

Slip Rate Determination of Dasht-e Bayaz Fault Using Single Grain OSL Dating of Miam Qanat System in Eastern Iran

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ABSTRACT

This article uses, for the first time, the absolute age for a Qanat system, to determine the slip rate of an earthquake fault. In Iran, many of Qanat galleries were dug in the vicinity of, or directly upon, active faults. In some areas such as Dasht-e Bayaz fault, line of craters are displaced by the activity of the fault, which lead to dry Qanat stream, and consequently to dig new shafts by habitants. By means of measuring the offset between new shafts and old shafts, and considering Qanat antiquity, the estimation of fault slip-rate, which is one of the prominent elements in hazard assessment, becomes possible. This study uses absolute age for a Qanat system, obtained through optically stimulated luminescence dating of grains in spoil heaps of Qanat wells. Feldspar single-grain dating of silt sediments that overlie the construction spoil show that the Miam Qanat was maintained until at least 1.6-2.6 ka. Combination of this age and the 10 meter displacement of Qanat line of shafts by Dasht-e Bayaz fault provide a slip rate of 5.2-4.3 mm/yr for this fault.

Keywords:

Iran, Dasht-e Bayaz,
OSL dating, Slip-rate

1. Introduction

The Qanat (also referred to as Karez in Iran and other names in other countries) is a sustainable system of underground irrigation channels. It provides water for irrigation and domestic use. It uses gravity in order to tap water in highlands from beneath the water table at its upper end and continuously distribute it through gently sloping tunnels to a ground surface outlet at tunnel lower end.

The Qanat design was so simple and effective that it was adopted in many other arid regions of the Middle East and around the Mediterranean. Along

the length of the Qanat tunnel, a series of vertical shafts were used for excavation of the tunnel at intervals of 10 to 140 meters to remove excavated material and to provide air circulation, light and access for maintenance (Figure 1). It can be marked on aerial photos by a line of circular craters which is often extended several kilometers long (Figure 2). Earth and rock excavated from the tunnel face are winched to the surface through the shafts. Sightings over a pair of oil lamps help to keep the tunnel diggers' progress on a straight line. A lamp flame that burns badly also gives warning of bad air.

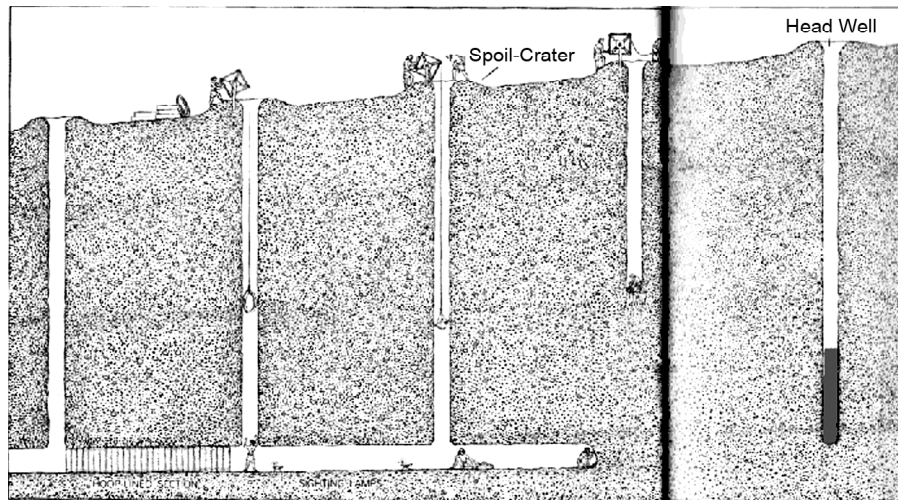


Figure 1. Schematic cross-section through part of a Qanat system; Excavation of a Qanat begins at the downhill end after a trial well (right) has successfully tapped the uphill water table. Where the gradually sloping tunnel passes through zones of loose earth (left) hoops of tile support the walls, but a tunnel generally lacks masonry except at the discharge point [1].



Figure 2. Example of a line of circular craters; Spoil from the excavation of the Qanat and from subsequent periods of maintenance is piled around the vertical access shafts to provide a wall to protect the shafts and the tunnel below from erosional damage from the inflow of water during a heavy desert rainstorm [1].

Before the tunnelers break through to the head well, men at the surface hail it dry. The main gallery taps elevated ground-waters beneath highlands and allows water to flow underground to low-lying agricultural regions, thus minimizing loss through evaporation (Figure 1).

In most seismic regions, the earthquake faults are located at the boundary of plains and mountains where streams or Qanats provide water and fertile soil for settlement and agriculture. As a result, it seems that the earthquakes often exactly target the human population centers. In some parts of Iran, such as North Tabriz fault (Figure 3), and Dasht-e Bayaz fault (Figure 4), the line of wells of the Qanat

systems have been displaced by faulting, which lead to dry Qanat stream and consequently to dig new shafts by habitants. For example in the case of Qanat that was displaced by North Tabriz fault, new shafts and canal (A in Figure 3) was dug after the older canal (B in Figure 3) was offset right-laterally for about $11.7 \text{ m} \pm 0.5$ [2].

If we can date the age of Qanat wells displaced by Earthquakes faults and measure the amount of offset, we can estimate the fault slip-rate, which is an important factor for Earthquake hazard assessment. The existing constraints on age of ancient Qanats in Iran are circumstantial and are typically assigned from archaeological investigations of

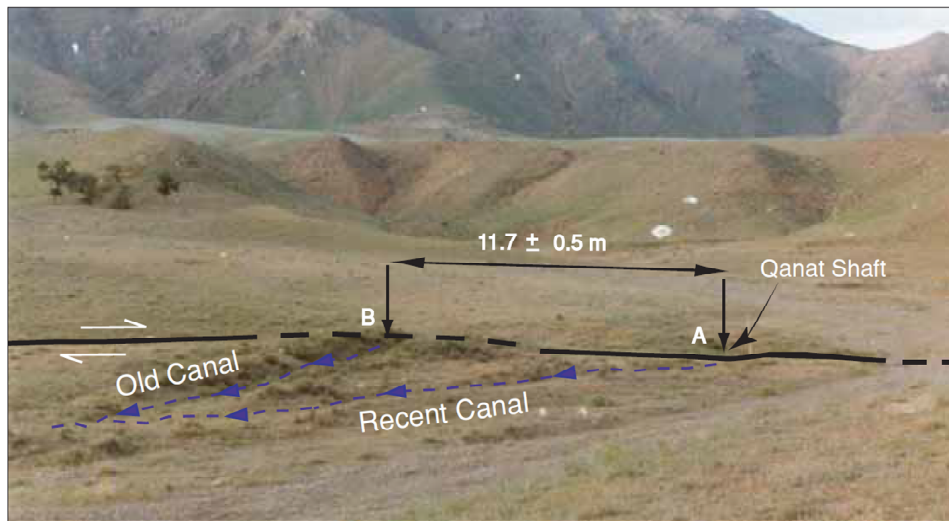


Figure 3. The North Tabriz Fault has displaced the old Qanat tunnel (looking north). The distance between old canal and its original position (i.e. the Qanat shaft) is 11.7 m. The new canal is built where the old canal used to be (from Hessami et al. [2]).

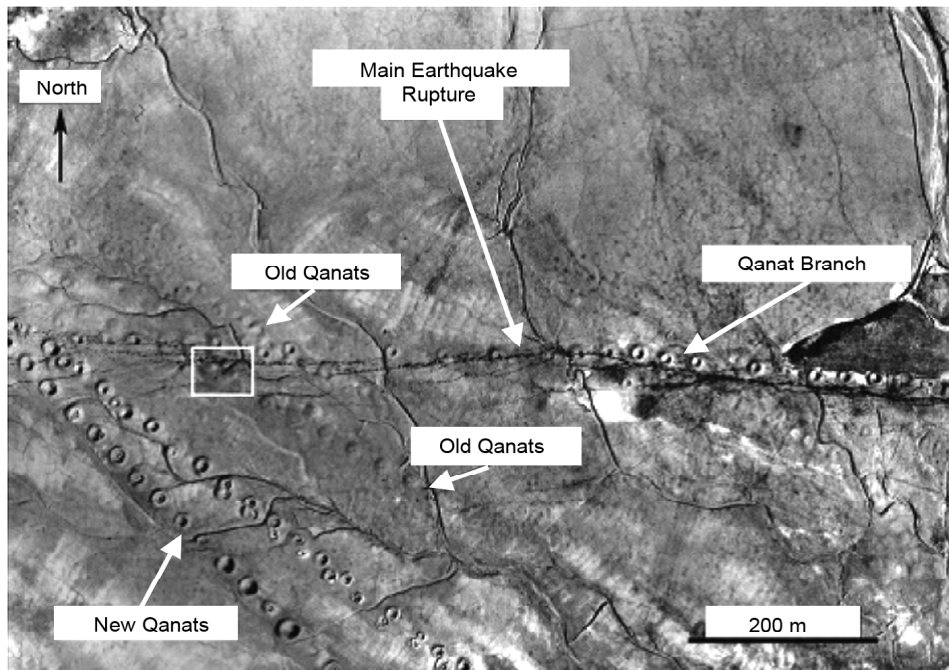


Figure 4. Aerial photo of Qanats in the Nimbluk valley, taken after the 1968 Dasht-e Bayaz earthquake. The white box shows the location of current sampling [4].

nearby habitation sites. The method of Qanat construction and maintenance has remained almost the same within last thousands of years. Vertical shafts were dug and material removed from underground during the construction or maintenance of the tunnel, and spread around the shaft to form the circular spoil heaps (up cast). This should have happened during the day time. A proportion of the grains in the spoil will have been reset by exposure to sunlight, which makes it suitable for optically stimulated luminescence dating.

This document explains the sampling site and the

dating method. It will explain why the attempt to date spoils associated with Miam Qanat using quartz single aliquot OSL procedures were much earlier than expected, and how the quartz single grain OSL procedures has tried to overcome this problem and present the slip rate of the fault.

2. Sampling Site

The Dasht-e Bayaz left-lateral strike-slip fault in east-northeast of Iran is an important feature within the active tectonics of Iran. On the August 31, 1968, the western 80 km of the left-lateral Dasht-e Bayaz

fault was ruptured in an earthquake of Mw 7.1 that killed an estimated 7000 to 12000 people [4]. The Miam Qanats were first noted following the 1968 Dasht-e Bayaz earthquake. Detailed mapping of the rupture was facilitated by a post-earthquake aerial photographic survey [4], which also enabled the identification of several separate generations of Qanat (Figure 3).

In the thirty years following 1968, the region has been subject to numerous further destructive earthquakes, including four events of Mw 5.5-6, four events of Mw 6-7, and a further two events of Mw 7.1. The first of these two Mw 7.1 earthquakes, the Khuli-Buniabad earthquake of the November 27, 1979, ruptured the eastern 60 km of the Dasht-e Bayaz fault. The second (the May 10, 1997 Zirkuh earthquake) ruptured the north-south right-lateral Abiz fault. Together, the sequence of destructive earthquakes within 30 years at Dasht-e Bayaz forms one of the most outstanding examples of clustered large-magnitude seismic activity in the world (e.g. Berberian et al. [5]; Berberian and Yeats [6]). Determining the slip rate and recurrence interval between large events on the Dasht-e Bayaz fault is important in estimating the hazard posed by the fault to local populations and also for the more general issue of the clustering in time of large earthquake events.

The extreme antiquity of the oldest series of Qanat mounds is inferred from their level of preservation, and also because they appear to be

displaced left-laterally by 10 m across the Dasht-e Bayaz fault, at a place where the 1968 displacement was only 3 m (Figures 4 and 5). This observation indicates that they have been displaced by multiple earthquakes upon the fault. Modification of the land surface around Miam during the past few decades has eradicated most of the ancient Qanat wells. However, it was possible to identify a short stretch of four consecutive mounds and to locate these four wells in the field (Figures 5 and 6). Besides, the displacement in field was measured, which suggested 10 m left lateral is correct.

Short trenches were excavated through circular spoil heaps (Figures 7 and 8). The central well was not excavated, dating of which would simply tell us when the Qanat was abandoned, but instead focused on identifying the pre-construction land surface as well as observing the main sedimentary features of the spoil. Log of the north wall of the trench revealed four main sedimentary units. A lower unit (palaeosol) was composed of horizontally-bedded cobbles from which sample Gh1 was collected. This unit graded rapidly upwards into a thin, fine-grained, silty unit with a concentration of cobbles at its upper surface (no sample was collected from this unit). We infer that these two lower units represent the land surface immediately prior to construction of the Qanat, with alluvial gravels overlain by a thin inflationary palaeosol, with partially developed desert armour at its surface.

The two upper sedimentary units exposed in the

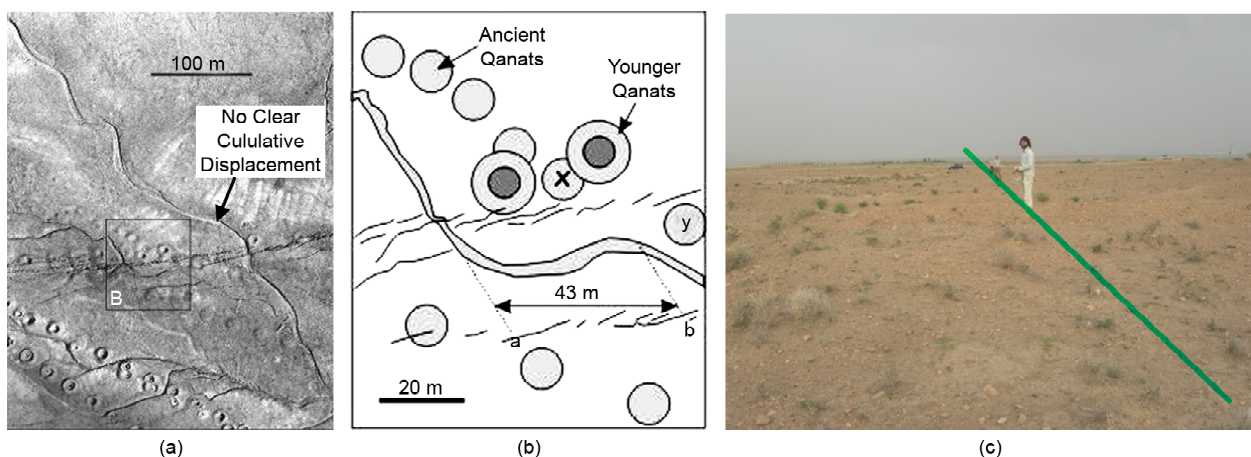
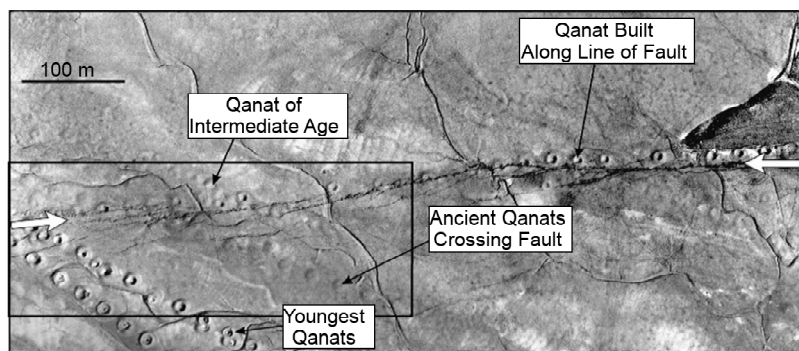
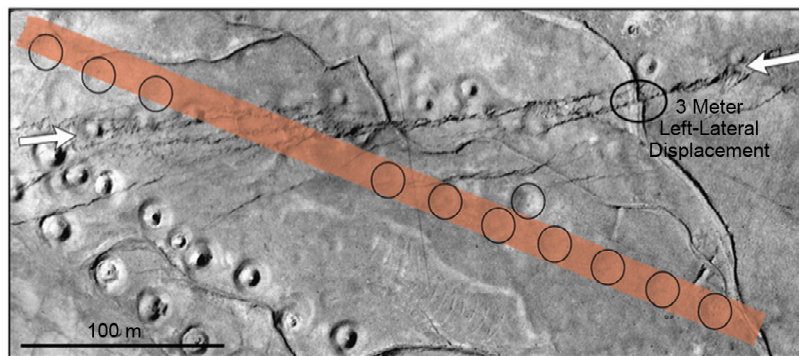


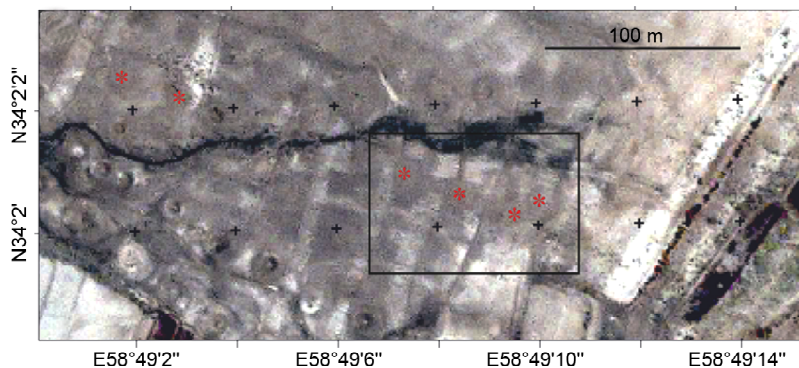
Figure 5. (a) Aerial photograph of the 1968 Dasht-e Bayaz earthquake ruptures (photograph is reproduced from Ambraseys and Tchalenko [4]). The ruptures run east to west between the white arrows. Scale was calculated by overlaying high-resolution Quick-bird imagery from Google Earth (<http://earth.google.com/>); (b) Map of drainage and Qanat systems displaced by faulting. A line of ancient, heavily eroded, Qanat tunnels is apparently displaced by ~10 m across the fault (between points x and y). The second line of ancient Qanats, which tracks across the southwest corner of the image, is also displaced by ~10 m at the fault [4]. The apparent stream displacement of 43 m is probably not real. (c) Field photo showing ancient Qanat systems.



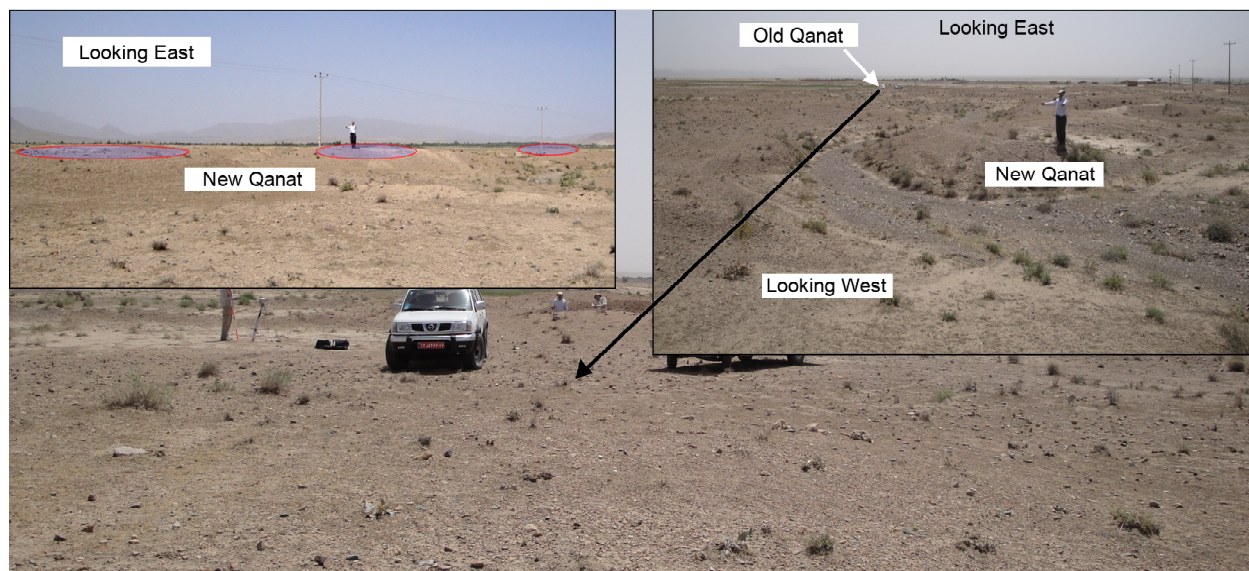
(a)



(b)



(c)



(d)

Figure 6. (a) Aerial photograph of the 1968 Dasht-e Bayaz earthquake ruptures; (b) Close-up view of the displaced qanat wells; (c) IKONOS satellite image (acquisition date: 2003/07/07) showing the same area as in 'b'; (d) Field photo showing old and new Qanats.'

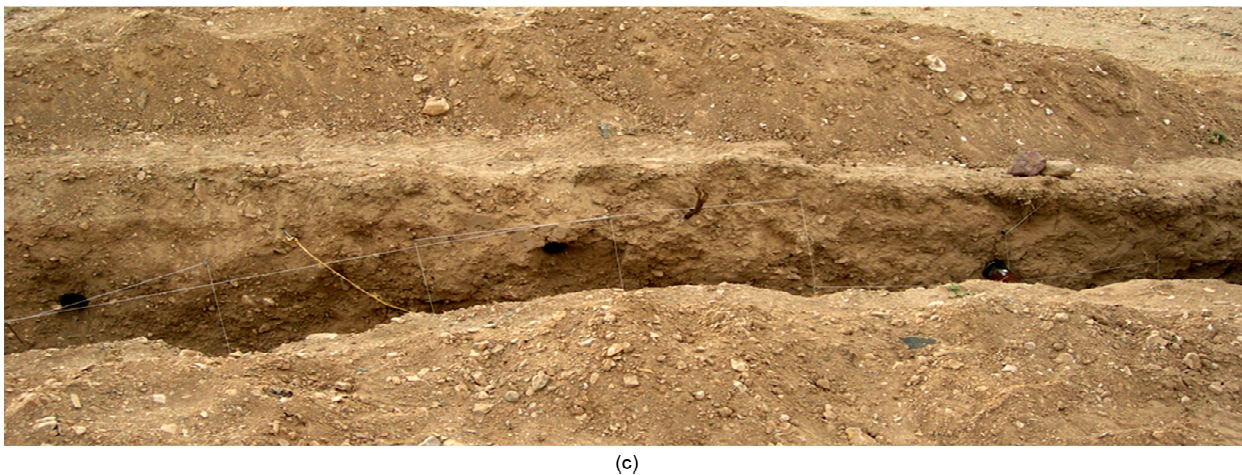
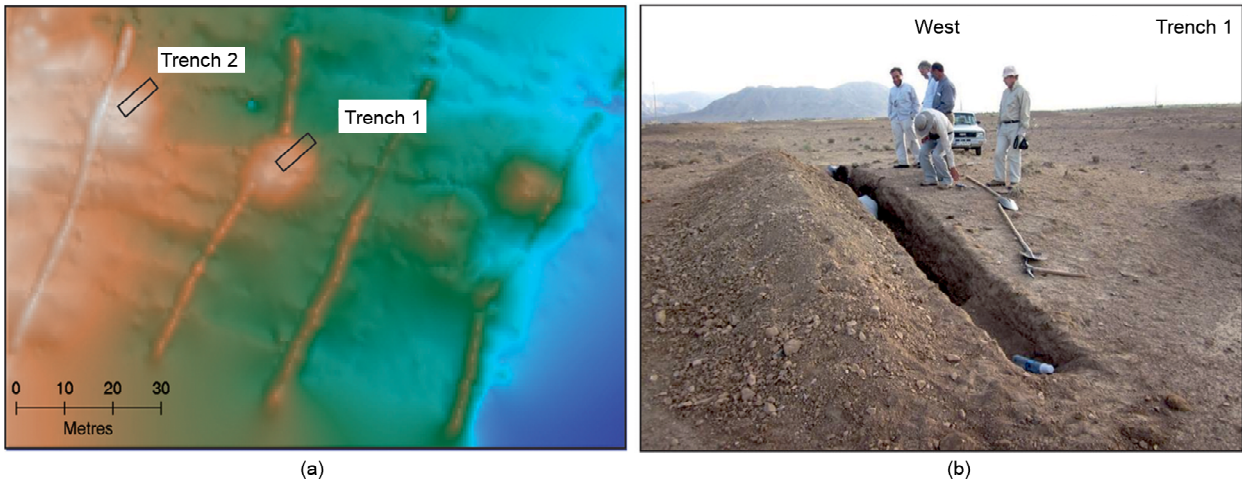


Figure 7. (a) Digital elevation model (DEM) of the Qanat wells, made in the field from kinematic GPS measurements. The two trench locations are shown; (b) Photograph looking west at Trench 1; (c) Trench 2.

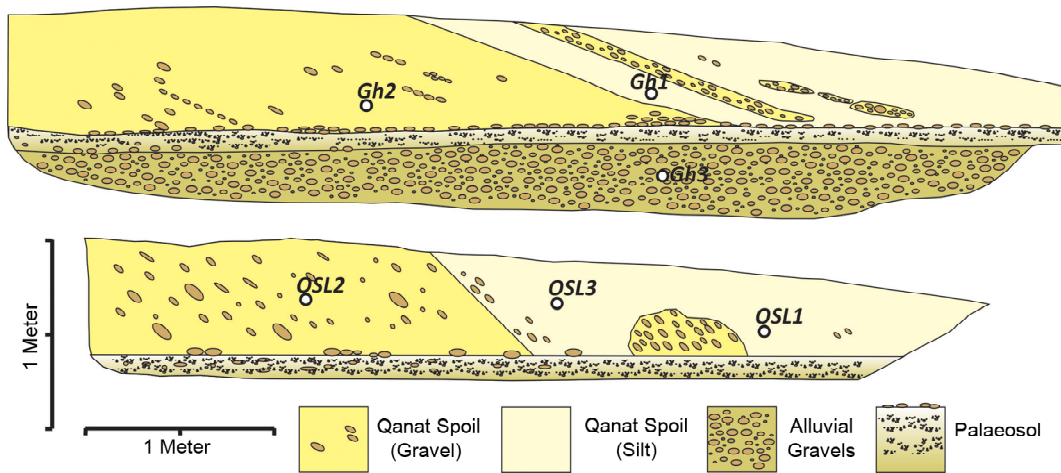


Figure 8. Stratigraphic logs through Trenches 1 (above) and 2 (below).

trenches consist of coarse gravel dipping at $\sim 30^\circ$ (Qanat spoil, gravel) overlain by a light-colored, and predominantly silt unit (Qanat spoil, silt), with occasional sand and gravel clasts highlighting a dip of $\sim 30^\circ$. We interpret these two units to represent stages in the construction and maintenance of the

Qanat. Initial excavation of the vertical well and underground gallery would have been through the same coarse gravel that is exposed in the lower unit (palaeosol), and the coarse gravel in the underlying spoil layers reflects this. Later maintenance, through the dredging of material accumulated

within the gallery, yields spoil that is predominantly fine-grained. The occasional coarser lenses within the silty maintenance spoil may represent the repair of damage to the Qanat gallery. Apart from the occasional gravel layers, there is an overall lack of structure within the fine-grained silt unit, and so we do not sub-divide it into individual maintenance events.

Moisture concentrates along the boundary between the spoil and underlying alluvium, and any organic matter that may have been presented, and suitable for radiocarbon dating, has decayed. Instead, the main sedimentary units were sampled for OSL dating. Three light-protected samples were collected from the vertical trench faces by hammering in steel tubes (Figure 8). These represent the time of maintenance (Gh1), construction (Gh2) and the age of sediments underlying the pre-construction land surface (Gh3).

3. OSL Dating Methodology

Optically stimulated luminescence (OSL) dating determines the age of the last exposure to daylight of the sediment grains. When sediment is exposed to sunlight prior to deposition, the OSL acquired over geological time is removed. The luminescence "clock" is thus set to zero. After burial, the luminescence clock starts and grains begin to accumulate a trapped-charge electron population that increases in response to the ionizing radiation dose from environmental sources. Stimulating samples of buried quartz and feldspar grains in the laboratory releases the trapped electrons, along with photons of light (luminescence). The level of OSL observed in quartz and feldspar is dependent on the absorbed radiation dose. The burial age of grains that were well bleached by daylight at the time of deposition can then be calculated by dividing the equivalent dose D_e (which is the radiation level responsible for producing the luminescence signal) by the dose received per year (during burial).

The samples were treated in the laboratory as outlined by Fattahi et al. [7-8]. The 90-250 μm size fractions were chemically pre-treated and quartz and feldspar were separated. Purity of the quartz samples was checked by IR exposure and revealed feldspar contamination. Therefore, Quartz fractions were treated with hydrofluorosilicic acid

for two weeks. Little amount of quartz from Gh1, Gh2, and almost none from Gh3 samples had remained. The dried samples were then, sieved further using 90 and 150 μm sieves.

The quartz and feldspar grains in eastern Iran are often very dim, with only small proportions of grains yielding any luminescence signal at all. Therefore, initially, standard large single-aliquot dating of the 90-150 μm quartz fractions of samples Gh1 and Gh2, and potassium feldspar of sample Gh3 was performed using standard protocols as outlined in Fattahi et al. [9]. This provided the minimum ages of 15.8 ± 1.6 ka and 22.1 ± 2.7 ka for Gh1 and Gh2, respectively and average age of 9 ± 1 ka using Central age model for Gh3. The age of Gh3 is consistent with a quartz age of 8.7 ± 1.1 ka calculated for a single sample of fine-grained fluvial silt that was collected from a depth of ~ 1.25 m within the sediments in the surface of the Nimbluk plain [10], which is nearby and located just south of Khezri Dasht-e Bayaz village. However, the application of the single aliquot OSL to date the deposition of spoils associated with this Qanat in Iran provided pre-Holocene but consistent ages with the stratigraphy within the shaft, which were older than the estimated date of construction and maintenance [9].

The first thing to note is that the age sequence of the single-aliquot analyses is stratigraphically inverted, with the younger age obtained from the deepest stratigraphic layer sampled (Gh3), and the maintenance (Gh1) yielding older age. The age inversion is expected. Material removed from underground during the construction or maintenance of the tunnel, and spread around the shaft to form the circular spoil heaps (up cast), may have had only brief exposure to sunlight. A proportion of the grains in the spoil will have been reset by exposure to sunlight, whereas others will be only partially bleached, or not bleached at all. Standard single-aliquot methods provide the luminescence response of large numbers of grains, with many retaining significant inherited signal. Standard single-aliquot methods are hence likely to provide ages that are older than the deposition of the construction or maintenance spoil unit. Even when the minimum age model is applied, the ages of each single aliquot are still an average signal of many grains ranging

from unbleached to fully bleached grains. If the number of fully bleached grain in aliquots is limited, the calculated ages can greatly overestimate the true probable age. By performing single-grain measurements, it is possible to separate out those grains that were fully bleached by exposure to sunlight. In order to determine the timing of maintenance of the two excavated wells we used single-grain analysis of the luminescence signal of (Gh1, OSL3) samples.

First, quartz single-grain analyses (grain sizes of 150-250 μm) were performed, with subsequent statistical analysis of the equivalent dose (D_e) distributions to help identify the true deposition age. The quartz grains were very dim and despite of many measurements, quartz single grain method could not provide a meaningful D_e for none of the samples. Following single grain measurements, no quartz grain remained from Gh1 sample.

The potassium feldspar fraction was therefore employed for single grain measurement of sample Gh1. As the number of completely bleached grains was expected to be limited, large numbers of measurements was required for single-grain dating of feldspar (for Gh1). The feldspar grains were also very dim and less than 2% of grains produced any signal. Therefore, the experiments were carried out in two steps. In the first step, natural and test dose signal was measured. In the next step, the rest of SAR was carried out only for grains, which had produced sufficient amount of signal for the test dose.

A total of 20000 grains of Gh1 were measured, of which less than 1% of single-grain analyses were successfully used for D_e determination and passed the SAR method acceptance criteria [11-12]. For sample OSL3, small single aliquot of quartz produced sufficient amount of luminescence signal and enabled us to measure the D_e . As both samples suffer from partial bleaching, the minimum age model was used to calculate the D_e for both samples. Figure (9) shows D_e value of both samples (Gh1 feldspar and OSL3 quartz grains extracted from paleosoil). Dose-rates were calculated based on the method outlined in Fattahi et al. [9]. The experimental detail is presented elsewhere [13]. The D_e , annual dose rate and ages are shown in Table (1).

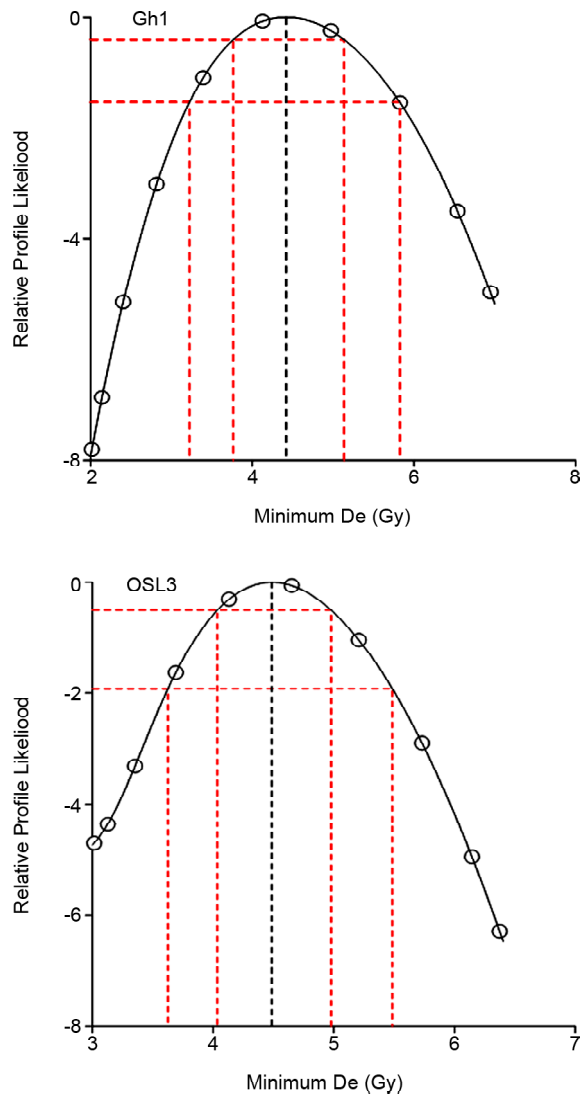


Figure 9. The D_e value of samples from maintenance layers, representative minimum age model plots of 'mixed and scattered' single-grain D_e distributions from potassium feldspar Gh1 and multi-grain small single aliquots of quartz OSL3.

Table 1. Dose rate data, D_e values and optical ages for two sediment samples from the Dasht-e Bayaz Qanat.

Sample ID	D_e (Gy)	Total Dose Rate (GY/ka)	Age (ka)
Gh1	4.4±0.7	2.30±0.08	1.92±0.3
OSL3	4.5±0.5	1.97±0.08	2.28±0.3

Dose rates are based on analysis of sediment by ICP-MS (for OSL3) field Gamma spectrometry (GH1).

4. Conclusions

This study provided the first slip rate determination using direct age of an ancient Qanat system through optically stimulated dating of feldspar sediment single grains and small size single aliquot of quartz within the circular spoil heaps of Mian Qanat which is displaced by Dasht-e Bayaz fault. This method can also be used for slip rate determination of other faults, which have displaced Qanat system.

Our OSL dating thus gives the ages of last maintenance of these wells at 1.6-2.6 ka. Combination of this age and the 10 meter displacement of Qanat line of shafts by Dasht-e Bayaz fault provide a slip rate of 5.2-4.3 mm/yr for this fault.

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