Investigation on the Potential of OSL for Dating Qanat in the Dasht-e Bayaz Region of Northeastern Iran Using the SAR Protocol for Quartz

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ABSTRACT

In some parts of Iran, such as Dasht-e-Bayaz, the line of wells of the Qanat systems have been displaced by coseismic faulting. If we can date the age of these Qanat wells and measure the amount of offset, we will be able to estimate the slip-rate of the fault. The existing constraints on age of ancient Qanats in Iran are typically assigned from archaeological investigations of nearby habitation sites. We present for the first time the results of OSL dating from spoil deposits associated with the Dasht-e-Bayaz Qanat. We further explore the possibility of dating Qanat directly using the novel method of OSL. The minimum ages which are assigned to maintenance and construction of Dasht-e-Bayaz Qanat, using SAR protocol are 15.8±1.6ka and 22.1±2.7ka, respectively. Archeological investigations suggest that the Qanat ages are much younger than ages obtained by OSL. We present evidence that the SAR approach that we have chosen is operative but not relevant. The OSL method has provided ages that are consistent with stratigraphic layers in the well, but these layers were not fully bleached during construction. The single aliquot method to which dim samples we've applied in the recent research is not an efficacious way to achieve the age of Qanats and may need to test for more samples.

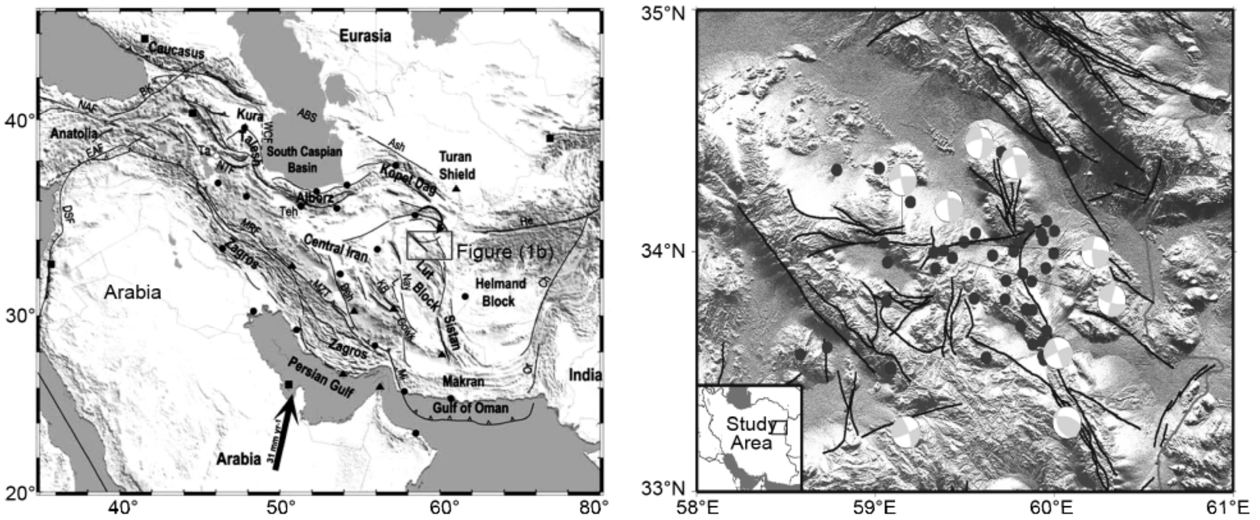
Keywords:
Qanat; OSL dating; Dasht-e-Bayaz Fault; SAR

1. Introduction

Iran is tectonically active, accommodating *N-S* convergence between Arabia and Eurasia [1]. Eastern and northwestern of Iran, are the regions which are known for most surface faulting in whole plateau [2]. The total amount of $30 mmyr^{-1}$ of Arabia-Eurasia convergence [3] acts different in east and west of Iran. According to Vernant et al [4] most of the shortening east of $58^{o}E$ is accommodated by Makran subduction zone (~$19.5\pm2 mmyr^{-1}$), and least by Kope Dagh (~$6.5\pm 2 mmyr^{-1}$). Therefore, the amount of convergence in eastern Iran should be something more than that of Kope Dagh. This shortening is thought to be accommodated by left-lateral strike-slip faults in north-eastern Iran [5]. The strike-slip faults, which can be over 100*km* in length, have produced several large earthquakes over the last century [6] and are important elements in deformation of the continents [5]. Within *NE* Iran, because of large and no-deep seismic events, active faulting changes the topography and drainage patterns on the surface, and the geomorphology is able to retain information about fault evolution over relatively thousands of years [5]. In eastern Iran, the main structures are Dorouneh and Dasht-e-Bayaz left-lateral strike-slip faults, which construct the northern part of namely Lut zone, eastern Iran, see Figure (1a). The east and west margins of Lut zone, respectively Nehbandan and Nayband strike-slip faults, have right-lateral shear of 10-12$mmyr^{-1}$, north-southward. It is believed that such a *NS* right-lateral shear is accommodated in eastern Iran by rotating counterclockwise [5], which caused mainly by left-lateral shear of Dorouneh and Dasht-e-Bayaz systems.

The Dasht-e-Bayaz strike-slip fault in Khorasan province, north-eastern Iran, is one of the dominant seismogenic faults in the Iranian plateau [7]. Although, records of events in Dasht-e-Bayaz fault system are not as quantitative as other seismic region (like Zagros and Alborz) in Iran, it has produced large and destructive earthquakes of Lut zone, in both historical [8] and instrumental [9] records, see Figure (1b). Recently, two major earthquakes in this region (1968 August 31, Dasht-e-Bayaz and 1979 November 27 Khuli-Buniabad with $M \geq 7$) have attracted attention to this active fault. Particularly, after the August 31, 1968 earthquake, because of sharp ruptures on surface, many researchers represented field reports and explorations [9-10]. It also enabled other seismologists to calculate the mechanism of source parameters [6, 11]. However, lack of seismic data, and complexity of region (bending with Ferdow thrust and Abiz right-lateral strike-slip fault) prevents of detailed explanation of fault's behavior. It is also suggested that due to small offset on the whole fault system, in comparison to total amount of Tertiary deformation in this region, Dasht-e-Bayaz left-lateral strike-slip fault is relatively young structure [6]. Therefore, we choose to investigate the Holocene activity of this region, by studying manmade tunneling artifacts called Qanats that have preserved their structural characteristics for thousands of years after their creation, in order to figure out the last event occurred in region. The presence of faults provides unexpected resources useful for continual human habitation by producing a reliable water supply and this, in turn, supports agriculture for settlement and sustenance.

The Iranian plateau is an arid land with a low annual rainfall. According to groundwater resources of the world [12], Iran is largely desert and with the exception of the northwestern provinces and along the southern shores of the Caspian Sea, receives only 6 to 10 inches of rainfall per year [13], which is less than 30 percent of the global average of annual rainfall. Additionally, more than 60 percent of the total precipitation evaporates, and only about 15 percent reaches the surface. Because of this lack of significant rainfall, groundwater resources are of great importance in Iran. In fact, in recent decades it has become evident that groundwater is one of the most important and most vulnerable of earth's natural resources [14]. Although, most people of the world dig wells to reach the groundwater table, some ingenious ancient people find a more innovative and lasting method for extracting groundwater.



(a) (b)

Figure 1. (a) Simplified tectonic map of Iran within the Middle East region superimposed on topography. The heavy arrow shows NUVEL-1A plate motion relative to Eurasia [4]. Lut zone and its position in eastern Iran are shown. The box displays the region of Figure (1b). Scheme is from Vernant et al [4]. (b) Part of eastern Iran included the Dasht-e-Bayaz fault system on topography. Ferdows thrust and Abiz right-lateral strike-slip fault have complex bending with Dasht-e-Bayaz. Epicenters of earthquakes from 1960-2007 were taken from ISC catalog. Fault plane solutions are from the data of CMT Harvard.

2. Application of Qanats

Range front faults in the mountainous region sometimes cause a damming effect on the local water table. This is because the grinding of rock on the trace of an active fault creates very fine impermeable clay, known as “fault gouge”. This layer acts as an underground dam that impedes the flow of water and causes the water table to rise up the gradient of the fault trace [15]. In this case, the fault is responsible for the subsurface aquifer of the lake beds, and ensures their continual uplift and elevation above the plain, causing the formation of springs [15]. We know that alluvial fans are the most appropriate for habitants, due to fertility, but only if water is available. That is the case which some people decide to transfer water from piedmont region to their settlement, see Figure (2). This situation is typical in Iran. The country is mountainous except for flat regions in the interior, which are barren salt flats [15]. The most widespread landscape in central Iran is Great Kavir, which acts as a reservoir for groundwater on its boundaries. Almost all of the Qanat systems of Iran are found associated with large alluvial fans in the piedmont zone between the high mountains and the kavir or salt desert, or in large alluvial valleys on the desert margin [16]. This shows an interesting overlap between active faults and evidences of Qanats. One can infer the existence of fault plane by the evidence of Qanat craters.

The indigenous Iranians utilized a groundwater extraction and an irrigation management system called Qanat. It mainly consists of a gently sloping tunnel to convey water from uplifted dam of fault plane to further center of habitat, see Figure (2). English [17] states that Qanats appear to have originated in the vicinity of Armenia more than 2500 years ago and spread rapidly throughout south-west Asia and north Africa during Achaemenid times (550 to 331 *B.C.*). Certainly, by 209 *B.C.* Qanats were an important feature of the Persian landscape and were described by Polybius during the campaign of Antiochus against Arsaces [18]. Considerable research has been done on the Qanat system, especially after the 2003 December 26 Bam earthquake which brought world attention to the immense body of that region’s hydrogeological, archaeological and geo-historical cultural artifacts [15].

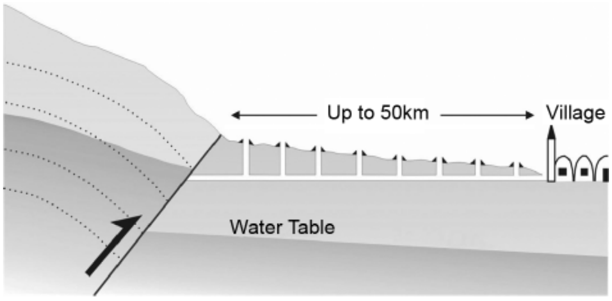


Figure 2. Sketch of an irrigation tunnel (Qanat) dug through alluvium towards a range-front, where the water-table is elevated because of impermeable clay ('gouge') on a thrust fault. Qanats can be up to 100m deep at the range front, and have many vertical shafts for ventilation and further maintenance. Scheme is from Jackson [15].

The Qanat is an engineering invention for developing and supplying groundwater to distal parts of the alluvial fan from its proximal head source, which cut through alluvial material, and drains water by gravity from beneath the water table at its upper end to a ground surface outlet and irrigation canal at its lower end [16]. 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 [13]. The underground tunnel is connected to the surface by a series of vertical shafts, which can be seen on aerial photos. These vertical shafts would have provided access for ventilation and removal of excavated material during construction. The development of the Qanat technology may reflects the response of the ancient people to the climatic changes, which are inferred by archeologists to have occurred in Iranian territory about several thousand years ago. The most developed systems of Qanat irrigation are found exclusively through coarse alluvial sand and gravel, such that the bed of the Qanat often has very high permeability [18], and in fact, large quantities of water would remain useless or lost by infiltration and percolation, until Qanat discovery. Qanats are strongly controlled by the availability of groundwater resources which are usually fed by streams and rivers emerging from the highland areas which have greater rainfall. As a result, most of the Qanat systems of Iran are found in the Central Plateau groundwater province of Iran [19], which is the surrounding peripheral zone of Great Kavir in central Iran. This zone is located by the major active faults of the region owing to the favorable hydrologic conditions produced by the aquifer damming effect.

Qanat technology exists in more than 34 countries in the world [14]. Actually, the first documented Qanats were dug in the north-western areas of Iran and date back to 800 B.C. [18, 20]. Wulff [13] estimated the antiquity of Qanat in Iran by 3000 years. These verifications are often achieved by historical records or occasionally by inscriptions within the tunnels preserved as archeological evidence. Nevertheless, most of the evidence we have for the age of Qanat is only circumstantial, and therefore, the precise dating of Qanats is a difficult but important requirement of answering the question of the Qanat antiquity. The development of technology for resolving measurements on original creation ages of various artifacts has been accompanied with enough progress that we can begin to sample and systematically place reproducible dates to many events or artifacts.

As mentioned above, many of the Qanat galleries were dug in the vicinity of, or directly upon, active faults. This has been explored by some researchers in understanding and interpretation of seismologic behavior [21-22]. Qanat offers a useful tool for paleoseismologists and archeoseismologists, because in some cases there are no direct records of seismic events, and even the displacement of the fault is covered or concealed due to erosion or anthropologic development. Some have suggested that tectonic displacement would offset the tunnels of the Qanat system and would require the construction of a new tunnel. The reconstructed tunnels would preserve a record of tectonic displacement. By measuring the offset between new shafts and old shafts, and determining the age of the offset features, the estimation of fault slip-rate -which is an important element in hazard assessment - becomes possible. We determined the antiquity of Qanat constructions using the novel method of optically stimulated luminescence (*OSL*) which has yet to be used on these features. We explore whether or not the *OSL* method can be used in such studies and if the results are reliable. The Dasht-e-Bayaz region has been previously studied by our group [23] and there would be good criteria for interpretation of the results of dating the Qanat systems. Here, we report the preliminary results of our attempt to date one Qanat assemblage which was displaced by the Dasht-e-Bayaz fault.

3. OSL Sampling and Experimental Treatment

After the August 31, 1968 earthquake of Dasht-e-Bayaz ($Mw7.1$), which caused about 12000 people death, Ambraseys and Tchalenko [9] made a report of the field ruptures and structural damage. Although they reported length of rupture about 80*km*, further studies indicated some segments of about 20*km* on the fault [13]. One of the brightest offsets Ambraseys captured was the displacement in line of craters of a Qanat which crossed by fault rupture, see Figure (3). Figure (3), the aerial photo taken by Ambraseys after August 31, 1968, shows the offset of at least 10*m* [9] on the elder generation of Qanats. One can assume that after the earlier event, which might be as far back as ninth century A.D., according to Ambraseys and Tchalenko [9], or even much earlier, shifted shafts dried out and thus abandoned. This led the habitants to generate new shafts, which could trigger water resources from newly cracked bed rock. Another line of Qanat pursues exactly the line of fault rupture to enrich the water supply to main Qanat [15]. As the old generation of Qanat excavated certainly before the last earthquake, we choose them as a sampling location, so the age of samples tell us the nearest time of early earthquake. Therefore, samples were taken from abandoned shaft, see Figure (3). A trench through the well surface (at 34:02:01.3*N*

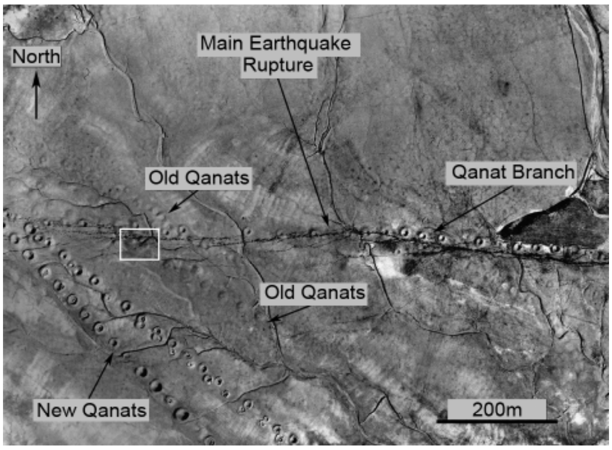


Figure 3. Air photo of Qanats in the Nimbluk valley, taken after the 1968 Dasht-e-Bayaz earthquake. The earthquake fault rupture runs east-west across the center of the picture and moved horizontally, with the north side sliding to the west. Multiple generations of Qanats are visible, the most recent were cut by the 1968 faulting, but these were replacements for earlier Qanats, whose lines of craters are now heavily eroded, that were presumably abandoned after earlier earthquakes. One Qanat follows precisely the line of the fault rupture, increasing the water flow into the main northwest-southeast Qanats by tapping an underground change in water-level, ponded by impermeable clay gouge on the fault [8]. The white box shows the location of current sampling. Photo courtesy of N. Ambraseys.

58:49:08.0*E* 1559*m* from Dasht-e-Bayaze in *NE* Iran) revealed three layers as expected. The detailed geological setting; trench site, excavation, stratigraphy and interpretations will be presented in future publications. Therefore, three samples were taken from a shaft, going deep vertically into a trench. *GPS* coordinates of samples are displayed in Table (1).

Table 1. Sample data frp, Dasht-e-Bayaz Qanat.

Sample Code	Lat.	Long.	Depth in Trench (m)	Elev. from Sea Level (m)
Gh1	34:02:01.3N	58:49:08.0E	0.35	1559
Gh2	34:02:01.3N	58:49:08.0E	0.40	1559
Gh3	34:02:01.3N	58:49:08.0E	0.75	1559

However, this three layers structure over surface was anticipated according to archeologists. Wulff [13] discussed the process of digging Qanat comprehensively. During the construction of a Qanat well, excavated sediment is transferred from the well tunnel and poured on the surface around the well. We assume that thousands of years ago, before the development of strong artificial light, digging Qanat should have happened only during the day time, see Figure (4a). Therefore, sediments that had been removed from the underground tunnel during the construction would have been spread around the well's surface should have been exposed to day light for long intervals of time. As a result, the luminescence signal of the dosimeters inside these sediments should have been totally or partially bleached due to sunlight exposure.

In addition, people have cleaned and repaired the Qanats, decades or centuries or thousands of years later. During maintenance, the well shaft would have been used to transfer the sediment from the Qanat to the earth surface [13]. The same scenario for both construction and maintenance would have been utilized, and the sediment and the mineral grains used in luminescence dating would have been exposed to light. Therefore, it can be assumed that around the well surface we would find three well-defined layers. The bottom layer should be the natural surface before digging the well, which we call it “paleosoil”. On top of that, there should be a layer that contains sediment that belongs to original construction period, and the very topmost layer should be related to maintenance, whether the maintenance occurred in one or several stages, see Figure (4b). Based on this scenario, it may be possible to date the time of construction as well as maintenance of the Qanat well.

Although there were many candidate wells in the area, we chose one of the oldest ones, hypothesizing that we understood and studied it well enough to know that its construction occurred before the last episode of tectonic activity. Therefore, if we can date the time of construction of this well, we can use it for minimum slip-rate determination on the fault. From the historical sagas (as Wulff 1968 mentioned) and what local "moqanni"s (the local term for Qanat excavators) mentioned, it is found that the uppermost layer of silty sand deposits is presumably related to maintenance, see Figure (4b). Therefore, the age of these sediments can also provide a valuable constraint

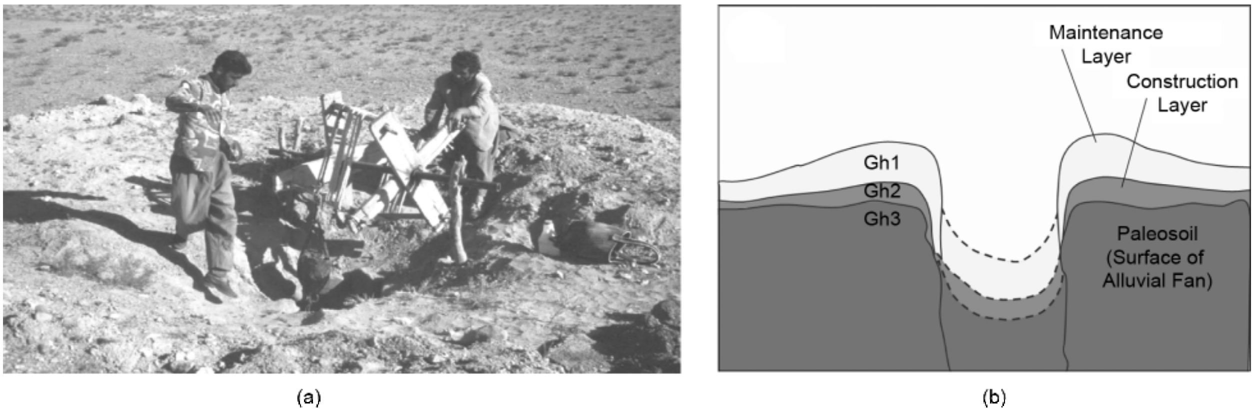


Figure 4. (a) A windlass working at a vertical Qanat shaft, bringing excavated material to the surface from an underground worker below. The discarded material forms a crater rim at the surface, preventing flash-floods from washing material back into the hole [15]. Workers always work in daylight. (b) Sketch of hole crater of Qanat shaft, which buried after abandonment. Three major layers from ground of alluvial fan (paleosoil) which samples taken, are indicated. The Gh1, Gh2 and Gh3 relate to maintenance, construction and paleosoil layers, respectively.

on the last faulting event on the Dasht-e-Bayaz fault. When combined with estimates of the displacement, the ages can provide information on the slip-rate of the fault which can be used to estimate earthquake recurrence intervals.

One sample (*Gh*1) was collected from the uppermost layer of this trench which, if it had been completely reset during deposition from maintenance, should date pre-faulting, see Figure (5). Another sample (*Gh*2) was collected from the middle layer (construction of well) which if the sediment had been completely reset during deposition would date prior to Qanat maintenance and subsequent faulting. The last sample (*Gh*3) was collected from the bottom layer (surface of well) for stratigraphic control and should date the surface of the alluvial fan.

The samples were collected using stainless steel tubes (5*cm* by 25*cm*) and both ends were sealed and covered using both aluminum foil and black tape. The samples were opened in the laboratory under red light conditions, and 5*cm* of each end were extracted before *OSL* pretreatments, because the ends were presumably exposed to light during sampling. This extra material was used to determine sample moisture content. Elemental concentrations were calculated via in situ Gamma spect. The middle part (light unexposed) was used for determination of the equivalent dose (D_e). The Single Aliquot Regenerative (*SAR*) dose protocol for quartz (15) was applied to aliquots of 90-150μm sized quartz, and these were prepared by wet sieving, *HCL* and H_2O_2 treatment, followed by heavy liquid separation ($<2.7 g/cm^3$), *HF* and *HCL* treatment, and checked with *IR* (infrared) stimulation for feldspar contamination during analyses. All the experiments reported here were carried out using a Rixϕ *TL-DA*-15 automated

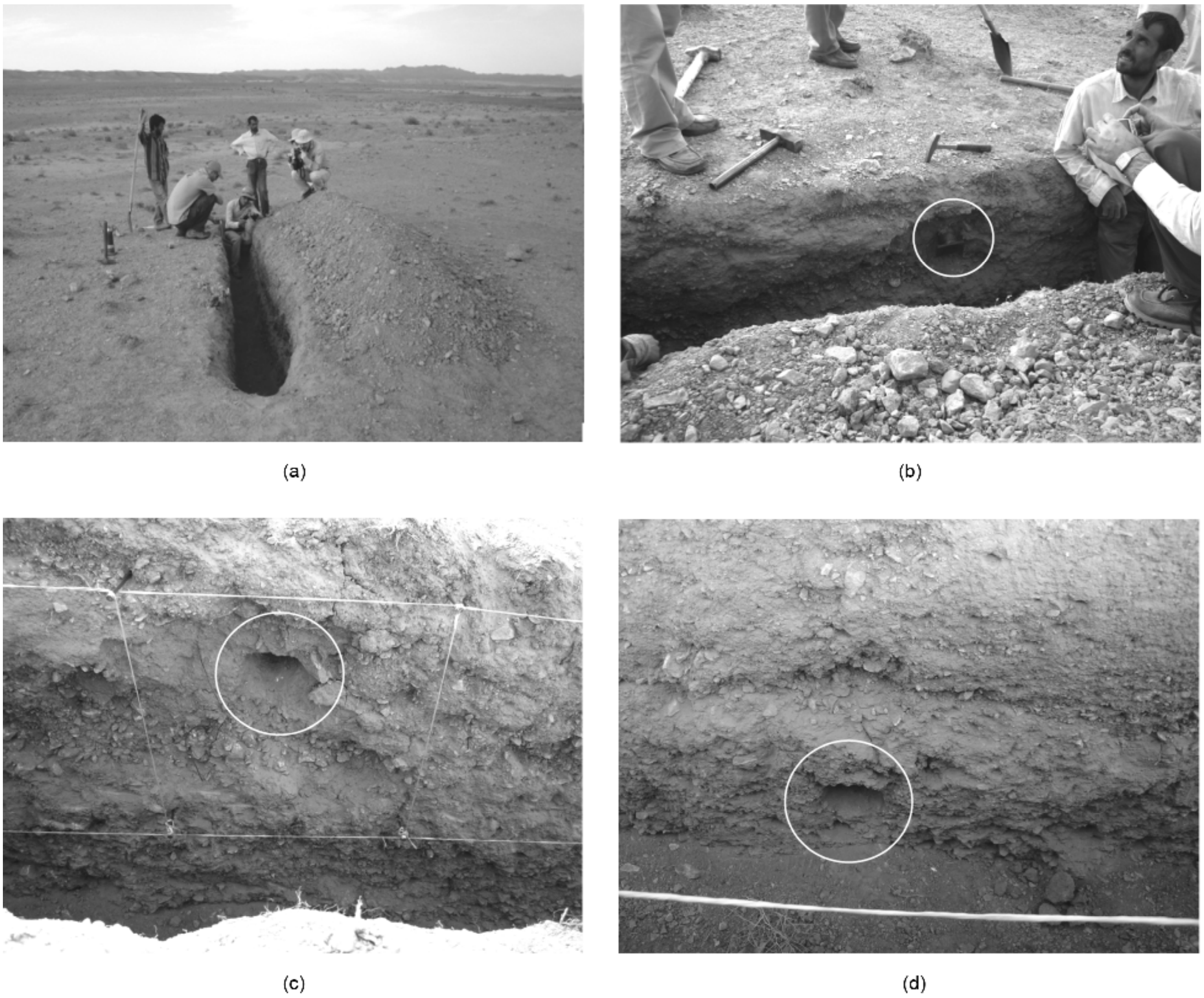

(a) (b) (c) (d)

Figure 5. (a) The trench over the surface of Qanat shaft in Dasht-e-Bayaz. The view is toward the north, and mountains are thrust uplifted, north of Dasht-e-Bayaz fault, as shown in Figure (1b). Location of (b) Gh1, (c) Gh2 and (c) Gh3 samples in the trench, as stratigraphy indicates.

thermo luminescence /optically stimulated luminescence (*TL/OSL*) system (fitted with a $_{90}Sr/_{90}Y$ beta source delivering ~6*Gy/minute*) equipped with an *IR* laser diode and blue *LEDs* as stimulation sources. *OSL* was detected using an Electron Tubes bialkaline *PMT*. Luminescence was measured through 7*mm* Hoya *U*-340 filters. Uranium, thorium and potassium concentrations were measured using Gamma spect, see Table (2). Annual dose was estimated as described in Fattahi et al [24] and Fattahi and Walker [25].

4. Luminescence Characteristics

OSL is the light emitted due to the release of stored energy accumulated in crystalline materials through ionising radiation from natural radioactivity. This method dates the last sunlight exposure event for mineral grains in sediment. When sediment is exposed to sunlight prior to deposition, the luminescence acquired over previous geological time is removed. The luminescence "clock" is thus set to zero. If all the signal is not removed, this is known as partial bleaching or partial removal of the signal. In many cases, it is not known how much of the signal is removed without extensive study. After burial, the *OSL* accumulates in response to natural ionising radiation (from radioactive isotopes in the Thorium and uranium decay chains and 40*K*, as well as from cosmic rays) received during the burial period of the sediment. Quartz and feldspar grains in the bulk sediment have different dosimetric properties. The level of *OSL* observed in these minerals is dependent on the absorbed radiation dose. For age determinations, two values are required: the equivalent dose D_e (which is the radiation level responsible for producing the luminescence signal) and the dose received by the mineral grains per year (during burial).

Over the past decade, the single aliquot regeneration *SAR* protocol [26] for quartz has been developed and used repeatedly to measure equivalent doses (D_e) in quartz luminescence dating. The *SAR* procedure, see Table (3), depends on the assumption that it is possible to measure a signal after each dose and stimulation cycle, which acts as a surrogate measure of the sensitivity of the aliquot during the preceding measurement cycle. As such, any sensitivity changes which have occurred in the course of a regenerative analysis can be corrected for both the natural and regenerated signals. This protocol requires careful selection of the appropriate preheat and test doses used within it to ensure correct monitoring of sensitivity changes. The suitability of the samples for the *SAR* protocol was tested by examining its luminescence characteristics such as thermal transfer and dose sensitivity, through quality control procedures on the *SAR* data and via dose recovery tests [23, 27]. After testing the samples, they passed the basic assumptions of *SAR* method, and thus the D_e obtained using this method, see Table (3), for quartz can be considered robust and reliable.

Table 3. Generalized single aliquot regenerated sequence.

Step	Treatment	Observed*
1	Give Dose	–
2	Pre-Heat	–
3	Stimulation	L_x
4	Give Test Dose	–
5	Pre-Heat	–
6	Stimulation	T_x
7	Return to 1	–

Note: In steps 2 and 5, the sample has been heated to the pre-heat temperature using *TL* and held at that temperature for 10*s*. In steps 3 and 6 *OSL* was measured at 125°*C*.

***Observed:** L_x and T_x are derived from the initial *IRSL* signal (5*s*) minus a background estimated from the last part of the stimulation curve. Corrected natural signal $N = L_0/T_0$; Corrected regenerated signal $R_x = L_x/T_x$ (x =1-5).

5. D_e Determination and Age Calculation

Attention was initially focused on determining the D_e for samples *Gh*1 and *Gh*2 which should resolve more accurately the timing of the well maintenance and construction. The amount of the cleaned quartz for these samples was limited in quantity; however, making the results that are presented less precise

Table 2. The result of elemental concentrations for dose rate calculation.

Sample ID	Depth (m)	±	Water (%)	K (%)	±	U (ppm)	±	Th (ppm)	±	Cosmic (Gy/ka)	±
Gh1	0.5	0.5	5	0.88	0.051	1.63	0.13	5.63	0.41	0.165	0.056
Gh2	1	0.5	5	0.76	0.051	1.65	0.13	4.45	0.41	0.185	0.056
Gh3	1.5	0.5	5	0.8	0.051	1.6	0.13	5	0.41	0.207	0.056

than we would wish. Eleven and seventeen 8*mm* diameter aliquots were prepared and following measurement of the D_e, a dose-response curve was constructed from six regeneration dose points including four regenerative doses (12.5, 21, 33 and 66.6*Gy*), and a zero dose. A replicate measurement of the lowest regenerative dose was carried out at the end of each *SAR* cycle. The net initial *OSL* signal (first 0.5*s* - average of 40-60*s*) was used for natural, regenerated and test dose measurements. The D_e was determined by interpolation, and the sensitivity was corrected by dividing L by T_x. The result of aliquots that produced no significant recuperation signals and produced recycling ratio between 0.90 and 1.15 were chosen for further D_e analysis and age determination. The range of De values are around 30 to 131*Gy* for *Gh*1, and 37 to 123 *Gy* for *Gh*2. Further information on *SAR* method could be found on Murray and Wintle [26].

Results of the replicate De data for samples *Gh*1 and *Gh*2 are shown in Figure (6) and Table (4). From plots, it is apparent that for *Gh*1 and *Gh*2 quartz

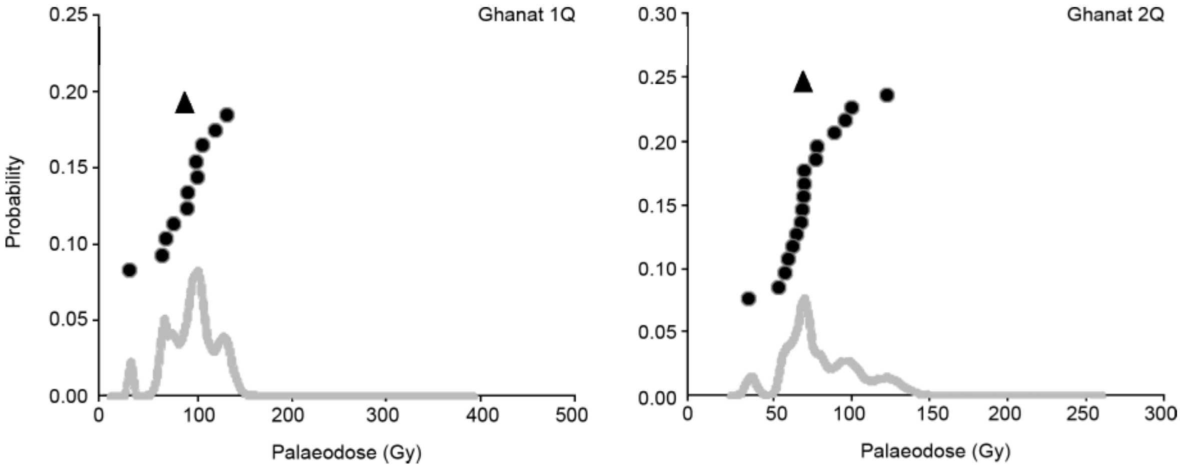


Figure 6. D_e distributions for samples Gh1 (left) and Gh2 (right) showing probability (P) density plots with individual aliquot D_e (paleodose) in Gy, plotted above (closed circles) and the arithmetic mean of the data (closed triangle).

Table 4. Values used to determine sample age and the derived age estimate for Gh1 and Gh2.

Sample ID	D_e (*Gy*)	±	Total (*Gy/ka*)	±	Age (*ka*)	±
All Data Gh1 (90-150) Quartz						
Unweighted	88.86	28.13	1.89	0.16	**47.1**	**15.5**
Weighted	59.12	29.5	1.89	0.16	**31.3**	**15.9**
Probability	87.34	23.86	1.89	0.16	**46.3**	**13.3**
Central Age Model	83.42	9.79	1.89	0.16	**44.2**	**6.6**
Minus outliers						
Unweighted	94.76	21.29	1.89	0.16	**50.2**	**12.2**
Weighted	81.05	21.29	1.89	0.16	**43.0**	**12.0**
Probability	92.44	17.45	1.89	0.16	**49.0**	**10.3**
Central Age Model	92.59	6.39	1.89	0.16	**49.1**	**5.6**
All Data Gh2 (90-150) Quartz						
Unweighted	75.04	19.73	1.69	0.16	**44.3**	**12.5**
Weighted	67.58	12.31	1.69	0.16	**39.9**	**8.3**
Probability	70.4	10.72	1.69	0.16	**41.6**	**7.6**
Central Age Model	72.66	4.44	1.69	0.16	**42.9**	**5.0**
Minus Outliers						
Unweighted	70.44	9.16	1.69	0.16	**41.6**	**6.8**
Weighted	67.49	9.16	1.69	0.16	**39.9**	**6.7**
Probability	69.14	6.62	1.69	0.16	**40.8**	**5.7**
Central Age Model	69.85	2.38	1.69	0.16	**41.2**	**4.4**
Minimum						
Min. Gh1 (90-150) Quartz	29.83	1.21	1.89	0.16	**15.8**	**1.6**
Min. Gh2 (90-150) Quartz	37.42	2.53	1.69	0.16	**22.1**	**2.7**

samples there are, respectively, one and four outliers on the D_e distribution (outliers are defined as those D_e that are greater than the arithmetic mean of the data). We applied four different statistical approaches for calculating the suitable single D_e value for age determination [27]. Means based on unweighted values, weighted values (by inverse variance), combined probability values and the Central Age Model (*CAM*) produced mean D_e values in the range of 59±29 to 89±28*Gy* for *Gh*1 and 68±12 to 75±20 *Gy* for *Gh*2.

If statistical outliers are excluded (outside two standard deviations of the unweighted mean) the unweighted, weighted, combined probability, and *CAM* means changed significantly at 81 ± 21 to 95 ± 21 *Gy* for *Gh*1 and 69 ± 7 to 70 ± 9 *Gy* for *Gh*2 , see Table 4). These calculations result in ages that range from 31 ± 16 to 50 ± 12*ka* for *Gh*1 and 40 ± 8 to 44 ± 12*ka* for *Gh*2, see Table (4). Although, we have not been able to extract sufficient quartz to provide an age for *Gh*3, the potassium feldspar age for *Gh*3 using the *CAM* for D_e determination is 9 ± 1*ka*. This age 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 [23], which is nearby and located just south of Khezri Dasht-e-Bayaz village. This is consistent with a partial bleaching stratigraphy, because *Gh*3 is a paleosoil sample that presumably did not interrupt by workers, covered with sediment from anthropogenic activity (other two layers), and the other two sediment samples were collected from deeper layers within the fan via digging a well shaft. However, if *Gh*1 and *Gh*2 had been completely reset during the construction or maintenance of the well as initially expected, these two samples should have provided younger ages than *Gh*3.

Given the depositional setting, the D_e distributions as shown in Figure (6), and the calculated ages using mean D_e, it is obvious that the anthropogenic samples were only partially bleached prior to being dug up and scattered on the surface. As measurements were conducted at the multi-grain level, multiple D_e populations within a sample will be largely masked [27-28], as *OSL* will come from a relatively few bright and poorly bleached grains on each aliquot. In this case, basing age calculations on a mean has led to an over-estimation of true burial age. The probability plots each show a small peak at around 25 *Gy* (*Gh*1) to 40 *Gy* (*Gh*2), and these small peaks will be more intensively investigated when more quartz for *OSL* dating is obtained. These peaks represent grains which may have been exposed at the time of well digging or maintenance. If we assume that these grains are a more accurate reflection of the periods of interest we can then calculate minimum ages based on these D_e for *Gh*1 and *Gh*2. The resulting ages are 15.8 ± 1.6*ka* and 22.1 ± 2.7*ka*, respectively. We speculate these ages are more likely to reflect construction and maintenance periods, though we think it is highly unlikely that such old ages are indicative of the ages of the Qanat systems.

6. Conclusion

The minimum ages of 14 to 17 ka for *Gh*1 and 19 to 25*ka* for *Gh*2, are much older than the estimated age for *Gh*3 (~9*ka*). This fact, combined with the widespread distribution of equivalent dose, proves that the vast majority of grains inside the *Gh*1 and *Gh*2 samples are partially bleached. In other words, very few of the grains were sufficiently exposed to light during construction and digging (around one minute fully bleaches these grains in laboratory tests). Therefore, the combination of different deposition and inherited ages from several hundred to several tens of thousands grains in one aliquot will provide an age that is only a mean of all these ages (each aliquot can contain up to 1500 grains). Even when the minimum age model is applied, the single aliquot ages are still greatly overestimating the true probable age.

An added complication is that the luminescence signal from these samples is dim; thus applying single grain analyses will be difficult due to the low *OSL* signal intensities. The single aliquot method to which dim samples were applied in the recent research is not an efficacious way to achieve the age of Qanats and may need to test for more samples. Therefore, a more extensive understanding of the equivalent dose distributions of the mixed grain populations is needed and is a subject of future study on Qanat sediments in Iran. Nevertheless, it appears that in spite of all these difficulties, the immediate direction and the most logical solution for accurately dating samples like *Gh*1 and *Gh*2 is to find dates on individual grains or experiment with luminescence on the potassium feldspar grains. Some combination of these methods might also be appropriate. This paper shows our preliminary result and our experiments will continue to find more reliable results.

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