"Human–Landscape Interactions during the Early and High Medieval Period in Central Spain Based on New Estimates of Sediment Yield from the Melque Agricultural Complex"

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ABSTRACT

An agrosilvopastoral system and millennium of human occupation make Santa Maria de Melque an important archaeological site in Europe. Previous archaeological work mainly focused on ceramics and wooden structural elements of a church and anthracological, palynological, and paleocarpological analyses of sediments around a rural monastery. In this paper, we extend the geoarchaeological work to dams that were constructed nearby, applying innovative techniques such as optically stimulated luminescence (OSL) dating and seismic refraction to help understand human–landscape interactions. Our OSL dating of dams and reservoir sediments provide a first detailed chronological framework for historical water storage in Central Spain. In Melque, the four dams were built consecutively during phases of Christian occupation, thereby assuring water availability to support agrosilvopastoral activities. The maximum splendor of the rural complex occurred during Phase III (Christian occupation, 12th–16th centuries A.D.). Dam construction was an integral part of the agricultural production system, and the reservoirs were effective as water harvesting systems in support of irrigated agriculture from the 7th to 16th centuries A.D. during the Early and High Medieval occupation of the site. Copyright © 2016 Wiley Periodicals, Inc.

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Human–Landscape Interactions during the Early and High Medieval Period in Central Spain Based on New Estimates of Sediment Yield from the Melque Agricultural Complex

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An agrosilvopastoral system and millennium of human occupation make Santa María de Melque an important archaeological site in Europe. Previous archaeological work mainly focused on ceramics and wooden structural elements of a church and anthropological, palynological, and paleocarpological analyses of sediments around a rural monastery. In this paper, we extend the geoarchaeological work to dams that were constructed nearby, applying innovative techniques such as optically stimulated luminescence (OSL) dating and seismic refraction to help understand human–landscape interactions. Our OSL dating of dams and reservoir sediments provide a first detailed chronological framework for historical water storage in Central Spain. In Melque, the four dams were built consecutively during phases of Christian occupation, thereby assuring water availability to support agrosilvopastoral activities. The maximum splendor of the rural complex occurred during Phase III (Christian occupation, 12th–16th centuries A.D.). Dam construction was an integral part of the agricultural production system, and the reservoirs were effective as water harvesting systems in support of irrigated agriculture from the 7th to 16th centuries A.D. during the Early and High Medieval occupation of the site. © 2016 Wiley Periodicals, Inc.

INTRODUCTION

Human–landscape interactions of the past can provide new insights into the environmental vulnerability of present human activities. Human societies evolved in a changing landscape, where human activities impacted environmental systems but might also have been affected by environmental change (Vanacker et al., 2001; Chin et al., 2013). While there is plenty of qualitative and semiquantitative data that exemplify how human activities sculpted the landscape (Hooke, 2000; Boix-Fayos et al., 2007; Wollwage et al. 2012; Woodson et al., 2015), more quantitative data are needed to fully grasp the complexity of human–landscape interactions. The latter strongly hinges on precise and accurate dating of human occupation phases and high-resolution records of environmental change (Bellin et al., 2013).

Human occupation of archaeological sites can be dated by relative or numerical methods based on artifacts, architecture, and/or stratigraphic records. Numerical ages are often obtained from radiocarbon dating of organic materials embedded in sedimentary deposits or of those that were used for construction (Beeton & Mandel, 2011; Broothaerts et al., 2013). For example, wood beams employed in the construction of a ceiling can provide information on the age of construction. However, renovation or refurbishment of that ceiling can produce erroneous ages that are younger than expected. Optically stimulated luminescence (OSL) dating gives information on the age of the last daylight exposure of mineral grains before burial (Aitken, 1998). It offers the potential to date inorganic sediments accurately and precisely. Quartz-rich sediments in lacustrine and low energy fluvial systems (Fiebig et al., 2009; Rhodes, 2011) can be very suitable...
Human–Landscape Interactions in Medieval Central Spain

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Figure 1  Topographic map of the study area based on 30-m elevation data facilitated by IGNE (Instituto Geográfico Nacional de España). The four dams are identified as M1, M2, M3, and M4, corresponding to information in Tables I and III. The two ephemeral streams (Melque and Zorras) that drain the area that includes the dams are drawn in blue.

for OSL dating. Recently, OSL has been used to date lime mortars used in historical constructions (Goedicke, 2003, 2011; Beeton & Mandel, 2011; Stella et al., 2013; Kraushaar et al., 2015; Urbanova et al., 2015), and has great potential for geoarchaeological studies (Woodward et al., 2001).

To unravel past human–landscape interactions, it is important to extend geoarchaeological analyses to a wide geographic area beyond archaeological site boundaries. A broader survey may include natural or artificial lakes (reservoirs) that are of great interest for environmental reconstructions (e.g., Battarbee et al., 2001; Pelle et al., 2013; Vanacker et al., 2014). The mineralogy and geochemistry of lake and reservoir deposits can provide information on past environmental changes (Foucher et al., 2014). Geophysical methods, such as seismic reflection and refraction, have proven to be effective in determining the volume of hillslope and lake deposits, allowing one to reconstruct past erosion and deposition rates (Leopold et al., 2008). When applying these techniques to reservoirs used for water storage and irrigation, it becomes possible to reconstruct agricultural land use and link high-resolution land use data with environmental proxies. Reservoirs are of particular interest as they can provide us with insights into changing water availability for humans, livestock, and cropland, as well as erosion and degradation processes during phases of land occupation or abandonment.

In this study, we illustrate this concept using new data on the agricultural features at Santa Maria de Melque in Central Spain. This archaeological complex is one of the most significant Early Medieval sites in Spain with human occupation lasting more than 1000 years (Caballero, 1994, 1995; Figure 1).

ARCHAEOLOGICAL COMPLEX

The archaeological complex of Santa Maria de Melque is located in the municipality of San Martin de Montalban, in the Spanish province of Toledo (Figure 1). It is situated 30 km south of the city of Toledo on the left bank of the Tagus River, one of the largest rivers in Spain with a mean annual discharge of $10 \times 10^3$ m$^3$ (1940–2006, CHT, 2015). The area is underlain by Palaeozoic granitic rocks, and soils are typically very shallow having a high permeability and low water holding capacity. Dystric Cambisols are found on the hillslopes, Leptosols at the ridge crests, and young and little evolved Fluvisols in the valley bottoms (Nieves & Gómez-Miguel, 1992). At an altitude of 565 m above sea level, the climate is meso-Mediterranean with an annual average temperature of 15°C and mean annual precipitation of 387 mm. The natural vegetation is Mediterranean oak forest (*Quercus ilex rotundifolia*), but only a few remnants of forest have been spared from intense anthropogenic disturbance (Monje, 1988). Today,
most of the area (55%) is occupied by cropland, and used for the production of cereals or devoted to vineyards and orchards (olive, fruit, and almond orchards). On less productive land, the so-called *dehesas* are prominent, which are seminatural agrosilvopastoral systems (Martin & Pastor, 1984).

The archaeological complex of Melque is surrounded by a stone embankment that is 0.7 m wide and 1 m in height, enclosing an area of approximately 25 ha (Caballero, 2006; Figure 2). The circular embankment is assumed not to have had a defensive military purpose, but instead marked property and protected crops and livestock (Caballero & Murillo, 2005). The icon of the archaeological site is the church that is now restored (Figure 3c). During archaeological excavations, Caballero and Meier (1999) also discovered a monastery (0.8 ha), village (4.5 ha), and irrigated terraces (10 ha). The monastery is located on an elevated plateau, surrounded by two seasonal streams: “Melque” to the west and “Zorras” to the east (Figure 1). On each stream, there is a pair of human-constructed dams that blocked seasonal runoff and created shallow reservoirs. The stone embankment surrounding the site crosses the two most upstream dams. All four reservoirs are (now) fully silted. Siltation at Melque 3 and 4 has diverted the “Zorras” stream east of its original course (Figure 2).

The church of the archaeological complex was discovered in 1907, and two extensive archaeological excavations were conducted in 1970–1973, and 1994–2002, including various archaeobotanical studies (Arnanz, 1999; Maicas & López, 1999; Uzquiano, 1999). The church is estimated to date from A.D. 680 to 773 (Rubinos-Pérez, 1999), and can either be Visigothic (second half of seventh century; Caballero & Latorre, 1980, 1982), or Mozarabic (second half of eighth century; Garen, 1992; Caballero, 1994, 1995). Archaeological surveys indicated that Melque was not only an early medieval monastery (phase I: 7–8th to 9th century), but also a rural complex. The agricultural complex became an Islamic town during phase II (9–10th to 11th century), and later a Christian town and fort until the modern and contemporary era (phase III: from 11th century onwards; Caballero & Meier, 1999).

**MATERIAL AND METHODS**

**Reservoir Sedimentation Record**

Seismic refraction is a non-invasive method that is here applied to reconstruct the original topography of the valley bottom before construction of the dams (so-called predisturbance valley morphology). Distinguishing the present surface topography from the predisturbance surface then allows quantification of the amount of sediment accumulated in the reservoirs. First, arrivals of the seismic signals are inverted to get an image of the P-wave...
velocity distribution under the surface. Contrasts in the velocity of refracted seismic waves are used to identify the interface between young sedimentary deposits, soils, weathered bedrock or saprolite, and fresh bedrock. Seismic refraction waves were measured using a 24-channel digital seismograph SmartSeis model (Geometrics) and vertical geophones SM-4U (Sensor Nederland) with a natural frequency of 10 Hz. Twenty-four geophones were spaced at intervals of 3 m. Seismic signals were generated by impact of an 8 kg mace on a metallic plate. The seismic records were processed in Firstpix (Interpex) and Rayfract (Intelligent Resources) software using the tomogetic Delta-t-V method, which combines elements from CMP intercept time refraction (Gebrande & Miller, 1985), Plus-Minus (Hagedoorn, 1959), and Wavefront methods (Brückl, 1987).

**Dating of Dams and Reservoir Sediments**

To better constrain human occupation phases of the archaeological site, all reservoir dams and sedimentary sequences were dated using OSL. This technique provides the time elapsed since the last exposure to sunlight of mineral grains (Aitken, 1998), and is applicable to mineral grains shielded from daylight, such as minerals buried in sediments or within lime mortars (Aitken, 1998; Goedicke, 2003). Samples were taken from mortar used in dam construction and sedimentary sequences about 1 m upslope of the dam. When clear differences in texture or color of the mortars were observed, several independent samples of mortar were measured to discard possible reworking of the dam walls. For mortar dating, the 2 mm outer layer of each mortar sample was removed under subdued red light and the central part was used for luminescence. The samples were gently crushed in a vice, dried, and sieved. Sand grains within the range 90–180 μm were extracted by sieving. For one sample, the 180–250 μm fraction was used due to the limited amount of smaller grains. Pure quartz extracts were obtained following a coarse grain extraction procedure (Aitken, 1985, 1998). For each of the sedimentary deposits, samples were taken at the top and/or bottom of the sedimentary sequence (Table I). The upper sample was taken at 20 cm depth to avoid bias on the OSL signals from bioturbation and concurrent partial bleaching of the sediment after deposition. To collect sediment samples, 30-cm long horizontal steel cores were introduced horizontally in the profile wall, by hammering on the top of the steel cores. The sediment cores were opened inside a laboratory under subdued red light, and only material from the central part of the core was sampled for luminescence analyses. All samples were dried, and sand grains of 90–180 μm diameter were extracted by sieving. Similarly, the extraction procedure described by Aitken (1985, 1998) was used to obtain pure quartz extracts.
An OSL single-aliquot regenerative dose (SAR) protocol was used to estimate the equivalent dose of quartz grains (Murray & Wintle, 2000). All measurements were made on an automated Risø TL/OSL-DA-15 reader equipped with an EMI 9635 QA photomultiplier tube, and using an internal 90Sr/89Y source that provides 0.130 ± 0.003 Gy/s. A small amount of sample grains (< 100 grains) were mounted on stainless steel discs using silicone spray. The OSL was stimulated with blue light emitting diodes (LEDs) and signal measurements were carried out with an optical Hoya U-340 filter. Aliquots were first bleached twice in the OSL reader (for 200 seconds in blue light at room temperature) and a known beta dose was given that approximately equals the natural dose prior to the SAR. The measurements were performed for 40 seconds for the samples that were heated to 125°C. The preheat temperature was set after preheat temperature tests were completed for all samples. Recovery tests were carried out for all samples.

Additionally, to estimate the dose rate, the uranium and thorium content of the sediments was determined by inductive coupled plasma mass spectrometry (ICP-MS), while the potassium content was determined with X-ray fluorescence (XRF). Conversion factors published in Guerin et al. (2011) were used to estimate annual dose rates. The external gamma dose of the mortar samples was calculated using a geometric model approach based on Guibert et al. (1998). Feathers et al. (2008) have shown that this method provides similar results to dose rates estimated from dosimeters (TLDs).

**Reconstruction of Water Storage Capacity**

Based on the seismic profiles and OSL ages of the sedimentary sequence and dams, we can reconstruct the temporal evolution of the potential water storage capacity of the reservoirs. The original reservoir capacity is remodeled based on data collected during the geophysical and topographic surveys. First, the area of sedimentation behind each dam (Figures 2 and 3) was delimited using differential GPS (12 Channels Pathfinder PRO XRS), and a 3D topographic model of the surface topography was created. Second, the depth of sedimentation was derived from the sedimentation profiles (Figure 4) and cross-checked by manual augering. The depth information from the longitudinal and transversal seismic resection profiles was then interpolated on a regular grid with 1 m horizontal resolution using kriging interpolation techniques in order to obtain a 3D model of the predisturbance valley morphology (Johnson & Wichern, 1992). Third, the volume of sediment was calculated based on the predisturbance and modern surface topography using 3D surface differencing techniques in Surfer 10 software (Golden Software Surfer 10. (2011)).

The average erosion rate of the catchments draining to the four man-made dams was obtained from the sedimentation data as following:

\[
E = \frac{1}{t - t_0} \int_{t_0}^t \frac{V(t) \, dt}{A \times E(t) \, dt} \times 10^3,
\]

where \(E\) (mm/yr) is the average erosion rate over the time period of sedimentation \((t - t_0)\), \(t\) and \(t_0\) are the

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**Table 1** Ages for the Melque dams and reservoir deposits based on single-aliquot regenerative dose optically stimulated luminescence.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sample Type</th>
<th>Depth (m)</th>
<th>Annual Dose (Gy/ky)</th>
<th>(n)</th>
<th>Equivalent Dose (Gy)</th>
<th>Time(yr)</th>
<th>Age (AD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melque 1</td>
<td>M</td>
<td>0.20</td>
<td>3.58 ± 0.37</td>
<td>34</td>
<td>3.34 ± 0.21</td>
<td>933 ± 113</td>
<td>1078 ± 113</td>
</tr>
<tr>
<td>M1-2</td>
<td>S</td>
<td></td>
<td>6.83 ± 0.32</td>
<td>44</td>
<td>3.91 ± 0.21</td>
<td>572 ± 41</td>
<td>1439 ± 41</td>
</tr>
<tr>
<td>M2-1</td>
<td>M</td>
<td></td>
<td>3.76 ± 0.19</td>
<td>32</td>
<td>2.34 ± 0.08</td>
<td>622 ± 38</td>
<td>1389 ± 38</td>
</tr>
<tr>
<td>M2-2</td>
<td>M</td>
<td></td>
<td>3.71 ± 0.28</td>
<td>38</td>
<td>2.59 ± 0.13</td>
<td>698 ± 63</td>
<td>1313 ± 63</td>
</tr>
<tr>
<td>M2-3</td>
<td>S</td>
<td>0.20</td>
<td>6.48 ± 0.44</td>
<td>42</td>
<td>1.46 ± 0.11</td>
<td>2250 ± 23</td>
<td>1786 ± 23</td>
</tr>
<tr>
<td>M2-4</td>
<td>S</td>
<td>3.90</td>
<td>6.20 ± 0.39</td>
<td>39</td>
<td>3.52 ± 0.14</td>
<td>568 ± 42</td>
<td>1434 ± 42</td>
</tr>
<tr>
<td>Melque 2</td>
<td>M</td>
<td></td>
<td>3.19 ± 0.30</td>
<td>33</td>
<td>4.51 ± 0.29</td>
<td>1414 ± 161</td>
<td>597 ± 161</td>
</tr>
<tr>
<td>M3-2</td>
<td>M</td>
<td></td>
<td>5.42 ± 0.36</td>
<td>31</td>
<td>7.28 ± 1.08</td>
<td>1343 ± 218</td>
<td>668 ± 218</td>
</tr>
<tr>
<td>M3-3</td>
<td>S</td>
<td>2.60</td>
<td>6.13 ± 0.51</td>
<td>44</td>
<td>6.53 ± 0.52</td>
<td>1065 ± 123</td>
<td>946 ± 123</td>
</tr>
<tr>
<td>M3-4</td>
<td>S</td>
<td>0.20</td>
<td>6.36 ± 0.28</td>
<td>43</td>
<td>4.37 ± 0.29</td>
<td>687 ± 55</td>
<td>1324 ± 55</td>
</tr>
<tr>
<td>Melque 3</td>
<td>M</td>
<td></td>
<td>3.93 ± 0.34</td>
<td>33</td>
<td>3.27 ± 0.18</td>
<td>832 ± 85</td>
<td>1179 ± 85</td>
</tr>
<tr>
<td>M4-1</td>
<td>M</td>
<td>0.20</td>
<td>6.73 ± 0.32</td>
<td>47</td>
<td>1.37 ± 0.11</td>
<td>204 ± 19</td>
<td>1807 ± 19</td>
</tr>
</tbody>
</table>

Samples taken from mortars (M) or sediments (S). Depth of sampling (m) is given for reservoir deposits only. Most of the samples are analyzed for 90–180 μm grain sizes, with the exception of sample M2-5 where the 180–250 μm fraction was analyzed. The uncertainties on dating are derived after error propagation on the annual and equivalent dose, and represent one standard deviation.
Figure 4 Velocity (m/s) of the p-seismic waves ($V_p$) obtained from seismic refraction analyses. The four cross-sections were taken in the river valleys, about 5 m upstream of the dams. The morphology of the sediment body is easily recognizable, and allows estimation of the volume of sediment deposits from the 17 transversal and longitudinal seismic profiles obtained in the area.

timing of, respectively, start and end of sediment accumulation as derived from OSL dating of sediments (years, Table I), $A$ (km$^2$) is the surface area of the catchment draining to the reservoir, $TE(t)$ (%) is the sediment trapping efficiency of the structure as a function of time, and $V(t)$ (m$^3$) is the volume of sediment deposited in the reservoir as a function of time.

As a result of ongoing sedimentation, the reservoir capacity, $C(t)$, declines over time, leading to a decrease in the sediment trapping efficiency, $TE$, and the rate of sediment deposition. As no information is available on flow volumes and/or velocities during runoff events for the ephemeral streams, we were not able to use the sediment trap model for small ponds (STEP) that was developed by Verstraeten and Poesen (2001a) and later adapted by Bussi et al. (2013). In this study, we were limited to use the empirical equation of Brown (1943) to estimate the sediment trapping efficiency, $TE(t)$, as a function of reservoir capacity, $C(t)$:

$$TE(t) \, dt = \left( 1 - \frac{1}{1 + 0.0021 \, D \, C(t) \, dt} \right),$$

(2)

where $C(t)$ is the storage capacity of the reservoir (m$^3$) as a function of time, $t$, and $D$ is an empirical parameter ranging between 0.046 and 1 and depending on the type of reservoir (Verstraeten and Poesen, 2000, 2001b). At the time of their construction, the four Melque dams efficiently blocked stream flow and created normally ponded reservoirs. Given the low runoff volumes in the two seasonal streams, the $D$-value is here set at 1 as suggested by Brown (1943) which results in high estimates of sediment trapping efficiency. A similar approach was used by Bellin et al. (2011) to estimate sediment yields based on sediment retention behind small dams in southern Spain.

Based on the chronology of sedimentation, we can obtain new insights into water availability at Santa Maria de Melque. Shortly after construction of the dams, the potential water storage in the reservoirs is maximal and equals the capacity of the reservoir, $C(t = t_0)$. With ongoing erosion in the catchment and subsequent sedimentation in the reservoir, there is a gradual decline of the potential water storage. Assuming a constant sediment delivery rate, the potential water storage at a given time, $t_i$, can be estimated as:

$$WS_{t_i} = V_{max} - \int_{t_0}^{t_i} V(t) \, dt,$$

where $V_{max}$ (m$^3$) is the maximum storage capacity of the reservoir and $\int_{t_0}^{t_i} V(t) \, dt$ is the volume of sediment accumulated in the reservoir up to time $t_i$.

The construction of the four dams was not simultaneous (Table I). Therefore, the information from the four sedimentary sequences can be used to reconstruct
Table II Different phases of human occupation at the Melque agricultural complex based on Caballero and Meier (1999).

<table>
<thead>
<tr>
<th>Phase</th>
<th>Subphase</th>
<th>Century A.D.</th>
<th>Human Activity</th>
<th>Occupation Phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Ia</td>
<td>7–8th</td>
<td>Construction of church and monastery</td>
<td>Visigotic/Mozarabic</td>
</tr>
<tr>
<td></td>
<td>lb</td>
<td>8–9th</td>
<td>Second phase of construction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>lc</td>
<td>8–9th</td>
<td>Abandonment and destruction</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>Iia</td>
<td>9–10th</td>
<td>First Islamic settlement</td>
<td>Islamic</td>
</tr>
<tr>
<td></td>
<td>Iib</td>
<td>10–11th</td>
<td>Second Islamic settlement</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>IIIa</td>
<td>11–12th</td>
<td>Christian occupation</td>
<td>Christian</td>
</tr>
<tr>
<td></td>
<td>IIIb</td>
<td>12–13th</td>
<td>First Christian settlement and necropolis</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IIIc</td>
<td>14–15th</td>
<td>First and Second fortified outpost, second &amp; third necropolis</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IIId</td>
<td>16th</td>
<td>Fourth necropolis</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>IVa</td>
<td>17–18th</td>
<td>Modern period</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IVb</td>
<td>19th</td>
<td>Confiscation and modern agriculture</td>
<td></td>
</tr>
</tbody>
</table>

The OSL dating of mortars revealed that the four dams were constructed consecutively between the seventh and fourteenth centuries (Figure 4, Table I). New dams were constructed when the older dams were largely filled with sediment and not functional as water storage systems. The oldest dam very likely dates from the seventh or eighth century A.D. (Melque 3, M3-1: A.D. 597 ± 161), and is considered contemporary with the construction of the church, which is estimated to date from the second half of the seventh to eighth century A.D. (Garen 1992; Caballero 1994, 1995). Melque 3 is located on the “Zorras” stream east of the monastery (Figure 2), and the reservoir could store a maximum of approximately $15 \times 10^3$ m$^3$ water. The decision to dam this eastern stream is logical from a practical point of view. The Zorras Valley could here be blocked at its widest point, thereby optimizing the water storage capacity with minimal manual effort. During more than three centuries (8th–11th century A.D.), this reservoir was the only permanent water source close to the rural monastery.

The second dam (Melque 1) was built on the Melque stream west of the monastery in the 11th century A.D. at a time when the oldest reservoir (Melque 3) was at 37% of its initial maximum water storage capacity (Figure 5). The crest of the Melque 1 dam was about 2 m higher than that of the older Melque 3 dam (Table III), and its construction allowed for increased potential water availability to approximately $15.8 \times 10^3$ m$^3$ (Figure 5). Due to sedimentation in the reservoirs, the total water storage capacity decreased rapidly to less than $9 \times 10^3$ m$^3$ at the end of the 12th century A.D. At this time, a third dam (Melque 4) was built on the Zorras stream, just upstream of the area of influence of Melque 3 (Figure 2). Due to reservoir siltation, the impounded area of Melque 3 became restricted to a small lake close to the dam site, and its water storage capacity was only about 1/5 of its original capacity. Interestingly, Melque 4 is much larger than previous constructions, and might

changes in erosion rates and water availability for a prolonged period of time. As we are particularly interested in agricultural land use during the four human occupation phases described by Caballero and Meier (1999), we estimated the potential water availability during the four phases described in Table II (Figure 5). This new information on historical land use is then discussed in the context of earlier work by Arnanz (1999), Caballero and Meier (1999), Macías and López (1999), and Uzquiano (1999).

RESULTS

Our chronological framework is established by OSL dating of dam mortar and reservoir sediments. The OSL dates from the dams are systemically older than the oldest sediment sampled behind the dams, which supports our methodological framework. We assume here that erosion rates were relatively constant over the time span of dam filling. Additional OSL analyses of depth samples can help to further constrain the temporal evolution of sediment delivery rates.
have had an important impact on agricultural development in the area. Its initial capacity is estimated at 24 × 10 m³, bringing the total potential water availability to 32 × 10 m³ at the beginning of the 13th century A.D. (Figure 5).

The last dam (Melque 2) was constructed in the middle of the 14th century A.D., when the maximum storage capacity of the three older dams was reduced to 2/3 of the maximum capacity of the early 13th century A.D. At this moment, the two oldest reservoirs (Melque 1 and 3) retained less than 10% and 25% of their original water storage. Melque 2 is technically the most demanding and sophisticated construction, with a dam height of more than 6.5 m and impounding area of about 2700 m². After the construction of Melque 2, the water storage facilities reached their maximum capacity of 50 × 10 m³ (Figure 5).

During the various occupation phases of the rural monastery, erosion rates ranged between 8 ± 3 and 39 ± 10 Mg km⁻² yr⁻¹ (Table III), leading to continuous but slow filling of the reservoirs. The erosion rates are systematically higher for the Zorras subcatchment as compared to the Melque subcatchment, which can be related to differences in local topography and/or catchment size. To our knowledge, our data provide one of the first historical erosion rate estimates for this environment. Local analogues to the Early and Middle Medieval agrosilvopastoral system at Melque are not evident, and direct comparison of historical and modern erosion rates on agricultural land is not straightforward given changing agricultural production systems. Short-term modern erosion rates from experimental plots in the region range between 50 Mg km⁻² yr⁻¹ for abandoned croplands on the nearby Higueruela field station (De Alba et al., 2003), 63 Mg km⁻² yr⁻¹ for seminatural wooded rangelands (dehesa landscape), and 12 Mg km⁻² yr⁻¹ for scrublands (Schnabel et al., 2009). As such, the historical erosion rates measured at Melque are within the range of the reported values for seminatural landscapes in central Spain.

**DISCUSSION**

The origin of traditional water harvesting and supply systems in the Western Mediterranean is still controversial (Glick & Kirchner, 2000). In Western and Central Spain, water and hydraulic infrastructure date from as early as the Roman Period. Large dams and aqueducts were constructed to supply water to urban settlements such as Merida (Emerita Augusta) and Toledo (Toletum). In rural zones, the construction of small reservoirs for irrigation and livestock drinking was quite common. Caballero and Sánchez-Palencia (1982) suggested that the dams of Proserpina, Cornalvo, Alcantarilla, the latter Moracanta, Mesa Valhermoso, and Vega de Santa María all date from this period.

During the Islamic era, there was an important development of irrigated agriculture throughout Al-Andalus (Glick & Kirchner, 2000). In the Andalusian orchards, intensive agricultural systems were present and earthen and stone embankments were part of the irrigation system (García-Sánchez, 1996). The construction of dams for water supply to downstream terraces was not common in Al-Andalus (Caballero & Fernandez, 1999), but has been reported for the Alpujarras (Almeria), Segura valley and part of the province of Jaen by Cressier (1989).

Acién-Almansa (1989) suggested that there is evidence of continuity of Roman irrigation schemes in the Islamic world, based on his analysis of the monastic settlement...
of Trampal (Caceres). The continuous development of the water harvesting and supply systems of Melque during almost eight centuries might be indicative of continuity in the agricultural systems from the 7–14th centuries A.D. Barceló (1989) also suggested that the Melque complex can be considered as one of the northern-most settlements in Al-Andalus, and its uniqueness is based on a settlement of Christian origin, that was turned into an Islamic village and went back to Christian hands again.

To grasp the complexity of human–landscape interactions in Central Spain, we present here our results from the perspective of earlier archaeological work in the Toledo region. We use the human occupation phases that were identified by Caballero and Meier (1999; Table II) for the Melque complex as a framework for our discussion.

Phase I: Visigotic-Mozarabic Era

It is very likely that the construction of the first dam (Melque 3, Table I) can be situated in the same time period as the church, that is, the second half of the seventh to eighth century A.D. following Garen (1992) and Caballero (1994, 1995). Palynological data of the Visigotic-Mozarabic occupation layer provide evidence of riparian vegetation consisting of elm, ash, and to a lesser degree poplar trees (Macıás & López, 1999). This might either be an indicator that the environment surrounding the site was rather humid as suggested by Macıás and López (1999), or might directly result from impounding of the Zorras stream. The water storage capacity of the Melque 3 reservoir was still low (maximum of 15 × 10 m^3), but probably enough for the development of agricultural activities that were mainly supplying the local needs of the monastery, given the civil instability in the area with the continuous threat from the Nafza Muslim tribe (Moreno-Martín, 2009).

Phase II: Muslim Era

During this short period of less than one century, no new dams were built. The water storage capacity of Melque 3 decreased slightly by 15%, as a result of reservoir siltation (Table II). Pollen records indicate that the natural tree vegetation was dominated by Quercus pyrenaica, Q. ilex and Q. suber, with the presence of Pinus pinaster and P. pinea (Macıás & López, 1999). Riparian tree species were also present, similar as in the Visigotic-Mozarabic era. Irrigated agriculture was integrally part of the farming system, and there is evidence of peach, apricot, and olive orchards and irrigated flax (Arnanz, 1999). At the same time, rain-fed cultivation of cereals (barley, wheat, and rye) was an important part of the agricultural production system (Uzquiano, 1999).

Phase III: Christian Era

The Christian era starts with the Christian conquest (ca. 11th century A.D.) and lasts for six centuries (Table II). It is divided into four periods by Caballero and Meier (1999). During the first period (IIia, 6–11th centuries A.D.), the church was refurbished (Caballero & Meier, 1999). At the same time, the second dam (Melque 1) was built on the western stream, increasing the total water storage capacity of the site to 15.8 × 10 m^3 (Table III). The site was intensively used for agricultural production (Macıás & López, 1999). Anthracological and palynological records suggest that (1) shrublands were converted to forests for timber production, (2) wheat (Triticum durum aestivum) became an important staple crop, and (3) olive and fruit tree cultivation remained important (Arnanz, 1999; Uzquiano, 1999).

Contemporary with further establishment of the Christian village in the second period (IIib, 12–13th centuries A.D.), the large dam Melque 4 was built increasing the total water storage capacity to about 32 × 10 m^3 (Figure 4). The palynological record of this period has to be analyzed with caution, as the sample material from a trash pit sampled in the northern part of the archaeological site was very poor in palynomorphs (Macıás & López, 1999). Riparian vegetation is only poorly represented in the pollen record of the IIib period (Caballero & Fernandez-Mier, 1999). A similar observation can be made for cereals, with rye (Secale cereale) being poorly represented although it is known that this crop was very common in the Iberian Peninsula during the Christian era (Glick, 1991). It is likely that this results from underrepresentation bias in the pollen record. The absence of Secale pollen grains is therefore not indicative of the absence of cereal crops.

The third period (IIic, 14–15th centuries A.D.) corresponds to the Christian occupation of the site, and the construction of the first and second barbicans (Caballero & Meier, 1999). During the Christian era, the last and most sophisticated dam (Melque 2) was built so as to further extend the potential water availability for the site to 47 × 10 m^3 (Figure 5). From the 16th century onwards, there is a rapid drop in the water storage capacity as a result of reservoir siltation and lack of maintenance. We hypothesize that this is an indication of agricultural extensification.

Phase IV: Modern Era

At the beginning of the modern era, the potential water storage capacity was low (8 × 10 m^3) and similar to the one at the end of the Muslim phase (Figure 5). There is evidence of agricultural extensification during this era, with replacement of agricultural crops by legu-
mous shrubs and herbaceous plants. At the end of the 20th century, only 56% of the surface area is used for agricultural crops (Macías & López, 1999). The reservoirs quickly fell into disuse, and were completely silted by the beginning of the 19th century.

CONCLUSIONS

Extending geoarchaeological research to the rural landscape surrounding archaeological sites can provide new insights into human–landscape interactions. In this study, we provide a high resolution temporal record of water storage capacity in reservoirs that were crucial for agricultural production in Central Spain. Our record spans more than 1000 years, and covers various occupation phases, including Visigotic/Mozarabic, Muslim, and Christian communities.

Our OSL ages for the Melque dams and sediments provide a first detailed chronological framework for historical reservoirs in Central Spain. The first dam was constructed during the Visigotic-Mozarabic era (8th century A.D.), roughly at the same time as the church. During the Muslim era, the existing infrastructure was used for irrigated agriculture, but no new dams were built. A new phase of construction coincides with the period of Christian occupation. The highest and technically most sophisticated dam was built at the end of the 14th century A.D., expanding the potential water storage capacity of the dams to about 47 x 10⁴ m³. This suggests that the maximum splendor of the rural complex occurred during phase III (Christian occupation, centuries 12–16th centuries A.D.), synchronous with construction of the barbicans, necropolis, and part of the village. However, the palynological data are less conclusive in this respect.

Our study suggests that the construction of dams was an integral part of the production system of the rural complex. There is clear evidence of riparian vegetation from the pollen record, supporting our statement that the reservoirs were effective as water harvesting systems over a prolonged period of time (7th until 16th centuries A.D.). Irrigated agriculture (fruit and olive orchards, flax) was part of the food production system during more than eight centuries, suggesting continuity in the agricultural production system during various phases of occupation of the site. Only during the modern era is there a shift in the agricultural production with conversion of croplands to grasslands, and less dependence on the traditional water harvesting systems.

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REFERENCES


