Luminescence dating of sediment mounds associated with shaft and gallery irrigation systems

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Abstract

Optically stimulated luminescence (OSL) techniques, supported by geomorphological analysis, have been applied to date the construction of shaft and gallery irrigation systems, more commonly referred to as qanats, falaj and foggara. The approach developed was tested on four hydraulic systems located in semi-arid landscape settings, three in Murcia, Spain, and the fourth in the Sus Tekna region, Morocco. Excavation of the characteristic sediment mounds that surround each ventilation shaft enabled a detailed examination of strata containing upcast deposits and their assignment to the main stages in the construction and use of the hydraulic feature. OSL techniques with single grain resolution applied to samples taken from the key strata provided age estimates for their deposition on the mound and, from these, dating of the construction and use of the system. Of the four irrigation systems analysed, the OSL dates indicated that the youngest had been constructed in the 19th century AD and the oldest, located in Murcia, was dated to the Roman period. The latter is of archaeological significance because the introduction of this particular form of hydraulic technology to Spain is widely identified as an Islamic innovation of the early 8th century AD.

1. Introduction

For many centuries groundwater has been extracted from upslope aquifers in the world's most arid regions (e.g., Manuel et al., 2017). The hydraulic feature constructed to enable this form of water harvesting is commonly referred to as a qanat, although there are regional variations of the terminology (e.g., foggaras in North Africa and falaj in the Arabian Peninsula). More recently it has been suggested that a 'shaft and gallery system' is an appropriate general term for this type of hydraulic technology (Chiotis, 2017). As the term implies, a characteristic feature of a shaft and gallery system is the series of vertical shafts open to the surface that trace the direction of the underground gallery in which water is transported. Archaeological evidence of qanats and their use can be found from the Near East to the Mediterranean basin and further afield in Central Asia and the New World (English, 1968), and those reported in the literature are structurally similar, but vary in size, shape and length depending on the particular conditions of hydrology, geology and terrain.

This technology is thought to have been introduced in the early 1st millennium BC in Persia, and to have spread by diffusion both eastwards and westwards, although the genesis and timing of this hydraulic innovation are disputed. Magee (2005), for example, argues for a southeastern Arabian origin early in the 1st millennium BC and that, as a technique born of environmental necessity, it had been developed in response to circumstances of increasing aridity and difficulties in obtaining groundwater, rather than by diffusion. There is evidence of early use of the technology during the mid-second half of the 1st millennium BC in Egypt (Wuttmann et al., 2000) and, further west along the North African coastline, in association with early Garamantian sites in Libya (Mattingly et al., 2009). Its relatively late introduction to Spain (Glick 1970; Rotolo, 2014) is attributed to the infusion of expertise that accompanied the Islamic conquest during the 8th century AD, although hydraulic technology was not new to the Iberian Peninsula, having been introduced to Roman Spain (Gerrard and Gutiérrez, 2018). These differences of interpretation reflect the difficulties in obtaining direct evidence to date individual hydraulic features, other than by proxy association with adjacent settlements or irrigated 'spaces' (Barceló et al. 1996; Wilson, 2012) or, more directly, using diagnostic artefacts incorporated into the upcast sediment associated with their construction. With few exceptions (Mattingly et al., 2009; Wilson et al., forthcoming), it has proved very difficult to recover suitable organic material for radiocarbon dating from contexts that can be securely associated with the initial construction. This absence of a generally available chronometric tool has blunted the enquiry of technology transfer and the examination of local settlement and landscape evolution, in particular correlation with climatic and palaeoenvironmental data, and economic conditions, culture contact and technology innovation, transfer and transitions.

The vertical shafts, which were dug at intervals to provide ventilation, also provide a means of transferring upcast from the gallery to the ground surface. During construction, some of the upcast was gathered around the rim to form a mound, and further upcast was added during periodic cleaning and maintenance (English, 1968). Given these processes, the shaft mounds potentially contain a sequence of upcast deposits, starting with the initial construction upcast dumped on the ground surface, burying the palaeosol, and overlain successively by upcast collected periodically from the gallery during maintenance operations, less any material lost by surface erosion or disturbance. The sediment deposits contained within the mound, produced by an event-related formation history of this type, are potentially suitable for the application of optically-stimulated luminescence (OSL) dating techniques (Aitken 1998). OSL has been applied to date many types of sedimentary depositional events and processes (for more recent summaries see Duller, 2004; Lian and Roberts, 2006; Rhodes, 2011), including hydraulic features such as canals (Rittenour, 2008). Exploratory luminescence dating studies applied to qanat shaft mounds in Spain (Bailiff et al., 2015) and in Iran (Fattahi, 2015) have shown that OSL has the potential to provide date estimates for the burial of key deposits preserved within the mounds (Bailiff et al., 2018). In this paper we discuss an investigation of several shaft and gallery systems in southeastern Spain and southwest Morocco with the objective of developing a working methodology for applying OSL dating to shaft mounds. One of the primary questions in widening the scope of this investigation is the extent to which the chronostratigraphic record within a shaft mound related to the construction and use of the hydraulic feature can be reconstructed. Although gathering evidence of the earliest development of qanat technology has remained of keen interest amongst water historians, we have selected accessible sites for this methodological study that, according to the prevailing diffusion model, are expected to be amongst those constructed by later adopters of the technology.

2. Selection of sites and their landscape settings

Potentially suitable sites were identified by performing an extensive desk-based search using bibliographic searches, analysing aerial photography and accessing the comprehensive FOGGARA database of qanats (Antequera et al., 2014; Hermosilla, 2006; 2008). Of some 20 sites with potentially intact mounds identified in the Spanish provinces of Alicante, Albacete, Almería, Granada and Murcia (Fig. 1) a ground-based inspection narrowed down the number of sites with sufficiently preserved mounds to 10, from which preliminary surface sediment samples were taken for laboratory testing of their mineralogy and OSL characteristics. A surface sample obtained from a site in the Sus-Tekna region of southern Morocco, located near the village of Ksabi (10 km W of the regional capital Guelmim) was also tested. On the basis of positive outcomes of the laboratory testing, the sites selected for more detailed investigation comprised (Fig. 1) three in Spain: two located near Jumilla, Murcia (Mina Casa del Manzano and Pocico de los Frailes), one near Totana, Murcia (La Balsa Grande) and the fourth, the Moroccan site.

2.1 Jumilla

The Casa del Manzano system, over 1 km in length, is one of three set in the foothills of an alluvial fan situated 10 km northwest of Jumilla that are no longer active. The mother well is located high above the valley floor and the shaft mounds were amongst the largest of the systems examined in this study, extending up to ca 15 m in diameter and nearly 2 m in height. The valley contains a Quaternary sedimentary infill within a highly folded succession of Cretaceous sandstones and sandy limestones, Miocene sandstones, limestones and marls. Hitherto, no archived historic records of irrigation work within the valley have been identified. Although the original irrigated spaces can be mapped, and a large water storage basin survives, the agricultural landscape is today transformed by industrial drip irrigation systems. Likely produce in the past may have included vines, olives, fruit trees and fodder crops, all of which are typical of this region. Domestic use of water is also documented at dispersed historic farmsteads.

The Pocico de los Frailes system is located some 12 km southwest of Jumilla on the banks of a creek that drains a small catchment off the Sierra Larga mountain range. It is sited on a Quaternary valley infill that unconformably overlies an anticline comprising of Cretaceous age limestones, sandstones, marls and dolomites. Comprising two shafts, although only one mound had remained intact, the hydraulic feature resembles a short qanat system rather than a cimbra. The latter is a special form of shaft and gallery system where a subterranean drainage tunnel crosses beneath a stream bed and harvests water from the river bed aquifer and not via a mother well. The outlet fed water to a reservoir constructed of *opus signinum,* suggesting Roman origin if contemporary with the construction of the shafts and gallery. This reservoir today feeds water to a set of descending terraces used for olives, almonds and cereals. There is nothing to indicate earlier agricultural practice, though there is Roman and later settlement nearby (Noguer and Antolinos, 2009).

2.2 Totana

The Balsa Grande system is located ca 10 km NW of Totana (elev. ~740 m) in the foothills of the Sierra Espuña and comprises 15 shafts irregularly spaced over a distance of ~500 m. It eventually outflows into a large reservoir, from which conduits carry the water downslope to irrigate farms located in the surrounding valleys. The system currently passes through a modern planted forested park and, although some shaft mounds were recently removed and the shafts capped, a few mounds remain intact. The upcast indicates that the qanat gallery cuts through a series of Permo-Triassicaged units comprising a mixture of reddish clays and slate, quartzites, sandstones, and conglomerates, with the latter found outcropping at the surface in the region around the site. The area, known collectively as Las Alquerías, contained several qanats in use at least from the 18th century AD, but most are now dried up and some have been obliterated. Searches of archives yielded no further information related to the construction and use of the qanat, although there are records of maintenance of another qanat to the north during the early 19th century AD (unpublished archives, Ayuntamiento de Totana, Archivo Municipal). This implies that qanat technology was already in use in this area before that date, which is in keeping with the documenting of extensive building of mills and irrigation channels in Totana during the 18th century (Palao et al. 1995).

2.3 Ksabi

The Ksabi system, resembling a cimbra, is located within the wide alluvial basin of the Wadi Nun near the modern village of Ksabi, at a topographic high point in the floodplain of the wadi. It was selected because of its association with the ancient caravan settlement of Tagaos that is the subject of ongoing archaeological investigation (Pintado et al., 2015). The cimbra gallery was cut into the valley floor to chase an old palaeochannel between two extant channels and extends westwards from the modern village for some 600 m, after which it appears as an open channel (due to collapse of the gallery roof) for a further 900 m in the same direction. The feature is thought to be associated with the medieval trading settlement of Tagaos (Tagawst), which came to prominence as an important nexus point of European, Moroccan and trans-Saharan trade routes in the 15th century AD. With an estimated eight thousand households, it was one of the largest walled cities in southwestern Morocco at that time. The archaeological evidence for the settlement lies to the west of the modern village of Ksabi, and preliminary sondages (test pits) indicate five phases of occupation (Pintado et al., 2015). A single radiocarbon date for short-lived organic material from the second phase tentatively places the onset of urban expansion broadly to the late 15th- mid-17th centuries AD. The cimbra may therefore have been constructed during a period of urban expansion assigned to phase II of the site chronology (late 15th-mid-17th centuries AD) and not more recently than the 18th century AD, by which time Guelmim had become the prominent destination for trans-Saharan trade caravans and Tagaos had been abandoned. During fieldwork the opportunity was also taken to obtain preliminary samples from a mound of another hydraulic feature near the village of Tarmgiste, located to the east of Guelmim, but unfortunately the quartz grains extracted from both palaeosol and construction deposits were insufficiently reset preventing the production of reliable estimates of the depositional age.

3. Methods and results

3.1 Fieldwork

The internal structure of the shaft mounds was examined in archaeological trenches which exposed one or more sections. This enabled the stratigraphy, including that of the underlying palaeosol, to be assessed and recorded, and for sediment samples to be extracted for luminescence and micromorphological analysis in the laboratory. Providing the contacts between the strata of primary interest (i.e., palaeosol, construction and maintenance upcast) could be identified, the positioning of OSL samples within the upcast strata had not been expected to be critical because of the coeval nature of the upcast deposition, in contrast to the palaeosol where processes of natural sediment aggradation in the particular landscape setting potentially apply. However, if the mound is left exposed for a long period of time (i.e., before the deposition of further upcast), the effects of pedoturbation can be expected to progressively reset grains (see Sec. 4.3) within the uppermost deposits of the mound (Bush and Feathers, 2003; Bateman et al., 2007). Such resetting processes, which potentially affect the ground surface deposits before burial and exposed maintenance deposits, are of benefit when dating the burial of the ground surface, but could potentially cause age underestimation in the case of dating the deposition of the maintenance deposits, depending on the thickness of the unit and the location of the sample. While we did not attempt to investigate the latter systematically, samples were generally positioned below the upper surface of the maintenance units to reduce such potential effects.

Trenches of ca 50 cm width were excavated radially from the crest of the mound to a distance sufficient to differentiate mound construction deposits from the palaeosol. To examine the spatial uniformity of the mound stratigraphy, comparisons were made of the sections revealed by excavating two trenches in one mound or, where this was not feasible, by comparing two opposing faces of the same trench. Providing a consistent interpretation of the mound stratigraphy had been obtained, the contexts of primary interest for the purposes of dating key stages in the development of the shaft mounds were identified and sampled from: a) the palaeosol underlying the buried ground surface, b) the overlying construction deposits and c) subsequent maintenance upcast deposits. The OSL samples were obtained by driving opaque tubes (40-50 mm dia. and ca 20 cm length) horizontally into a cleaned section face and extracting, wrapping and sealing these in opaque plastic sheet. Where the use of plastic tubes was not viable due to the sediment texture (e.g., limestone rubble, hard clay), samples were collected after nightfall in dim red light conditions using tools to excavate into the cleaned faces of trench sections. If the insertion of tubes was likely to cause significant disturbance of the sediment structure, sediment blocks were extracted and these also provided the opportunity to obtain thin-layer OSL samples, if required. Using either procedure, the material extracted was promptly wrapped in opaque plastic sheet. Sediment blocks taken for thin-section analysis were positioned primarily to examine the contacts between the significant sedimentological boundaries including the palaeosol, construction and maintenance deposits in each trench. The blocks were excised by cutting three faces of the block into a cleaned section to a depth of ca 10-15 cm (further details of the block sizes are given with the section drawings in Supplementary Material Doc. 1), encasing the cut faces in a jacket formed using Plaster of Paris bandage and finally cutting the rear face to allow extraction of the whole block, which was promptly wrapped in opaque sheet. For each section sampled, the total volume of sample typically amounted to at least several litres of sediment.

The samples collected from each site are discussed in more detail in Section 5.

3.2 Micromorphology

Thin section microscopy of the sediment blocks identified their source and mode of deposition and helped verify stratigraphic interpretation in the field. Sediment blocks were encapsulated using polyester resin following conventional procedures. After curing, the blocks were sliced and the thin sections produced (prepared by Spectrum Petrographics, Vancouver, Canada, and Stirling University, UK), were analysed using an Olympus BX51 polarising binocular microscope with a coupled Infinity-1, 1.3 megapixel colour digital camera. High resolution scans of the thin sections were obtained using an Epson Expression 10000XL flatbed scanner, and sedimentological analysis was recorded using current terminology (Stoops, 2003). We selected for more detailed discussion below (Sec 5.4) the results of an analysis of the thin sections from one of the sites (Pocico de los Frailes) that was found to have a full sequence of preserved palaeosol, construction and maintenance deposits.

3.3 Luminescence dating

Following the approach taken in earlier work (Bailiff et al., 2015), the preferred luminescent mineral extracted for OSL measurements was quartz rather than feldspar because of the generally shorter exposure to daylight required to optically 'reset' quartz grains (Godfrey-Smith et al. 1988) and the avoidance of anomalous fading (Aitken, 1985). The sample preparation and experimental procedures applied to determine the equivalent dose, D_e, and the dose rate, Dr, are briefly summarised in this section and further detail is given in the Supplementary Material. Coarse quartz grains (150-200 μm) were extracted from sediment samples using standard preparation procedures as applied in the quartz inclusion technique (Aitken, 1998), employing acid etching treatments to isolate quartz grains and remove their outer alpha-dosed surface layer. The presence of HF resistant feldspar grains in measurement samples was checked by testing the response of each aliquot or grain to infrared stimulation. The luminescence measurements were performed using two instrumental techniques applied to a) individual grains with a Risø DA 15 reader and single grain (SG) attachment and b) single aliquots of multiple grains with a Risø DA 12 reader. In the case of the latter, an OSL scanner was additionally deployed to determine the number of brightly emitting grains contributing to the detected luminescence in each aliquot (Bailiff et al., 2015). Both single aliquot and single grain techniques were applied to measure the equivalent dose, D_e, using a single aliquot regeneration (SAR) measurement procedure (Murray and Roberts, 1998; Murray and Wintle, 2000; Murray and Wintle, 2003). The latter was performed with the selected grain size fraction to determine D_e, applying a series of criteria to identify 'accepted' D_e values (Supplementary Material, Doc. 3, Sec. 2.5). The overdispersion (OD) in the distribution of accepted D_e values was calculated using the central dose model (CDM; Galbraith et al., 1999) and its value and the form of distribution of D_e values was taken into account when assessing which statistical dose model was most appropriate to calculate the weighted mean value of D_e. To determine the latter, the CDM was applied where the grains were assessed to have been sufficiently reset at deposition to apply this model, and the minimum dose model (MDM; Galbraith et al., 1999) was applied where the majority of grains had been incompletely reset, assessed on the basis of the OD and depositional process. By assuming that only a proportion of the grains measured were fully optically reset before burial, the MDM identifies a subset of the D_e values that fall within a minimum dose group. In these circumstances the overall uncertainty in the calculated OSL age is usually increased compared with that obtained with the same number of D_e values where the grains were fully reset (i.e., applying the CDM), and for this group of samples the uncertainty in the OSL age was typically increased by a factor of 2. Although the values of OD for the samples where the central dose model (CDM) was applied ranged widely - from ca 15% to nearly 50% - the form of distribution of D_e values was judged to indicate that the sediment had been sufficiently reset at the time of burial for the CDM to be applied. About two thirds of the samples required the application of the MDM, but the use of either model was not confined to a particular type of deposit (Palaeosol/ Construction/ Maintenance). A more detailed discussion of the assessment of the measured D_e distributions is included in Section 2.7 of the Supplementary Material, Doc. 3.

Estimates of the dose rate, Dr, for each sample were obtained by applying a combination of experimental (high resolution gamma ray spectrometry) and computational dosimetry techniques (Bailiff et al., 2015), taking into account the effects of uranium disequilibrium, and uncertainties in moisture content and burial conditions. By determining D_e and Dr experimentally, the luminescence age, A, was calculated using the age equation (in its simplest form, $A = D_e/Dr$). The calculation of uncertainty in the OSL age was based on an analysis of the propagation of experimental errors (ISO, 2004), similar to that described by Aitken (1985), and also taking into account the sample conditions during their burial history that potentially may affect the values of parameters used in age calculation. For reasons of space, a detailed summary of the technical information related to OSL age determination measurements and calculations is provided in the Supplementary Material (Doc. 3).

4. Interpretation of results

A discussion of the mound stratigraphy and geomorphological assessment of the sedimentary units follows, together with details of the samples obtained for dating and micromorphological analysis. The depositional processes that formed each mound are interpreted on the basis of the OSL dating results (Table 1) and the sedimentological analysis. Also, a selection of trench sections sufficient to illustrate the mound stratigraphy is included, and further stratigraphic and lithological information is provided in the Supplementary Material (Doc. 1). The sites are discussed in chronological order of construction of the systems starting with the most recent, as dated by OSL. To simplify interpretation of the mound stratigraphy in the sections shown in Figs 2-5, the major lithological units have been coloured and shaded according to deposit type (palaeosol, pink; construction upcast, yellow; maintenance, brown), and the archaeological stratigraphic units included where samples were taken and where the lithology is discussed. A detailed stratigraphy for each site is given in the Doc. 1 of the Supplementary Material.

4.1 Casa del Manzano, Jumilla

Three mounds were selected for investigation, two of which were adjacent (Mounds 1 and 2) and located near the mother well, and the third was situated about 1 km downslope, close to the outlet (Mound 3). One trench was excavated in each mound and examination of the sections revealed a sedimentary structure consistent with the deposition of upcast transported via the shaft (Fig. 2). Although the upcast was formed from a common source of calcareous sediment derived from the limestone geology, there was a progressive change in stratigraphic complexity with distance from the mother well, with a differing number of upcast layers; four in the proximal mound (Mound 1), seven in Mound 2 and ten in Mound 3 (Fig. 2). While the overlying units that extend laterally from the shaft in Mound 3 suggest an equivalent number of different depositional events, the deposits were distinguished in appearance by colours that reflect changes in the underlying geology, comprising sands and sandy clay deposits of Pliocene age from which the lower shaft and qanat gallery were excavated.

The positions of OSL samples and one micromorphology block taken from the palaeosol (unit 301) and the construction (units 302 and 303), maintenance (units 308 - 314) deposits of Mound 3 are indicated in Fig. 2, and those taken from Mounds 1 and 2 are shown on their respective sections given in the Supplementary Material (Doc. 1, Figs. SM.D1 1.1-1.4).

4.1.1 Luminescence results

OSL tests with quartz extracted from the palaeosol sampled under Mounds 1 (JUM-15-01) and 3 (JUM-15-09 and -12) indicated adequate resetting before deposition in the case of sample JUM-15-12 for a high proportion of the grains with accepted D_e values. In the case of samples JUM-15 -01 and -09, the extent and form of the dispersion of the D_e values indicated that they had been incompletely reset before deposition, requiring the application of the MDM. The OSL age estimates obtained for these three palaeosol samples were similar (samples JUM-15-01, 160±20; 15-09, 130±50; 15-12, 160±10 a), from which a pooled mean date of AD 1855±10 was calculated. The differences observed between the dispersion of D_e values for samples taken from opposite faces of the same trench in Mound 3 (samples -09 and -12) are a reminder of the variability in the resetting of grains inherent in the agency of the anthropogenic process of upcast deposition. The yields of quartz from the limestone-rich construction upcast (and also overlying clay-rich units), however, were low and only sufficient in Mound 3 (unit 308). The results of OSL tests performed on quartz grains extracted from samples taken from this deposit indicated that the grains had not been adequately reset at deposition. This suggests a lack of sufficient disaggregation of the sediment before deposition on the mound, and consequently preventing the calculation of a reliable OSL age. Despite the lack of age determinations for upcast, the consistency obtained in the OSL age estimates (providing a terminus post quem, TPQ) for the burial of the upper palaeosol under the three mounds located at the proximal (Mound 1) and distal (Mound 3) ends of the qanat suggests that deposits associated with a significantly earlier construction date had not been removed and that the qanat is relatively modern. The dating results obtained with samples taken from Mounds 1 and 3 were considered to be sufficient and the samples extracted from Mound 2 were not tested. No published nor unpublished records have been located that document the construction of this system.

4.2 La Balsa Grande, Totana

Two mounds were selected as potentially the most intact, one located nearer the mother well (Mound 1; Fig. 3) and the other near the outlet (Mound 2; Supplementary Material, Doc. 1, Fig. SM.D1.2.2). The mounds differ from those of the Casa del Manzano qanat, being much smaller (height < 1 m), and they also form an 'orbital' feature with crests some 2.5-3 m from the centre of the shaft with relatively little upcast abutting the shaft rim. A succession of similar sedimentary units was observed in both trenches; the palaeosol was overlain by a small upcast mound, interpreted as the initially formed mound (units 102 and 103 in Mound 1; 202 in Mound 2). This initial mound was overlain by units interpreted as a second stage of qanat construction upcast deposition (units 104, 105 in Mound 1 and 203 in Mound 2) derived from the excavation of the qanat gallery. There was evidence of frequent root penetration within the upper units and care was taken to avoid sampling sediment volumes disturbed by this process. The latter is of potential concern because of the possibility of the percolation of grains from levels higher in the stratigraphy into the volume sampled. Nine OSL samples were taken from the mounds, sampling the palaeosol and construction layers (Fig. 3 and Supplementary Material, Doc. 1, Figs SM.D1.2.1-2.3), corresponding to three from each of both faces of the Mound 1 trench and from the south-facing trench of Mound 2. It was not found feasible to extract blocks for micromorphological analysis due to the unconsolidated nature of the gravels forming these mounds.

4.2.1 Luminescence results

Although the palaeosol was predominantly a clay deposit, sufficient quartz was extracted for OSL measurements from the palaeosol and from the gravels that formed the construction deposits. The extent and form of the dispersion of values of the equivalent dose, D_e, for quartz grains extracted from both the palaeosol and the construction upcast (Supplementary Material, Doc. 3, Table SM.D3.1a) indicated that they had been incompletely reset before deposition, and this required the application of the MDM in all cases. The OSL age estimates obtained for palaeosol samples at two depths below the buried ground surface, of 1640±200 a (TOT-15-01; depth 18±2 cm) and 1010±90 a (TOT-15-04; depth 9±2 cm), indicate an average rate of aggradation of the colluvium of ~14 mm/century. By extrapolation of these depth-age data, a burial age of the ground surface of ca 500 years was estimated. The latter is consistent with the OSL age estimate of 425±90 a obtained for sample TOT-15-07 (depth 7.5±2.5 cm), which was taken from the relatively thin layer of palaeosol (10 cm) overlying the bedrock in Mound 2 and likely to have been more heavily disturbed during construction of the qanat.

The OSL ages for the samples taken from the initial construction deposits on both sides of the Mound 1 trench (TOT-15-02, 310±60 a; 15-05, 290±60 a) produced a pooled mean date AD 1715±40 (T=0.1; $\chi^2_{1,0.05}$=3.84). However, the results of OSL measurements with quartz extracted from the overlying construction deposits in Mound 1 (TOT-15-03 and -06) and the initial (15-08) and later (15-09) construction deposits in Mound 2 indicated that the grains had been reset insufficiently before burial, preventing the calculation of reliable OSL ages.

The OSL ages and their ranges obtained for the upper palaeosol (as discussed above) and construction (TOT-15-02 and -05) deposits overlap and they indicate a likely construction date for the qanat of the mid-late 17th century AD. Although an archive and bibliographical search for a documented building and use of the Balsa Grande qanat yielded no independent dating information, this area (Sierra de Espuña) is known to have contained several qanats and the extensive building of mills and irrigation channels during the 18th century in Totana (Palao 1995). Although most of these hydraulic installations are now redundant, and in some cases obliterated entirely, there are records of maintenance work and general upkeep of a different qanat (possibly the Pinos Donceles nearby to the north of Totana) during the early 19th century (Ayuntamiento de Totana, Archivo Municipal). Consequently, the dating results for Totana suggest that qanat technology was already in use in this area well before that date.

4.3 Ksabi

Two shaft mounds (Mounds 1 and 2) were selected for study, where Mound 2 was located ca 60 m downstream and closer to (E) Ksabi; three trenches were excavated, two in Mound 1 and one in Mound 2. The stratigraphy of both mounds (Fig. 4 shows the section of Trench 3 in Mound 2) can be subdivided into two basic sections comprising a basal sub-horizontal unit (unit 301 in Trench 3) overlain with a succession of dipping lenticular units. The sedimentary units reflect the processes of intermittent flooding and overbank deposition followed by aeolian reworking and biological mixing that were active in forming the Wadi Nun landscape (Supplementary Material, Doc. 1, Figs SM.D1.3.1-3.3). Although Mound 1 was selected for the insertion of two comparative trenches (1 and 2), the sequence of upcast units in Mound 2 (Trench 3) appear to contain a more intact and detailed record of the upcast deposition, including the position of the mound crest (Fig. 4). In this mound, the upper part of the palaeosol (sandy loam; unit 301) forming the ancient ground surface had been reworked, with aeolian material incorporated into the deposit. Common to all three trenches, the ground surface was buried by a 'ramped' layer (unit 302) formed from a heavy clay and interpreted as an initial construction deposit. Although the composition of this basal mound deposit differed according to trench, it dipped away from the shaft, suggesting a mounding of material, but lacking a crest; the upper contact of this unit formed a sharp boundary with the overlying unit. The latter and a further three units (i.e., units 303-306) in Mound 2 show an outward radial development that reflect the evolution of the mound. These units were dominated by clay, the main difference between them being in texture, whereas in Mound 1 the equivalent units of upcast were formed from a sandy loam. Within each mound section, sediment blocks were obtained (5 in the S-facing section of Trench 1; 3 in the NW-facing section of Trench 3) and three OSL tube samples were taken from the palaeosol and construction units in Mound 1 (KSA-T2 -1, -2, and -3) and Mound 2 (KSA-T3 -1, -2 and -3, as indicated in Fig 4). Five OSL samples (KSA-T1-1, -2, -3, -4 and -5) were extracted in the laboratory from the sediment blocks taken from Trench 1.

4.3.1 Luminescence results

As anticipated, the yield of quartz grains was high from the sandy palaeosol and relatively poor from the clay-rich construction deposits. Subsequent sedimentological assessment of thin sections and the sample blocks confirmed distinct changes in grain size between the palaeosol, construction and maintenance layers and the clay-rich nature of the construction deposits, which are likely to have been derived from excavation of the qanat gallery. The dispersion of D_e values for most of the samples (Supplementary Material, Doc. 3, Table SM.D3.1) from this site indicated that although the populations of quartz grains tested from three (palaeosol) samples had been adequately reset, the remainder (8), comprising a mixture of palaeosol and upcast deposits, had been incompletely reset before deposition and required the application of the MDM.

A total of 11 OSL ages were obtained from the three trenches (Table 1; Fig. 4). The samples from the palaeosol underlying the two mounds provided consistent age estimates (KSA-T1-2, 440±40 a; T1-1, 440±100 a; T2-1, 390±80 a; T3-1, 370±30 a), from which a pooled mean date of AD 1620±25 was calculated for the burial of the palaeosol, and this can be considered as a *terminus post quem* (TPQ) for the burial of the ground surface by the construction deposits. Of the remaining seven samples extracted from the construction and three overlying layers of presumed maintenance deposits, the OSL ages for samples from the basal construction deposits are consistent between the two mounds when comparing Trenches 2 (KSA-T2-2, 320±30 a) and 3 (KSA-T3-2, 380±40 a), but the OSL age for the equivalent construction deposit in Trench 1 is significantly younger (KSA-T1-3, 250±20 a), raising the question of stratigraphic uniformity. Closer inspection of the results for the upcast deposits, and taking into account the stratigraphic position of the samples, the OSL dates obtained for the upper palaeosol and the upcast are in good agreement between Trenches 2 and 3 which were separated by some 60 m. The OSL ages obtained for the Trench 1 upcast samples (KSA-T1 -3, 4 and 5), on the other hand, support a trend of younger deposits (Fig. 4), as indicated but not resolved by the dates for samples from the lower upcast layers, and these differences suggest spatial variation of the mound stratigraphy. An estimate for the date of construction of the qanat was derived from the group of four samples (KSA-T2-2 and -3 and T3-2 and -3) in Trenches 2 and 3, the dates for which form a statistically coherent group, with a pooled mean date of AD 1665±20. This estimate for the construction date is stratigraphically consistent with that calculated for the burial of the upper palaeosol (AD 1620±25) and a 17th century date is also consistent with the occupation of Ksabi, correlating with the end of the second phase of the settlement that has been linked to a significant expansion in population.

4.4 Pocico de los Frailes, Jumilla

The two shaft mounds of this short hydraulic feature were located on the shallow incline of a hill and one mound was sufficiently intact for study. The morphology of the upcast deposits surrounding the shaft had formed a horizontal platform on the slope with a slight mounding encircling the shaft at a distance of ca 2 m. The location of the shaft on an incline can be expected to introduce topographically related factors that also affect mound formation, such as colluvial processes, that do not arise, or are a minor component, when mounds are formed on level ground. To investigate this issue, two trenches were oriented orthogonally and extending across (Trench 1, E-W) and down (Trench 2, N-S) the hill slope. Archaeological excavation of the trenches revealed limestone bedrock overlain by sedimentary units, the mound-like forms of which are consistent with the deposition of upcast; all four sections, two from each trench, are shown in Fig. 5.

The thin remnant of palaeosol present in both E and W sections of Trench 1 was overlain by construction and maintenance upcast deposits that followed the dip of the slope. The uppermost deposits of the mound (units 100, 201) were found to contain modern artefactual debris (timber) and consequently assumed to be a relatively recent addition to the mound. In Trench 2, the palaeosol was overlain successively by a truncated mounded deposit of construction upcast and units above these were interpreted as maintenance upcast, similar in composition to that in Trench 1. The upper units of the mound section were interpreted, as in Trench 1, to be relatively modern, and overlain with slope-wash derived sediment and gravels comparable to the capping deposits in Trench 1. The locations of the 14 OSL samples are indicated in Fig. 5, positioned to extract material from the accessible palaeosol (JUM-16-01 and -09), the construction deposits (JUM-16 -02, -03 and -05), the putative maintenance deposits (JUM-16-04, -06, -07, -08, -10, -11, -12, -13 and -14). The locations of 9 blocks taken for micromorphological analysis are also indicated (the sizes of the blocks are given in the captions to Figs SM.D1.4.1 and 4.2, Supplementary Material)

We highlight here some of the key structural features gleaned from the analysis of thin sections produced from the sediment blocks, the scanned photomicrograph images of which are included in the Supplementary Material (Doc. 2). Block 1 was positioned to examine the boundary between units 106 and 103 (Fig. 5). In the lower layer of this block (unit 106), the chaotic nature of the fine fraction rich (porphyric to close enaulic) sediment, the variability of fabric types at an equivalent level across the block and the presence of anorthic nodules were consistent with the deposition of construction upcast (Supplementary Material, Doc. 2, PMG 1 and 2). The deposits were overprinted by a short-lived period of pedogenesis (Supplementary Material, Doc. 2, PMG 3), signalled by the presence of red iron oxide and dark humic staining of the fine fraction and the incorporation of black organic matter. A change to a sandy composition of the uppermost layer of unit 103 (Supplementary Material, Doc. 2, PMG 4) could represent either construction or maintenance upcast, but the presence of an increased concentration of weathered and eroded calcrete indicates the deposition of maintenance upcast. The calcrete is presumed to have been derived from the rock-cut lining of the upper shaft, shed into the shaft and combined with sediment accumulated in the gallery channel that was subsequently transferred to the mound in a cleaning operation. Overlying unit 103, the basal deposits of unit 101 comprised a fine fraction rich sediment containing weathered limestone identified as yellow/red clasts in the macro stratigraphy. The combination of chaotic bedding of these sediments, the presence of anorthic nodules and the higher abundance of weathered limestone suggest a further deposit of maintenance upcast.

Thin sections obtained from Block 2 were consistent with the main features of those obtained from Block 1, except that the structure of the basal deposits reflected a lateral dispersal of construction upcast down the rambla (dry stream bed) slope, with the presence of reverse bedding structures (Supplementary Material, Doc. 2, PMG 5) that are indicative of dry grain flow processes (Karkanas et al. 2012). Under these conditions, the deposition of upcast containing a variety of grain size fractions on a slope leads to a basal lag of sand, upon which larger pebbles and granules are deposited and travel further down the slope, leading to a fining upwards sequence from the slope toe to source origin. Where the upcast is deposited from buckets, a spatial variation in the effect of this process is likely to occur with the potential for reverse bedding to be observed, evidence of which was found in the thin section.

In Trench 2, the composition of construction upcast was similar to that observed in Blocks 1 and 4 from Trench 1, but the dumping of upcast onto a near-horizontal local topography produced a chaotic jumble of poorly sorted materials. This is reflected in the structure of Block 1, where porphyric and enaulic distribution patterns (Supplementary Material, Doc. 2, PMG 6) indicate that the deposits were remobilised after deposition, either through dry grain avalanche or by water action, as discussed above. The presence of well-sorted very fine sand-sized clay aggregates with dusty clay bands suggests the latter, and the laterally discontinuous nature of these features indicates the channelisation of both water and entrained sediments between pre-existing topographic relief. From this structural examination (Supplementary Material, Doc. 2, PMG 7 and Doc. 1, Sec.4), units 10, 11, 17 and 32 were interpreted as deposits formed of dumped upcast modified by an influx of slope wash deposits within small ephemeral rill features which eventually collapsed.

From the North section of Trench 2, the structure of the lower part of Block 4 indicated that unit 18 also contained dumped upcast that had been reworked. The thick rhythmic bedding sets of well-sorted layers in the basal layers indicate sediment transport caused by dry grain colluvial reworking of both mound and hill slope sediments down-slope towards the rambla (Supplementary Material, Doc. 2, PMG 8). The increase in fine fraction at the top of the unit indicates a short period of stabilisation and the continuation of colluvial deposition is evident in the overlying unit (15), but the fineness of the lenses and the deposition of fine fraction cappings indicates that it was associated with sheet wash (Supplementary Material, Doc. 2, PMG 9).

Within the basal layer of unit 15 the presence of a high proportion of weathered limestone and calcrete and an undulating lower contact is indicative of further anthropogenic deposition. The surface of the latter was subsequently churned up and the absence of fresh limestone within it points to a maintenance event. Furthermore, a well-sorted silty clay (Supplementary Material, Doc. 2, PMG 10) present in the deposit indicates micro-topographic infilling (as in Block 1 from this trench), where sediments were probably saturated with water at the time of deposition, which is consistent with the conditions under which of maintenance upcast is collected and deposited.

4.4.1 Luminescence results

All the samples taken from this site yielded coarse-grained quartz with OSL characteristics of individual grains suitable for age determination. The dispersion of D_e values for the samples taken from the palaeosol (JUM-16 -01 & -09) indicated that the quartz grains had been adequately reset, yielding OSL burial dates of 2635±290 BC and 1065±160 BC, respectively, which is consistent with their expected deposition during the late Holocene. Of the remaining (upcast) samples, there were comparable numbers of samples that had been adequately (CDM, 8) and incompletely (MDM, 6) optically reset before deposition. The construction upcast, sampled in three locations (JUM-16-02, -03 and -05) in Trench 1 and in two locations in Trench 2 (JUM-16-11 and -08), produced two groups of individually broadly concordant but differing pooled mean (Ward and Wilson, 1978) dates when grouped as JUM-16-02 and -05 (AD 120±90; T=2.1; $\chi^2_{1,0.05}$=3.84) and JUM-16 -03, -08 and -11 (AD 490±60; T=3.6; $\chi^2_{2,0.05}$=5.99).

The overlying maintenance deposits, sampled in six locations, also produced self-consistent date estimates for samples taken from equivalent units in Trench 1 (JUM-16-04, AD 1825±20; JUM-16-14, AD 1775±20) and in Trench 2 (JUM-16-10, AD 1845±20; JUM-16-12, AD 1915±20 and -13, AD 1895±30), although in Trench 1 a significantly earlier date of AD 735±70 was obtained for the single sample taken from unit 209 in the W section of Trench 1 (JUM-16-06). However, the distribution of the measured D_e values for this sample contained an isolated 'spur' in the radial plot defined by a few grains that produced a group of substantially lower values of D_e; these were interpreted as intrusive grains resulting from either bioturbation or penetration of the sampling tube into disturbed deposit and excluded from the MDM calculations (discussed further in Sec. 2.7 of Doc. 3, Supplementary Material).

The OSL date for JUM-16-07 (AD 1865±20), which overlies JUM-16-06, is stratigraphically consistent, indicating that the date for the latter represents the survival of an earlier phase of deposition (and statistically it is an outlier of the construction deposit group comprising of JUM-16-03, -08 and -11 discussed above). The dates for sample JUM-16-07 and those from Trench 2 form a coherent group with a pooled mean date of AD 1880±11 (T=6.5; $\chi^2_{3,0.05}$=7.81), indicating that two phases of maintenance during the early and late 19th centuries were preserved in the mound. The differences in dates for the maintenance deposits in Trenches 1 and 2 highlight the potential for disturbance or removal of earlier maintenance deposits, the extent of which may vary spatially within the mound.

Interpreting the evidence obtained from both trenches, the better-preserved construction deposits present in Trench 1 confirm a Roman origin of the feature and the date estimates for the overlying maintenance deposits indicate the continued use of the qanat extending into the early medieval period (5th century AD and possibly the 8th century AD) and resumed during the 13th century AD. This appears to be followed by disuse of the qanat until the 18th century when maintenance deposits reappear on the mound. A late 18th century date for the reactivation of the Roman system corresponds with the date of the domestic architecture of a nearby abandoned farmstead and tracing the water channels exiting from the reservoir suggested a likely limit of cultivation in an upland area which is otherwise waterless. This area had been terraced and field survey recovered 19th century glazed and decorated wares, but no obvious Roman pottery fabrics, which suggests that the terraces, the farm and reactivated qanat are likely to be contemporary.

5. Discussion

5.1 Practical issues

The results produced from the four sites with their differing landscape settings illustrate various aspects of issues that potentially influence the outcome of OSL dating tests applied to shaft mound deposits. These include a) the extent to which the internal structure of a mound had survived since the initial construction of the qanat, b) whether the sediments forming the mound contain sufficient quantities of coarse grained luminescent minerals with characteristics suitable for dating measurements, c) the degree to which the luminescent grains were optically reset by exposure to daylight before deposition and burial and d) whether an examination of the sediment microstructure reveals aspects of depositional history that potentially may affect the outcome of luminescence age determination.

5.1.1 Integrity of mound

The excavation of a trench that sections part of the mound enables a detailed inspection of the major sedimentary boundaries of palaeosol, construction and maintenance upcast. This also allowed units lying below the mound crest to be examined for evidence of partial rebuilding to offset the effects of natural erosion processes that, for example, may enlarge the shaft throat (Bailiff et al., 2015). Where the depth of palaeosol permits, examination and sampling at deeper levels also provides the opportunity to test for disturbance, modes of deposition and rates of aggradation of the ground surface (e.g., La Balsa Grande). In the four qanat systems examined, the internal structure of the mound, as revealed in the trench sections, appeared to be largely intact, with evidence that the basal deposits overlying the buried land surface were formed from the original construction upcast, the composition of which is expected to be related to the underlying geology into which the shaft and gallery were cut. The contact between palaeosol and construction upcast and the association between upcast and regional geology was confirmed in the mounds examined. As observed at Casa del Manzano, the composition of the upcast may vary within a given qanat system depending on changes in the underlying geological strata and the depth of the shafts, which generally reduces with distance from the mother well. In terms of mound uniformity, a comparison of opposing sections in the same (0.5 m) trench and of sections in two trenches excavated in the same mound (e.g., Ksabi) generally confirmed continuity of the relative stratigraphy where the mound was located on nominally level ground. Where formed on a slope, differences in mound stratigraphy arising from differing post-depositional processes are likely to be encountered, as confirmed in the case of Pocico de los Frailes by excavating two orthogonal trenches.

The duration of use of the hydraulic feature is of particular interest in the study of settlement. The maintenance deposits suggest continued use of the hydraulic system, although the upper layers of the mound containing maintenance upcast are likely to be the most susceptible to disturbance and alteration following deposition, particularly in the case of older hydraulic systems that have been long abandoned. At Pocico de los Frailes, the phases of maintenance upcast deposition were more clearly identified and deposits as late as the 19th century had survived. However, the sequence of OSL dates suggest spatially complex patterns of post-depositional disturbance may arise, particularly in such upper mound deposits. This is likely to be encountered with other gallery and shaft systems, although in the absence of studies of mound structures, a systematic study of the general variation and uniformity of deposits within them is lacking.

5.1.2 Suitable minerals
Testing in advance to establish the suitability of the luminescent minerals for dating is advisable where no previous OSL work has been undertaken in the region of interest. The collection of ground surface grab samples alone may not be sufficient, as found at Ksabi where some of the clay–rich upcast deposits had poor yields of coarse quartz grains and at Casa del Manzano where the highly calcareous upcast deposits lacked suitable quartz. Hence, where possible, the testing of both palaeosol and upcast is advisable, particularly for landscape settings within regions of limestone geology and, given the effort required to excavate a mound, coring of a mound to obtain test samples of the key deposits within the interior would be appropriate.

5.1.3 Optical resetting of grains
The degree to which the luminescent grains analysed were adequately reset before deposition is expected to vary according to the (cumulative) exposure of sediment to daylight before final burial, and consequently may differ between layers within each mound and different hydraulic features. For the majority of samples, the results of the OSL measurements confirmed incomplete resetting of quartz grains before burial, but there was not a simple correlation of the degree of resetting with category of mound deposit (palaeosol, construction and maintenance). Accordingly, the use of OSL measurement techniques that have the capability of ‘single grain’ resolution is essential, which also confirms earlier work in Spain (Bailiff et al., 2015) and Iran (Fattahi, 2015), and the application of the minimum dose model (MDM) is required where the grains are expected to have been partially reset. The coupled use of micromorphological examination to establish the source and mode of deposition of sediments, including an examination of the structural environment of individual grains, has a potentially important role to play in assessing OSL results (e.g., D_e values). For example, where clay-rich deposits contain clods that were not disaggregated in the process of deposition on the mound, coarse grains of quartz on the surface of clods may be adequately exposed to daylight, but those remaining within the interior will not be reset. Where such clods are sufficiently small, their selective removal during conventional sample preparation procedures is problematic, and this potential issue was identified in the field during the Ksabi excavation. Although likely not to significantly influence the outcome of the application of the MDM, this condition can significantly reduce the proportion of grains tested that fall within a minimum dose group, considerably lengthening the instrument time required to date a sample. In contrast, aeolian deposits identified within the mound, if present, are likely to yield grains that are fully reset and can provide a marker in the mound formation history, although their deposition may not be related to a specific phase of deposition (e.g., maintenance).

It is worth noting that, while the MDM serves the purpose of identifying a sub-set of grains (yielding D_e estimates) that are assumed to be fully reset, a means of quantifying the degree of optical resetting in a particular grain is lacking. However, progress is being made in developing alternative models that do not make this assumption for partially reset granular quartz extracted from building mortars (Urbanová and Guibert, 2017). In this work we have also maintained a preference for using quartz as the mineral dosimeter because of its more rapid resetting characteristics and while feldspar minerals remain an alternative for dating work, recent experience in their use (Fattahi, 2015) confirms the problems and issues arising from their generally inferior characteristics when applied to deposits that have a history of limited cumulative exposure to daylight before burial.

6.2 Consistency, accuracy and resolution

One measure of the general consistency of the performance of OSL is provided by a comparison of the age estimates produced for samples assessed to be coeval on the basis of their stratigraphic position and supported by micromorphological analysis. The concordance of dates obtained for the upper palaeosols underlying three different mounds in two networks is encouraging (4% RMSD, Casa del Manzano; 10% RMSD, Ksabi), and similarly for the construction deposits across two trenches (18% RMSD, Ksabi) and maintenance deposits within the same trench (17% RMSD, Pocico de los Frailes). The OSL dates for the Ksabi and Pocico de los Frailes qanats are also consistent with available archaeological evidence in the form of the settlement studies of Tagaos, and the presence of a nearby Roman reservoir, respectively. Unfortunately, the opportunities for further investigation in SE Spain appear to be limited. From our searches of the records of hundreds of qanats recorded in the Spanish provinces of Albacete, Alicante, Almería and Murcia, we concluded that relatively few well-preserved mounds were likely to have survived in the intensively farmed regions, often having been ploughed in, or the upper sections of the shafts lined and capped to control access and erosion, and this may account for the absence of a qanat system dated to the Islamic period amongst those we examined. Also, in such areas, access to field systems for surface find evidence that can link the use of a qanat with historically earlier periods of cultivation is often prevented by the widespread use of intensive horticultural growing methods that cover open farmland.

The general absence of short-lived organic material in mound contexts suitable for radiocarbon testing is likely to continue to restrict opportunities for direct comparisons of OSL dates with independent dating evidence. Better prospects of obtaining such dating comparisons may lie in the examination and testing of hydraulic features that can be directly linked with cultivated field systems (e.g., Avni et al., 2012; Beckers et al., 2013; Rhodius et al., 2013) and settlement activity.

Conclusions

This study of shaft and gallery hydraulic features located in different landscape settings has enabled the luminescence method to be tested more widely, building on a formative methodology that previously had been applied only on single sites in Spain (Bailiff et al., 2015) and in Iran (Fattahi, 2015). By applying OSL techniques with 'single grain' resolution, individual quartz grains were found to be sufficiently bright to enable depositional events as recent as the early 20th century to be dated. The OSL results confirm that the optical resetting characteristics of quartz are better suited to this type of application when compared with the results obtained in previous work with feldspars (Fattahi, 2015). Although coarse quartz grains were present in the majority of the deposits sampled, sediments of highly calcareous or clay-rich composition are potentially problematic, and consequently testing their yield in contexts of interest is important in preparatory work. However, where this problem was encountered with upcast deposits, the testing of the upper palaeosol provided an alternative means of providing a TPQ for dating the construction of the feature. The examination of the internal structure of the shaft mounds also revealed the potential for complex depositional histories, particularly for longer-lived systems, and the excavation of at least one trench is important to assess the depositional history and the potential for disturbance. At a finer scale of analysis, microscopic examination of thin-sections of sediment enabled the source and mode of deposition at different stages of formation of the mound to be assessed, providing essential information that supports the choice of the statistical model applied when analysing OSL equivalent dose (D_e) data.

Of the 33 OSL age determinations produced in the study, the estimated construction dates of the hydraulic features ranged from modern to the Roman period. The evidence of Roman origin of the Pocico de los Frailes hydraulic feature is of archaeological significance because it indicates that this type of technology, already applied in Roman Syria and North Africa (Lightfoot, 1996; Wilson, 2012) for example, had reached Spain well before the Islamic conquest. The dating of the Pocico de los Frailes feature places a marker for a much earlier presence of the hydraulic technology that otherwise might have been overlooked and, moreover, provides the first independently dated qanat in a Roman Spanish context. The study has demonstrated the strong capabilities of luminescence to contribute chronometric data to the study of hydraulic features associated with shaft and gallery systems and further development of this approach would benefit from application to more systems that can be directly linked to dated settlements.

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Table 1. OSL sample locations and dates

Site	Mound/ Trench	Context[1]	Sample	OSL Date[2]	Outcome
(1)	(3)	(4)	(2)	(5)	(5)
Mina Casa del Manzano Jumilla	M1T1	PS	JUM-15-01	AD 1855 ± 20	Modern, indicated by the burial of ground surface during the late 19th century
	M3/T3SF	PS	-09	AD 1865± 10	
	M3/T3NF	PS	-12	AD 1855 ± 10	
La Balsa Grande Totana	M1/T1EF	PS	TOT-15-01	AD 375 ± 200	Construction dated to the mid-18th century, which is consistent with documented irrigation construction in the region.
	“	C	-02	AD 1705 ± 60	
	M1/T1WF	PS	-04	AD 1005 ± 90	
	“	C	-05	AD 1725 ± 60	
	M2/T1EF	PS	-07	AD 1590 ± 90	
Ksabi Guelmim	M1/T1WF	PS	KSA-T1-1	AD 1575 ± 100	Construction dated to the mid-17th century, correlating with archaeological evidence of a second phase of expansion of the Ksabi settlement.
	“	PS	T1-2	AD 1575 ± 40	
	“	C	T1-3	AD 1765 ± 20	
	“	C	T1-4	AD 1785 ± 40	
	“	C	T1-5	AD 1905 ± 20	
	M1/T2NF	PS	KSA-T2-1	AD 1625 ± 80	
		C	T2-2	AD 1695± 30	
		C	T2-3	AD 1655 ± 40	
	M1/T3WF	PS	KSA-T3-1	AD 1645 ± 30	
		C	T3-2	AD 1635 ± 40	
		C	T3-3	AD 1665 ± 30	
Pocico de los Frailes Jumilla	T1NF	PS	JUM-16-01	BC 2635 ± 290	With the most complex mound stratigraphy of the four systems, the construction of the feature is dated to the Roman period, with indication of use extending to the 5th century AD. Reactivated use in the 13th century AD was followed by disuse until the 18th century.
	T1WF	C	-02	AD 5 ± 130	
	“	C	-03	AD 385 ± 100	
	“	M	-04	AD 1825 ± 20	
	T1EF	C	-05	AD 225 ± 120	
	“	M	-06	AD 735 ± 70	
	“	M	-07	AD 1865± 20	
	T2SF	C	-08	AD 625 ± 100	
	“	PS	-09	BC 1065 ± 160	
	“	M	-10	AD 1845 ± 20	
	T2NF	C	-11	AD 455 ± 110	
	“	M	-12	AD 1915 ± 20	
	“	M	-13	AD 1895 ± 30	
	T1WF	M	-14	AD 1775 ± 20	

1. PS= palaeosol; C= construction upcast; M= maintenance upcast
2. The OSL dates, calculated from the OSL ages using a test year of AD 2016, are given with their associated overall error (1σ)

Figures

Figure 1

Map showing locations of sites in Spain and Morocco, where those inspected and those sampled are identified separately.

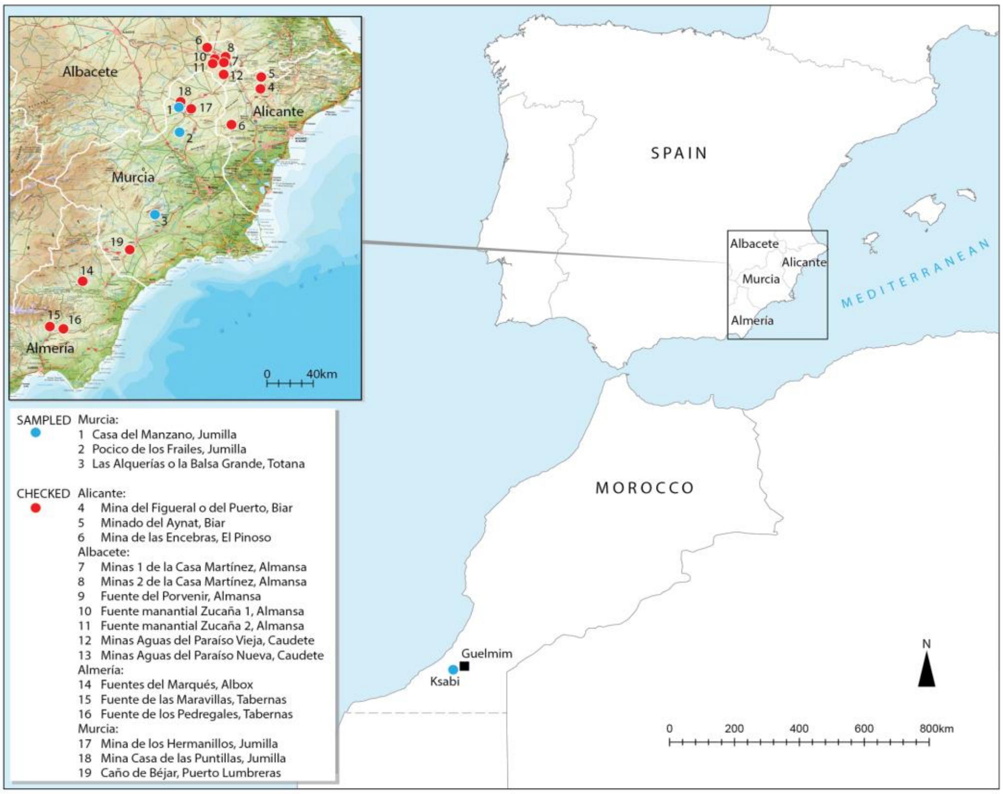


Figure 2

Casa del Manzano, Jumilla. N-facing Section, Mound 3 showing main units overlying limestone bedrock: Palaeosol (301); Construction (302 and 303); Maintenance (306-314). Detailed lithological descriptions are given in the Supplementary Material (Doc. 1). The locations of the sediment samples are indicated by filled circles (OSL) and a rectangle (micromorphology).

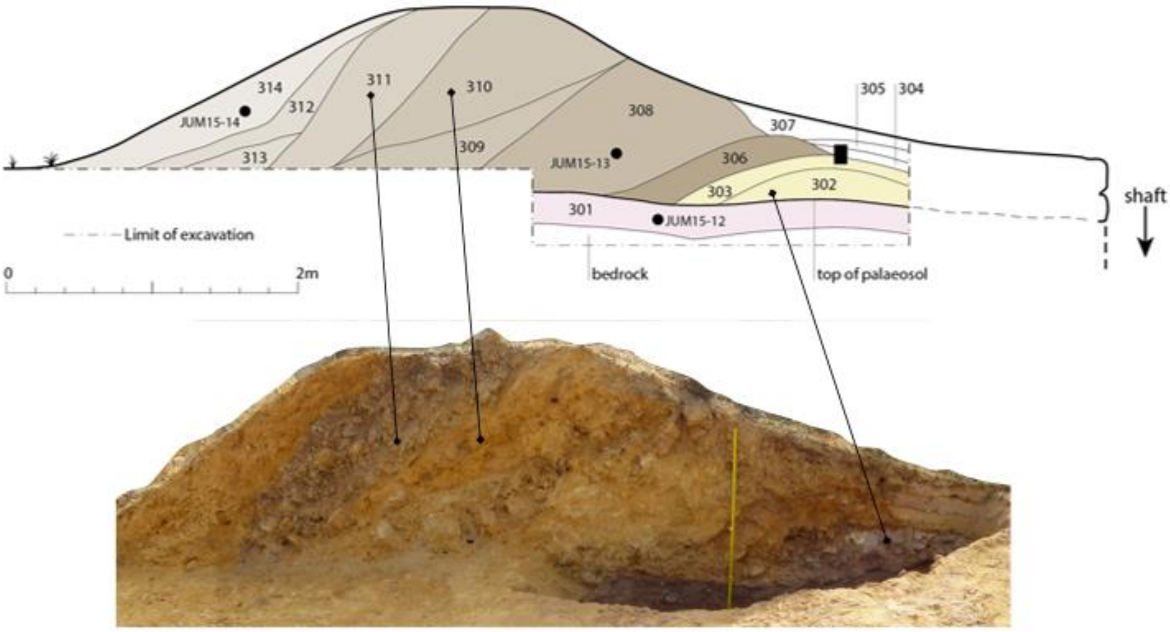


Figure 3

La Balsa Grande, Totana. E facing Section, Mound 1 trench showing main units overlying a conglomerate bedrock: Palaeosol: (Unit 101); Construction (Units 102-104); Maintenance (Units 105-106). Detailed lithological descriptions are given in the Supplementary Material (Doc. 1). The locations of the sediment samples are indicated by filled circles (OSL).

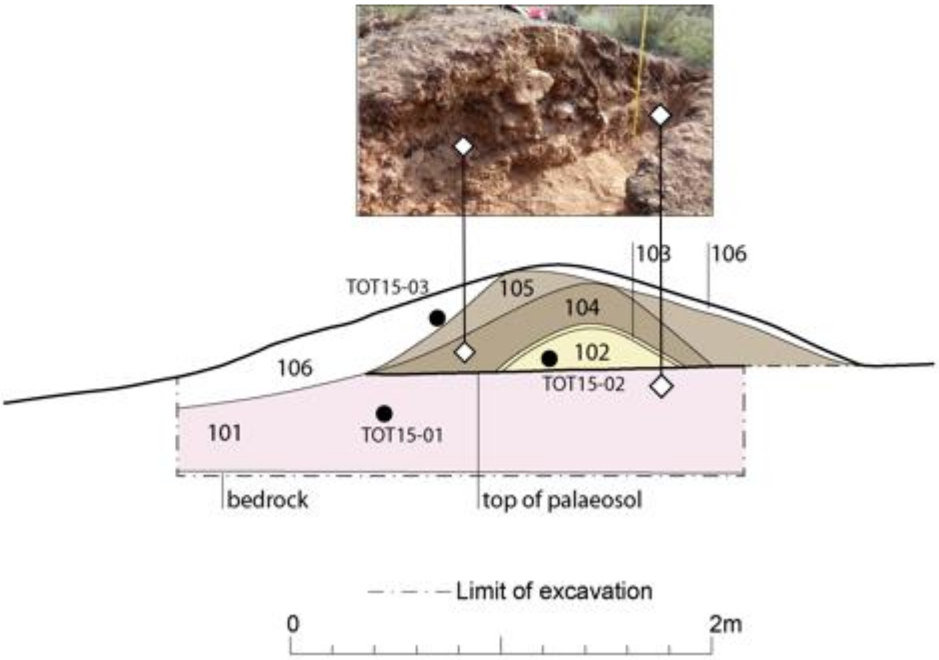


Figure 4

Ksabi, Guelmim. a) West-facing section of Mound 2 in Trench 3, Main units overlying alluvium: Palaeosol: (Unit 301); Construction (Units 302-306); Maintenance (Units 307-308). Detailed lithological descriptions are given in the Supplementary Material (Doc.1); b) Images of the three trench sections of the two mounds, marked with boundaries between various units of the palaeosol, construction and maintenance deposits, together with their translation between trenches indicated by the interconnecting broken lines. The locations of OSL samples, abbreviated to the number assigned within each trench, and the OSL ages in years are also indicated. The locations of the sediment samples are indicated by filled circles (OSL).

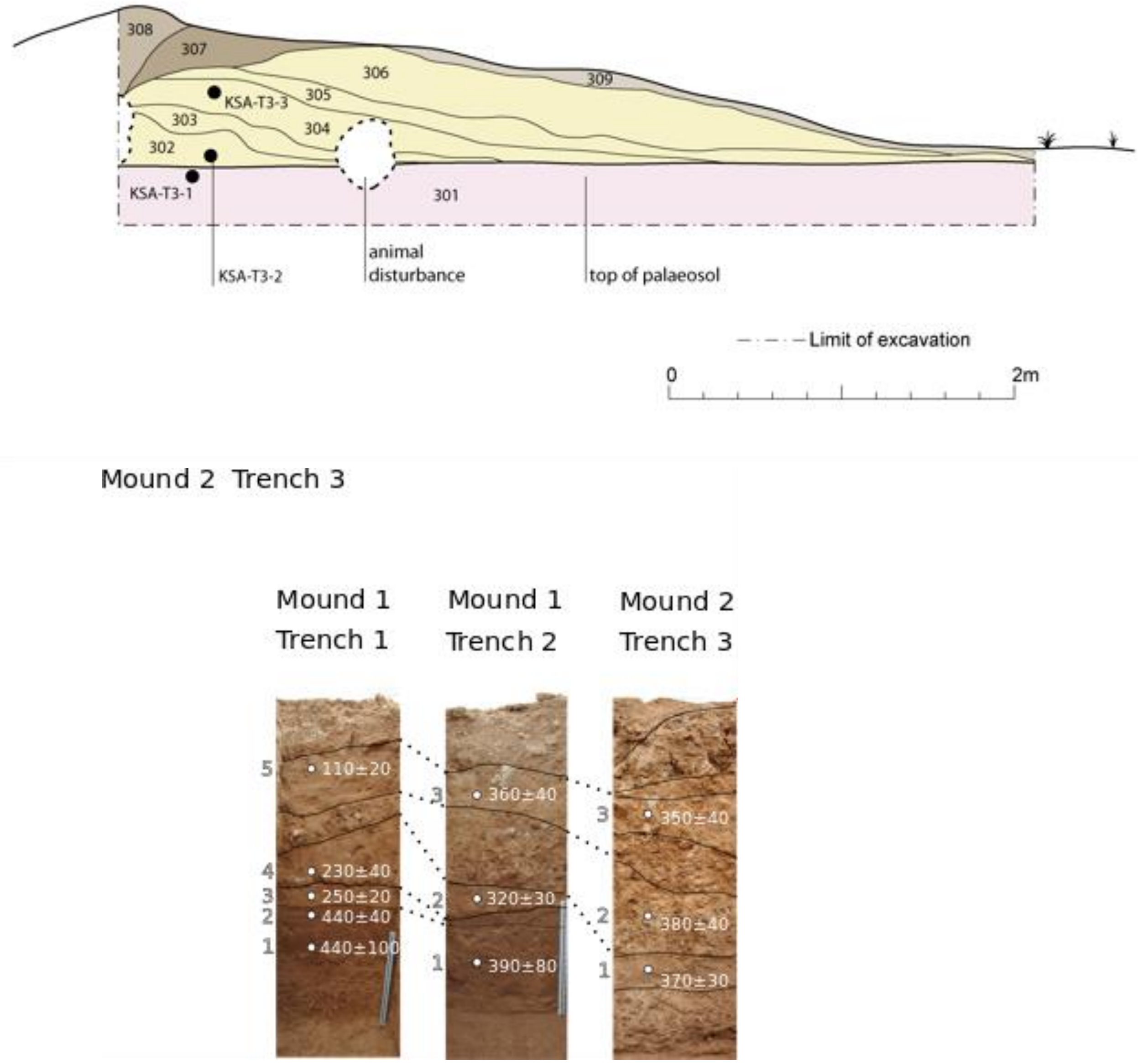
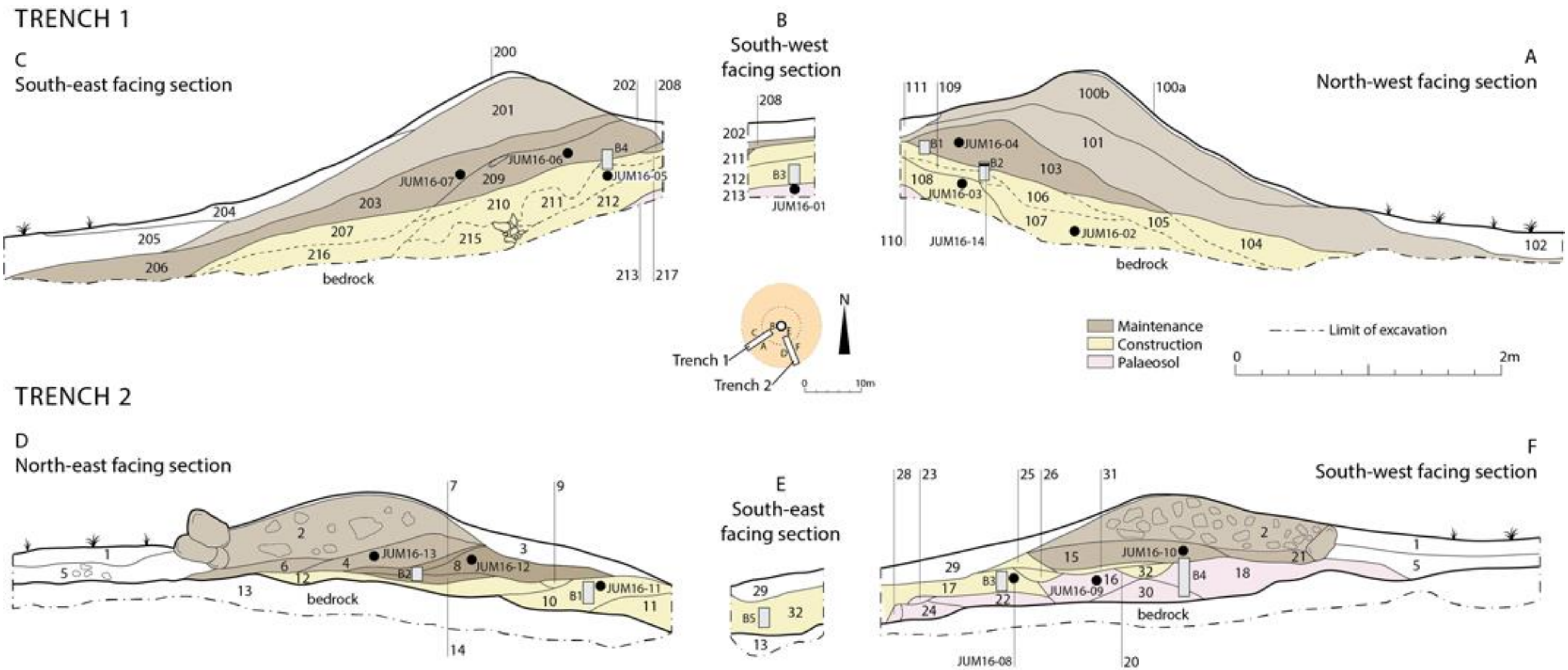


Figure 5

Pocico de los Frailes, Jumilla. Sections of Trenches 1 (a) and 2 (b), expanded to show trench end in centre and opposing faces in Trench 1 and in Trench 2. Main units overlying limestone bedrock indicated by colour shading: palaeosol: (pink); construction (yellow); maintenance (brown). Detailed lithological descriptions are given in the Supplementary Material (Doc. 1). The locations of the sediment samples are indicated by filled circles (OSL) and rectangles (micromorphology, Blocks B1-B4 and B1-B5 in Trenches 1 and 2 respectively).



TRENCH 1
C
South-east facing section
200
201
202
208
204
205
203
209
JUM16-07
JUM16-06
B4
JUM16-05
207
210
211
212
215
216
206
bedrock
213
217
B
South-west facing section
208
202
211
212
213
B3
JUM16-01
A
North-west facing section
111
109
100b
100a
B1
JUM16-04
101
B2
103
108
JUM16-03
106
107
105
JUM16-02
104
110
JUM16-14
bedrock
102
N
Trench 1
Trench 2
0
10m
Maintenance
Construction
Palaeosol
Limit of excavation
0
2m
TRENCH 2
D
North-east facing section
7
9
2
3
1
5
6
4
JUM16-13
8
JUM16-12
12
B2
13
bedrock
10
B1
JUM16-11
11
14
E
South-east facing section
29
B5
32
13
F
South-west facing section
28
23
25
26
31
2
1
29
15
JUM16-10
21
5
17
B3
32
16
18
B4
22
JUM16-09
30
24
bedrock
JUM16-08
20