0.05550
C -2.58250 -4.96470 -0.94140
H -2.50270 -3.20620 -3.85460
H -1.94830 -1.37450 -2.27510
H -2.19610 -4.14960 1.01130
H -2.77260 -5.96640 -0.56770
H -0.42780 -2.22130 2.78660
C 3.27540 -4.05850 5.13850
C 1.97250 -3.73430 5.53280
C 1.09440 -3.18910 4.60690
C 1.51420 -2.95670 3.27340
C 2.83910 -3.29130 2.89070
C 3.70650 -3.83930 3.82050
H 3.96460 -4.48780 5.86230
H 1.65230 -3.90950 6.55590
H 0.07750 -2.93140 4.89770
H 3.18060 -3.12700 1.87230
H 4.72050 -4.10070 3.53170
C -3.00940 -5.75790 -3.31260
O -3.26150 -6.94420 -2.75750
O -3.05400 -5.56450 -4.51350
C -3.60210 -8.00970 -3.66070
H -3.77100 -8.88500 -3.03420
H -4.50700 -7.75580 -4.21800
H -2.78020 -8.18960 -4.35750

10.3.1.6.4. TS$_{mig}$ma-co-*trans-E*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3239.45422
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3239.944076

G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3239.59511

C 0.42150 -1.15920 0.63960
C 1.53490 -1.62610 1.39820
C -0.05290 0.21770 0.64680
H 2.13520 -0.87340 1.90440
C -0.70170 0.71770 -0.51580
O -0.81800 -0.13700 -1.51820
O -1.15090 1.88440 -0.66450
C -1.45230 0.34060 -2.72310
C 0.00220 1.05390 1.79450
O 0.44900 0.51470 2.91810
O -0.38070 2.25430 1.82420
C 0.46410 1.35270 4.09280
C 2.64100 -3.25450 2.82110
C 1.67660 -2.98960 1.92090
H 0.95720 -3.73820 1.59360
H 3.30980 -2.43880 3.10510
C 3.51680 -6.91520 4.84640
C 4.23560 -5.75270 5.12590
C 3.93250 -4.57010 4.45280
C 2.90770 -4.53150 3.49390
C 2.18910 -5.70850 3.22150
C 2.49370 -6.88890 3.89230
H 5.03140 -5.76610 5.86610
H 4.49430 -3.66340 4.67010
H 1.39040 -5.70960 2.48340
H 1.93360 -7.79410 3.67250
H 0.87320 0.72360 4.88210
H 1.09720 2.22500 3.92140
H -0.55260 1.66690 4.33500
H -1.41060 -0.49820 -3.41590
H -2.48590 0.62060 -2.51270
H -0.90330 1.19820 -3.11560
Ti -0.82290 3.58600 0.37270
Cl -1.30270 4.81100 -1.49520
Cl -0.29220 5.29890 1.78860
Cl 1.43890 3.30270 -0.28720
Cl -3.02179 3.48060 1.06550
H -0.25440 -1.91750 0.24130
C 3.52990 -1.50290 -2.49580
C 3.54640 -0.37620 -1.66230
C 2.71470 -0.33680 -0.55260
C 1.88840 -1.43750 -0.25730
C 1.86570 -2.56180 -1.10620

C 2.68030 -2.58470 -2.22810
H 4.19870 0.46290 -1.88400
H 2.70010 0.54480 0.08500
H 1.21040 -3.40490 -0.89560
H 2.67000 -3.43840 -2.89940
H 3.75100 -7.83990 5.36780
C 4.39840 -1.58370 -3.72190
O 5.30380 -0.61400 -3.77290
O 4.28070 -2.44900 -4.56540
C 6.17260 -0.60270 -4.92320
H 6.82880 0.25560 -4.78380
H 6.75050 -1.52890 -4.96210
H 5.58280 -0.49240 -5.83600

10.3.1.6.5. TS$_{cycl}$ma-co-*trans-Z*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3239.456477
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3239.947986
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3239.596533

C -2.23820 -0.32790 8.74620
C -1.25770 -1.24610 9.46650
C -2.43030 -0.80760 7.31520
H -3.20660 -0.46030 9.25910
H -0.52260 -0.82250 10.14780
C -1.30780 -0.83910 6.43140
O -0.14390 -0.57890 6.99350
O -1.33560 -1.11320 5.20200
C -3.71330 -1.00780 6.73370
O -4.74890 -0.93540 7.55590
C -1.33510 3.88900 9.26360
C -1.56740 3.37910 7.98500
C -1.84470 2.02570 7.80720
C -1.88790 1.15530 8.89920
C -1.65950 1.67560 10.18170
C -1.38460 3.02810 10.36740
H -1.53520 4.04760 7.12910
H -2.04340 1.66240 6.80320
H -1.71280 1.02530 11.05360
H -1.21550 3.41540 11.36760
C -2.30140 -3.09840 8.33040
C -1.26680 -2.56280 9.20470
H -0.49330 -3.22820 9.57179
H -3.32980 -2.81280 8.56390

C -1.92880 -6.32010 5.65620
C -3.19930 -5.89350 6.05950
C -3.31200 -4.81940 6.92770
C -2.14790 -4.18240 7.42720
C -0.86770 -4.62880 7.00950
C -0.76620 -5.68670 6.12330
H -1.83930 -7.15300 4.96240
H -4.08760 -6.39080 5.68070
H -4.29130 -4.47080 7.25120
H 0.02890 -4.13590 7.38010
H 0.20900 -6.02850 5.78780
C 1.02050 -0.54770 6.14010
H 1.85310 -0.33060 6.80730
H 1.15330 -1.51300 5.64870
H 0.90450 0.23990 5.39250
C -6.06450 -1.08700 6.97580
H -6.75520 -0.99860 7.81300
H -6.23520 -0.29440 6.24470
H -6.15450 -2.06310 6.49620
O -3.93179 -1.30930 5.52910
Ti -2.82890 -1.11940 3.83670
Cl -2.97920 1.20750 4.25100
Cl -1.31000 -0.77030 2.17940
Cl -2.62760 -3.39770 3.73790
Cl -4.75830 -1.09410 2.60360
C -1.05510 5.34940 9.39720
O -0.87210 5.73630 10.66220
O -0.99990 6.12060 8.45670
C -0.61110 7.13490 10.86810
H -0.47560 7.25130 11.94290
H 0.29270 7.43340 10.33200
H -1.45910 7.73010 10.52100

10.3.1.6.6. 182ma-co-*trans-E'*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3239.465451
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3239.955343
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3239.605688

C -1.68050 -1.44770 0.58530
C -0.21710 -1.38250 0.29840
C -2.44880 -0.25290 0.06320

H 0.07210 -1.02140 -0.69080
C -1.86180 1.02170 -0.01140
O -0.61520 1.13220 0.44670
O -2.41520 2.07560 -0.44720
C 0.02450 2.41980 0.33800
C -3.84280 -0.32200 -0.17960
O -4.44880 -1.44070 0.19900
O -4.55440 0.60370 -0.65310
C -5.86090 -1.54930 -0.07110
C 2.07680 -1.90820 0.65670
C 0.75850 -1.91090 1.11430
H 0.49570 -2.27870 2.10390
H -6.13880 -2.54470 0.27200
H -6.40700 -0.78270 0.48179
H -6.04600 -1.44190 -1.14150
H 1.02850 2.27130 0.73360
H 0.06140 2.73250 -0.70730
H -0.51870 3.15590 0.93330
Ti -4.09450 2.35690 -1.48570
Cl -3.24290 4.32860 -2.32280
Cl -6.10220 2.35120 -2.61020
Cl -5.00110 3.41170 0.37820
Cl -3.05080 1.09660 -3.19560
H -1.83450 -1.59550 1.66420
C -2.55270 -5.19800 -1.40730
C -2.36820 -4.03100 -2.15560
C -2.09550 -2.82770 -1.51440
C -2.00980 -2.77980 -0.11750
C -2.17840 -3.94940 0.62980
C -2.45920 -5.15420 -0.01080
H -2.44520 -4.07210 -3.23830
H -1.97280 -1.91860 -2.10020
H -2.11770 -3.91830 1.71790
H -2.61020 -6.05710 0.57340
H 2.24950 -1.53330 -0.35580
C 5.56390 -3.14820 2.67540
C 5.63830 -2.68910 1.35580
C 4.48050 -2.28400 0.70630
C 3.23170 -2.33990 1.37230
C 3.17390 -2.80670 2.71060
C 4.33490 -3.20510 3.35120
H 6.47080 -3.46350 3.18660
H 6.59610 -2.64830 0.84500
H 4.52150 -1.92220 -0.31960
H 2.22840 -2.84700 3.24540
H 4.29660 -3.55940 4.37750

C -2.85040 -6.46200 -2.14810
O -3.05470 -7.50640 -1.34330
O -2.90320 -6.53880 -3.36150
C -3.35840 -8.75680 -1.98620
H -3.48540 -9.47740 -1.17900
H -4.27820 -8.66550 -2.56860
H -2.53460 -9.05240 -2.63990

10.3.1.6.7. 181ma-co-TiCl₄
E(M06-2X/6-31+G(d)(CH₂Cl₂)) =
-3239.486147
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-3239.977289
G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-3239.626654

C -0.71370 1.05840 -0.59680
C 0.02720 0.07760 -0.03300
C 1.52110 -0.06890 0.07530
C 1.84810 -1.21830 -0.85370
C 2.50370 -1.04220 -2.00870
C 2.78600 -2.06670 -3.03030
C -2.20490 0.97780 -0.49730
C -0.17760 2.28170 -1.24070
O 1.00720 2.16970 -1.77210
O -0.79870 3.34920 -1.30180
C 1.57360 3.35980 -2.38560
O -2.94190 1.96179 -0.53980
O -2.67280 -0.22390 -0.34690
C -4.10710 -0.35370 -0.15980
C 2.18500 -3.33660 -3.02360
C 2.47179 -4.25970 -4.02600
C 3.35910 -3.93150 -5.05580
C 3.95790 -2.67130 -5.07640
C 3.67050 -1.74730 -4.07190
C 1.91130 -0.29190 1.53420
C 2.84400 -1.26260 1.90860
C 3.22460 -1.40000 3.24380
C 2.66850 -0.56730 4.21900
C 1.72970 0.40310 3.85190
C 1.35710 0.53780 2.51960
H -0.53060 -0.74050 0.42730
H 2.03280 0.82850 -0.28210
H 1.46630 -2.19680 -0.55980
H 2.87890 -0.04330 -2.23880
H 2.57280 3.06560 -2.70090

438

H 0.95940 3.65150 -3.23920
H 1.61470 4.18200 -1.64810
H -4.27610 -1.42210 -0.04120
H -4.40560 0.19590 0.73450
H -4.62170 0.03380 -1.04020
H 1.47610 -3.60400 -2.24350
H 1.99440 -5.23630 -4.01110
H 4.64470 -2.40510 -5.87610
H 4.13730 -0.76390 -4.09330
H 3.29080 -1.90900 1.15730
H 3.95580 -2.15260 3.52340
H 1.30340 1.04920 4.61400
H 0.63610 1.30510 2.24250
Ti -2.59280 4.02840 -0.43780
Cl -1.81250 6.13240 -0.46770
Cl -4.59430 4.32940 0.52640
Cl -1.52230 3.49640 1.57370
Cl -3.36680 4.05080 -2.58650
H 3.57480 -4.65240 -5.84030
C 3.04660 -0.66310 5.66110
O 3.95680 -1.60700 5.90520
O 2.57750 0.04760 6.53090
C 4.37940 -1.74760 7.27230
H 5.11280 -2.55340 7.27110
H 4.83130 -0.81690 7.62320
H 3.52640 -2.00500 7.90440

10.3.1.6.8. 180ma-co-*cis*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3239.501982
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3239.993826
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3239.642111

C 0.97660 0.15040 1.21810
C -0.32310 0.11880 1.49270
C -1.21710 0.25040 0.28830
C -0.18000 0.23810 -0.93280
C 1.29290 0.29460 -0.24960
H -1.83550 -0.65170 0.18670
H -0.75220 0.00800 2.48620
H 1.77620 0.06800 1.94860
C -3.95590 3.59730 0.35080
C -4.21720 2.48200 -0.44620
C -3.33570 1.39960 -0.44020

C -2.17820 1.42690 0.34400
C -1.92620 2.54590 1.14420
C -2.81180 3.62310 1.15150
H -4.64430 4.43880 0.35480
H -5.11040 2.44820 -1.06490
H -3.55110 0.52560 -1.05100
H -1.02770 2.58320 1.75600
H -2.60700 4.48540 1.78140
C -0.29830 -1.11290 -1.62040
O -0.07510 -2.11010 -0.80990
O -0.59670 -1.31990 -2.79600
C -0.19640 -3.45280 -1.34940
C -0.40000 1.38780 -1.89650
O -0.26990 2.54990 -1.34020
O -0.69570 1.29080 -3.09130
C -0.52170 3.72420 -2.14800
H -0.36920 4.56460 -1.47420
H 0.18300 3.75040 -2.98130
H -1.54940 3.69420 -2.51540
H 0.00710 -4.11260 -0.50850
H -1.20840 -3.59900 -1.73090
H 0.53670 -3.59030 -2.14600
H 1.84110 -0.59320 -0.59220
C 3.83130 3.63390 -1.30720
C 3.67870 2.55010 -2.17720
C 2.86290 1.48120 -1.81810
C 2.17360 1.48510 -0.59990
C 2.32540 2.57570 0.26280
C 3.15230 3.64240 -0.08320
H 4.21180 2.54350 -3.12360
H 2.76770 0.63070 -2.49020
H 1.79460 2.59800 1.21150
H 3.27090 4.47950 0.59830
Ti -1.02310 -0.19830 -4.52200
Cl -1.28270 -2.08920 -5.70990
Cl -1.40900 1.35340 -6.09140
Cl 1.27210 -0.18130 -4.76770
Cl -3.17900 -0.21220 -3.71350
C 4.74280 4.74410 -1.71810
O 4.83680 5.70850 -0.80010
O 5.34600 4.77390 -2.77480
C 5.70800 6.80860 -1.11240
H 5.64980 7.47790 -0.25450
H 6.73070 6.45000 -1.25060
H 5.36630 7.31390 -2.01880

10.3.1.7. R^1 = t-Bu, R^3 = Ph

10.3.1.7.1. 179da-co-*trans*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-2937.89635
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2938.31216
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$))=
-2937.969937

C -0.69230 -0.39350 -0.32410
C 0.74320 -0.38650 0.00179
C -0.03220 0.98540 0.00060
H 1.41970 -0.41150 -0.85070
C 0.32000 1.94750 -1.07540
O 0.95450 1.43880 -2.09540
O 0.05650 3.15480 -1.05710
C 1.26520 2.32470 -3.20170
C -0.43410 1.60620 1.28790
O -0.69179 0.76720 2.25230
O -0.53090 2.82360 1.48660
C -1.12500 1.31900 3.52330
C 2.61390 -1.22179 1.37400
C 1.30050 -0.98950 1.23590
H 0.59310 -1.27890 2.00820
H 3.28980 -0.89830 0.57940
C 4.58480 -3.04330 4.71510
C 5.31100 -2.34210 3.75190
C 4.65370 -1.76510 2.66520
C 3.26150 -1.87070 2.52810
C 2.54280 -2.59179 3.49680
C 3.19870 -3.16900 4.58060
H 5.09370 -3.49690 5.56180
H 6.38980 -2.24550 3.84480
H 5.22340 -1.22040 1.91510
H 1.46740 -2.72110 3.39800
H 2.62920 -3.72670 5.32020
H -1.32200 0.45240 4.15180
H -0.32820 1.93750 3.93920
H -2.03040 1.90880 3.37090
H 1.72860 1.68600 -3.95200
H 0.34340 2.77210 -3.57880
H 1.95530 3.09900 -2.86260
H -1.31560 -0.65890 0.52980
Ti -0.77230 4.51330 0.29440
Cl -0.88730 6.06950 -1.32179

Cl -1.64310 5.64360 2.03080
Cl 1.41780 4.95260 0.84660
Cl -2.78080 3.50320 -0.28550
C -1.34250 -0.81940 -1.65610
C -0.33120 -1.33450 -2.68760
C -2.26860 -1.99450 -1.28510
C -2.20080 0.30930 -2.23750
H -2.77530 -0.06520 -3.09280
H -2.90760 0.69080 -1.49240
H -1.59860 1.15340 -2.59300
H -2.74710 -2.39330 -2.18650
H -1.70260 -2.80610 -0.81220
H -3.05650 -1.67430 -0.59340
H -0.87480 -1.71120 -3.56140
H 0.35690 -0.55990 -3.03000
H 0.25540 -2.18310 -2.27540

10.3.1.7.2. 181da-co-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-2937.9003676
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2938.31692
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2937.974128

C -0.59900 1.43330 -0.43710
C 0.09040 0.27420 -0.30650
C 1.56300 -0.00400 -0.32540
C 1.75890 -1.31580 -1.04780
C 2.49850 -1.43230 -2.15750
C -2.07510 1.40480 -0.27760
C 0.00740 2.77400 -0.62420
O 1.17730 2.79670 -1.19760
O -0.53940 3.82630 -0.27370
C 1.81960 4.09000 -1.35010
O -2.76340 2.39390 0.00550
O -2.63090 0.23840 -0.45020
C -4.06110 0.13750 -0.22180
H -0.52590 -0.60650 -0.12040
H 2.09960 0.77640 -0.86810
H 1.26390 -2.18640 -0.61500
H 2.96120 -0.53170 -2.56730
H 2.77960 3.87360 -1.81530
H 1.20670 4.72530 -1.99150
H 1.94980 4.54850 -0.36790

H -4.29990 -0.90860 -0.40360
H -4.28340 0.41960 0.80880
H -4.58610 0.79030 -0.92060
Ti -2.31670 4.29830 0.74410
Cl -1.42400 6.25980 1.37550
Cl -4.33310 4.42040 1.72640
Cl -1.35470 3.10480 2.50020
Cl -3.03240 5.02880 -1.30330
C 2.14710 -0.01410 1.14350
C 3.58710 -0.53520 1.07910
C 2.18270 1.42240 1.67920
C 1.31970 -0.89980 2.08330
H 1.81440 -0.95840 3.05970
H 0.31520 -0.49170 2.25050
H 1.22020 -1.92250 1.70130
H 2.58040 1.43550 2.69320
H 2.78780 2.06940 1.05050
H 1.15790 1.85510 1.74070
H 4.06130 -0.42360 2.06110
H 3.62300 -1.59330 0.80080
H 4.18010 0.02760 0.34730
C 3.38500 -4.96640 -4.42070
C 3.83050 -3.71380 -4.84260
C 3.53130 -2.57740 -4.09050
C 2.78200 -2.67050 -2.90800
C 2.34230 -3.93860 -2.49180
C 2.64040 -5.07300 -3.24179
H 3.61650 -5.85490 -5.00260
H 4.41170 -3.62010 -5.75660
H 3.88220 -1.60170 -4.42310
H 1.76660 -4.04850 -1.57580
H 2.29350 -6.04680 -2.90470

10.3.1.7.3. 180da-co-*cis*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -2937.9042752
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -2938.32179
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -2937.976152

C 0.92820 0.14020 1.16590
C -0.37470 0.08800 1.42010
C -1.24870 0.29680 0.21420
C -0.16580 0.31360 -0.98890
C 1.28170 0.37660 -0.28260

H -1.89250 -0.57930 0.05570
H -0.82040 -0.07530 2.39910
H 1.70030 0.01040 1.92000
C -3.87940 3.72130 0.43370
C -4.18710 2.64450 -0.39920
C -3.34070 1.53550 -0.44640
C -2.17410 1.49670 0.32410
C -1.87750 2.57500 1.18330
C -2.72590 3.68050 1.22010
H -4.53970 4.58400 0.47740
H -5.08940 2.66180 -1.00520
H -3.58960 0.69320 -1.08920
H -0.97390 2.55710 1.76930
H -2.48570 4.51170 1.87870
C -0.26390 -1.06010 -1.64680
O -0.02210 -2.03640 -0.81770
O -0.54920 -1.30770 -2.81990
C -0.10360 -3.39150 -1.32970
C -0.48870 1.41800 -1.98080
O -0.44430 2.60590 -1.46890
O -0.81350 1.26510 -3.18190
C -0.83410 3.72290 -2.30280
H -0.70550 4.60080 -1.67210
H -0.18720 3.77070 -3.18180
H -1.87710 3.59750 -2.60120
H 0.13180 -4.02600 -0.47780
H -1.11370 -3.58060 -1.69670
H 0.62510 -3.52070 -2.13180
H 1.81490 -0.50650 -0.65960
Ti -1.09110 -0.26610 -4.54970
Cl -1.27700 -2.19720 -5.68980
Cl -1.62630 1.22780 -6.13470
Cl 1.18480 -0.09760 -4.88450
Cl -3.22050 -0.39640 -3.66990
C 2.31380 1.53630 -0.49230
C 2.52170 1.85560 -1.98090
C 1.99900 2.80010 0.32100
C 3.66140 0.98280 0.02050
H 4.42940 1.76030 -0.06000
H 3.61300 0.67460 1.07010
H 3.99000 0.12340 -0.57650
H 3.44030 2.44140 -2.10350
H 2.63630 0.93720 -2.56910
H 1.71830 2.44520 -2.42580
H 2.75400 3.56580 0.10530
H 1.01660 3.21680 0.09480

441

H 2.03830 2.58980 1.39620

10.3.1.7.4. 182da-co-*trans-E-*TiCl₄

E(M06-2X/6-31+G(d)(CH₂Cl₂)) = -2937.881727
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) = -2938.29779
G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) = -2937.955772

C -0.31840 -1.20430 -0.36650
C 1.07340 -1.71830 -0.25910
C -0.36940 0.25210 -0.82860
H 1.21680 -2.79740 -0.29670
C 0.29179 0.70090 -1.98850
O 0.97050 -0.20100 -2.68360
O 0.30050 1.89520 -2.42470
C 1.63750 0.24380 -3.88110
C -1.09470 1.21910 -0.09780
O -1.78270 0.79000 0.95100
O -1.14710 2.46080 -0.35630
C -2.52910 1.76970 1.70040
C 3.41990 -1.57200 0.18250
C 2.18480 -0.94420 -0.02420
H 2.08840 0.13810 0.02840
H 3.44680 -2.66290 0.09740
C 7.11190 0.27840 1.00420
C 7.02390 -1.11760 0.94110
C 5.80430 -1.71480 0.65720
C 4.65380 -0.91690 0.44070
C 4.76179 0.49660 0.50750
C 5.98400 1.08340 0.78530
H 8.06820 0.74750 1.22430
H 7.90650 -1.72700 1.11220
H 5.71860 -2.79860 0.60300
H 3.89360 1.12700 0.33610
H 6.07090 2.16510 0.83300
H -2.97240 1.21550 2.52660
H -1.86080 2.54950 2.06980
H -3.30350 2.21020 1.06940
H 2.15530 -0.63610 -4.26060
H 0.90400 0.60130 -4.60680
H 2.34460 1.04110 -3.64420
Ti -0.04830 3.62820 -1.53310

Cl 1.37870 4.68650 -2.99920
Cl -0.54850 5.43780 -0.19790
Cl 1.78840 3.02610 -0.10260
Cl -1.88940 3.94730 -2.89680
H -0.61960 -1.17290 0.70110
C -1.33690 -2.18980 -1.02540
C -1.05230 -2.40640 -2.51550
C -1.27830 -3.54210 -0.29670
C -2.75320 -1.62310 -0.86280
H -2.11540 -4.16810 -0.62530
H -0.36080 -4.10179 -0.51010
H -1.36150 -3.41510 0.79010
H -3.47610 -2.30390 -1.32640
H -3.01770 -1.50980 0.19450
H -2.85310 -0.64620 -1.34770
H -1.74060 -3.18250 -2.90960
H -1.19850 -1.48650 -3.09010
H -0.02690 -2.75470 -2.68750

10.3.1.7.5. 182da-co-*trans-Z-*TiCl₄

E(M06-2X/6-31+G(d)(CH₂Cl₂)) = -2937.876372
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) = -2938.29173
G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) = -2937.949724

C -1.65990 -1.91810 -0.80380
C -0.17140 -2.03810 -0.62520
C -2.14580 -0.52040 -0.43730
H 0.44510 -1.90240 -1.51300
C -1.48040 0.65310 -0.84680
O -0.30140 0.49050 -1.43780
O -1.89260 1.84190 -0.69020
C 0.34150 1.66260 -1.97680
C -3.32450 -0.35150 0.31810
O -3.88990 -1.44680 0.81470
O -3.88390 0.75720 0.57860
C -5.15570 -1.28710 1.48640
C -0.15550 -2.52830 1.75480
C 0.51179 -2.29050 0.54390
H 1.59760 -2.30140 0.50580
H -5.45179 -2.29470 1.77550
H -5.04070 -0.64930 2.36450

H -5.88650 -0.84950 0.80300
H 1.25030 1.29570 -2.45230
H -0.31240 2.13920 -2.71020
H 0.57810 2.36370 -1.17470
Ti -3.66220 2.59179 -0.18180
Cl -3.12320 4.59260 -1.16880
Cl -5.79370 3.12690 0.53340
Cl -2.71670 3.23460 1.87179
Cl -4.46530 1.70280 -2.19450
H -2.13560 -2.59730 -0.08670
H -1.24450 -2.58520 1.72770
C 1.44820 -3.09560 5.60450
C 0.06880 -3.20650 5.39230
C -0.43980 -3.02060 4.11660
C 0.42940 -2.72450 3.03340
C 1.82680 -2.61940 3.26750
C 2.32380 -2.80330 4.54560
H -0.59620 -3.43350 6.22060
H -1.50970 -3.10700 3.93630
H 2.50860 -2.38670 2.45400
H 3.39020 -2.71910 4.73350
H 1.84950 -3.23630 6.60570
C -2.12600 -2.41810 -2.21260
C -3.65890 -2.47080 -2.22770
C -1.65630 -1.50720 -3.35200
C -1.57850 -3.83820 -2.41800
H -1.99720 -1.92260 -4.30760
H -2.08220 -0.50170 -3.25800
H -0.56510 -1.41870 -3.39890
H -4.00410 -2.87360 -3.18690
H -4.04320 -3.11420 -1.42740
H -4.09440 -1.47200 -2.10980
H -1.95330 -4.25790 -3.35670
H -0.48180 -3.85430 -2.46350
H -1.89460 -4.50050 -1.59980

10.3.1.7.6. TS$_{mig}$da-co-*trans-E*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-2937.856535
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2938.27317
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2937.933136

C 0.14810 -1.08610 1.22260
C 1.35500 -1.73680 0.96950

C -0.18630 0.30370 0.93179
H 2.01310 -1.34580 0.20040
C 0.51520 1.13280 0.01700
O 1.44080 0.54650 -0.72850
O 0.31940 2.36460 -0.18079
C 2.19320 1.38480 -1.63360
C -1.28510 0.88980 1.62210
O -1.99580 0.08550 2.39820
O -1.63680 2.09860 1.55200
C -3.07600 0.67560 3.15300
C 3.03780 -3.39900 1.41900
C 1.83180 -2.85120 1.72630
H 1.24070 -3.19460 2.57360
H 3.57730 -2.98610 0.56310
C 5.13790 -6.54920 3.37440
C 5.67570 -5.92630 2.24650
C 4.97310 -4.89740 1.62350
C 3.72420 -4.47920 2.11780
C 3.19350 -5.11380 3.25780
C 3.89700 -6.14010 3.87780
H 5.68360 -7.35150 3.86490
H 6.64010 -6.24040 1.85580
H 5.39050 -4.40750 0.74530
H 2.23470 -4.80470 3.66680
H 3.48200 -6.62390 4.75830
H -3.50240 -0.14810 3.72400
H -2.68510 1.44860 3.81760
H -3.81530 1.10290 2.47310
H 2.91290 0.71710 -2.10480
H 1.52480 1.82170 -2.37720
H 2.70179 2.17190 -1.07450
Ti -0.82700 3.74840 0.74179
Cl 0.33640 5.40900 -0.32190
Cl -2.28150 5.04220 1.94400
Cl 0.72290 3.65490 2.50140
Cl -2.31930 3.48350 -1.02780
H -0.43320 -1.49970 2.04460
C -0.51440 -2.43720 -0.22100
C 0.41110 -2.70540 -1.39390
C -0.88690 -3.67650 0.55740
C -1.71530 -1.61080 -0.63110
H -1.50650 -4.29200 -0.11050
H -0.01840 -4.28010 0.83340
H -1.48660 -3.45300 1.44600
H -0.17910 -3.25480 -2.14220
H 0.75880 -1.77930 -1.86280

H 1.26690 -3.33290 -1.12690
H -2.28179 -2.23310 -1.33990
H -2.37250 -1.37410 0.21040
H -1.43390 -0.69210 -1.15230

10.3.1.7.7. TS$_{cycl}$da-co-*trans-Z*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-2937.868077
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2938.28469
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2937.94068

C -2.26830 -0.33150 8.73930
C -1.28840 -1.22830 9.47310
C -2.44210 -0.81230 7.29930
H -3.23620 -0.51320 9.23930
H -0.59270 -0.80680 10.19620
C -1.33630 -0.94860 6.40510
O -0.13380 -0.87190 6.94290
O -1.40940 -1.19380 5.16820
C -3.73910 -0.94590 6.71980
O -4.76580 -0.85350 7.55080
C -2.23150 -3.10810 8.29680
C -1.23040 -2.53980 9.17130
H -0.43230 -3.17570 9.54980
H -3.27330 -2.86320 8.51580
C -1.64560 -6.27560 5.59490
C -2.94330 -5.92680 5.98560
C -3.13120 -4.86860 6.86070
C -2.01350 -4.17260 7.38210
C -0.70480 -4.54020 6.97900
C -0.52830 -5.58050 6.08350
H -1.49930 -7.09700 4.89710
H -3.79630 -6.47179 5.59150
H -4.13400 -4.57760 7.16870
H 0.15450 -3.99940 7.36940
H 0.46990 -5.86300 5.76080
C 1.00120 -0.92690 6.05430
H 1.87240 -0.85300 6.70380
H 1.00410 -1.86690 5.50000
H 0.96380 -0.08510 5.35880
C -6.08850 -0.93090 6.97670
H -6.77080 -0.82860 7.82040
H -6.22620 -0.11810 6.26270
H -6.22670 -1.89100 6.47660

O -3.98800 -1.20170 5.50980
Ti -2.89000 -1.03370 3.82310
Cl -2.83270 1.28460 4.31750
Cl -1.36800 -0.75410 2.12960
Cl -2.87680 -3.32310 3.64280
Cl -4.82810 -0.80150 2.61560
C -2.03610 1.20360 8.92310
C -0.72710 1.69610 8.29670
C -3.20860 1.95480 8.27680
C -2.03240 1.52400 10.42590
H -0.59470 2.76010 8.52630
H 0.14250 1.14930 8.67910
H -0.74300 1.59840 7.20570
H -3.08260 3.03420 8.42080
H -3.25940 1.77010 7.19780
H -4.18370 1.65770 8.72470
H -1.97240 2.60870 10.57170
H -2.94810 1.18230 10.91080
H -1.17310 1.08480 10.94470

10.3.1.7.8. 182da-co-*trans-E'*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-2937.876818
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2938.29221
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2937.95082

C -1.48950 -1.51530 -0.10030
C -0.05450 -1.25150 0.19930
C -2.27630 -0.24710 -0.40970
H 0.49370 -0.57640 -0.45510
C -1.86750 0.75660 -1.31010
O -0.65970 0.64050 -1.85590
O -2.54340 1.77870 -1.64300
C -0.28120 1.61430 -2.84840
C -3.52210 -0.04710 0.23150
O -3.88060 -0.93970 1.14550
O -4.32940 0.90610 0.01260
C -5.17560 -0.78110 1.75710
C 2.01480 -1.62560 1.32440
C 0.63270 -1.85290 1.22340
H 0.11650 -2.51950 1.91120
H -5.27170 -1.62650 2.43730

H -5.22070 0.18170 2.30340
H -5.95480 -0.80780 0.99270
H 0.71650 1.31720 -3.17010
H -0.98100 1.58460 -3.68620
H -0.26570 2.61370 -2.41040
Ti -4.43520 2.31220 -1.38670
Cl -4.24100 3.84380 -3.10050
Cl -6.65700 2.65990 -0.87560
Cl -3.71700 3.85900 0.21440
Cl -4.96990 0.57410 -2.88750
H -1.92070 -1.94040 0.81250
H 2.45100 -0.91540 0.61730
C 4.79980 -3.45070 3.89690
C 5.22720 -2.51650 2.94590
C 4.29430 -1.915202.11470
C 2.91900 -2.24640 2.22640
C 2.50310 -3.20470 3.20090
C 3.44210 -3.78590 4.02590
H 5.53030 -3.92620 4.54770
H 6.28100 -2.26790 2.86030
H 4.60790 -1.18890 1.36690
H 1.45430 -3.45670 3.30820
H 3.13170 -4.51220 4.77179
C -1.66450 -2.67440 -1.17870
C -3.15930 -3.00790 -1.25690
C -1.16920 -2.26130 -2.56750
C -0.90870 -3.92700 -0.71670
H -3.31030 -3.81290 -1.98580
H -3.54250 -3.34570 -0.28720
H -3.74930 -2.14580 -1.58570
H -1.27720 -3.11060 -3.25280
H -1.75610 -1.43070 -2.97310
H -0.11360 -1.96610 -2.55810
H -1.18370 -4.76870 -1.37060
H 0.17810 -3.79460 -0.76020
H -1.18320 -4.20550 0.30900

C -1.47860 -0.49730 -0.58230
C -0.04370 -0.41140 -0.25500
C -0.93650 0.91200 -0.27600
H 0.64070 -0.40500 -1.10380
C -0.57350 1.87510 -1.33760
O -0.44100 1.36830 -2.53180
O -0.36660 3.08330 -1.15110
C 0.00670 2.25300 -3.59170
C -1.26260 1.51179 1.04340
O -1.86100 0.71330 1.88480
O -0.99000 2.67050 1.37920
C -2.14270 1.22860 3.21170
C 1.87110 -0.87100 1.21800
C 0.54360 -0.87770 1.02080
H -0.14770 -1.22570 1.78550
H 2.50720 -0.49450 0.41300
C 4.05130 -2.00280 4.72430
C 4.68820 -1.36550 3.65860
C 3.96180 -1.01700 2.52000
C 2.58900 -1.29230 2.43040
C 1.96080 -1.94360 3.50570
C 2.68570 -2.29320 4.64179
H 4.61340 -2.27550 5.61390
H 5.74990 -1.13870 3.71300
H 4.46090 -0.51830 1.69090
H 0.90300 -2.18950 3.45630
H 2.18690 -2.79680 5.46630
H -2.62730 0.40740 3.73560
H -1.20840 1.51340 3.69790
H -2.80790 2.08910 3.13200
H 0.07179 1.62170 -4.47640
H -0.72250 3.05300 -3.73170
H 0.98370 2.66540 -3.33190
H -2.09870 -0.83140 0.24700
Ti 0.09300 4.23110 0.51810
Cl 1.21410 5.70410 -0.76840
Cl 0.40690 5.14050 2.55420
Cl 1.89270 2.77030 0.70590
Cl -1.96530 5.19380 0.17760
C -2.01190 -0.92110 -1.93540
H -1.25690 -0.85980 -2.71910
H -2.34040 -1.96230 -1.85190
H -2.87550 -0.31480 -2.22720

10.3.1.8. R¹ = Me, R³ = Ph

10.3.1.8.1. 179ha-co-*trans*-TiCl₄

E(M06-2X/6-31+G(d)(CH₂Cl₂)) =
-2820.017523
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-2820.40205
G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-2820.139424

10.3.1.8.2. 182ha-co-*trans-E*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -2820.00099

E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -2820.385501

G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -2820.124613

C -0.36670 -1.16670 -0.25310
C 1.00410 -1.70570 -0.01830
C -0.39870 0.27490 -0.70820
H 1.07890 -2.78870 0.11650
C 0.17470 0.66790 -1.93110
O 0.74300 -0.28840 -2.65590
O 0.19620 1.84890 -2.40120
C 1.32620 0.09530 -3.91730
C -1.07590 1.26830 0.02640
O -1.74750 0.87670 1.10250
O -1.10470 2.50630 -0.25650
C -2.44440 1.89330 1.85140
C 3.36770 -1.58110 0.36140
C 2.14480 -0.95170 0.09280
H 2.08360 0.12790 -0.02380
H 3.36260 -2.66910 0.46710
C 7.12720 0.26930 0.80660
C 7.00830 -1.11980 0.93980
C 5.76600 -1.71860 0.78960
C 4.62400 -0.92820 0.50580
C 4.76390 0.47880 0.37390
C 6.00770 1.06620 0.52350
H 8.10100 0.73970 0.92340
H 7.88510 -1.72200 1.15880
H 5.65640 -2.79700 0.88940
H 3.90230 1.10350 0.15520
H 6.11850 2.14210 0.42190
H -2.87680 1.37030 2.70320
H -1.74480 2.66290 2.18220
H -3.22610 2.34030 1.23410
H 1.75650 -0.82060 -4.31970
H 0.55370 0.48360 -4.58400
H 2.09650 0.85280 -3.76060
Ti -0.04990 3.61120 -1.52700
Cl 1.31250 4.59000 -3.10810
Cl -0.41480 5.47179 -0.21490
Cl 1.85410 3.00010 -0.19770

Cl -1.96260 3.95560 -2.78270
H -0.81940 -1.20510 0.75450
C -1.20480 -2.12670 -1.12520
H -0.81080 -2.17230 -2.14340
H -1.20410 -3.13530 -0.69860
H -2.23600 -1.76590 -1.18340

10.3.1.8.3. TS$_{mig}$ha-co-*trans-E*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -2819.973986

E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -2820.358137

G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -2820.099159

C 0.01780 -1.10060 1.17270
C 1.12550 -1.86210 0.75660
C -0.28940 0.29070 0.85100
H 1.71690 -1.52000 -0.08630
C 0.45920 1.11000 -0.03660
O 1.40030 0.51710 -0.75420
O 0.29050 2.34680 -0.20050
C 2.20320 1.35330 -1.61850
C -1.41680 0.88060 1.49030
O -2.19040 0.06070 2.18280
O -1.73700 2.09720 1.44040
C -3.30930 0.64220 2.88800
C 2.85710 -3.47830 1.20530
C 1.64490 -2.97200 1.52350
H 1.08130 -3.29650 2.39730
H 3.35610 -3.08640 0.31820
C 5.19450 -6.33570 3.34420
C 5.69270 -5.72620 2.20450
C 4.90880 -4.80300 1.50300
C 3.62020 -4.47580 1.95690
C 3.12800 -5.09730 3.11850
C 3.91040 -6.02060 3.80320
H 5.80370 -7.05400 3.88690
H 6.68990 -5.96710 1.83380
H 5.29720 -4.32300 0.60670
H 2.13520 -4.86080 3.49340
H 3.52260 -6.49510 4.70060
H -3.78560 -0.19380 3.39770
H -2.95090 1.38300 3.60490
H -3.99360 1.10680 2.17640
H 2.92060 0.67550 -2.07890

H 1.56900 1.82010 -2.37360
H 2.71190 2.11670 -1.02750
Ti -0.78280 3.74600 0.78280
Cl 0.54220 5.38140 -0.11190
Cl -2.15100 5.05370 2.06490
Cl 0.70770 3.38520 2.56560
Cl -2.23830 3.74660 -1.02400
H -0.45620 -1.45130 2.08960
C -0.58390 -2.31500 -0.02500
H -0.19020 -2.24710 -1.04040
H -0.64970 -3.33360 0.35380
H -1.57120 -1.84260 0.00300

10.3.1.8.4. 182ha-co-*trans*-E'-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -2819.995588
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -2820.379862
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -2820.11964

C -0.45600 -1.20430 -0.25140
C 0.93600 -1.74520 -0.12680
C -0.46960 0.11350 -1.01500
H 1.04790 -2.83260 -0.11170
C -0.02740 0.05680 -2.35590
O 0.30050 -1.15060 -2.80610
O 0.08490 1.02600 -3.16690
C 0.76720 -1.24800 -4.16630
C -0.90610 1.37520 -0.55880
O -1.45450 1.469000.64270
O -0.82290 2.45460 -1.22890
C -1.88150 2.77520 1.07790
C 3.29630 -1.54010 0.27890
C 2.03860 -0.95570 0.08110
H 1.92320 0.12560 0.06000
H 3.35460 -2.63180 0.25930
C 6.95120 0.46780 0.89280
C 6.91250 -0.93210 0.87810
C 5.70340 -1.582400.67930
C 4.51340 -0.83420 0.49540
C 4.57180 0.58470 0.51790
C 5.78320 1.22420 0.71340

H 7.90000 0.97800 1.04350
H 7.82580 -1.50270 1.01880
H 5.65720 -2.66960 0.66150
H 3.67480 1.17880 0.37190
H 5.83080 2.30950 0.72490
H -2.26350 2.62490 2.08690
H -1.03690 3.46680 1.08190
H -2.66690 3.15110 0.41950
H 1.03250 -2.29590 -4.29890
H -0.02990 -0.96080 -4.85480
H 1.63660 -0.60470 -4.31200
Ti 0.14080 2.98720 -2.86810
Cl 1.37030 3.24410 -4.80360
Cl 0.13930 5.18940 -2.18010
Cl 2.14040 2.55380 -1.61200
Cl -1.88010 3.19840 -3.97470
C -1.01179 -1.20430 1.19650
H -1.04450 -1.94540 -0.80560
H -0.46310 -0.49290 1.82980
H -2.06540 -0.90710 1.18340
H -0.92870 -2.19790 1.62150

10.3.1.9. R^1 = H, R^3 = Ph

10.3.1.9.1. 179ja-co-*trans*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -2780.725794
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -2781.099779
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -2780.863463

C -1.50550 -0.49940 -0.70470
C -0.07300 -0.43200 -0.35290
C -1.04710 0.90880 -0.33200
H 0.63140 -0.34310 -1.17850
C -0.71450 1.88170 -1.38790
O -0.71520 1.39670 -2.61050
O -0.41030 3.07360 -1.18660
C -0.28350 2.28480 -3.69140
C -1.33990 1.47070 1.00320
O -1.95650 0.65840 1.83200
O -1.01710 2.61430 1.37230
C -2.19800 1.13870 3.19520
C 1.81310 -0.85020 1.16880

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C 0.48780 -0.91300 0.91720
H -0.21820 -1.28600 1.65710
H 2.45830 -0.43920 0.39100
C 3.92730 -1.83570 4.76910
C 4.58060 -1.22040 3.69550
C 3.87630 -0.92410 2.52530
C 2.50480 -1.22970 2.40600
C 1.86179 -1.85790 3.49420
C 2.56560 -2.15570 4.66100
H 4.47179 -2.06660 5.68250
H 5.63680 -0.96900 3.76910
H 4.38970 -0.43970 1.69610
H 0.80880 -2.12280 3.43010
H 2.05390 -2.63920 5.49080
H -2.70290 0.31290 3.69620
H -1.24370 1.37220 3.67370
H -2.83270 2.02670 3.17930
H -0.34179 1.67360 -4.59190
H -0.95810 3.14180 -3.74820
H 0.74060 2.61520 -3.50179
H -2.18260 -0.96220 0.00920
Ti 0.09670 4.17260 0.51480
Cl 1.21800 5.68710 -0.75310
Cl 0.45390 5.05070 2.57520
Cl 1.88740 2.68860 0.64240
Cl -1.97600 5.18050 0.22170
H -1.77320 -0.63590 -1.74890

10.3.1.9.2. 182ja-co-*trans-E*-TiCl₄

E(M06-2X/6-31+G(d)(CH₂Cl₂)) = -2780.7097
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) = -2781.083607
G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) = -2780.850113

C -0.33610 -1.22930 -0.49370
C 0.97480 -1.73440 0.00340
C -0.38230 0.22810 -0.86580
H 1.01680 -2.79530 0.26179
C -0.01060 0.66090 -2.15180
O 0.34760 -0.28010 -3.01720
O 0.01070 1.86530 -2.55600
C 0.73360 0.15290 -4.33750

C -0.81150 1.20890 0.04740
O -1.22230 0.78450 1.23550
O -0.84150 2.46110 -0.16840
C -1.67179 1.78320 2.17440
C 3.28840 -1.54250 0.62120
C 2.10000 -0.96580 0.14450
H 2.05550 0.09120 -0.10860
H 3.26750 -2.60610 0.87340
C 6.98360 0.39420 1.20620
C 6.84650 -0.96480 1.51730
C 5.62600 -1.59300 1.31900
C 4.52260 -0.86280 0.80780
C 4.68190 0.51420 0.49900
C 5.90390 1.13150 0.69730
H 7.94110 0.88700 1.35960
H 7.69320 -1.52010 1.91000
H 5.50300 -2.64840 1.55500
H 3.85240 1.09280 0.10410
H 6.02850 2.18420 0.45960
H -1.94630 1.22700 3.06940
H -0.86450 2.48700 2.38680
H -2.53430 2.31790 1.77030
H 1.03430 -0.75570 -4.85710
H -0.11500 0.62280 -4.83880
H 1.56480 0.85730 -4.27340
Ti -0.04090 3.59670 -1.58590
Cl 1.01650 4.60950 -3.36780
Cl -0.10750 5.41700 -0.17440
Cl 2.07430 2.91800 -0.66640
Cl -2.14800 4.00179 -2.43340
H -1.08290 -1.46560 0.28010
H -0.62010 -1.87030 -1.34310

10.3.1.9.3. 182ja-co-*trans-E'*-TiCl₄

E(M06-2X/6-31+G(d)(CH₂Cl₂)) = -2780.708131
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) = -2781.08247
G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) = -2780.849745

C -0.41300 -1.20820 -0.29600
C 0.94900 -1.75860 -0.02700
C -0.40930 0.07070 -1.09800

H 1.02830 -2.83240 0.15730
C 0.03860 0.05740 -2.43220
O 0.41100 -1.12210 -2.91280
O 0.11050 1.05960 -3.20880
C 0.87590 -1.18020 -4.27750
C -0.88860 1.29230 -0.59120
O -1.43000 1.27970 0.62090
O -0.85000 2.40730 -1.20000
C -1.92810 2.53270 1.13390
C 3.30890 -1.56550 0.38040
C 2.07290 -0.97940 0.07340
H 1.99230 0.08960 -0.11060
H 3.33180 -2.64880 0.52630
C 7.01280 0.40680 0.76770
C 6.93170 -0.97830 0.95900
C 5.70710 -1.61760 0.83230
C 4.54400 -0.87200 0.51320
C 4.64580 0.53220 0.32580
C 5.87220 1.17920 0.45190
H 7.97350 0.90790 0.86340
H 7.82470 -1.54600 1.20330
H 5.62800 -2.69360 0.97550
H 3.76950 1.12210 0.07500
H 5.95300 2.23360 0.30440
H -2.30190 2.30230 2.13060
H -1.12190 3.26720 1.18060
H -2.73290 2.90310 0.49600
H 1.16580 -2.19700 -4.44810
H 0.07080 -0.86810 -4.95420
H 1.72990 -0.49280 -4.40180
Ti 0.10140 3.01100 -2.83590
Cl 1.31680 3.37880 -4.76070
Cl 0.04570 5.18480 -2.07030
Cl 2.11480 2.59000 -1.59580
Cl -1.92480 3.19720 -3.92630
H -0.84710 -0.99610 0.69570
H -1.03930 -1.98890 -0.74380

10.3.1.9.4. 182ja-co-*trans-Z*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-2780.701847
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2781.075019

G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2780.839721

C -2.93090 -1.83670 1.22380
C -1.84760 -2.61670 0.55830
C -3.17620 -0.47080 0.62620
H -2.06780 -2.93990 -0.46140
C -2.30710 0.59540 0.92830
O -1.31700 0.32140 1.77500
O -2.38610 1.77790 0.48430
C -0.41940 1.40190 2.10070
C -4.26130 -0.21090 -0.23370
O -5.07930 -1.22170 -0.49370
O -4.52470 0.90990 -0.76440
C -6.21030 -0.95340 -1.34760
C -0.17970 -2.49630 2.31820
C -0.60070 -2.92500 1.04580
H 0.07340 -3.48500 0.40320
H -6.73700 -1.90340 -1.42740
H -6.84860 -0.19360 -0.89290
H -5.86770 -0.61810 -2.32740
H 0.30180 0.97380 2.79570
H 0.08000 1.75990 1.19860
H -0.97010 2.21750 2.57250
Ti -3.55710 2.64700 -0.88290
Cl -2.20420 4.50990 -0.82320
Cl -5.04980 3.37090 -2.47410
Cl -4.88220 3.42090 0.87600
Cl -2.19140 1.60790 -2.49840
H -2.76050 -1.74350 2.30010
H -0.90050 -1.96780 2.93880
C 3.61190 -2.88100 4.10370
C 2.56500 -2.26010 4.79600
C 1.32150 -2.14960 4.19300
C 1.11090 -2.66110 2.88520
C 2.18480 -3.28930 2.19930
C 3.42180 -3.39470 2.81030
H 2.72730 -1.86810 5.79600
H 0.49530 -1.67410 4.71940
H 2.04740 -3.68190 1.19540
H 4.24770 -3.87130 2.29010
H 4.58940 -2.96630 4.57320
H -3.84950 -2.42700 1.11250

10.3.1.9.5. TS$_{mig}$ja-co-*trans-E*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-2780.682176
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2781.053728
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2780.824249

C 1.97560 -0.21960 0.23580
C 2.77470 -0.88370 1.19710
C 1.23040 1.01570 0.40680
H 3.13730 -0.31960 2.05340
C 0.60370 1.58090 -0.74510
O 0.96120 1.06610 -1.90800
O -0.24750 2.50550 -0.73890
C 0.27270 1.54920 -3.08380
C 0.90740 1.57700 1.67660
O 1.50350 1.06130 2.73810
O 0.08390 2.50920 1.86310
C 1.06280 1.52980 4.03440
C 3.57070 -2.89630 2.23020
C 3.04830 -2.29300 1.13370
H 2.65700 -2.85340 0.28700
H 3.92680 -2.25860 3.04260
C 3.66290 -7.05460 3.17930
C 4.07670 -6.10560 4.09630
C 4.06220 -4.75250 3.76360
C 3.62950 -4.33190 2.49390
C 3.21830 -5.29860 1.55680
C 3.23830 -6.64820 1.88980
H 3.66610 -8.11080 3.41860
H 4.40360 -6.41850 5.08440
H 4.37570 -4.00970 4.49530
H 2.87480 -5.00080 0.56920
H 2.91460 -7.38820 1.18150
H 1.64980 0.96190 4.75460
H 1.25700 2.59910 4.12900
H -0.00280 1.32720 4.15720
H 0.70190 0.98770 -3.91170
H -0.79720 1.35260 -2.99290
H 0.45080 2.61880 -3.20290
Ti -1.32180 3.40250 0.72240
Cl -2.76990 4.22100 -0.83860
Cl -2.32130 4.21800 2.60760
Cl 0.12760 5.19990 0.53630
Cl -2.47630 1.35810 0.87360

H 1.69680 -0.82380 -0.62960
H 3.23210 -0.11230 0.08540

10.3.1.9.6. TS$_{cycl}$ja-co-*trans-Z*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$))=
-2780.693165
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2781.067662
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2780.83266

C -2.29980 -0.35090 8.75580
C -1.43980 -1.30900 9.54900
C -2.50200 -0.80940 7.32680
H -3.27260 -0.24720 9.25800
H -0.80540 -0.90770 10.33740
C -1.38660 -0.75520 6.43850
O -0.23150 -0.46150 7.00740
O -1.40340 -0.98190 5.19880
C -3.77410 -1.05340 6.74780
O -4.80800 -1.06520 7.57670
C -2.34010 -3.15770 8.27270
C -1.39770 -2.61810 9.22860
H -0.65820 -3.28280 9.66980
H -3.38940 -2.900608.42590
C -1.67000 -6.33760 5.60500
C -2.97900 -5.95260 5.91430
C -3.18970 -4.89060 6.77980
C -2.08710 -4.22600 7.37180
C -0.76630 -4.63179 7.05090
C -0.56550-5.67540 6.16510
H -1.50380 -7.18030 4.91460
H -3.82100 -6.47200 5.46590
H -4.20090 -4.57270 7.02740
H 0.08370-4.11710 7.49470
H 0.44230-5.98610 5.90410
C 0.92390 -0.35070 6.14790
H 1.74740 -0.09360 6.81230
H 1.10930 -1.30120 5.64480
H 0.75960 0.43690 5.40970
C -6.11830 -1.24370 6.99550
H -6.80940 -1.18380 7.83490
H -6.31300 -0.44650 6.27560
H -6.18350 -2.21510 6.50240
O -3.98830 -1.31560 5.53130
Ti -2.90310 -1.03520 3.85150

450

Cl -3.15870 1.27480 4.32750
Cl -1.41870 -0.56830 2.16630
Cl -2.57490 -3.30020 3.70130
Cl -4.83740 -1.07860 2.62200
H -1.83650 0.64150 8.77980

10.3.1.9.7. 181ja-co -TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-2780.7210653
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2781.096106
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2780.860184

C -0.36810 1.53110 1.39110
C 0.12710 0.39300 1.92530
C 1.45179 -0.25720 1.61560
C 1.50050 -0.69500 0.16720
C 2.45940 -0.31690 -0.68780
C 2.59320 -0.71670 -2.10330
C -1.77630 1.91210 1.65010
C 0.36490 2.39030 0.42820
O 1.65410 2.44900 0.60260
O -0.18410 3.03810 -0.47030
C 2.41370 3.24350 -0.34430
O -2.44970 2.60740 0.87900
O -2.28830 1.45610 2.75850
C -3.69300 1.73330 2.99980
C 1.60750 -1.44200 -2.79300
C 1.79620 -1.80360 -4.12420
C 2.96930 -1.44730 -4.79650
C 3.95230 -0.72040 -4.12550
C 3.76220 -0.35850 -2.79140
H -0.54240 -0.17900 2.58380
H 2.27770 0.42760 1.83090
H 0.70110 -1.36380 -0.15030
H 3.25280 0.33620 -0.31680
H 3.44880 3.15770 -0.01770
H 2.27600 2.83760 -1.34880
H 2.07410 4.27960 -0.30270
H -3.92060 1.23800 3.94170
H -3.83940 2.81180 3.07540
H -4.28780 1.32090 2.18320
H 0.68250 -1.72300 -2.29560
H 1.02260 -2.36360 -4.64360
H 3.11110 -1.73200 -5.83610

H 4.86760 -0.43560 -4.63870
H 4.53480 0.20520 -2.27100
Ti -2.17860 3.19680 -1.12030
Cl -1.47740 3.78700 -3.16730
Cl -4.40810 3.22680 -1.41300
Cl -2.05470 5.31210 -0.23930
Cl -1.98370 0.91810 -1.52200
H 1.55810 -1.12890 2.26960

10.3.1.9.7. 180ja-co-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-2780.7405085
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2781.114767
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2780.878608

C 0.54660 0.39530 1.33150
C -0.76530 0.22450 1.47640
C -1.45420 -0.18350 0.20040
C -0.33400 -0.05630 -0.88710
C 1.04070 0.11670 -0.06770
H -1.82240 -1.21370 0.25980
H -1.31470 0.32580 2.40870
H 1.24430 0.65650 2.12380
C -0.24130 -1.30540 -1.74110
O -0.06350 -2.38520 -1.03390
O -0.29950 -1.36300 -2.97140
C 0.03080 -3.64960 -1.74130
C -0.53300 1.19580 -1.71910
O -0.87510 2.22930 -1.01440
O -0.33940 1.28680 -2.93640
C -1.02050 3.49630 -1.70840
H -1.29750 4.21070 -0.93510
H -0.06880 3.76040 -2.17390
H -1.80470 3.40340 -2.46170
H 0.17710 -4.39450 -0.96179
H -0.89660 -3.82690 -2.28870
H 0.88070 -3.62130 -2.42510
H 1.54980 -0.85600 -0.07870
C 3.73690 2.97750 -1.86320
C 3.70870 1.65470 -2.30780
C 2.84790 0.73750 -1.70660
C 1.99810 1.13070 -0.66680
C 2.03220 2.45880 -0.22670
C 2.90010 3.37690 -0.81950

H 4.41200 3.69370 -2.32500
H 4.35940 1.33600 -3.11810
H 2.83590 0.29510 -2.05350
H 1.37670 2.77700 0.58180
H 2.92330 4.40410 -0.46390
Ti -0.79260 -0.00840 -4.50250
Cl -1.30870 -1.72690 -5.85330
Cl -1.32360 1.72340 -5.82460
Cl 1.42800 -0.00130 -4.95660
Cl -2.90370 -0.04880 -3.43410
H -2.31290 0.45010 -0.04200

10.3.1.10. R^1 = cyclopropyl, R^3 = Ph

10.3.1.10.1. 179ea-co-*trans*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -2897.375611
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -2897.778276
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -2897.483484

C -0.20250 -0.59330 -0.50390
C 1.18460 -0.36840 -0.07400
C 0.18880 0.85850 -0.05260
H 1.90179 -0.23170 -0.88210
C 0.39740 1.89390 -1.09110
O 1.04890 1.49590 -2.14920
O 0.00450 3.06470 -1.01320
C 1.24950 2.45970 -3.21810
C -0.37880 1.32750 1.22900
O -0.55140 0.40100 2.13179
O -0.69180 2.49900 1.47850
C -1.14290 0.80070 3.39670
C 3.08660 -0.87400 1.40410
C 1.76670 -0.92270 1.17130
H 1.08490 -1.39590 1.87210
H 3.72730 -0.36980 0.67700
C 5.18840 -2.37330 4.82440
C 5.80940 -1.50230 3.92840
C 5.11240 -1.03460 2.81410
C 3.78360 -1.42060 2.58180
C 3.17340 -2.30830 3.48380
C 3.86920 -2.77700 4.59500

H 5.72840 -2.74240 5.69250
H 6.83640 -1.18750 4.09510
H 5.59940 -0.35500 2.11670
H 2.15560 -2.65090 3.31200
H 3.38440 -3.46570 5.28240
H -1.21710 -0.11870 3.97440
H -0.49190 1.52530 3.88800
H -2.12860 1.23130 3.21410
H 1.76310 1.90610 -4.00000
H 0.28140 2.82640 -3.56070
H 1.86280 3.28410 -2.84860
H -0.85410 -1.04330 0.24650
Ti -1.02790 4.22660 0.36990
Cl -1.21380 5.87970 -1.14240
Cl -2.11040 5.14210 2.11580
Cl 1.07220 4.84050 1.08910
Cl -2.88179 3.05770 -0.40560
H 0.21300 -0.82590 -2.64810
C -0.59140 -0.87170 -1.92070
C -1.65760 -1.91060 -2.18380
C -1.96340 -0.45770 -2.38830
H -1.53300 -2.55400 -3.03060
H -2.09790 -2.39530 -1.29710
H -2.06050 -0.09580 -3.40750
H -2.60350 0.04180 -1.66510

10.3.1.10.2. 182ea-co-*trans-E*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -2897.358154
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -2897.76093
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -2897.467849

C -0.34890 -1.18250 -0.24660
C 1.02540 -1.69250 0.00210
C -0.38790 0.27950 -0.70110
H 1.10070 -2.77470 0.13650
C 0.16610 0.66930 -1.93450
O 0.72170 -0.28930 -2.66560
O 0.18270 1.84870 -2.40750
C 1.28890 0.09090 -3.93540
C -1.05840 1.27040 0.04110
O -1.70750 0.87830 1.13070

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O -1.09940 2.50730 -0.24700
C -2.39690 1.89100 1.89060
C 3.38480 -1.57090 0.37970
C 2.18270 -0.93730 0.10750
H 2.10400 0.14210 -0.01260
H 3.37420 -2.65870 0.48900
C 7.15170 0.25870 0.82690
C 7.02420 -1.12890 0.96770
C 5.77870 -1.72030 0.81680
C 4.64240 -0.92410 0.52510
C 4.79100 0.48179 0.38630
C 6.03820 1.06179 0.53590
H 8.12820 0.72370 0.94360
H 7.89660 -1.73530 1.20490
H 5.66110 -2.79720 0.92180
H 3.93360 1.10980 0.18030
H 6.15670 2.13610 0.42850
H -2.80630 1.36740 2.75340
H -1.69760 2.66820 2.20370
H -3.19610 2.32900 1.28920
H 1.71800 -0.82490 -4.34179
H 0.50720 0.47620 -4.59320
H 2.05990 0.85000 -3.79080
Ti -0.06330 3.61260 -1.53350
Cl 1.27300 4.59430 -3.13450
Cl -0.42380 5.47450 -0.22310
Cl 1.86000 3.01470 -0.22790
Cl -1.99480 3.94330 -2.76740
H -0.81860 -1.20550 0.75440
H -0.75840 -2.25240 -2.13280
C -1.14380 -2.13110 -1.12410
C -1.78010 -3.33680 -0.49060
C -2.63280 -2.18350 -0.95690
H -1.80510 -4.26250 -1.05930
H -1.65760 -3.47250 0.58250
H -3.24179 -2.31830 -1.84690
H -3.07510 -1.54010 -0.19940

10.3.1.10.3. 183ea-co-*trans*-TiCl₄

E(M06-2X/6-31+G(d)(CH₂Cl₂)) =
-2897.34411
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-2897.746823

G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-2897.454494

C -1.75600 -1.13080 0.99860
C -2.44470 0.07430 0.41280
C -1.78960 1.29850 0.20060
O -0.50380 1.36170 0.54500
O -2.31800 2.34870 -0.26840
C 0.17340 2.61870 0.33820
C -3.84260 0.03770 0.20910
O -4.45870 -1.07290 0.57950
O -4.54530 0.97390 -0.27200
C -5.88480 -1.14090 0.37520
H -6.17120 -2.13730 0.70840
H -6.38360 -0.37520 0.97230
H -6.11910 -1.00260 -0.68190
H 1.19780 2.44730 0.66530
H 0.14390 2.88980 -0.71860
H -0.29710 3.39810 0.93990
Ti -4.08440 2.71660 -1.13020
Cl -3.23250 4.65200 -2.03290
Cl -6.19520 2.82560 -2.03230
Cl -4.73520 3.77590 0.83450
Cl -3.28430 1.42390 -2.94110
H -2.05950 -1.31800 2.03660
C -1.94270 -2.44050 0.17040
C -0.29430 -1.19580 0.87260
H 0.12880 -1.07110 -0.12860
C 0.57270 -1.44980 1.94470
C 2.01130 -0.82850 1.79060
C 1.87760 -2.26920 1.67690
H 0.16700 -1.49670 2.95120
H 2.17660 -0.24140 0.89220
H 2.34960 -0.38610 2.72370
H 1.94760 -2.73179 0.69670
H 2.13210 -2.90060 2.52360
C -2.01240 -3.65120 0.75000
H -1.99240 -2.29180 -0.90610
H -1.93650 -3.71000 1.83850
C -2.73010 -7.41440 -1.14710
C -2.66050 -7.31730 0.24280
C -2.41830 -6.08230 0.84270
C -2.24090 -4.92820 0.06260
C -2.30820 -5.03960 -1.33810
C -2.55140 -6.27190 -1.93480
H -2.92230 -8.37500 -1.61850

H -2.79820 -8.20140 0.86000
H -2.36650 -6.00670 1.92760
H -2.16910 -4.16590 -1.97010
H -2.60310 -6.34440 -3.01810

10.3.1.10.4. 182ea-co-*trans-E'*-TiCl₄

E(M06-2X/6-31+G(d)(CH₂Cl₂)) = -2897.352754
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) = -2897.755507
G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) = -2897.462919

C -0.44860 -1.20390 -0.27280
C 0.94430 -1.74800 -0.14630
C -0.47170 0.11440 -1.03440
H 1.05910 -2.83460 -0.13060
C -0.04540 0.05910 -2.38000
O 0.27100 -1.14940 -2.83490
O 0.06390 1.02970 -3.18960
C 0.72530 -1.24690 -4.19920
C -0.89220 1.37580 -0.56350
O -1.40690 1.47260 0.65120
O -0.81890 2.45560 -1.23610
C -1.81890 2.78040 1.09410
C 3.29930 -1.53910 0.28820
C 2.04440 -0.95660 0.07280
H 1.92820 0.12440 0.04570
H 3.35820 -2.63080 0.27380
C 6.94370 0.47110 0.96060
C 6.90520 -0.92870 0.94800
C 5.70000 -1.57950 0.72790
C 4.51370 -0.83200 0.52030
C 4.57190 0.58680 0.53960
C 5.77940 1.22690 0.75700
H 7.88910 0.98180 1.12910
H 7.81560 -1.49900 1.10740
H 5.65400 -2.66680 0.71200
H 3.67800 1.18050 0.37510
H 5.82660 2.31220 0.76690
H -2.17870 2.63250 2.11170
H -0.97280 3.47030 1.07870
H -2.61820 3.15910 0.45410
H 0.97570 -2.29760 -4.33890

H -0.07350 -0.94560 -4.87960
H 1.60190 -0.61420 -4.34910
Ti 0.13240 2.98960 -2.87950
Cl 1.34690 3.24480 -4.82640
Cl 0.15000 5.19030 -2.18610
Cl 2.14020 2.53960 -1.64179
Cl -1.89640 3.21910 -3.96940
H -1.04710 -1.94620 -0.81910
H -0.45140 -0.50620 1.83600
C -0.96790 -1.18910 1.16820
C -2.43250 -1.39750 1.41080
C -1.45540 -2.48450 1.76840
H -2.88600 -0.82210 2.21290
H -3.06830 -1.54560 0.54140
H -1.24310 -2.66210 2.81900
H -1.43810 -3.37620 1.14550

10.3.1.10.5. TS_mig ea-co-*trans-E*

E(M06-2X/6-31+G(d)(CH₂Cl₂)) = -2897.339751
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) = -2897.741856
G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) = -2897.449771

C 0.73370 -0.49400 0.09500
C 1.90110 -1.28710 0.30960
C 0.49100 0.52880 -0.94440
H 2.59220 -1.45190 -0.51020
C 1.27880 0.69240 -2.10750
O 2.26300 -0.17880 -2.28770
O 1.11730 1.58070 -2.98860
C 3.10660 0.00179 -3.44610
C -0.63490 1.37730 -0.79030
O -1.41420 1.14440 0.25640
O -0.95450 2.32380 -1.56100
C -2.53660 2.029400.45630
C 3.52390 -2.31060 1.79030
C 2.34060 -1.67980 1.63670
H 1.72770 -1.37790 2.48520
H 4.08590 -2.56750 0.88940
C 5.52580 -3.39630 5.40420
C 6.10610 -3.65250 4.18050
C 5.43430 -3.29280 2.99400
C 4.17560 -2.67260 3.05230
C 3.60110 -2.41800 4.31070

C 4.27210 -2.77850 5.47460
H 6.04660 -3.67410 6.31720
H 7.08060 -4.13000 4.10150
H 5.88770 -3.49050 2.02420
H 2.63080 -1.93350 4.38720
H 3.82030 -2.57670 6.44240
H -3.02280 1.66860 1.36170
H -2.18380 3.05410 0.58640
H -3.21320 1.97120 -0.39780
H 3.83540 -0.80610 -3.39130
H 2.51000 -0.07450 -4.35640
H 3.59910 0.97440 -3.39820
Ti -0.11850 3.15220 -3.18550
Cl 1.06510 3.83690 -5.02490
Cl -1.68000 4.82810 -3.13320
Cl 1.30420 4.27800 -1.70790
Cl -1.49570 1.74890 -4.45440
H 0.19800 -0.27560 1.01820
H 0.60210 -2.17800 -1.43290
C 0.39880 -2.03060 -0.37790
C 0.09930 -3.31270 0.43110
C -1.02880 -2.45320 0.08540
H 0.28880 -4.21910 -0.13770
H 0.44190 -3.32960 1.46179
H -1.67280 -2.71000 -0.75240
H -1.48250 -1.84730 0.86320

10.3.1.10.6. TS$_{migStyryl}$ea-co-trans

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -2897.343836
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -2897.745561
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -2897.452525

C -1.88410 -1.18340 1.17680
C -2.49020 0.05630 0.57370
C -1.85140 0.86780 -0.38740
O -0.61330 0.52430 -0.73480
O -2.34730 1.88990 -0.94080
C 0.03870 1.33590 -1.73750
C -3.80920 0.41360 0.95350
O -4.38190 -0.32310 1.89300
O -4.46590 1.38770 0.48770

C -5.72240 0.03250 2.29390
H -5.99550 -0.70680 3.04560
H -5.72790 1.03830 2.71790
H -6.39450 -0.01880 1.43540
H 1.01830 0.87790 -1.88180
H -0.53900 1.31870 -2.66360
H 0.14010 2.36110 -1.37770
Ti -4.24040 2.52070 -1.15000
Cl -3.64970 3.66070 -3.05270
Cl -6.48720 2.97370 -1.15240
Cl -3.73310 4.30390 0.23580
Cl -4.57190 0.51810 -2.37460
H -2.52230 -1.57890 1.95500
C -1.49030 -2.28150 0.14580
C -0.49180 -1.43250 1.39680
H 0.23650 -0.91050 0.78150
C 0.01650 -2.19410 2.54170
C 1.34390 -1.70620 3.11780
C 1.28760 -3.00140 2.38630
H -0.72100 -2.54730 3.25890
H 1.81830 -0.85600 2.63320
H 1.42000 -1.71580 4.20080
H 1.72070 -3.04770 1.39020
H 1.34470 -3.92450 2.95540
C -1.74670 -3.60240 0.39220
H -1.23900 -1.91380 -0.84210
H -1.95800 -3.89640 1.42370
C -1.87920 -6.82120 -2.36760
C -2.13260 -7.03780 -1.01110
C -2.08390 -5.96930 -0.12120
C -1.78080 -4.67110 -0.58060
C -1.52690 -4.46640 -1.95460
C -1.57620 -5.53590 -2.83710
H -1.91800 -7.65410 -3.06570
H -2.36810 -8.03570 -0.65180
H -2.28360 -6.13000 0.93670
H -1.29100 -3.47710 -2.33760
H -1.38150 -5.37470 -3.89390

10.3.1.11. R^1 = Ph, R^3 = p-MeOC$_6$H$_4$

10.3.1.11.1. 179ai-co-trans-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -3126.169464

E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3126.628677
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3126.290813

C -0.86490 -0.39700 -0.21750
C 0.57540 -0.47570 0.07040
C -0.11530 0.94420 0.05580
H 1.23080 -0.55860 -0.79490
C 0.20370 1.81670 -1.10300
O 0.66290 1.19340 -2.14970
O 0.05130 3.04450 -1.12460
C 0.91700 1.97740 -3.34340
C -0.40880 1.63920 1.32940
O -0.66680 0.85790 2.34010
O -0.41830 2.86830 1.47530
C -0.98030 1.48750 3.61080
C 2.42370 -1.29570 1.48730
C 1.11140 -1.07350 1.31810
H 0.38770 -1.35040 2.07750
H 3.11050 -0.99270 0.69370
C 4.37810 -2.98840 4.91010
C 5.12000 -2.48560 3.83230
C 4.46610 -1.95310 2.73020
C 3.06140 -1.90140 2.66650
C 2.33900 -2.42090 3.74890
C 2.97800 -2.95980 4.86400
O 5.09430 -3.48410 5.95310
H 6.20570 -2.51980 3.88180
H 5.05390 -1.56130 1.90140
H 1.25150 -2.41900 3.73640
H 2.37930 -3.35040 5.68060
H -1.18310 0.66130 4.28930
H -0.12250 2.07330 3.94500
H -1.85850 2.12440 3.49240
H 1.27220 1.25890 -4.07940
H -0.01050 2.45180 -3.66890
H 1.67760 2.72930 -3.12840
H -1.51250 -0.63820 0.62670
C -2.69240 -1.17050 -4.02450
C -3.24140 -0.22250 -3.15740
C -2.63680 0.02840 -1.92660
C -1.47520 -0.65980 -1.55920
C -0.92870 -1.60820 -2.42650
C -1.53860 -1.86390 -3.65620
H -3.16590 -1.37020 -4.98240

H -4.14179 0.31850 -3.43770
H -3.06590 0.76300 -1.24720
H -0.03020 -2.15270 -2.14240
H -1.11250 -2.60650 -4.32600
Ti -0.62090 4.50370 0.20150
Cl -0.75200 5.98350 -1.48350
Cl -1.34070 5.76640 1.91800
Cl 1.61210 4.84930 0.61770
Cl -2.71500 3.57260 -0.21810
C 4.38080 -3.98730 7.07760
H 5.13430 -4.31250 7.79540
H 3.75890 -3.20570 7.52900
H 3.75320 -4.83980 6.79400

10.3.1.11.2. 181ai-co-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3126.1655922
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3126.625715
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3126.286094

C -0.91560 1.02150 -0.57510
C -0.15830 0.02520 -0.06150
C 1.33830 -0.13340 -0.05860
C 1.68260 -1.25170 -1.01770
C 2.54550 -1.07100 -2.02730
C 2.98600 -2.06050 -3.02430
C -2.36980 1.04730 -0.28060
C -0.39260 2.17430 -1.34590
O 0.69620 1.94680 -2.02410
O -0.94510 3.28040 -1.38940
C 1.24400 3.05320 -2.78950
O -3.05130 2.08080 -0.28490
O -2.90240 -0.10360 0.01530
C -4.29870 -0.11010 0.41810
C 2.42190 -3.34560 -3.14760
C 2.88110 -4.23590 -4.10450
C 3.92180 -3.86810 -4.97460
C 4.49530 -2.59870 -4.87240
C 4.01980 -1.71420 -3.90140
C 1.78450 -0.36960 1.38730
C 2.51560 -1.49500 1.77400
C 2.92790 -1.64550 3.10120
C 2.61310 -0.67440 4.05179
C 1.88170 0.45370 3.67090

C 1.46980 0.60210 2.34750
H -0.69290 -0.75970 0.47650
H 1.82080 0.78060 -0.41470
H 1.19990 -2.21420 -0.84210
H 3.00870 -0.08700 -2.12850
H 2.13080 2.64750 -3.27190
H 0.50880 3.37960 -3.52660
H 1.50180 3.87060 -2.11380
H -4.51890 -1.15070 0.64620
H -4.42370 0.52340 1.29600
H -4.91350 0.25130 -0.40940
H 1.60790 -3.65370 -2.49490
H 2.44490 -5.22720 -4.20290
O 4.29920 -4.80810 -5.88170
H 5.29990 -2.28570 -5.52970
H 4.47510 -0.72800 -3.82610
H 2.77910 -2.25350 1.04150
H 3.50100 -2.52350 3.38900
H 2.93800 -0.79190 5.08230
H 1.63680 1.21910 4.40310
H 0.90890 1.48920 2.05530
Ti -2.55940 4.11890 -0.34030
Cl -1.65410 6.15980 -0.57960
Cl -4.39220 4.60740 0.85870
Cl -1.27270 3.60360 1.54460
Cl -3.61080 4.10510 -2.36820
C 5.34270 -4.47680 -6.79190
H 5.48250 -5.35520 -7.42240
H 5.06140 -3.61930 -7.41360
H 6.27310 -4.25690 -6.25650

10.3.1.11.3. 18Oai-co-*cis*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3126.1825402
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3126.643634
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3126.298653

C 0.94580 0.85220 1.42970
C -0.34610 0.71450 1.71190
C -1.14179 0.16520 0.54620
C -0.14890 0.38850 -0.67780
C 1.28420 0.42260 0.01730
H -1.21970 -0.92240 0.68120
H -0.80960 0.88140 2.68070

H 1.72340 1.15210 2.12750
C -5.18520 1.58920 -0.00980
C -4.82490 0.30180 -0.40720
C -3.51690 -0.14330 -0.22110
C -2.55220 0.68910 0.35630
C -2.92670 1.97480 0.76640
C -4.23460 2.42360 0.58179
H -6.20490 1.93860 -0.15220
H -5.56100 -0.35630 -0.86150
H -3.24550 -1.15370 -0.52630
H -2.19460 2.62400 1.24170
H -4.51310 3.42290 0.90730
C -0.24040 -0.76570 -1.66400
O 0.00100 -1.92530 -1.11250
O -0.50730 -0.69430 -2.86360
C -0.06300 -3.10120 -1.96120
C -0.43690 1.72580 -1.35150
O -0.36450 2.73560 -0.53680
O -0.71830 1.90340 -2.53820
C -0.62520 4.05400 -1.07920
H -0.50570 4.73480 -0.23770
H 0.09840 4.26980 -1.86780
H -1.64240 4.08720 -1.47460
H 0.18090 -3.93570 -1.29990
H -1.06560 -3.19110 -2.38310
H 0.67910 -3.01570 -2.75700
H 1.62300 -0.62170 0.06380
C 4.37050 2.58860 -2.10640
C 4.15990 1.23060 -2.35540
C 3.15850 0.55830 -1.65320
C 2.35710 1.20470 -0.71210
C 2.59960 2.56480 -0.46010
C 3.59040 3.25200 -1.14770
O 5.31340 3.34460 -2.73240
H 4.75410 0.68840 -3.08340
H 3.00840 -0.50250 -1.85220
H 2.01490 3.08910 0.29270
H 3.78330 4.30410 -0.95130
Ti -0.96810 0.79450 -4.29370
Cl -1.12920 -0.79020 -5.89150
Cl -1.41380 2.65910 -5.47150
Cl 1.30690 1.00390 -4.49650
Cl -3.12390 0.52470 -3.56620
C 6.11450 2.71880 -3.72860
H 6.78860 3.49020 -4.10200
H 6.69870 1.89700 -3.29960

H 5.49440 2.34360 -4.55040

10.3.1.11.4. 182ai-co-*trans-E*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -3126.158593
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3126.618252
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3126.275509

C -0.38340 -1.22710 -0.28250
C 0.97910 -1.78870 0.01120
C -0.38080 0.22660 -0.71580
H 1.02480 -2.86170 0.21120
C 0.17260 0.61500 -1.95110
O 0.69480 -0.35060 -2.69110
O 0.21590 1.79940 -2.41200
C 1.23270 0.00940 -3.97800
C -0.99040 1.23180 0.05820
O -1.62200 0.85210 1.18180
O -0.99370 2.47360 -0.21460
C -2.23190 1.88310 1.96510
C 3.35980 -1.62730 0.44460
C 2.11130 -1.04320 0.10850
H 2.04740 0.02670 -0.07260
H 3.38220 -2.70370 0.63320
C 7.00390 0.45120 0.75640
C 6.96180 -0.94700 1.00020
C 5.77080 -1.61840 0.89670
C 4.56850 -0.92570 0.54740
C 4.64370 0.48030 0.30830
C 5.83000 1.18130 0.40780
O 8.19130 1.02360 0.87640
H 7.88600 -1.45350 1.26560
H 5.73080 -2.69050 1.08220
H 3.75430 1.04179 0.04140
H 5.85500 2.23000 0.22040
H -2.64220 1.36280 2.82950
H -1.48110 2.61340 2.27220
H -3.02480 2.37720 1.40010
H 1.62300 -0.91940 -4.39210
H 0.44230 0.41210 -4.61490
H 2.02830 0.74780 -3.86010
Ti 0.02280 3.56340 -1.52660

Cl 1.34690 4.52250 -3.15400
Cl -0.26480 5.43020 -0.20170
Cl 1.96630 2.93260 -0.26210
Cl -1.92590 3.93810 -2.70780
H -0.88130 -1.25860 0.70179
C -2.85290 -3.69380 -2.85470
C -3.42950 -2.81120 -1.93730
C -2.61780 -2.03570 -1.11179
C -1.22280 -2.12530 -1.20440
C -0.65350 -3.00560 -2.11520
C -1.46410 -3.78920 -2.94010
H -4.51110 -2.72930 -1.86350
H -3.07030 -1.34860 -0.39800
H 0.42840 -3.07070 -2.20890
H -1.00670 -4.46890 -3.65510
H -3.48370 -4.30100 -3.49900
C 8.32670 2.43790 0.65180
H 9.38140 2.65500 0.81320
H 8.04410 2.68750 -0.37500
H 7.71520 2.99310 1.36860

10.3.1.11.5. 182ai-co-*trans-Z*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -3126.148191
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3126.607066
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3126.264712

C -1.76440 -1.34790 0.72510
C -0.28790 -1.28110 0.47490
C -2.48680 -0.07820 0.30710
H -0.01700 -0.89200 -0.50770
C -1.87520 1.18630 0.34400
O -0.64570 1.24600 0.84790
O -2.39860 2.27990 -0.03500
C 0.01820 2.52530 0.84420
C -3.87020 -0.09670 0.01820
O -4.51930 -1.22100 0.26730
O -4.54140 0.87790 -0.44120
C -5.90230 -1.29400 -0.12940
C 0.55690 -2.32350 2.52340
C 0.73610 -1.78730 1.23410
H 1.72730 -1.77800 0.78870

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H -6.21830 -2.30290 0.13100
H -6.49010 -0.55190 0.41330
H -5.99030 -1.12580 -1.20470
H 1.01120 2.32890 1.24200
H 0.07520 2.91500 -0.17400
H -0.52430 3.22560 1.48370
Ti -4.02020 2.67630 -1.11130
Cl -3.11060 4.69900 -1.75440
Cl -5.98810 2.79890 -2.30930
Cl -4.99410 3.60500 0.79230
Cl -2.93340 1.54540 -2.88000
H -1.98470 -1.60020 1.76980
C -2.72840 -4.82070 -1.69290
C -2.50140 -3.58630 -2.30460
C -2.20120 -2.46470 -1.53179
C -2.13240 -2.57020 -0.13860
C -2.34740 -3.80860 0.47010
C -2.65200 -4.92900 -0.30240
H -2.56040 -3.49310 -3.38620
H -2.04150 -1.50120 -2.01320
H -2.30150 -3.89510 1.55460
H -2.83460 -5.88540 0.18170
H -0.42400 -2.22260 2.99100
C 3.38150 -4.42000 4.83950
C 2.08170 -4.17610 5.34570
C 1.17980 -3.47680 4.58280
C 1.53300 -2.99260 3.28680
C 2.85000 -3.24600 2.80470
C 3.76210 -3.94480 3.56100
O 4.18910 -5.11180 5.63520
H 1.82600 -4.55580 6.33150
H 0.17760 -3.28770 4.96430
H 3.15340 -2.89680 1.82170
H 4.75700 -4.12840 3.17030
H -2.96450 -5.69410 -2.29580
C 5.52640 -5.41460 5.20620
H 5.97130 -5.98320 6.02200
H 5.50490 -6.02180 4.29680
H 6.08980 -4.49150 5.04280

10.3.1.11.6. TS$_{mig}$ai-co-*trans-E*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3126.1389712
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3126.597959

G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3126.259308

C 0.48730 -1.16640 0.65030
C 1.62440 -1.62840 1.38690
C 0.00010 0.21260 0.65210
H 2.21480 -0.87170 1.90020
C -0.62220 0.70900 -0.52310
O -0.71190 -0.14650 -1.52700
O -1.07320 1.87500 -0.68560
C -1.30020 0.33420 -2.75440
C 0.03630 1.05100 1.79450
O 0.47910 0.52280 2.92390
O -0.35450 2.25179 1.81810
C 0.48720 1.37280 4.09100
C 2.61730 -3.25420 2.91890
C 1.75680 -2.99170 1.91880
H 1.10050 -3.75780 1.50940
H 3.22179 -2.43010 3.30510
C 3.31380 -6.98130 4.90650
C 3.86760 -5.79010 5.39790
C 3.63050 -4.59380 4.73710
C 2.83420 -4.54650 3.57690
C 2.28570 -5.74730 3.10520
C 2.51840 -6.95780 3.75280
H 4.48110 -5.82660 6.29480
H 4.06870 -3.67540 5.12470
H 1.67130 -5.75700 2.20790
H 2.08210 -7.86650 3.35130
H 0.88000 0.74840 4.89210
H 1.13090 2.23760 3.91940
H -0.52880 1.70020 4.31800
H -1.24440 -0.50650 -3.44400
H -2.33730 0.62680 -2.58090
H -0.72880 1.18470 -3.13040
Ti -0.78390 3.57180 0.35970
Cl -1.23970 4.79620 -1.52080
Cl -0.30470 5.29840 1.78380
Cl 1.49400 3.32670 -0.25760
Cl -2.99870 3.45220 1.00420
H -0.19800 -1.93170 0.28450
C 3.44190 -1.44480 -2.57880
C 3.48560 -0.32920 -1.73250
C 2.71840 -0.31420 -0.57930
C 1.92280 -1.43400 -0.24980
C 1.88050 -2.55250 -1.11240

C 2.63720 -2.55050 -2.27370
H 4.03520 -1.44910 -3.49030
H 4.10920 0.52450 -1.98320
H 2.72040 0.55920 0.06980
H 1.25080 -3.40780 -0.87470
H 2.60440 -3.40330 -2.94570
O 3.60300 -8.10740 5.60650
C 3.07760 -9.34650 5.13810
H 3.42910 -10.10630 5.83660
H 1.98220 -9.32970 5.13390
H 3.44920 -9.57280 4.13250

10.3.1.11.7. TS$_{cycl}$ai-co-*trans-Z*

E E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3126.1443995
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3126.605487
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3126.262244

C -2.37320 -0.31760 8.70250
C -1.49520 -1.32430 9.43080
C -2.61090 -0.71490 7.25870
H -3.35230 -0.36100 9.20670
H -0.79330 -0.93210 10.18380
C -1.52770 -0.84330 6.35840
O -0.31730 -0.74700 6.88790
O -1.61230 -1.07270 5.11500
C -3.91050 -0.77450 6.71290
O -4.92370 -0.60410 7.55550
C -0.98180 3.74760 9.39130
C -1.25070 3.31850 8.09300
C -1.69130 2.01370 7.85600
C -1.85700 1.11370 8.91050
C -1.60420 1.56070 10.21500
C -1.16840 2.86290 10.45580
H -0.63930 4.76290 9.57550
H -1.12220 3.99930 7.25470
H -1.91440 1.71220 6.83630
H -1.76400 0.89310 11.06100
H -0.97970 3.18820 11.47600
C -2.32830 -3.33640 8.26140
C -1.46120 -2.65150 9.19700
H -0.69179 -3.24590 9.68730
H -3.39510 -3.10450 8.29060
C -1.13380 -6.42650 5.69600

C -2.51830 -6.16510 5.88580
C -2.90090 -5.14250 6.70870
C -1.92550 -4.36920 7.41960
C -0.53990 -4.67140 7.22840
C -0.14230 -5.66780 6.37510
O -0.84700 -7.40570 4.85740
H -3.23690 -6.77150 5.34270
H -3.95750 -4.91710 6.84330
H 0.21800 -4.08580 7.74710
H 0.91400 -5.86560 6.22580
C 0.80690 -0.78500 5.98760
H 1.68540 -0.69010 6.62520
H 0.82140 -1.72940 5.43920
H 0.74720 0.05000 5.28540
C -6.25179 -0.56590 6.99390
H -6.91200 -0.40210 7.84440
H -6.32850 0.25760 6.28110
H -6.48180 -1.51010 6.49800
O -4.19630 -1.02410 5.50290
Ti -3.12480 -0.94080 3.81550
Cl -3.03980 1.39900 4.19310
Cl -1.62890 -0.77890 2.07500
Cl -3.15910 -3.25220 3.75250
Cl -5.07450 -0.74820 2.60380
C 0.52320 -7.73900 4.57410
H 0.47720 -8.55830 3.85810
H 1.03770 -6.88250 4.12880
H 1.02880 -8.06520 5.48760

10.3.1.12. *R^1 = Ph, R^3 = p-CO$_2$MeC$_6$H$_4$*

10.3.1.12.1. 179ah-co-*trans-*TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3239.4907
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3239.981053
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3239.63288

C -0.97030 -0.40810 -0.18630
C 0.46460 -0.50970 0.12580
C -0.19660 0.91690 0.09820
H 1.12110 -0.61080 -0.73630
C 0.16590 1.78290 -1.05510

O 0.63480 1.14780 -2.08920
O 0.04110 3.01310 -1.07960
C 0.94740 1.92410 -3.27410
C -0.51430 1.61800 1.36320
O -0.82850 0.83930 2.36110
O -0.50090 2.84590 1.51050
C -1.20610 1.47700 3.61030
C 2.32980 -1.34320 1.47820
C 1.01480 -1.09860 1.37280
H 0.31790 -1.34100 2.16920
H 2.97150 -1.07110 0.63760
C 4.53750 -2.96850 4.76970
C 5.18720 -2.48990 3.62890
C 4.44560 -1.97630 2.57080
C 3.04320 -1.92750 2.62730
C 2.39890 -2.42380 3.77400
C 3.13710 -2.93560 4.83550
H 6.27200 -2.52030 3.57910
H 4.95840 -1.60060 1.68770
H 1.31390 -2.41930 3.84300
H 2.62740 -3.31190 5.71720
H -1.47200 0.65780 4.27530
H -0.35840 2.04430 3.99720
H -2.05950 2.13390 3.43380
H 1.30090 1.19370 -3.99890
H 0.04490 2.42700 -3.62570
H 1.72450 2.65130 -3.03470
H -1.64380 -0.63300 0.64170
C -2.66990 -1.10530 -4.06790
C -3.20020 -0.11940 -3.23210
C -2.64220 0.10130 -1.97380
C -1.54410 -0.65460 -1.54800
C -1.01730 -1.64180 -2.38340
C -1.58210 -1.86780 -3.64020
H -3.10610 -1.27960 -5.04840
H -4.04850 0.47640 -3.55940
H -3.05550 0.86820 -1.32080
H -0.16840 -2.23820 -2.05430
H -1.17120 -2.63990 -4.28570
Ti -0.61360 4.49550 0.23300
Cl -0.64370 5.98100 -1.44860
Cl -1.33410 5.77910 1.93180
Cl 1.61730 4.75400 0.71240
Cl -2.72590 3.63880 -0.24080
C 5.37700 -3.49920 5.88450
O 4.66050 -3.89790 6.93830

O 6.59240 -3.56230 5.84770
C 5.40330 -4.40950 8.05680
H 4.65620 -4.67000 8.80590
H 5.97410 -5.29150 7.75740
H 6.08140 -3.642708.43850

10.3.1.12.2. 182ah-co-*trans-E*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -3239.463049
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3239.954315
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -3239.604883

C -0.43390 -1.23720 -0.25910
C 0.91000 -1.80980 0.05010
C -0.38070 0.04540 -1.07000
H 0.94760 -2.85710 0.36060
C 0.18320 0.05700 -2.36030
O 0.66950 -1.09550 -2.79840
O 0.26710 1.06420 -3.12770
C 1.22070 -1.11910 -4.13110
C -0.98100 1.23520 -0.61670
O -1.64780 1.17880 0.52990
O -0.94320 2.35310 -1.21690
C -2.25590 2.39930 1.00090
C 3.28220 -1.657400.42460
C 2.06680 -1.06850 0.06350
H 2.02040 -0.02300 -0.23300
H 3.27970 -2.71150 0.71550
C 7.03190 0.28030 0.43630
C 6.93830 -1.05880 0.84040
C 5.69940 -1.68790 0.83480
C 4.54280 -0.98070 0.42830
C 4.65980 0.37140 0.02230
C 5.89490 0.99170 0.02760
H 7.82660 -1.59830 1.15310
H 5.61300 -2.72800 1.14360
H 3.79230 0.93540 -0.30470
H 5.99550 2.02640 -0.28580
H -2.72490 2.13450 1.94730
H -1.49290 3.16630 1.14600

H -3.00150 2.74510 0.28260
H 1.58610 -2.13590 -4.26990
H 0.44100 -0.88640 -4.85910
H 2.03590 -0.39770 -4.21280
Ti 0.14590 3.01490 -2.74820
Cl 1.53440 3.44040 -4.53370
Cl -0.06500 5.17280 -1.97390
Cl 2.03330 2.65080 -1.30710
Cl -1.76480 3.13650 -4.03330
H -0.78179 -0.93700 0.74990
C -3.37560 -3.99180 -1.84140
C -3.76430 -2.89750 -1.06420
C -2.80210 -2.03410 -0.54390
C -1.44150 -2.24900 -0.79580
C -1.05880 -3.34420 -1.57480
C -2.02180 -4.21370 -2.09260
H -4.81740 -2.71690 -0.86310
H -3.10820 -1.18060 0.05840
H -0.00840 -3.51540 -1.80060
H -1.71110 -5.05990 -2.70060
H -4.12490 -4.66500 -2.25000
C 8.34180 1.02170 0.41510
O 9.37090 0.27780 0.80430
O 8.43670 2.18300 0.07490
C 10.65580 0.93040 0.80760
H 11.36590 0.17700 1.14550
H 10.90350 1.27070 -0.20050
H 10.63860 1.78170 1.49190

10.3.1.12.3. 182ah-co-*trans-Z-*TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3239.457169
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3239.94692
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3239.597551

C -1.75830 -1.35630 0.66270
C -0.30130 -1.34120 0.39130
C -2.47470 -0.09070 0.25470
H -0.02230 -0.97120 -0.59580
C -1.83960 1.18160 0.25220
O -0.574301.19340 0.66600
O -2.36860 2.26350 -0.08620

C 0.10670 2.46460 0.64030
C -3.87010 -0.10510 0.03000
O -4.49740 -1.24140 0.28300
O -4.56110 0.87650 -0.37300
C -5.90670 -1.30370 -0.01530
C 0.53870 -2.30180 2.46720
C 0.72650 -1.88830 1.18020
H 1.70120 -1.96950 0.68720
H -6.20300 -2.32230 0.23080
H -6.45190 -0.58280 0.59640
H -6.07320 -1.09680 -1.07410
H 1.12440 2.24720 0.96170
H 0.09790 2.87380 -0.37170
H -0.37720 3.15740 1.33120
Ti -4.06560 2.68990 -1.04550
Cl -3.18150 4.70860 -1.71290
Cl -6.10390 2.84750 -2.10179
Cl -4.88950 3.57830 0.94080
Cl -3.10690 1.56830 -2.89180
H -1.99170 -1.64260 1.69460
C -2.60110 -4.79850 -1.84750
C -2.44870 -3.53800 -2.42810
C -2.17420 -2.42820 -1.63010
C -2.06260 -2.57690 -0.24270
C -2.20460 -3.84390 0.33530
C -2.47400 -4.94980 -0.46330
H -2.81800 -5.66270 -2.47100
H -2.54590 -3.41570 -3.50380
H -2.07210 -1.44310 -2.08210
H -2.09900 -3.96340 1.41370
H -2.59490 -5.92940 -0.00780
H -0.42970 -2.12710 2.93970
C 3.28460 -4.34080 4.95850
C 2.00980 -4.01260 5.43380
C 1.13180 -3.32210 4.60670
C 1.51820 -2.95920 3.29750
C 2.81130 -3.28970 2.83660
C 3.68490 -3.972903.66540
H 1.70820 -4.29830 6.43630
H 0.13700 -3.06460 4.96530
H 3.13300 -3.02340 1.83390
H 4.68030 -4.23680 3.32090
C 4.27170 -5.10320 5.79710
O 3.78060 -5.45940 6.97960
O 5.39660 -5.369005.42420
C 4.66080 -6.21050 7.83610

H 4.07900-6.42330 8.73190
H 4.96000 -7.13610 7.33910
H 5.54290 -5.61330 8.07770

10.3.1.12.4. 181ah-co-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3239.486889
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3239.978215
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3239.625327

C -0.72210 1.13730 -0.65100
C 0.05360 0.14170 -0.18390
C 1.55090 0.02350 -0.08590
C 1.90740 -1.12510 -1.00470
C 2.66240 -0.97180 -2.10010
C 3.03210 -2.02800 -3.06140
C -2.19640 1.02350 -0.50920
C -0.22620 2.40360 -1.24250
O 0.94610 2.34330 -1.80890
O -0.86840 3.46010 -1.23170
C 1.47300 3.57370 -2.37510
O -2.96500 1.99270 -0.48710
O -2.64920 -0.20460 -0.39400
C -4.07370 -0.35800 -0.18380
C 2.43970 -3.30280 -3.05770
C 2.82220 -4.26100 -3.98690
C 3.80310 -3.96870 -4.94340
C 4.39650 -2.70250 -4.96179
C 4.00890 -1.74390 -4.02870
C 1.95470 -0.20490 1.37290
C 2.91130 -1.17940 1.72710
C 3.29570 -1.31310 3.06140
C 2.72550 -0.51590 4.05430
C 1.76970 0.44110 3.70690
C 1.38850 0.59490 2.37440
H -0.47570 -0.71030 0.26630
H 2.04000 0.92990 -0.44910
H 1.49780 -2.09820 -0.72950
H 3.07290 0.01690 -2.31300
H 2.46030 3.30880 -2.74860
H 0.82080 3.90490 -3.18490
H 1.53660 4.33470 -1.59560
H -4.21950 -1.43310 -0.08000
H -4.35230 0.15240 0.75860

H -4.62510 0.05040 -1.01280
H 1.66550 -3.55010 -2.33600
H 2.35960 -5.24380 -3.98360
H 5.15480-2.46590 -5.70179
H 4.47240 -0.75930 -4.04840
H 3.36980 -1.78270 0.96250
H 4.04440 -2.05690 3.32290
H 3.02500 -0.63750 5.09220
H 1.32260 1.06980 4.47290
H 0.64990 1.35190 2.11410
Ti -2.66090 4.06120 -0.30720
Cl -1.92990 6.18300 -0.26790
Cl -4.65190 4.28050 0.70170
Cl -1.54340 3.47179 1.65900
Cl -3.47470 4.15000 -2.44030
C 4.17090 -5.03420 -5.92200
O 5.12900 -4.65640 -6.77050
O 3.65680 -6.13780 -5.95120
C 5.53560 -5.62850 -7.74820
H 6.33050 -5.15200 -8.32110
H 5.90550-6.52860 -7.25190
H 4.69380 -5.88230 -8.39690

10.3.1.12.5. TS$_{mig}$ah-co-*trans-E*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3239.458853
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3239.948553
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3239.599637

C 0.31390 -1.23320 0.49220
C 1.44630 -1.71910 1.22410
C -0.11670 0.18110 0.54050
H 2.03060 -0.96240 1.74460
C -0.63790 0.77180 -0.63100
O -0.71250 -0.00430 -1.69760
O -1.00420 1.97350 -0.73470
C -1.17510 0.60580 -2.92210
C -0.10280 0.92110 1.73970
O 0.22720 0.28790 2.85320
O -0.42000 2.13950 1.82240
C 0.20600 1.05300 4.07770
C 2.51690 -3.29570 2.73060
C 1.58290 -3.07650 1.79010
H 0.89230 -3.84820 1.45330

H 3.15230 -2.45500 3.01730
C 3.46990 -6.85450 4.90780
C 4.11650 -5.64580 5.17930
C 3.78660 -4.50480 4.45650
C 2.80350 -4.54470 3.45420
C 2.15700 -5.76480 3.19070
C 2.48820 -6.909303.90810
H 4.87640 -5.60770 5.95460
H 4.29690 -3.56770 4.66960
H 1.39290 -5.82960 2.42010
H 1.98610 -7.84750 3.69290
H 0.50370 0.35060 4.85480
H 0.91179 1.88310 4.01010
H -0.80179 1.42990 4.26100
H -1.13430 -0.18700 -3.66730
H -2.19630 0.96910 -2.79570
H -0.51510 1.43150 -3.19460
Ti -0.68320 3.57900 0.43980
Cl -0.94390 4.95430 -1.36990
Cl -0.18900 5.16580 2.01100
Cl 1.61200 3.23170 -0.06200
Cl -2.93360 3.55680 0.94400
H -0.38350 -1.97140 0.09510
C 3.23900 -1.54110 -2.74830
C 3.31820 -0.43440 -1.89150
C 2.58050 -0.42260 -0.71990
C 1.77660 -1.53590 -0.38260
C 1.70050 -2.64560 -1.25570
C 2.42970 -2.64100 -2.43460
H 3.80780 -1.54120 -3.67550
H 3.94540 0.41430 -2.14990
H 2.60650 0.44400 -0.06190
H 1.06600 -3.49560 -1.01140
H 2.37010 -3.48600 -3.11450
C 3.86760 -8.05530 5.70330
O 3.23180 -9.16720 5.32980
O 4.68900 -8.03130 6.60130
C 3.56850 -10.36510 6.05080
H 2.95370 -11.15140 5.61420
H 4.62960 10.59310 5.92530
H 3.33930 -10.24210 7.11190

10.3.1.12.6. TS$_{cycl}$ah-co-*trans-Z*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-3239.450885

E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3239.943072
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-3239.594272

C -2.27920 -0.34710 8.73840
C -1.23450 -1.21510 9.42870
C -2.42680 -0.79180 7.28980
H -3.23560 -0.57750 9.24030
H -0.50130 -0.75690 10.08970
C -1.28830 -0.73620 6.42690
O -0.15800 -0.40090 7.01740
O -1.27270 -0.99190 5.19450
C -3.68880 -1.037606.68060
O -4.74310 -0.99990 7.48070
C -1.65430 3.89150 9.43930
C -1.85880 3.42930 8.14050
C -2.05250 2.06680 7.89870
C -2.03760 1.14880 8.95060
C -1.84440 1.62270 10.25520
C -1.65180 2.98190 10.49920
H -1.50510 4.95180 9.62680
H -1.87180 4.12800 7.30740
H -2.22660 1.73360 6.87850
H -1.85760 0.92900 11.09530
H -1.50520 3.33190 11.51810
C -2.22830 -3.08410 8.31340
C -1.18850 -2.53260 9.14310
H -0.36570 -3.18090 9.47660
H -3.25360 -2.79110 8.54900
C -1.92630 -6.35720 5.68370
C -3.18450 -5.90810 6.09940
C -3.27010 -4.82060 6.95420
C -2.09340 -4.19179 7.42170
C -0.82820 -4.65510 6.99140
C -0.74890 -5.72890 6.12040
H-4.07940 -6.40610 5.73840
H -4.24179 -4.46150 7.28810
H 0.08210 -4.16780 7.33390
H 0.21680 -6.08350 5.77510
C 1.01490 -0.25900 6.18690
H 1.81070 0.03300 6.87010
H 1.24640 -1.20610 5.69680
H 0.83990 0.51680 5.43860
C -6.04090 -1.18390 6.87020
H -6.75290 -1.12070 7.69170

H -6.21590 -0.38980 6.14179
H -6.09260 -2.15760 6.38050
O -3.87020 -1.33950 5.47060
Ti -2.73580 -1.13080 3.80140
Cl -3.02040 1.19650 4.17010
Cl -1.20600 -0.73600 2.14850
Cl -2.39000 -3.39600 3.79450
Cl -4.62730 -1.24870 2.52600
C -1.88410 -7.52790 4.74080
O -0.65070 -7.83060 4.35240
O -2.87610 -8.12480 4.37420
C -0.52179 -8.93000 3.43179
H 0.54470 -9.01200 3.22500
H -0.89840 -9.84620 3.89190
H -1.07760 -8.71560 2.51790

10.3.1.12.7. 180ah-co-*cis*-TiCl₄

E(M06-2X/6-31+G(d)(CH₂Cl₂)) =
-3239.501982
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-3239.993826
G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-3239.642111

C 0.97660 0.15040 1.21810
C -0.32310 0.11880 1.49270
C -1.21710 0.25040 0.28830
C -0.18000 0.23810 -0.93280
C 1.29290 0.29460 -0.24960
H -1.83550 -0.65170 0.18670
H -0.75220 0.00800 2.48620
H 1.77620 0.06800 1.94860
C -3.95590 3.59730 0.35080
C -4.21720 2.48200 -0.44620
C -3.33570 1.39960 -0.44020
C -2.17820 1.42690 0.34400
C -1.92620 2.54590 1.14420
C -2.81180 3.62310 1.15150
H -4.64430 4.43880 0.35480
H -5.11040 2.44820 -1.06490
H -3.55110 0.52560 -1.05100
H -1.02770 2.58320 1.75600
H -2.60700 4.48540 1.78140
C -0.29830 -1.11290 -1.62040
O -0.07510 -2.11010 -0.80990
O -0.59670 -1.31990 -2.79600

C -0.19640 -3.45280 -1.34940
C -0.40000 1.38780 -1.89650
O -0.26990 2.54990 -1.34020
O -0.69570 1.29080 -3.09130
C -0.52170 3.72420 -2.14800
H -0.36920 4.56460 -1.47420
H 0.18300 3.75040 -2.98130
H -1.54940 3.69420 -2.51540
H 0.00710 -4.11260 -0.50850
H -1.20840 -3.59900 -1.73090
H 0.53670 -3.59030 -2.14600
H 1.84110 -0.59320 -0.59220
C 3.83130 3.63390 -1.30720
C 3.67870 2.55010 -2.17720
C 2.86290 1.48120 -1.81810
C 2.17360 1.48510 -0.59990
C 2.32540 2.57570 0.26280
C 3.15230 3.64240 -0.08320
H 4.21180 2.54350 -3.12360
H 2.76770 0.63070 -2.49020
H 1.79460 2.59800 1.21150
H 3.27090 4.47950 0.59830
Ti -1.02310 -0.19830 -4.52200
Cl -1.28270 -2.08920 -5.70990
Cl -1.40900 1.35340 -6.09140
Cl 1.27210 -0.18130 -4.76770
Cl -3.17900 -0.21220 -3.71350
C 4.74280 4.74410 -1.71810
O 4.83680 5.70850 -0.80010
O 5.34600 4.77390 -2.77480
C 5.70800 6.80860 -1.11240
H 5.64980 7.47790 -0.25450
H 6.73070 6.45000 -1.25060
H 5.36630 7.31390 -2.01880

10.3.1.13. R¹ = Ph, R³ = i-Pr

10.3.1.12.1. 179ac-co-*trans*-TiCl₄

E(M06-2X/6-31+G(d)(CH₂Cl₂)) =
-2898.602409
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-2899.007821
G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) =
-2898.694484

C -0.92030 -0.39370 -0.21420
C 0.51510 -0.48360 0.09540
C -0.15940 0.93890 0.07140
H 1.17410 -0.57770 -0.76540
C 0.19070 1.81040 -1.08020
O 0.67470 1.18530 -2.11430
O 0.04060 3.03870 -1.10710
C 0.96890 1.96750 -3.29940
C -0.47190 1.63500 1.33980
O -0.77180 0.854802.33980
O -0.46040 2.86390 1.49050
C -1.12100 1.48460 3.60060
C 2.34500 -1.40200 1.46920
C 1.05170 -1.09010 1.33920
H 0.34910 -1.31710 2.13830
H -1.33380 0.65870 4.27720
H -0.27760 2.08000 3.95450
H -2.00070 2.11490 3.45890
H1.33380 1.24550 -4.02730
H 0.05670 2.45460 -3.64860
H 1.73380 2.70910 -3.06390
H -1.58660 -0.62660 0.61740
C -2.65390 -1.14660 -4.06930
C -3.20690 -0.18179 -3.22380
C -2.63530 0.06130 -1.97560
C -1.50220 -0.65190 -1.56940
C -0.95240 -1.61840 -2.41480
C -1.52940 -1.86620 -3.66180
H -4.08450 0.37940 -3.53480
H -3.06760 0.80960 -1.31340
H -0.07670 -2.-2.10010
H -1.10070 -2.62270 -4.31430
Ti -0.63840 4.50100 0.21270
Cl -0.73700 5.98250 -1.47280
Cl -1.37040 5.77060 1.91970
Cl 1.59140 4.83530 0.65830
Cl -2.73330 3.58360 -0.22970
C 2.95290 -2.06130 2.67590
C 3.56420 -3.41380 2.28500
C 4.01850 -1.14970 3.29700
H 2.15870 -2.23360 3.41370
H -3.10120 -1.33920 -5.04130
H 3.03780 -1.17470 0.65260
H 4.46670 -1.62630 4.17610
H 4.82050 -0.94910 2.57520
H 3.59050 -0.18990 3.60480

H 4.01290 -3.90190 3.15740
H 2.80610 -4.08380 1.86660
H 4.35100 -3.27500 1.53280

10.3.1.12.2. 182ac-co-*trans-E*-TiCl₄
E(M06-2X/6-31+G(d)(CH₂Cl₂)) = -2898.572426
E(M06-2X/6-311+G(d,p)(CH₂Cl₂)) = -2898.978553
G(M06-2X/6-311+G(d,p)(CH₂Cl₂)) = -2898.664637

C -0.40200 -1.11760 -0.18130
C 0.94960 -1.58660 0.24220
C -0.37690 0.12430 -1.03320
H 1.04280 -2.61960 0.58760
C 0.21280 0.08220 -2.31170
O 0.76010 -1.07290 -2.66470
O 0.26480 1.03980 -3.14130
C 1.31430 -1.16630 -3.99330
C -1.00580 1.32230 -0.64520
O -1.68370 1.30730 0.49580
O -0.98010 2.40890 -1.29920
C -2.32860 2.53340 0.89930
C 3.28780 -1.29790 0.67050
C 2.06420 -0.77240 0.28850
H 1.99330 0.27260 -0.01340
H 3.35420 -2.36020 0.93150
C 4.53090 -0.50430 0.64080
H -2.78390 2.30970 1.86280
H -1.59080 3.33190 0.99410
H -3.08940 2.81179 0.16730
H 1.72090 -2.17460 -4.06180
H 0.52710 -1.01710 -4.73500
H 2.09890 -0.41890 -4.12670
Ti 0.09550 3.00880 -2.87010
Cl 1.45670 3.36530 -4.69170
Cl -0.16880 5.19970 -2.22850
Cl 1.99890 2.75920 -1.43140
Cl-1.83080 2.99490 -4.14370
H -0.81650 -0.80310 0.81960
C -3.07530 -4.17020 -1.67300

466

C -3.57300 -3.05440 -0.99500
C -2.69730 -2.08890 -0.50180
C -1.31560 -2.22440 -0.68150
C -0.82370 -3.34020 -1.36420
C -1.69980 -4.31080 -1.85480
H -4.64380 -2.93710 -0.84900
H -3.08860 -1.22010 0.02470
H 0.24450 -3.45180 -1.53680
H -1.30420 -5.17240 -2.38720
H -3.75700 -4.92360 -2.05920
C 5.08780 -0.66910 -0.80710
C 5.55990 -0.95880 1.67730
H 6.46230 -0.34600 1.58790
H 5.17380 -0.85050 2.69560
H 5.83830 -2.00680 1.51670
H 6.01340 -0.08760 -0.87370
H 5.31330 -1.71780 -1.02630
H 4.38300 -0.28760 -1.55150
H 4.28430 0.55670 0.77590

10.3.1.12.3. 182ac-co-*trans-Z*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-2898.568731
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2898.974178
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2898.660089

C -1.59470 -1.18270 0.63660
C -0.17700 -1.18470 0.26920
C -2.39230 0.00380 0.17820
H 0.05179 -0.86250 -0.74710
C -1.81800 1.28180 0.06190
O -0.52520 1.38540 0.37050
O -2.42120 2.33750 -0.28640
C 0.08600 2.68710 0.26030
C -3.79690 -0.09440 0.06420
O -4.33040 -1.25900 0.39350
O -4.57270 0.83320 -0.30780
C -5.75880 -1.40060 0.25200
C 0.83120 -1.74590 2.41370
C 0.90830 -1.64300 1.05560
H 1.85610 -1.82480 0.55170
H -5.96810 -2.43530 0.51860

H -6.27080 -0.71520 0.93010
H -6.05440 -1.19820 -0.77890
H 1.13420 2.53070 0.51230
H -0.01540 3.06310 -0.75920
H -0.38140 3.37750 0.96500
Ti -4.23280 2.64690 -1.07870
Cl -3.52350 4.67670 -1.89250
Cl -6.37090 2.67840 -1.92070
Cl -4.88370 3.55260 0.96210
Cl -3.40870 1.49870 -2.97270
H -1.77240 -1.43690 1.68700
C -2.19090 -4.83770 -1.63740
C -2.21900 -3.60520 -2.29390
C -2.00820 -2.42940 -1.57850
C -1.78270 -2.48610 -0.19530
C -1.72610 -3.72660 0.45580
C -1.94620 -4.89750 -0.26110
H -2.35460 -5.75450 -2.19820
H -2.40750 -3.55940 -3.36320
H -2.04290 -1.46600 -2.08380
H -1.53180 -3.77060 1.52640
H -1.92470 -5.85720 0.24860
H -0.10100 -1.49630 2.92980
C 1.95610 -2.17040 3.28790
C 1.56460 -3.51180 3.94320
H 2.85440 -2.31910 2.67690
C 2.23100 -1.10440 4.36080
H 3.05370 -1.43690 5.00200
H 2.51380 -0.14810 3.91000
H 1.34660 -0.94640 4.98880
H 2.38060 -3.84370 4.59370
H 0.66250 -3.39950 4.55580
H 1.38680 -4.28750 3.20410

10.3.1.12.4. 181ac-co-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-2898.598519
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2899.004868
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2898.687783

C -0.78330 1.04460 -0.61800
C -0.03200 0.04630 -0.09900
C 1.46090 -0.10970 -0.03310
C 1.79950 -1.25770 -0.96050

C 2.59970 -1.13340 -2.02150
C -2.25480 1.00170 -0.43440
C -0.25000 2.25200 -1.29070
O 0.90090 2.10540 -1.88260
O -0.84550 3.33620 -1.32650
C 1.46590 3.27270 -2.53660
O -2.98110 2.00410 -0.44920
O -2.75750 -0.18360 -0.23540
C -4.17940 -0.26880 0.04640
C 1.85640 -0.34060 1.42690
C 2.63780 -1.42840 1.82410
C 3.00600 -1.58150 3.18250
C 2.59480 -0.65070 4.11730
C 1.81310 0.43940 3.72720
C 1.44720 0.59100 2.39080
H -0.58090 -0.76860 0.37660
H 1.96810 0.78870 -0.39190
H 1.33870 -2.22180 -0.73310
H 3.05570 -0.18050 -2.23520
H 2.42580 2.93850 -2.92530
H 0.80280 3.59010 -3.34300
H 1.59370 4.07270 -1.80560
H -4.37200 -1.33010 0.19140
H -4.40270 0.29990 0.95060
H -4.74060 0.12310 -0.80320
H 2.97220 -2.15630 1.08980
H 3.61830 -2.43030 3.45860
H 1.49240 1.172104.46340
H 0.84560 1.44890 2.09300
Ti -2.57910 4.06020 -0.39090
Cl -1.75630 6.14820 -0.47780
Cl -4.53040 4.42030 0.65880
Cl -1.43360 3.52950 1.57820
Cl -3.45220 4.08120 -2.50190
H 2.88320 -0.77120 5.15840
C 2.94560 -2.24750 -2.97100
C 2.47460 -1.89720 -4.38850
C 4.45640 -2.51220 -2.95470
H 2.42480 -3.15630 -2.64180
H 2.71420 -2.70870 -5.08480
H 1.39360 -1.72660 -4.41550
H 2.97250 -0.98720 -4.74610
H 4.71250 -3.32480 -3.64380
H 5.00760 -1.61660 -3.26820
H 4.79940 -2.78950 -1.95250

10.3.1.12.5. 180ac-co-*cis*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-2898.615888
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2899.022466
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2898.70384

C 0.82070 0.08150 1.22590
C -0.49090 0.056801.43930
C -1.31890 0.28720 0.20410
C -0.19580 0.27020 -0.96070
C 1.21710 0.34070 -0.20820
H -1.98430 -0.56890 0.02610
H -0.97180 -0.10250 2.40170
H 1.57060 -0.08470 1.99430
C -3.83610 3.80360 0.30410
C -4.16930 2.71720 -0.50570
C -3.36040 1.57930 -0.51390
C -2.20610 1.51980 0.27380
C -1.88220 2.61040 1.08780
C -2.69340 3.74460 1.10520
H -4.46750 4.68860 0.31790
H -5.06220 2.74980 -1.12500
H -3.62930 0.73050 -1.13940
H -0.98470 2.58010 1.70140
H -2.43220 4.58450 1.74440
C -0.28490 -1.10290 -1.61440
O -0.05590 -2.07540 -0.77860
O -0.55030 -1.35179 -2.79220
C -0.12300 -3.43220 -1.28750
C -0.46210 1.37980 -1.96130
O -0.33750 2.57200 -1.46630
O -0.80550 1.23190 -3.13910
C -0.65540 3.69670 -2.32050
H -0.47260 4.57580 -1.70570
H -0.00410 3.68470 -3.19690
H -1.70330 3.63250 -2.62100
H 0.08730 -4.06370 -0.42670
H -1.12190 -3.62260 -1.68320
H 0.62950 -3.56350 -2.06700
H 1.82110 -0.50250 -0.57600
Ti -1.07430 -0.30310 -4.52280
Cl -1.24900 -2.22860 -5.67220
Cl -1.59610 1.19370 -6.11100
Cl 1.20680 -0.13220 -4.82450

Cl -3.21170 -0.43620 -3.66179
C 2.11040 1.58980 -0.39740
C 3.31200 1.51030 0.55470
C 2.63030 1.69950 -1.83430
H 3.20450 2.62400 -1.96020
H 3.29560 0.85590 -2.06060
H 1.84690 1.69870 -2.59930
H 4.01470 2.31960 0.32950
H 3.01850 1.60960 1.60340
H 3.84770 0.55960 0.43380
H 1.53730 2.48520 -0.13830

10.3.1.12.6. TS$_{mig}$ac-co-*trans-E-*TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -2898.571964
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -2898.977195
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -2898.663856

C 0.40970 -1.13940 0.66080
C 1.47240 -1.66300 1.45900
C -0.06630 0.23840 0.66070
H 2.05380 -0.95460 2.04330
C -0.72330 0.71580 -0.50650
O -0.83120 -0.14990 -1.49840
O -1.19690 1.87280 -0.66510
C -1.46060 0.31140 -2.71290
C 0.00060 1.10300 1.78480
O 0.48940 0.60870 2.90960
O -0.40650 2.29780 1.79340
C 0.52880 1.48780 4.05510
C 2.37980 -3.42830 2.89480
C 1.52470 -3.05870 1.93440
H 0.82040 -3.77310 1.50760
H 0.96090 0.88930 4.85610
H 1.15390 2.35580 3.83720
H 0.48270 1.80770 4.31190
H -1.38620 -0.52590 -3.40460
H -2.50420 0.56410 -2.51810
H -0.92900 1.18270 -3.09790
Ti -0.83010 3.59530 0.31410
Cl -1.29440 4.77250 -1.59450
Cl -0.25750 5.34640 1.67340

Cl 1.42140 3.26450 -0.34840
Cl -3.02790 3.57180 1.01960
H -0.26000 -1.87590 0.21820
C 3.62390 -1.42190 -2.32990
C 3.63610 -0.33770 -1.44290
C 2.77590 -0.33190 -0.35690
C 1.91800 -1.43070 -0.13580
C 1.91050 -2.51900 -1.03510
C 2.75910 -2.50550 -2.13170
H 4.30900 0.49880 -1.60920
H 2.75720 0.51720 0.32350
H 1.23660 -3.35900 -0.87800
H 2.75280 -3.33440 -2.83360
C 2.49280 -4.81140 3.46660
C 3.88870 -5.37920 3.17340
C 2.22960 -4.78280 4.97780
H 1.74020 -5.45100 2.98750
H 4.29100 -1.41840 -3.18880
H 3.06850 -2.68440 3.30850
H 2.31510 -5.79050 5.39870
H 2.96140 -4.14120 5.48420
H 1.22830 -4.40060 5.20040
H 3.98220 -6.39140 3.58200
H 4.08380 -5.42180 2.09700
H 4.66240 -4.75420 3.63650

10.3.1.12.7. TS$_{cycl}$ac-co-*trans-Z*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -2898.55017
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -2898.956853
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -2898.646382

C -2.59640 0.20240 8.73220
C -2.12020 -0.77110 9.79820
C -2.68150 -0.43440 7.36250
H -3.62570 0.46140 9.02210
H -1.87200 -0.34770 10.77060
C -1.49780 -0.73070 6.61520
O -0.35830 -0.51700 7.24100
O -1.46000 -1.19850 5.44350
C -3.93190 -0.62080 6.69690
O -4.99950 -0.11040 7.28030
C -0.51350 4.00670 8.59710
C -1.75260 3.83760 7.97490

C -2.40110 2.60560 8.03840
C -1.82690 1.52620 8.72140
C -0.58450 1.70050 9.33360
C 0.06700 2.93510 9.27550
H -2.21490 4.66520 7.44240
H -3.36670 2.47970 7.55020
H -0.10600 0.86920 9.84630
H 1.03420 3.05510 9.75760
C -2.26640 -2.90390 8.46430
C -1.97820 -2.09150 9.63400
H -1.50950 -2.67900 10.43820
C -3.55650 -3.53520 8.17980
C 0.86260 -0.71230 6.49690
H 1.65840 -0.43930 7.18810
H 0.95320 -1.75590 6.18940
H 0.87020 -0.06070 5.62100
C -6.26210 -0.24170 6.58860
H -6.97440 0.31590 7.19480
H -6.17990 0.18910 5.58900
H -6.54250 -1.29480 6.52170
O -4.08480 -1.26179 5.62220
Ti -2.85650 -1.44670 4.01070
Cl -2.96080 0.88300 3.91900
Cl -1.24150 -1.58980 2.42060
Cl -2.74680 -3.72780 4.55350
Cl -4.68880 -1.71760 2.67870
H -3.70560 -3.42490 7.07190
C -3.33440 -5.06720 8.37600
C -4.74910 -3.01540 8.95410
H -0.00490 4.96650 8.55179
H -1.40750 -3.28990 7.90020
H -4.27450 -5.56500 8.11960
H -2.54070 -5.45640 7.73290
H -3.09780 -5.28470 9.42230
H -5.66920 -3.45880 8.56090
H -4.66050 -3.29190 10.01100
H -4.84190 -1.92710 8.89980

10.3.1.13. R^1 = Ph, R^3 = Ph, EWG = CN

10.3.1.13.1. 179aa-CN-co-trans-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -4639.399079

E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -4639.886703
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -4639.669217

C -0.84780 -0.22890 -0.21930
C 0.60120 -0.33480 0.04200
C -0.09650 1.08900 0.14350
H 1.27680 -0.37940 -0.81230
C 2.39530 -0.79070 1.67640
C 1.10240 -0.87750 1.32850
H 0.35080 -1.27250 2.01220
H 3.09850 -0.36520 0.95680
C 4.08750 -1.54930 5.52830
C 4.84210 -0.94430 4.52310
C 4.28600 -0.74180 3.26060
C 2.96810 -1.13580 2.98630
C 2.22700 -1.76900 3.99730
C 2.78040 -1.96740 5.25820
H 4.51480 -1.70170 6.51830
H 5.86190 -0.62480 4.72210
H 4.87110 -0.25410 2.48280
H 1.21330 -2.11000 3.80440
H 2.19180 -2.45110 6.03380
H -1.50180 -0.55370 0.59220
C -2.55410 -0.24560 -4.15310
C -3.21110 0.39290 -3.09700
C -2.65410 0.37600 -1.82180
C -1.43680 -0.27960 -1.59430
C -0.78700 -0.92640 -2.64710
C -1.34870 -0.90820 -3.92620
H -2.98440 -0.22580 -5.15130
H -4.15290 0.90770 -3.26900
H -3.15830 0.88180 -0.99930
H 0.15040 -1.45240 -2.47840
H -0.83930 -1.41210 -4.74340
N 0.28450 2.67140 -1.85980
C 0.12500 2.01280 -0.92710
N -0.17720 1.88970 2.59150
C -0.18220 1.61320 1.47200
Cl -1.75690 3.82510 -3.68700
Ti 0.43060 3.72300 -3.84910
Cl 1.63330 5.18000 -2.70900
Cl 0.60820 4.73520 -5.82080
Cl 1.31170 1.79910 -4.47110
Cl -0.99380 3.78510 4.78060

Ti 0.18210 1.91170 4.84190
Cl -0.89080 -0.03030 4.68070
Cl 0.45630 1.83560 7.03750
Cl 2.27720 2.02830 4.28480

10.3.1.13.2. 182aa-CN-co-*trans-E*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -4639.383287
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -4639.873002
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -4639.654497

C -1.78400 -1.68179 0.66930
C -0.85300 -1.58250 -0.50270
C -1.63820 -0.36000 1.44840
H -1.12470 -0.86800 -1.28420
C 1.25360 -1.85420 -1.59360
C 0.34440 -2.23380 -0.57920
H 0.63180 -2.93710 0.20010
H 0.88740 -1.14870 -2.34480
C 5.37730 -2.61830 -1.69810
C 4.81330 -1.67090 -2.56640
C 3.44280 -1.47850 -2.56640
C 2.61880 -2.21200 -1.66800
C 3.20790 -3.18380 -0.81150
C 4.57600 -3.38370 -0.83780
H 6.45530 -2.76179 -1.69360
H 5.45020 -1.09130 -3.22810
H 2.98700 -0.74400 -3.22850
H 2.58970 -3.77930 -0.14480
H 5.03280 -4.12130 -0.18410
H -1.48620 -2.52310 1.30780
C -5.86230 -2.31670 -0.61240
C -5.21440 -3.26590 0.17700
C -3.89420 -3.05610 0.58070
C -3.21650 -1.89680 0.19600
C -3.87040 -0.94510 -0.59650
C -5.18810 -1.15540 -0.99750
H -6.89330 -2.47500 -0.91910
H -5.73630 -4.16740 0.48730
H -3.39260 -3.79210 1.20630
H -3.36270 -0.02640 -0.88940
H -5.69120 -0.40680 -1.60420

N 0.76610 0.32800 1.91670
C -0.36390 0.07680 1.75460
N -3.74620 0.79450 2.28790
C -2.75060 0.29710 1.93650
Cl 5.08350 0.62480 1.33910
Cl -4.89820 2.72610 4.17150
Ti -5.69310 1.59330 2.42890
Cl -5.40580 2.43400 0.39980
Cl -7.79310 2.41730 2.67820
Cl -6.33660 -0.52130 2.51880
Ti 2.84960 0.52140 1.64720
Cl 2.88030 -1.65960 2.10890
Cl 2.78650 2.05640 3.23130
Cl 2.37500 1.14580 -0.43660

10.3.1.13.3. 182aa-CN-co-*trans-Z*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -4639.379046
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -4639.868522
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -4639.650102

C -1.66480 -1.66990 0.50340
C -0.67070 -1.53180 -0.61530
C -1.61800 -0.34490 1.28900
H -1.00730 -0.94140 -1.46910
C 1.19179 -2.69179 0.44130
C 0.61870 -1.99150 -0.64360
H 1.21910 -1.76060 -1.51950
H 0.54480 -2.96800 1.27550
C 5.21720 -3.68740 1.09200
C 4.23830 -4.07410 2.01650
C 2.91370 -3.75470 1.77360
C 2.54890 -3.05170 0.59090
C 3.55680 -2.68880 -0.34760
C 4.87740 -3.00150 -0.08740
H 6.26140 -3.92200 1.28860
H 4.52040 -4.60580 2.92080
H 2.13990 -4.02950 2.48840
H 3.30110 -2.15980 -1.26179
H 5.65500 -2.71500 -0.78960
H -1.40460 -2.49580 1.17370
C -5.58780 -2.51440 -1.10040

C -4.96940 -3.41710 -0.23730
C -3.70410 -3.13420 0.28190
C -3.05260 -1.94740 -0.05970
C -3.68050 -1.03810 -0.92060
C -4.94210 -1.32220 -1.43840
H -6.57390 -2.73280 -1.50230
H -5.47010 -4.34220 0.03690
H -3.22450 -3.84000 0.95790
H -3.20440 -0.10000 -1.18450
H -5.42490 -0.60850 -2.10120
N 0.69179 0.51470 1.94430
C -0.39180 0.16510 1.67810
N -3.81220 0.72400 2.02310
C -2.78620 0.26680 1.70750
Cl 4.88610 1.69460 2.34440
Cl -5.05860 1.81070 4.49310
Ti -5.78730 1.37050 2.44700
Cl -5.49510 2.92110 0.89020
Cl -7.92740 1.97550 2.89710
Cl -6.33179 -0.68790 1.84250
Ti 2.72490 1.05840 2.15180
Cl 2.96380 -0.76050 3.39260
Cl 1.93760 2.92920 3.03790
Cl 2.85320 0.74560 -0.04840

10.3.1.13.4. 181aa-CN-co-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -4639.39361
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -4639.881201
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -4639.665166

C -0.79320 1.09910 -0.31240
C -0.08220 -0.03290 -0.08590
C 1.40980 -0.10370 -0.21800
C 1.82220 -1.25790 -1.10400
C 2.55600 -1.05610 -2.20610
C 3.10690 -2.07190 -3.12070
C 2.96740 -3.45340 -2.90830
C 3.52410 -4.36410 -3.80230
C 4.23080 -3.91440 -4.92260
C 4.37660 -2.54480 -5.14330
C 3.81880 -1.63290 -4.24740
C 2.01440 -0.18150 1.18610
C 1.79530 -1.28580 2.01760

C 2.38020 -1.33179 3.28360
C 3.18420 -0.27850 3.72650
C 3.39980 0.82580 2.90110
C 2.81180 0.87480 1.63660
H -0.62340 -0.92850 0.22760
H 1.77310 0.82210 -0.67930
H 1.52650 -2.25500 -0.77880
H 2.80490 -0.02640 -2.47080
H 2.42890 -3.82510 -2.03980
H 3.41140 -5.43040 -3.62380
H 4.66630 -4.62950 -5.61590
H 4.92580 -2.18460 -6.00970
H 3.93770 -0.56520 -4.42230
H 1.17680 -2.11770 1.68440
H 2.21010 -2.20490 3.92430
H 3.64220 -0.31950 4.71140
H 4.02700 1.64760 3.23750
H 2.98590 1.73340 0.99120
N 0.44360 3.25350 -1.03800
C -0.13800 2.31080 -0.71650
N -3.35680 1.25930 -0.02730
C -2.21470 1.16780 -0.15170
Cl -5.62830 -0.64000 -0.17310
Ti -5.60270 1.52870 0.21650
Cl -5.04150 2.22120 2.22850
Cl -7.79030 1.78840 0.43820
Cl -5.33660 2.92740 -1.46400
Cl 1.29220 5.79350 0.29310
Ti 1.84700 4.94420 -1.65410
Cl 0.42850 5.20150 -3.31020
Cl 3.28590 6.51010 -2.25970
Cl 3.28650 3.25270 -1.70500

10.3.1.13.5. 180aa-CN-co-*cis*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -4639.420401
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -4639.907711
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -4639.687377

C 1.11490 0.67780 1.21330
C -0.17940 0.69050 1.53070
C -1.06179 0.07100 0.46660

C -0.06500 0.08230 -0.76870
C 1.39179 0.04700 -0.13500
H -1.24930 -0.98420 0.71770
H -0.59650 1.03190 2.47490
H 1.92810 1.00580 1.85580
C -4.75790 2.02950 -0.58120
C -4.60520 0.65840 -0.79200
C -3.42040 0.02320 -0.41790
C -2.37710 0.75380 0.18030
C -2.53990 2.12690 0.37770
C -3.72590 2.76060 0.00910
H -5.67950 2.52630 -0.87360
H -5.40900 0.08270 -1.24370
H -3.31130 -1.04980 -0.57000
H -1.73610 2.70690 0.82810
H -3.84060 3.82820 0.17750
H 1.65090 -1.01380 0.00380
C 4.22150 1.92040 -2.79400
C 3.91830 0.56480 -2.93070
C 3.02870 -0.04310 -2.04420
C 2.42910 0.70050 -1.02170
C 2.74050 2.05790 -0.88700
C 3.63520 2.66400 -1.76870
H 4.91460 2.39520 -3.48370
H 4.37770 -0.01930 -3.72430
H 2.80600 -1.10470 -2.14290
H 2.27970 2.64760 -0.09670
H 3.86910 3.71970 -1.65800
N -0.33710 2.34130 -2.06870
C -0.23170 1.33440 -1.52430
N -0.44270 -1.92910 -2.39740
C -0.28920 -1.03190 -1.69290
Cl -1.76470 -2.28500 -5.04050
Cl -2.53340 3.90940 -3.31680
Ti -0.61360 -3.70610 -3.82670
Cl 1.58720 -3.54030 -3.82170
Cl -0.75000 -5.43180 -5.20380
Cl -1.61680 -4.64250 -2.10320
Ti -0.43770 4.43490 -2.93120
Cl 0.14310 4.97510 -0.86760
Cl -0.50650 6.50650 -3.72940
Cl 1.10680 3.66570 -4.29370

10.3.1.13.6. TS$_{mig}$aa-CN-co-trans-E

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) = -4639.359447
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -4639.84665
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) = -4639.631688

C -0.07750 -0.87150 0.66610
C 0.97520 -1.26340 1.55640
C -0.71220 0.46700 0.79810
H 1.46390 -0.47430 2.12670
C 2.11560 -2.81750 3.00720
C 1.21020 -2.61440 2.02450
H 0.59170 -3.41280 1.61940
H 2.68560 -1.95460 3.35770
C 3.01770 -6.40600 5.12490
C 3.60810 -5.19510 5.48880
C 3.30690 -4.03610 4.77660
C 2.40830 -4.07230 3.69690
C 1.81910 -5.29860 3.33870
C 2.12560 -6.45490 4.04750
H 4.29950 -5.15260 6.32620
H 3.76700 -3.09070 5.05920
H 1.12130 -5.35480 2.50660
H 1.66780 -7.39880 3.76400
H -0.70890 -1.66720 0.26660
C 3.36350 -0.71080 -2.04920
C 3.10180 0.38650 -1.21870
C 2.09490 0.30190 -0.27179
C 1.34830 -0.89280 -0.14390
C 1.61700 -1.99380 -0.98860
C 2.61960 -1.89370 -1.93910
H 4.15260 -0.64100 -2.79450
H 3.68080 1.30090 -1.31590
H 1.87680 1.15700 0.36530
H 1.03350 -2.90860 -0.89920
H 2.82610 -2.72970 -2.60070
H 3.25000 -7.31230 5.67840
N -1.65420 1.30200 -1.40690
C -1.26320 1.00790 -0.34860
Cl -3.28190 0.83000 -4.89030
N -0.32000 1.73700 2.96960
C -0.55200 1.20230 1.95860
Cl -0.98900 2.186206.08100

Ti -1.85630 1.67500 -3.42860
Cl -3.29110 3.26520 -2.67520
Cl -0.46280 3.05180 -4.41350
Cl -0.47100 -0.15430 -3.50230
Ti 0.56850 2.65900 4.64430
Cl 1.95230 0.85720 4.46040
Cl 2.06380 3.74570 5.91800
Cl -0.02130 4.53080 3.56170

10.3.1.13.7. TS_{mig}aa-CN-co-trans-Z

$E(M06-2X/6-31+G(d)(CH_2Cl_2)) =$
-4639.360728
$E(M06-2X/6-311+G(d,p)(CH_2Cl_2)) =$
-4639.848665
$G(M06-2X/6-311+G(d,p)(CH_2Cl_2)) =$
-4639.63353

C -2.39950 -0.62740 8.69670
C -1.43750 -1.56910 9.40110
C -2.70370 -1.10060 7.27890
H -3.34580 -0.67810 9.26460
H -0.81360 -1.13790 10.18170
C -1.15450 3.53730 8.95190
C -1.53620 3.00170 7.72450
C -1.92680 1.66310 7.63080
C -1.93010 0.83730 8.75870
C -1.56030 1.390209.99320
C -1.17490 2.72620 10.08950
H -0.85310 4.57910 9.02610
H -1.54080 3.62310 6.83190
H -2.23500 1.28440 6.66080
H -1.59100 0.78470 10.89750
H -0.89620 3.13730 11.05640
C -2.01500 -3.61970 8.13710
C -1.22330 -2.86260 9.08300
H -0.37540 -3.37190 9.54260
H -3.10030 -3.55870 8.22420
C -0.55440 -6.20210 5.17910
C -1.93820 -6.10470 5.39400
C -2.41260 -5.26710 6.38720
C -1.50070 -4.51660 7.18590
C -0.09790 -4.64170 6.95850
C 0.36240 -5.47970 5.96240
H -0.18240 -6.85150 4.38910

H -2.62600 -6.67820 4.77910
H -3.48190 -5.17120 6.56740
H 0.60520 -4.07240 7.56080
H 1.42780 -5.57660 5.77460
N -0.75520 -1.44179 5.65770
C -1.65500 -1.27610 6.37690
Cl 0.35940 -3.05880 3.40660
Ti 1.05660 -1.27960 4.50680
Cl 0.26860 0.68720 3.86010
Cl 3.00740 -1.07179 3.40360
Cl 2.02280 -1.57270 6.49350
N -5.05880 -1.02540 6.31130
C -3.97330 -1.05520 6.74690
Cl -8.18030 -2.35910 5.79240
Ti -6.90090 -0.60470 5.47840
Cl -7.16880 0.46680 7.47720
Cl -8.13100 0.93040 4.40930
Cl -5.80270 -1.17050 3.56960

10.3.2. Rearrangement of DACPs

10.3.2.1. $R^1 = R^2 = Ph$

10.3.2.1.1. 193aa-co-trans-TiCl₄

$E(M06-2X/6-31+G(d)(CH_2Cl_2))=$
-2934.317836
$E(M06-2X/6-311+G(d,p)(CH_2Cl_2)) =$
-2934.726094
$G(M06-2X/6-311+G(d,p)(CH_2Cl_2)) =$
-2934.4454

C -1.02610 -0.39120 -0.18330
C 0.39850 -0.50340 0.17810
C -0.22110 0.92490 0.10970
H 1.06540 -0.64830 -0.67070
C 0.18130 1.77179 -1.05050
O 0.63870 1.11650 -2.06930
O 0.04810 3.00210 -1.09550
C 0.96420 1.87190 -3.26310
C -0.54980 1.64670 1.36410
O -0.90150 0.88520 2.35750
O -0.50420 2.87660 1.49930
C -1.23990 1.52410 3.61500
H -1.49570 0.70510 4.28420
H -0.37570 2.07990 3.98250

H -2.09050 2.19150 3.46560
H 1.31030 1.12850 -3.97830
H 0.06890 2.38140 -3.62390
H 1.74990 2.59340 -3.03340
H -1.72340 -0.56800 0.65450
C -2.68190 -1.14980 -4.05230
C -3.25840 -0.19370 -3.21230
C -2.71210 0.04640 -1.95240
C -1.58130 -0.66080 -1.52810
C -1.00980 -1.62020 -2.36720
C -1.56130 -1.86480 -3.62650
H -3.10850 -1.33920 -5.03420
H -4.13390 0.36250 -3.53730
H -3.18070 0.78850 -1.29480
H -0.13680 -2.18200 -2.04020
H -1.11510 -2.61500 -4.27450
Ti -0.58080 4.50740 0.20750
Cl -0.57360 5.98120 -1.48820
Cl -1.27470 5.82530 1.89110
Cl 1.65960 4.72240 0.68280
Cl -2.70510 3.68620 -0.26980
C 1.96750 -2.12110 3.83320
C 2.64820 -1.10180 3.18140
C 2.12720 -0.57970 1.97960
C 0.91980 -1.06460 1.46500
C 0.24530 -2.08830 2.13330
C 0.76960 -2.61570 3.31500
H 2.37310 -2.53179 4.75460
H 3.58450 -0.71670 3.55840
H 2.66070 0.21070 1.45310
H -0.68900 -2.47830 1.73330
H 0.24170 -3.41430 3.83010

10.3.2.1.2. 193aa-co-*cis*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-2934.310038
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2934.718001
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2934.438329

C -0.83050 -0.62410 0.34100
C 0.63450 -0.70000 0.52330
C 0.02850 0.70440 0.26360
H -1.12980 -0.89710 -0.66870
H 1.13870 -1.04400 -0.38020

C -4.23660 -1.19860 2.91240
C -2.95780 -1.36260 3.44730
C -1.82790 -1.16580 2.65390
C -1.96250 -0.80950 1.30630
C -3.25220 -0.65680 0.77570
C -4.38210 -0.84200 1.57110
H -5.11380 -1.35230 3.53600
H -2.83580 -1.64500 4.49000
H -0.84400 -1.28210 3.09240
H 3.37370 -0.39510 -0.27430
H -5.37230 -0.71530 1.14110
C 0.23890 1.26960 -1.09680
O 0.23750 0.38100 -2.05280
O 0.40700 2.46560 -1.35790
C 0.46060 0.84880 -3.40970
C -0.08870 1.68800 1.36600
O -0.28150 1.17640 2.54260
O -0.02550 2.91650 1.22010
C -0.38150 2.07940 3.67230
H -0.52040 1.43090 4.53570
H 0.54150 2.65640 3.75660
H -1.23800 2.74170 3.53590
H 0.42780 -0.04970 -4.02280
H -0.33220 1.54540 -3.68760
H 1.43660 1.33320 -3.46830
Ti 0.55950 4.24200 -0.26530
Cl 1.20830 5.32700 -2.12440
Cl 0.63260 5.91840 1.22740
Cl 2.69010 3.44810 0.23650
Cl -1.69440 4.43000 -0.68620
C 3.00510 -1.88810 3.90280
C 3.14500 -0.59930 3.38340
C 2.35500 -0.18910 2.30940
C 1.41100 -1.05820 1.75600
C 1.28670 -2.35470 2.26670
C 2.07840 -2.76730 3.33900
H 3.62260 -2.20840 4.73810
H 3.87360 0.08570 3.80960
H 2.48190 0.81100 1.89690
H 0.56910 -3.04260 1.82260
H 1.97200 -3.77580 3.73090

10.3.2.1.3. 194aa-co-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-2934.314258

E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2934.723194
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2934.440793

C -0.48780 1.26600 -0.03830
C 0.20370 0.24260 0.51150
C 1.68430 0.01570 0.61720
C -1.96790 1.26280 0.07320
C 0.11070 2.47190 -0.65870
O 1.27720 2.30250 -1.21290
O -0.44530 3.57630 -0.67950
C 1.90770 3.47010 -1.80580
O 2.66280 2.28640 0.05860
O -2.51010 0.08640 0.20880
C -3.94580 0.03020 0.41860
C 2.08980 -0.28070 2.06060
C 3.24070 -1.03070 2.32970
C 3.65750 -1.23960 3.64380
C 2.92650 -0.70580 4.70770
C 1.77940 0.04290 4.44780
C 1.36690 0.25700 3.13070
H -0.39960 -0.54580 0.96470
H 2.23530 0.89810 0.28310
H 2.87130 3.11510 -2.16640
H 1.28830 3.83450 -2.62680
H 2.03180 4.24170 -1.04420
H -4.16970 -1.02900 0.52990
H -4.20010 0.58560 1.32290
H 4.45370 0.45330 -0.44930
H 3.81580 -1.45420 1.50920
H 4.55480 -1.82220 3.83780
H 3.25080 -0.87240 5.73170
H 1.20490 0.46580 5.26820
H 0.47820 0.85870 2.94630
Ti -2.20070 4.32750 0.20210
Cl -1.31820 6.39020 0.21780
Cl -4.18800 4.71570 1.16900
Cl -1.16620 3.69610 2.20000
Cl -2.97180 4.43730 -1.94600
C 2.47180 -3.18080 -2.19390
C 2.93179 -1.88940 -2.45260
C 2.68200 -0.86240 -1.53980
C 1.98100 -1.12240 -0.35970
C 1.52400 -2.42150 -0.10250
C 1.76800 -3.44540 -1.01790

H 2.66290 -3.98010 -2.90560
H 3.48570 -1.67920 -3.36410
H 3.04320 0.14370 -1.74110
H 0.99170 -2.64020 0.82250
H 1.41190 -4.45130 -0.80750

10.3.2.1.4. 233aa-co-*trans*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-2934.283797
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2934.69098
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2934.412401

C 0.07740 -0.56870 -0.09890
C 0.74150 -1.90890 -0.22770
C 0.25040 0.56590 -0.81480
H 1.59910 -1.85350 -0.90020
C 1.28190 0.77600 -1.85980
O 2.37530 0.07960 -1.72460
O 1.15260 1.57130 -2.79770
C 3.39880 0.24270 -2.74280
C -0.72360 1.67150 -0.63360
O -1.34270 1.68330 0.51310
O -0.96310 2.52840 -1.49310
C -2.36630 2.69400 0.70850
H -2.75460 2.50790 1.70800
H -1.91280 3.68390 0.63930
H -3.14350 2.57230 -0.04790
H 4.18680 -0.45330 -2.46150
H 2.98270 -0.00410 -3.72100
H 3.75710 1.27320 -2.72710
Ti 0.47740 2.68290 -3.52980
Cl 0.38370 2.59650 -5.60240
Cl -2.37330 3.82690 -3.90420
Cl 0.74980 4.50100 -2.86800
Cl -1.50150 0.60010 -3.69130
H -0.74260 -0.55400 0.62090
C 2.20179 -3.41470 3.56470
C 1.94340 -4.28920 2.50550
C 1.45510 -3.80010 1.29560
C 1.22179 -2.43000 1.12420
C 1.49250 -1.56000 2.18430
C 1.97560 -2.04910 3.40100
H 2.57670 -3.79790 4.51030
H 2.11980 -5.35570 2.62320

H 1.24910 -4.48860 0.47880
H 1.33730 -0.48820 2.07100
H 2.17630 -1.35870 4.21660
C -2.28090 -4.33090 -2.16920
C -1.20010 -3.83350 -2.89740
C -0.22670 -3.06140 -2.26170
C -0.32120 -2.78890 -0.89440
C -1.41170 -3.28390 -0.16880
C -2.38590 -4.05290 -0.80390
H -3.03880 -4.93460 -2.66250
H -1.11130 -4.04650 -3.95970
H 0.61570 -2.67780 -2.83490
H -1.49270 -3.08450 0.89880
H -3.22560 -4.44000 -0.23180

10.3.2.1.5. 233aa-co-*cis*-TiCl$_4$

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-2934.279397
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2934.686953
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2934.406109

C -2.76490 0.52450 8.32780
C -1.59650 -0.36350 8.12050
C -1.55750 1.14450 7.60890
H -3.54880 0.32660 7.59820
H -1.71179 -1.02410 7.26260
C -0.58590 2.04150 8.28179
O -0.72950 2.15460 9.56720
O 0.32650 2.64100 7.69900
C -1.64370 1.29550 6.13140
O -2.63860 0.66040 5.57700
C 0.26450 2.92220 10.29340
H -0.03810 2.85680 11.33710
H 1.24890 2.47630 10.13880
H 0.25130 3.95620 9.94540
C -2.73890 0.70320 4.12880
H -3.60550 0.08920 3.89230
H -2.88590 1.73580 3.80870
H -1.82870 0.29020 3.69060
O -0.84790 1.93900 5.43760
Ti 1.08010 2.68060 5.75460
Cl 0.06890 4.74220 5.64340
Cl 3.04620 3.45020 6.52050
Cl 1.58280 0.45040 6.17930

Cl 1.51450 2.55680 3.55030
C 1.33430 -2.09220 10.75830
C 1.26040 -2.44230 9.40940
C 0.29990 -1.85430 8.59000
C -0.59900 -0.90260 9.09690
C -0.52080 -0.56330 10.45530
C 0.43920 -1.15560 11.27610
H 2.07930 -2.55179 11.40290
H 1.94780 -3.17460 8.99400
H 0.24440 -2.13780 7.54120
H -1.20770 0.15650 10.88230
H 0.48060 -0.88560 12.32840
C -4.71240 1.76220 11.95060
C -4.33130 2.72120 11.00930
C -3.65970 2.33510 9.84990
C -3.35400 0.98990 9.62680
C -3.74990 0.03130 10.56420
C -4.42370 0.41550 11.72420
H -5.23940 2.06290 12.85250
H -4.56180 3.77060 11.17490
H -3.37260 3.08600 9.11820
H -3.53020 -1.01950 10.38450
H -4.72490 -0.33840 12.44730

10.3.2.1.6. TS$_{migDACP}$aa-co-*trans*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-2934.283848
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2934.691136
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2934.409884

C -0.38310 -1.17570 -0.39350
C 0.42420 -2.35390 -0.43360
C -0.26020 -0.03700 -1.31670
H 1.01800 -2.51690 -1.32880
C 0.94680 0.33810 -1.95520
O 2.01100 -0.42370 -1.75070
O 1.08240 1.34720 -2.70090
C 3.25270 -0.00050 -2.35450
C -1.40080 0.78910 -1.50060
O -2.49570 0.39130 -0.87320
O -1.46110 1.83150 -2.20570
C -3.66880 1.22380 -0.99420
H -4.43220 0.72510 -0.39930
H -3.46020 2.22030 -0.60070

H -3.97240 1.28880 -2.04020
H 3.98250 -0.74970 -2.05150
H 3.14970 0.02560 -3.44080
H 3.53070 0.98630 -1.97990
Ti -0.07590 2.91190 -3.20420
Cl 1.70980 3.89990 -4.22840
Cl -1.64180 4.53520 -3.57770
Cl 0.49600 3.79680 -1.10179
Cl -0.67700 1.69830 -5.09870
H -0.85530 -0.94179 0.56070
C 1.69450 -4.74680 2.87320
C 1.07780 -3.51800 3.11970
C 0.64840 -2.72240 2.05790
C 0.83410 -3.17900 0.73960
C 1.46600 -4.38850 0.49710
C 1.89190 -5.18070 1.55980
H 2.03090 -5.36120 3.70460
H 0.94100 -3.17230 4.14080
H 0.19650 -1.75510 2.26670
H 1.62040 -4.72290 -0.52790
H 2.38090 -6.13180 1.36550
C -3.26110 -4.11380 -1.92180
C -2.35080 -3.53810 -2.81840
C -1.32930 -2.73720 -2.33550
C -1.19860 -2.52410 -0.94390
C -2.11690 -3.11840 -0.04840
C -3.15050 -3.89770 -0.54130
H -4.06660 -4.73710 -2.30340
H -2.44760 -3.71370 -3.88610
H -0.62540 -2.27190 -3.02290
H -2.01910 -2.95220 1.02280
H -3.86720 -4.34590 0.14100

10.3.2.1.7. TS$_{migDACP}$aa-co-*cis*

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-2934.272111
E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2934.679792
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2934.399419

C 0.44179 -1.280100.07540
C 1.67940 -2.03900 0.17570
C 0.32040 0.14700 0.48700
H 1.75900 -2.88050 -0.51340
C 0.93390 1.15530 -0.29530

O 1.37110 0.78570 -1.49260
O 1.04780 2.36900 0.03020
C 2.01410 1.79510 -2.30000
C -0.58050 0.59820 1.47200
O -1.43370 -0.28830 1.96880
O -0.64050 1.78500 1.91490
C -2.28460 0.15080 3.04810
H -2.85420 -0.73140 3.33640
H -1.67620 0.51200 3.88010
H -2.94970 0.94350 2.70130
H 2.36330 1.26960 -3.18830
H 1.29280 2.56970 -2.56670
H 2.84980 2.23940 -1.75420
Ti 0.66190 3.29580 1.77940
Cl 2.30150 4.83700 1.30600
Cl 0.00550 4.08450 3.83940
Cl 2.21960 1.82760 2.75550
Cl -0.97620 4.52050 0.67310
H -0.26080 -1.64930 -0.67320
C -0.43900 -3.88780 3.41510
C 0.24370 -2.68850 3.66390
C 0.70640 -1.93500 2.60250
C 0.50850 -2.38310 1.26340
C -0.19350 -3.60600 1.03810
C -0.66070 -4.34680 2.10590
H -0.80690 -4.47450 4.25480
H 0.40330 -2.35070 4.68410
H 1.23040 -0.99660 2.77670
H -0.35280 -3.94840 0.01540
H -1.19300 -5.27860 1.93890
C 5.49340 -0.64840 1.64020
C 4.81760 -1.66460 2.31800
C 3.58230 -2.11490 1.85600
C 2.99540 -1.54630 0.72040
C 3.69670 -0.55630 0.02400
C 4.93550 -0.10770 0.48400
H 6.45130 -0.28870 2.00700
H 5.25080 -2.10690 3.21140
H 3.07350 -2.91390 2.39070
H 3.28630 -0.15210 -0.89270
H 5.45980 0.67130 -0.06370

10.3.2.1.8. TS$_{isomDACP}$aa-co

E(M06-2X/6-31+G(d)(CH$_2$Cl$_2$)) =
-2934.27407

E(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2934.681195
G(M06-2X/6-311+G(d,p)(CH$_2$Cl$_2$)) =
-2934.401592

C -1.34140 -0.19900 8.52830
C -0.19830 -1.08990 8.89650
C -0.89430 0.87570 7.55790
H -2.05630 -0.83440 7.98670
H 0.80750 -0.69250 8.74800
C 0.01650 1.87100 7.96540
O 0.46040 1.76420 9.21180
O 0.43970 2.83510 7.26350
C -1.44060 0.97440 6.26290
O -2.38930 0.10230 5.94030
C 1.37250 2.77750 9.68240
H 1.60720 2.49480 10.70770
H 2.27260 2.78690 9.06500
H 0.88780 3.75520 9.65320
C -2.95150 0.19340 4.61480
H -3.68590 -0.60940 4.56370
H -3.43120 1.18330 4.47790
H -2.16970 0.05300 3.86620
O -1.11380 1.83480 5.39280
Ti 0.31800 3.22890 5.30590
Cl -1.30340 4.81930 5.80240
Cl 2.03790 4.73860 5.51110
Cl 1.82340 1.42720 5.02540
Cl -0.01480 3.41530 3.03810
C -0.35540 -4.96370 10.43510
C 0.88890 -4.36500 10.18520
C 0.92920 -3.08640 9.66280
C -0.28950 -2.38750 9.38540
C -1.54670 -3.02550 9.64370
C -1.57010 -4.29910 10.16650
H -0.38570 -5.97110 10.84590
H 1.80620 -4.90470 10.40050
H 1.88080 -2.59720 9.45960
H -2.47800 -2.50450 9.43390
H -2.51470 -4.79490 10.37150
C -3.64100 1.41130 11.84130
C -2.43750 0.76000 12.10790
C -1.67750 0.22930 11.06210
C -2.11790 0.34770 9.74350
C -3.32320 1.00750 9.47890

C -4.08220 1.53540 10.52140
H -4.23190 1.82370 12.65520
H -2.08070 0.66830 13.13080
H -0.73420 -0.26140 11.29230
H -3.66880 1.11010 8.45170
H -5.01910 2.04200 10.3027

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