

# Luminescence dating of qanat technology: prospects for further development

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**Abstract** With few exceptions in which dating is implied by indirect association with adjacent settlements or incorporation of diagnostic artefacts in upcast sediment, individual qanats have proven very difficult to date. This absence of a chronological framework hampers both our understanding of technology transfer, as well as the study of local settlement and landscape evolution and the temporal correlation of land use with climatic and palaeoenvironmental data. However, surface shaft mounds potentially contain a sequence of upcast deposits collected periodically from the tunnel, starting with initial construction and persisting until the last maintenance episode, less any material lost by surface erosion. The sedimentary nature of the upcast lends itself to the application of luminescence dating to determine the burial age, in particular, using the techniques based on optically stimulated luminescence. We examine the results produced by two recent dating studies where luminescence techniques were applied to two qanat systems with the aim of building a chronostratigraphy for the deposits within their upcast mounds. These studies show that the extent to which a complete record of the deposition since initial construction survives may differ between qanat systems, and even shaft mounds within the same system. Providing there is a close coupling of luminescence and sedimentological analysis in the testing of qanat mounds, these formative studies suggest that there are good prospects for introducing a valuable tool in the study of various types of hydraulic feature where upcast has been preserved and guidance regarding further fieldwork is provided.

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## Introduction

Qanats in the past have been widely adopted in arid regions to extract groundwater passively from an upslope aquifer (Manuel et al. 2017; Beckers et al. 2013; Charbonnier 2015; Hermosilla 2008). This technology is thought to have been introduced during the early 1st millennium BC in Persia, but our understanding of the history of its development, together with other types of irrigation systems, is limited by not knowing when individual qanats were constructed. Although well within the range of radiocarbon ( $^{14}\text{C}$ ) dating, suitable organic material is rarely recovered (e.g., Mattingly et al. 2009) from undisturbed contexts that can be securely associated with the construction and use of the hydraulic feature. The absence of absolute dates has curtailed a detailed enquiry of technology transfer and the examination of local settlement and landscape evolution. However, the distinctive ventilation shaft mounds are formed of sediment containing mineral grains with potentially suitable properties for the application of optically stimulated luminescence (OSL) dating techniques (Aitken 1998). When applied to sedimentary deposits, OSL techniques can provide an estimate of when a sediment volume was last buried and they have been widely applied to date sedimentary depositional events and processes of palaeoenvironmental and archaeological interest (e.g., Duller 2004). This has included the dating of hydraulic features in the form of ancient canals (Berger et al. 2004, 2009; Huckleberry et al. 2012; Huckleberry and Rittenour 2014) where the strata preserved within the channel fills proved to be potentially suitable as dating markers. This earlier work on canals essentially formed the background for two independently conducted projects in Iran (Fattahi et al. 2011; Fattahi 2015) and in Spain (Bailiff et al. 2015) that investigated the potential of OSL for dating qanat systems and in this Qanat Workshop paper we review and identify the potential for wider use of the approach to date qanat hydraulic features.

## Shaft mound construction

Despite the many regional variations of the classification of qanats, those reported in the literature are structurally similar, but vary in size, shape and length depending on conditions of hydrology, geology and terrain. The method of construction of the qanat appears to have remained essentially unchanged for many centuries. By digging vertical shafts to provide ventilation within the tunnel, sediment upcast from the gallery is transferred up to the ground surface, some of which is used to form a mound on the shaft rim to prevent the ingress of sediment-laden surface water into the gallery. Subsequently, further upcast is usually added to the mound during cleaning and maintenance events. Given these processes, the mounds potentially contain a sequence of upcast deposits collected periodically from the tunnel, starting with the initial construction and continuing until the last maintenance episode, less any material lost to surface erosion. The extent to which an intact sedimentary record since construction is preserved in the mound depends in part on the degree of intervention and reworking by human activity. Unfortunately, many mounds in regions where agricultural activity has continued (e.g., southern Spain) have been ploughed out, often being considered inconvenient, even dangerous, to farm machinery when they fall out of use, in particular where the pumping of water direct from an aquifer has left the

qanat dry. However, where the mounds have survived, whether since construction or following subsequent rebuilding in the past, two depositional events in the formation of the mound are of particular relevance to dating their construction and use. They are principally (a) the burial of the ground surface by construction upcast and (b) the burial of the upper surface of the upcast mound by the addition of maintenance upcast. By excavating a mound to obtain an exposed section, the main sedimentary units can be examined with the aim of identifying a sequence of the depositional processes forming the mound. The sediment strata contained within the mound stratigraphy, produced by an event-related formation history of this type, are potentially suitable for the application of luminescence dating. Before assessing the potential and limitations of the method based on the formative studies mentioned above, a brief introduction to the main concepts of the method is provided in the following section, together with a discussion of issues related to the composition and modes of deposition of sediment that influence the outcome of its application.

## Luminescence dating of sediments

Luminescence dating is a radiogenic ‘trapped charge’ method (Aitken 1998) where the chronometer mechanism is based on the accumulation and storage of electric charge with time that occurs within grains of certain crystalline minerals with luminescent properties, such as quartz and feldspar. The cumulative charge stored increases with time because of the effect of ionising radiation emitted by naturally occurring radionuclides (uranium, thorium and potassium) that are present within most inorganic environmental materials, soil, sediment and rock. Luminescent grains, when exposed to ionising radiation, receive an absorbed dose (the unit is the gray, Gy) and they have the capability to register the cumulative effects of the radiation dose received by the grains. By stimulating grains previously exposed to ionising radiation, the release of stored charge leads to the emission of light, the intensity of which is related to the cumulative radiation dose. The form of stimulation employed when dating sediments is usually optical (typically blue light), producing OSL which is detected at other wavelengths (within the ultraviolet range for quartz) and the term OSL dating is commonly used when applying this experimental technique. For grains within a dating sample the cumulative dose received during burial, referred to as the equivalent dose,  $D_e$ , is unknown. To determine the latter, measurements are performed involving exposure of the grains to a known radiation dose, repeating the optical stimulation, and comparing the intensities of the luminescence recorded during each measurement, which enables  $D_e$  to be calculated on the basis of proportionality. In this way, luminescent grains perform the function of ‘dosemeters’ and it is the determination of  $D_e$  that is the objective of the experimental luminescence technique. The rate at which radiation dose is delivered to the grains is largely governed by the nature of radionuclides within the material surrounding the grains, the concentrations of which determine the intensity of radiation exposure and, in turn, the rate at which the stored charge accumulates in the grains. Analytical techniques enable the concentrations of the radionuclides to be determined and, from these, the rate at which dose is absorbed by the grains can be calculated (referred to as the dose rate,  $D_r$ , typically several milligray per year (mGy/a). Cosmic rays, which comprise high-energy ionising radiation, also provide a contribution to the stored charge in grains, but they typically only form a small part of the total dose rate. In addition, some of the dose rate components can be derived from on-site

measurements using portable instrumentation. By determining the quantities  $D_e$  and  $D_r$  in the laboratory, the time elapsed since resetting and burial of a sediment—the luminescence age—is calculated by evaluating the age equation, where,

$$\text{Luminescence age} = D_e/D_r,$$

and where  $D_r$  is an average dose rate during the burial period. The uncertainty in the age is calculated by the laboratory for each sample (Duller 2008).

A critical issue when applying OSL to the dating of all types of sedimentary deposits is the resetting of the chronometer mechanism before burial that removes previously stored charge and which is achieved by exposure of grains to sunlight (Huntley et al. 1985). Following resetting it is essential that sediment in the volume of interest is not re-exposed to light following burial and remains under dark conditions. Generally, quartz requires a significantly shorter exposure time for resetting compared with the feldspathic minerals: Godfrey-Smith et al. (1988) showed that 10 s of direct sunlight exposure was sufficient to approach full resetting of quartz grains, whereas 9 min exposure was required in the case of potassium feldspar grains. For upcast deposited under conditions where limited disaggregation of the sediment may have occurred before burial, there is a likelihood that only some of the grains were completely reset, the remainder retaining an inherited quantity of charge. This may arise if upcast is retrieved in buckets and upturned on the surface without much dispersal, and unexposed grains within upcast extracted from the gallery would have been last reset when originally deposited (i.e., on a geological timescale). In these circumstances quartz is the preferred mineral because of its generally faster resetting characteristics. However, whether quartz or feldspar grains are measured, partial resetting potentially causes the luminescence age to be overestimated. Fortunately, the instrumental capability has been developed to perform determinations of the cumulative dose  $D_e$  with individual grains, and this enables grains with different degrees of pre-burial resetting to be segregated, providing the grains have intrinsically bright luminescence characteristics. Such 'bright' grains are commonly present in sedimentary deposits, but only as a small proportion of the total, typically occurring as several per cent or less of the total. By analysing many individual grains, the degree of resetting can be assessed—this is referred to as 'single-grain' analysis, for which several statistical models have been developed (Galbraith and Roberts 2012). Where a dating sample lacks 'bright' grains, an adequate OSL signal may only be obtained with many grains (e.g., ~ 50 grains) included in the measurement, referred to as multiple-grain or single 'aliquot', and the ability to detect partially reset grains diminishes as the number of grains contributing to the detected OSL signal increases.

A further factor influencing the preference for quartz is the charge storage mechanism which is stable over dating timescales for quartz, whereas this is not always the case for feldspars. A long-term loss of stored charge over time (i.e., during the burial period), referred to as anomalous fading (Aitken 1998), is commonly observed in feldspar minerals and requires an empirical correction to avoid underestimating the age.

### Shaft mound stratigraphy and sampling for OSL

As indicated in the above discussion, the OSL method requires samples of sediment to be extracted from the volume(s) of interest and conventional sampling procedures employ steel tubes that are hammered horizontally into a profile. In the case of the relatively fragile shaft mounds this approach may disturb stratigraphic control, causing different deposits to

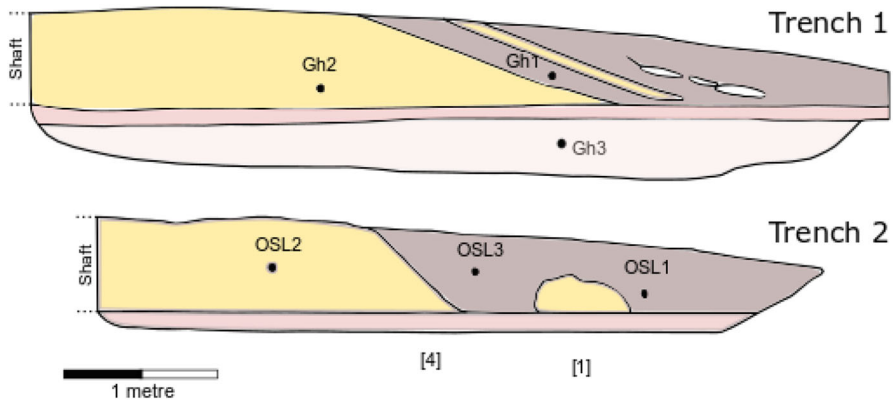
be mixed in the sampled volume. Some boundaries within mounds, such as the transition from the original ground surface to the initial construction layer, may be difficult to identify visually in the field, either because of partial and/or complete erosion and bioturbation of horizons, or compaction from younger overlying sediment. Better sampling selection is obtained by excising whole sediment blocks from which material can be extracted under controlled lighting conditions in the laboratory. This approach enables thin layers or horizons of interest, such as the ground surface buried by the construction process, to be sampled and tested using OSL procedures. This also provides the opportunity to prepare thin sections, the analysis of which enables a more detailed study of the microstructure of unconsolidated sediments using micromorphological techniques (Courtney et al. 1989; van der Meer and Menzies 2011). An OSL sampling issue of particular importance in the field is the penetration of light into a volume selected for sampling and in some circumstances extraction after sunset or with light shielding may be required. Using either approach, samples are usually wrapped in opaque plastic film to prevent further penetration of light.

## Application to Miam and Bureta qanats

The studies at the Miam and Bureta sites illustrate issues that are likely to affect the performance of the method when applied to other qanat systems. These primarily concern the characteristics of the luminescent minerals and the geological sources of the sediment rather than the assessment of the dose rate. Although equal attention to determining the latter is required, the two sites had not required special procedures beyond those established for routine dating, further details of which are discussed in the relevant publications (Miam, Fattahi 2015; Bureta, Bailiff et al. 2015).

### The Miam qanat

The Miam qanat, located in eastern Iran within an area of fault activity (near to the Dasht-e-Bayaz fault), is of interest in reconstructing a history of seismic activity because the qanat networks in the region were displaced by past seismic movements and the galleries subsequently realigned by the qanat engineers. Trenches cut through two mounds exposed sections that revealed a lateral progression of deposits within the mounds and OSL samples were obtained from four sedimentary units (Fig. 1). The results of laboratory testing of grains extracted from the sampled deposits indicated that the quartz grains were unfortunately of a 'dim' variety, but that the feldspar grains were sufficiently bright, enabling determinations of  $D_e$  with individual grains. Previous tests of the stability of feldspar grains found in sediments from the region were reported to have shown an absence of anomalous fading effects. However, very few of the feldspar grains tested were found to be suitable for determination of  $D_e$  and, in the case of sample Gh2 (construction upcast) from Trench 1 for example, of 7500 grains tested individually, 80 grains had satisfactory luminescence characteristics. From the latter, only 10 grains were identified by statistical analysis to form a group of more completely reset grains, the  $D_e$  values for which were used in the calculation of the age (Gh2,  $3790 \pm 500$  years). Nonetheless, the other two age estimates obtained for samples from the same trench, of  $9000 \pm 600$  years (sample Gh3, palaeosol) and  $1920 \pm 300$  years (sample Gh1, maintenance deposits), are stratigraphically consistent. In Trench 2, no feldspar measurements were reported and the age



**Fig. 1** Sections of trenches 1 and 2 of the Miam qanat showing the main lithostratigraphic units and the locations of the six OSL samples, Gh1-3 and OSL1-3. Colour Key: light pink, alluvial gravels; pink, palaeosol; yellow, gravel upcast; brown, silt upcast. The OSL ages, given with 1 sigma error ranges, are: Gh1 ( $1920 \pm 300$  years); Gh2 ( $3790 \pm 500$  years); Gh3 ( $9000 \pm 600$  years); OSL1 (not dated); OSL2 ( $4400 \pm 800$  years); OSL3 ( $2280 \pm 300$  years). OSL ages obtained using minerals and techniques discussed in the main text. (Redrawn from Fattahi 2015, Fig. 6)

estimates for samples OSL2 (construction) and OSL 3 (maintenance) of  $4400 \pm 800$  and  $2280 \pm 300$  years were obtained using multiple-grain aliquots of quartz. These dates are consistent with the comparable deposits tested Trench 1. While the similarity of the lower range of  $D_e$  values between individual feldspar grains and single aliquots of quartz (containing multiple grains) would be expected to provide a greater confidence in the estimate of the burial dose using two minerals possessing differing rates of resetting, the overlap of the OSL ages may be a fortuitous occurrence of grain averaging. Under the conditions encountered at this site age estimates obtained with multiple grain aliquots of quartz drawn from the population of poorly reset grains would be expected to be greater than those obtained with feldspar grains that had been fully reset. This also highlights an aspect of the statistical model applied to the analysis of  $D_e$  values for single grains where not all the grains were fully reset (in this case, the minimum dose model, MDM). Whereas the MDM assumes that there is a sub-population of grains that were fully reset, the group of  $D_e$  values identified by the analysis may have been derived from grains that were the most, but not fully, reset before burial. The scope for interpreting the OSL results under these conditions is consequently limited and the luminescence age calculated likely to correspond to a terminus post quem for the construction date.

## The Bureta qanat

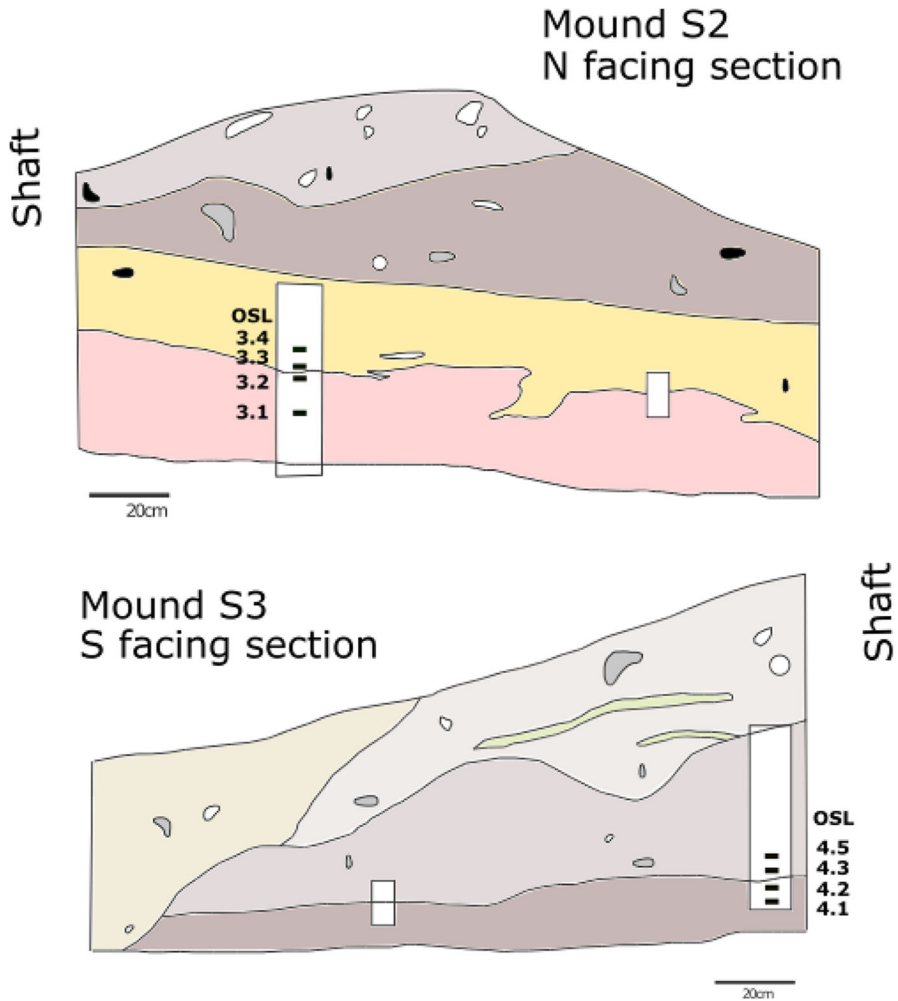
This relatively short qanat of  $\sim 170$  m is located in the Huecha Valley, near the village of Bureta in the province of Zaragoza, Aragón, in Spain. This region is one of the most arid of Europe and the study of irrigation is of particular interest in examining the sustainability of past communities (Gerrard and Gutiérrez 2012). The sedimentary geology, comprising beds of marls and gypsums, is well suited to the construction of qanats that tap the aquifer within the alluvial fans. Bureta appears to be the only hydraulic feature of this type in the Huecha Valley and although records are available for other irrigation networks operating

during the medieval and post-medieval periods (Gerrard 2011), the construction of the qanat is absent from these accounts. Pottery recovered from the palaeosol beneath one of the mounds (Mound S2, discussed below) was both late prehistoric and Roman, and doubtless associated with two nearby sites identified by fieldwalking. However, lacking direct dating evidence, construction of the qanat is assumed to have occurred after the 8th century AD during the period of Islamic administration, although the qanat is connected to a complex irrigation system that has evolved and changed in response to land-use and climatic change in the region during the last 2000 years.

The qanat mounds today are modest in size, being less than 1 m high and contained within an overall diameter of up to 8 m; of the six shafts, three mounds were investigated. Most of the shaft throats had been enlarged by erosion or collapse, causing parts of the mounds to extend further from the central axis of the shaft. Selecting the least eroded section of the three mounds, a narrow trench was cut through each to reveal their internal sedimentary structure, and within one of the mounds, an additional trench was cut to test the consistency of results from the same mound. Sections of trenches cut in the mounds of two adjacent shafts (S2 and S3) are shown in Fig. 2. The locations of the sediment blocks were placed to contain the required horizons below and above the presumed ground surface boundary, one extracted for luminescence testing and the other for micromorphological analysis, as indicated in the figure. The palaeosol, construction and maintenance deposits at Bureta contained ample quartz with individual grains of high luminescence brightness, and an OSL measurement procedure was applied to small aliquots of quartz grains that provided the equivalent of single grain analysis. The OSL dates obtained for the two sample sections of mounds S2 and S3, listed in the caption to Fig. 2 are generally consistent with the stratigraphic order of the samples, showing an increase in age with depth.

The OSL dates for the basal construction deposits (3.3, AD 1230  $\pm$  70) and the upper palaeosol (3.2, AD 1080  $\pm$  260) of the S2 shaft mound overlap, indicating that the ancient ground surface in S2 had been preserved, partly by a rate of aggradation of the ground surface (the OSL dates indicate a ground surface aggradation of ca 15 cm within 500 years) that was sufficient to isolate it from modern surface activity. However, the relatively large uncertainty associated with the date for sample 3.2 reflects a mixing of the sub-surface sediment with deeper deposits before burial (Bailiff et al. 2015), pointing to the potential for disturbance within these mounds. The OSL date obtained for a sample taken from the later maintenance deposits (3.4, AD 1430  $\pm$  125) confirms that use of the qanat extended into the 15th century AD. Although samples higher in this mound were not tested, the sequence of OSL dates (4.1, AD 1500  $\pm$  45; 4.2, AD 1600  $\pm$  45; 4.3, AD 1715  $\pm$  70; 4.5, AD 1630  $\pm$  135) obtained from the adjacent mound, S3, is consistent with the mound stratigraphy. While the OSL chronostratigraphy for each mound is internally self-consistent, the sequence in S3 is much more recent than that in mound S2. This apparent disagreement was resolved by examination of the sediment thin-sections for mound S3 (Bailiff et al. 2015, Supplementary Material) which indicated that samples 4.2 and 4.3 had been taken from two phases of upcast deposit and consequently the sequence had not captured the palaeosol lying below the buried ground surface. The sediment structure immediately below the boundary suggested a period of stabilisation and this had been mistakenly interpreted in the field as a buried ground surface. The OSL dates produced for the third mound (S4, not shown; see Bailiff et al. 2015) were similar to those obtained for mound S3, indicating a span of deposition between the mid-16th and early 19th centuries AD. One plausible explanation proposed for the contrast in preserved sedimentary record between S2 and the other two mounds is the effect of erosion of the shaft wall, resulting in the loss of the formative construction deposits and leading to





**Fig. 2** Sections recorded for excavations of mound S2 and mound S3. The rectangular outlines indicate the position of blocks extracted for OSL and micromorphological analysis, where the locations of the OSL samples are indicated by bars. The OSL dates, given with 1 sigma error ranges, are: OSL 3.1 ( $605 \pm 250$  BC); 3.2 (AD  $1080 \pm 260$ ); 3.3 (AD  $1230 \pm 70$ ); 3.4 (AD  $1430 \pm 125$ ). OSL ages were obtained with quartz samples applying techniques as discussed in the main text. Colour Key: pink, palaeosol; yellow, construction upcast; brown, maintenance upcast. (Redrawn from Bailiff et al. 2015, Supplementary Material)

rebuilding of the mound during the early 16th century AD. In terms of land usage and water management, the persistence of upcast deposition into the 17th century AD has important implications for the continued use of the qanat following the forced expulsion of Muslims from the region in AD 1610.



## Guidance for future work

The interpretation of the sedimentary sequence that defines key stages in the shaft mound formation process, notably the burial of the ground surface by the construction deposits and subsequent phases of deposition of maintenance deposits, necessarily governs the selection of sediment volumes that are sampled for OSL dating. Since this impacts on the reliability of the chronostratigraphy constructed, it is desirable that provision is made during the fieldwork to obtain sediment blocks containing the same strata for more detailed analysis of the sediment structure in the laboratory using micromorphological techniques. Also, the blocks enable finer resolution sampling of OSL samples which may be required, for example, to test for differences in the depositional ages between the major boundaries of interest, such as the uppermost layers of the palaeosol and the basal layers of the construction deposits, and similarly between later phases of maintenance deposits. Equally, depending on the landscape setting of the qanat and historic practices of land use (e.g., ploughing), ground disturbance is also a potentially serious issue. Finally, the penetration of light into the interior of a cut section, or an excised block, could give rise to the partial resetting of grains and the creation of a minimum dose group that is an artefact of the sampling process rather than the process of mound formation.

The study of the Spanish qanat illustrates the importance of examining the depositional sequences preserved in different mounds, especially when determining the relationship between deposit types and boundaries. Excavating and sampling more than one section of a mound and comparing the chronostratigraphies provides one means of testing the reliability of the interpretation of the site formation processes, coupled with detailed micromorphological investigations of the major horizons of interest. Also, incorrect assessments made in the field affecting the limits of excavation may restrict the overall range of samples obtained and it will be particularly important during future work to develop a means of obtaining confirmation of the presence or absence of the primary horizons associated with the construction phase of the hydraulic feature.

The mineralogy of the sediment sources forming the mound deposits and the luminescence characteristics of grains extracted from them play a pivotal role in determining the extent to which the potential of OSL techniques can be realised. The investigations at both sites confirm, as expected, the occurrence of partial resetting of grains in upcast deposits before burial, for which the availability of luminescence analysis at the level of individual grains is essential. The more rapid resetting characteristics of quartz favours the use of this mineral for the evaluation of the equivalent dose,  $D_e$ . While this mineral is commonly present in sediment deposits, the luminescence characteristics of quartz varies according to geological source and transport history of the sediment, and in some regions the quartz fraction may lack the presence of 'bright' grains, precluding the possibility of performing OSL measurements with individual grains. In these circumstances measurements with feldspar grains provide an alternative means of determining  $D_e$ , but, with the likelihood of partial resetting in upcast features and longer periods of light exposure required for the resetting process in feldspars, the latter may produce overestimates of the depositional age, as would be expected with the quartz OSL ages and, using either mineral, the age calculated may only represent a maximum age.

The primary motivation for applying OSL techniques to the dating of hydraulic features such as qanats—the general absence of diagnostic dating material associated with the construction of the qanat—inevitably presents a difficulty in testing the veracity of the OSL dates against independent dating evidence. Although the reliability and accuracy of the

OSL methodology is generally well proven across a wide range of depositional contexts (e.g., sand dunes, Banerjee et al. 2003; Holocene fluvial systems, Kermode et al. 2013; Middle Palaeolithic sites, Jacobs et al. 2016), the studies undertaken at Miam and Bureta illustrate a range of issues specific to upcast deposition that will require careful attention to detail, particularly in fieldwork, to build a sound body of results. To help achieve this, the following issues should be addressed when planning a sampling strategy:

To avoid unproductive fieldwork, it is advisable to undertake preparatory testing of the OSL characteristics of the minerals contained within both upcast and the palaeosol.

Archaeological excavation and topographical recording of trenches of sufficient length to establish the full width of the shaft and mound; exposing two sections within at least one upcast mound is advisable to test for disturbance within the mound.

It is essential that a series of samples is tested from deposits both above and below the buried ground surface to provide age estimates for the burial of the original ground surface (upper palaeosol), the deposition of the initial construction upcast (basal upcast), and also subsequent phases of deposition of maintenance upcast.

A detailed examination of the sedimentary structure of the mound deposits should be undertaken, applying micromorphological techniques, where available, to assess the effects of pedogenic and bioturbation processes and other environmental evidence contained within the deposits, particularly in the regions of contact between upcast and the buried ground surface.

The gathering of sufficient background contextual information, from oral evidence and written sources of information such as maps and surviving historic documents, to enable a wider understanding of the hydraulic landscape and settlement pattern gathered by archaeological prospection.

## Conclusions

Currently available techniques for sedimentological and luminescence analysis are suitable for building a chronostratigraphy of the deposits within an upcast mound of a qanat. However, depositional processes may give rise to partial resetting of the grains before burial and for this reason OSL techniques capable of individual grain resolution are the most appropriate. In these circumstances a close coupling of luminescence and micromorphological analysis is important because of the reliance placed by the luminescence techniques on the depositional histories that are reflected in the sediment microstructure. The extent to which a complete record of sediment deposition since initial construction of the hydraulic feature survives within a mound may differ between shaft mounds within the same network, and the testing of several mounds within a network is therefore advisable. Further work on a wider range of sites will enable better assessment of its reliability, and the testing of independently dated qanats, although hitherto elusive, will enable the luminescence methodology to be validated more robustly. Nonetheless, the formative work completed so far suggests that there are good prospects for introducing a valuable tool in the study of various types of hydraulic feature where upcast has been preserved in the form of mounds. Other types of hydraulic earthworks with subterranean tunnels that do not directly tap the aquifer may also benefit from the application of OSL. By employing dating approaches discussed in this paper, the potential now exists to develop an integrated study

that sets well-dated features of the hydraulic infrastructure within an appreciation of irrigable spaces and their wider landscape evolution.

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