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ORIGINAL PAPER

Evidence of prehistoric liquefaction in Kuwait and implications for the seismic vulnerability of the Arabian Gulf Countries

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Abstract
This paper presents and analyzes paleo-liquefaction features found in the State of Kuwait. The features are cemented sand and gravel-filled dikes of Pleisto–Holocene age with appearance and composition similar to typical "sandstone pipes." The significant age difference between the cemented dikes and the surrounding loose sand, the size and spatial distribution of the dikes, and the local geologic and hydrologic setting all suggest that the feature probably results from a single large event of seismic origin. Likely hypotheses include shaking during large earthquakes or seiching of tsunami-like waves. Additional research is needed to identify the exact cause of these dike formations, which is important for the purpose of improving seismic risk and vulnerability assessment of the Arabian Gulf countries. The search may also help explain the disappearance of an ancient civilization that lived in the same region approximately seven thousand years ago.

Keywords Liquefaction · Seismic risk · Kuwait

1 Introduction

The purpose of this paper is to document field evidence at Jal-Az-Zor, Kuwait, of paleo-liquefaction, as a result of either shaking associated with a large prehistorical earthquake, or inundation during a possible tsunami. This observation casts a new light on the long-term potential for seismic hazard in the State of Kuwait.

With an area of about 17,818 km^2, the State of Kuwait is located at the NW end of the Arabian Gulf (Fig. 1), to the SW of the Zagros Fold Belt, an active collisional plate boundary between the Arabian plate and the Iranian part of the Eurasian one (Fox 1959;

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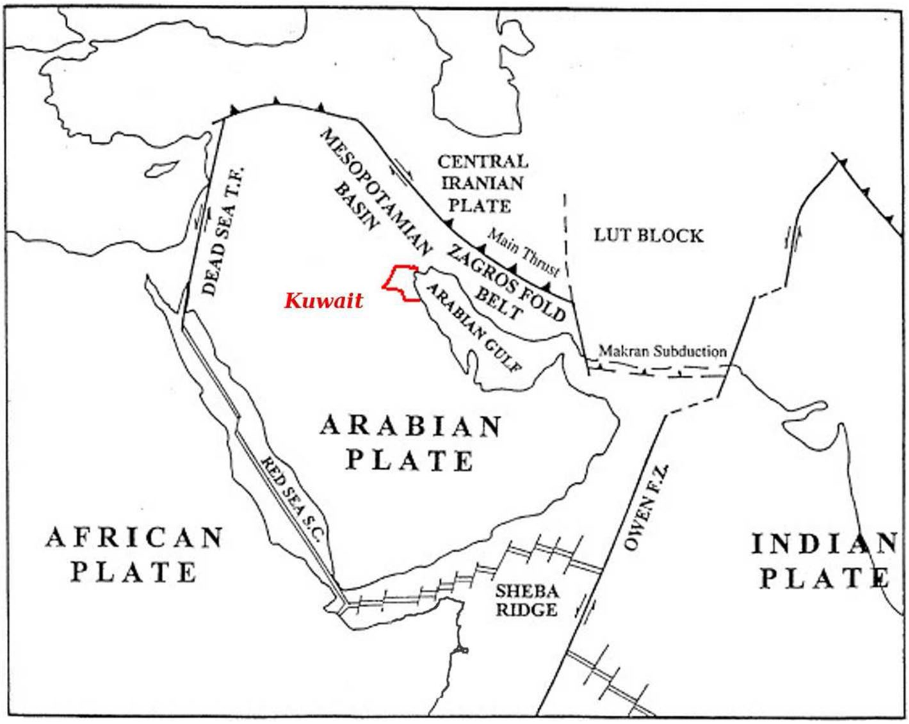

Fig. 1 Sketch of global tectonic features for Kuwait and surrounding area, after Bou-Rabee and VanMarcke (2001)

Bou-Rabee 1986). The topography of Kuwait is controlled by the relatively distant, but intense, folding of the Zagros Orogeny, characterized by SW–NE convergence.

We focus in this paper on the area of the Subbiya Peninsula, located across Kuwait Bay from Kuwait City (Fig. 2), which has been earmarked for the planned development of the "City of Silk" (Madinat al-Hareer). This longstanding project, initially approved by the Government of Kuwait on 26 October 2010, and reaffirmed in June 2014, is still in planning stages with a possible completion date around 2030–2035. It would feature a 1001-m tall skyscraper (Burj Mubarak al-Kabir), a new airport and a huge new seaport on Bubiyan Island, to be linked with Kuwait City by the 26-km Jaber Causeway, presently under construction.

The Subbiya area is transgressed by a mosaic of orthogonal geomorphologic lineaments oriented northeast and northwest, the most conspicuous one being Jal-Az-Zor, which constitutes a "lineament zone" about 25 km in width, extending from Subbiya across Bubiyan Island, offshore into the Arabian Gulf; it is further believed to be associated with differential movement and subsidence of the Northern part of the island (Al-Sarawi 1982). As such, the proposed site of the City of Silk may feature a significant seismic risk, but its distance from active fault lines across the area remains unknown.

Yet, to the authors' best knowledge, the possibility of large earthquakes has not been considered in the structural design of the City of Silk, due to the lack of awareness of the relevant seismic hazards; equally lacking is sufficient knowledge about the local differential

Fig. 2 GoogleEarth view of Kuwait Bay, identifying Jal-Az-Zor escarpment with archeological site H3 (Carter 2002), and location of liquefaction features and dug trenches (blue asterisk). Also shown are Subbiya, the proposed site of the "City of Silk," and to the North, Bubiyan Island

motion affecting its upper crustal layers. These circumstances warrant an urgent need to improve the assessment of seismic risk and vulnerability of Kuwait.

In this general context, we first review the potential for seismic and tsunami hazard in the State of Kuwait.

1.1 Local seismicity

If based solely on recent seismic records, Kuwait may be considered as an area of moderate seismicity. Bou-Rabee (1999) described the Kuwait National Seismic Network (KNSN) established at the Kuwait Institute for Scientific Research (KISR). In operation since March 1997, the network has recorded regional earthquakes originating along the Zagros fold belt as well as local events. The resulting seismicity map of Kuwait shown in Fig. 3 reveals that these local events occur principally in two main clusters, the first one around the Al-Minagish and Umm Gudair oil field zone to the SSW of Kuwait City, and the second one around the Ar-Raudhatain and Sabriyah oil fields, to the NNW. The spatial correlation between earthquake epicenters and oil fields suggests that this seismic activity is induced by oil production (Bou-Rabee 1986, 1994; Bou-Rabee and Nur 2002).

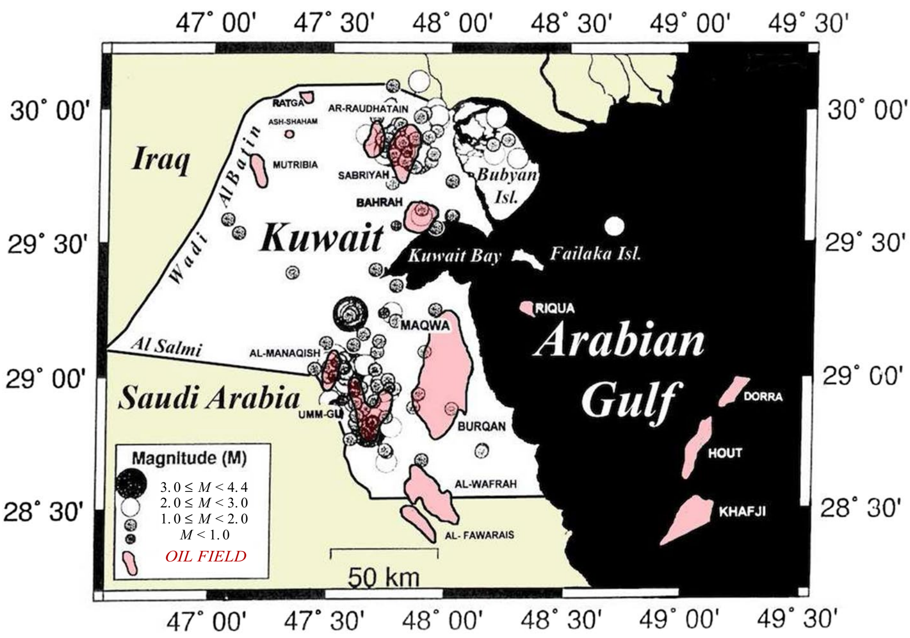

Fig. 3 Map of the seismicity detected within the State of Kuwait by the Kuwait National Seismic Network. Note significant clustering around oil fields (shown as pink patches)

The largest earthquake recorded in Kuwait ($m_b = 4.7$) occurred on 02 June 1993 in the Minagish area, southwest of Kuwait City and was followed by numerous aftershocks. Bou-Rabee and Nur (2002) have suggested that this event was induced by the burning of the oil fields during the 1990–1991 invasion of Kuwait by Iraq. Despite its modest magnitude, the earthquake was widely felt and caused panic in Kuwait City (Bou-Rabee 1999).

Two other moderate earthquakes took place in the Minagish area on 18 September and 30 December 1997 and were also felt in Kuwait City. There were given local magnitudes of 3.9 and 4.1, respectively, by the KNSN, and body-wave magnitudes m_b of 4.6 and 4.4 by the USGS (4.3 and 4.1, respectively, by the ISC).

More recently, two significant earthquakes occurred on 21 March 2015 ($M_w = 4.5$) and 18 August 2015 ($M_w = 4.1$) in the Southern and Northern oil/gas fields, respectively, and were felt all across Kuwait. For both events, Gu et al. (2017) determined focal mechanisms in general agreement with SW–NE compression and shallow source depths of 1 to 4 km.

Additional seismicity is present in the Arabian Gulf, immediately offshore of Kuwait, where five earthquakes are documented since 1960, with a maximum published magnitude $m_b = 4.5$ on 14 December 1996. We relocated earthquakes predating the digital era, from travel times listed in the International Seismological Summary (1960, 1962) or the Bulletin of the International Seismological Centre (1976), using the interactive iterative algorithm of Wysession et al. (1991), with results displayed in Fig. 4 and listed in Table 1. While the epicenters of the 23 June 1962 and 02 January 1976, events are essentially confirmed, the 1960 earthquake relocates to the Iranian shore of the Gulf and hence to the Zagros seismic belt. Similarly, the event reported by the USGS on 27 September 1976, in Southern Kuwait near Juleia ($m_b = 3.8$) relocates to Southern Iran, in agreement with the ISC solution, even though the latter's hypocentral depth (152 ± 8 km) is probably excessive.

Table 1 Significant earthquakes in and around Kuwait

Date	Origin time	Epicenter		Depth	Magnitude	Notes
D M (J) Y	GMT	(°N)	(°E)	(km)		
14 MAR (074) 1960	20:14:44.3	29.67	50.39	10		Relocates to Iranian shore
23 JUN (174) 1962	05:04:56.1	29.64	49.31	10		Offshore
02 JAN (002) 1976	04:30:28.5	28.39	48.97	43	4.1 m_b	Offshore
27 SEP (271) 1976	02:24:13.5	30.39	49.73	100	3.8 m_b	Relocates inside Iran, probably deep
02 JUN (153) 1993	22:01:48.2	28.94	47.61	10	4.7 m_b	Largest event measured in Kuwait
14 DEC (349) 1996	19:49:51.3	28.45	49.63	10	4.5 m_b	Offshore
18 SEP (261) 1997	20:24:46.3	28.99	47.44	10	4.6 m_b	Felt in Kuwait City
30 DEC (364) 1997	18:18:31.6	28.78	47.50	10	4.4 m_b	Felt in Kuwait City
02 AUG (213) 2008	20:45:17.0	29.43	49.15	25	3.8 m_b	Offshore
21 MAR (080) 2015	11:23:35.7	28.99	47.48	15	4.5 M_w	Southern oil field (Gu et al. 2017)
18 AUG (230) 2015	11:26:20.8	29.67	47.68	15	4.1 M_w	Northern oil field (Gu et al. 2017)

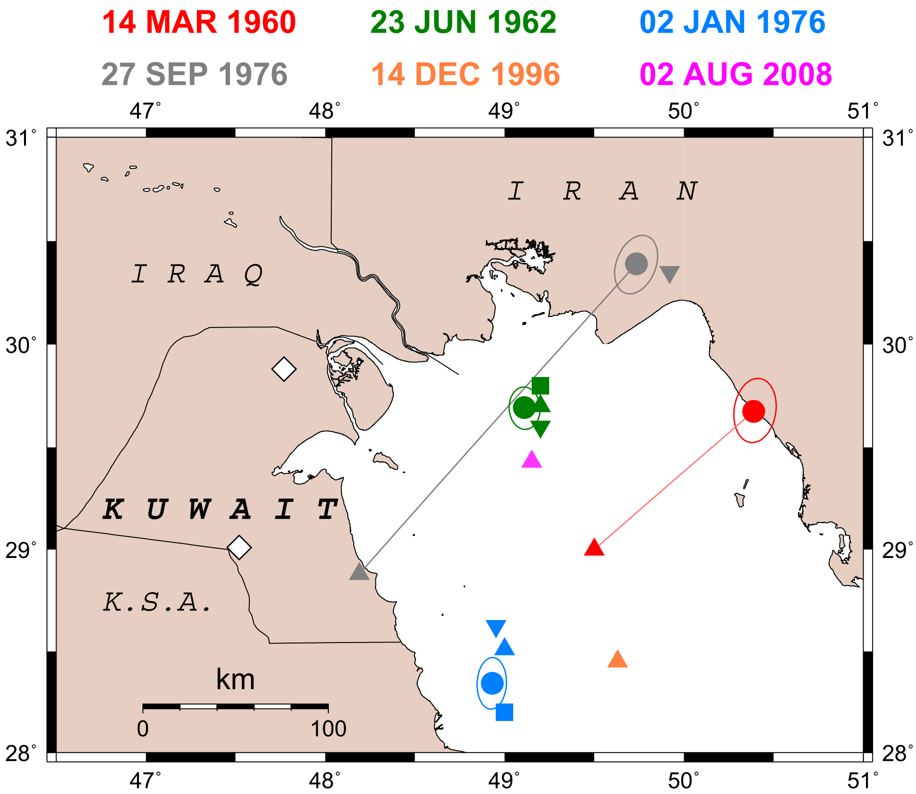

Fig. 4 Map of individually color-coded significant earthquakes teleseismically reported around Kuwait (see Table 1). For predigital events, the result of our relocation is shown as a solid dot, with associated Monte Carlo ellipse. Upward triangles denote USGS/NEIC epicenters, downward triangles ISC solutions (if different), and solid squares epicenters from other agencies (when available). The 1996 and 2008 events were not relocated. For reference, the open diamonds symbolize the Northern (Ar-Raudhatain) and Southern (Minagish) oil fields, where the 2015 earthquakes studied by Gu et al. (2017) took place

The case of the event of 02 January 1976 is interesting, since it locates in the vicinity of the Khafji oil field (see Fig. 3) and could thus represent induced seismicity. However, both the ISC solution and ours give it a significant depth (56 ± 14 km, and 43 km, respectively), which makes this interpretation unlikely.

1.2 Regional seismicity

Magnitude 5 earthquakes in the nearby Zagros Mountains are frequent, and at least two magnitude 7 events were recorded instrumentally, the Farsinaj (Kermanshah) earthquake of 13 December 1957, which featured an average $M_s = 6.8$, but was assigned an unspecified magnitude of 7.1 by Ambraseys et al. (1973) and a "Pasadena" magnitude of $7\frac{1}{4}$, and the recent Halabjah earthquake at the border of Iraq and Iran, on 12 November 2017 (34.91° N, 45.96° E; $M_w = 7.2$). The former had a mesoseismal area extending mostly to the Northeast, and as such was not felt in Kuwait, at a distance of 550 km; the latter was felt around MMI IV in Kuwait City, at a distance of 630 km, and all the way to Tehran, 1000 km away. Focal mechanisms for both the Farsinaj event ($\phi = 6°$, $\delta = 52°$, $\lambda = 126°$ (Shirokova 1962; McKenzie 1972)) and the Halabjah event ($\phi = 351°$, $\delta = 16°$, $\lambda = 137°$) express thrusting across the Zagros range. By contrast, the nearby smaller Sarpol-e-Zahab earthquake of 25 November 2018 (34.30° N, 45.74° E; $M_w = 6.3$) featured a strike-slip mechanism ($\phi = 121°$, $\delta = 83°$, $\lambda = 11°$); it was felt in Baghdad and Kuwait.

It is important to stress that the Halabjah earthquake took place in an area where no comparable seismicity was documented in historical times, although the formation of Lake Zaribar, only 40 km to the North, was due to a landslide itself probably triggered by a major prehistorical earthquake (Ambraseys and Melville 1982). In this context, it remains uncertain how close to the Gulf (and hence to the State of Kuwait) the Zagros seismic belt may feature large seismicity reaching magnitude 6.5 to 7. We note in particular the potential for strong events on the Gulf's Northern shore, as evidenced by the historical earthquakes of A.D. 978 and 1008, reported to have caused the demise of the port city of Siraf, Iran (Ambraseys and Melville 1982; Tofighian 2014), and possibly in 1871 near Bushehr, Iran (Bou-Rabee and VanMarcke 2001).

1.3 More distant mega-events and tsunami risk

The Southern end of the main Zagros thrust complex is connected to the Makran subduction zone, where the oceanic lithosphere of the Gulf of Oman subducts beneath the coastal ranges of Pakistan and Iran. Historical records indicate at least 28 great earthquakes ($M \geq 7$) in the Makran since A.D. 1668 (Ambraseys and Bilham 2003; Pararas-Carayannis 2006), but most of the documented seismicity is limited to its Eastern part (Byrne and Sykes 1992). The most recent event ($M_w = 8.1$), on 27 November 1945, generated a catastrophic tsunami which ran up to heights of 10 m in Eastern Iran and 15 m in Pasni (Okal et al. 2015; Heidarzadeh and Satake 2015). No large-magnitude instrumental seismicity is documented to the West of the 1945 event, but historical accounts mention a probably tsunamigenic earthquake in 1864 around the present border between Iran and Pakistan (∼ 62° E), and a possible event farther West (58°–60° E) in 1483, which may also have been felt in Oman, but whose location has not been verified, in a region featuring only very sparse seismicity (Ambraseys and Melville 1982). This latter event remains controversial and may involve separate shocks in Iran and Oman (Musson 2009; Deif et al. 2017).

In this context, the tectonics of the Western Makran could be interpreted under several models, where convergence could be either entirely taken up by onland orogeny; or largely accommodated by aseismic creep along the subduction zone; or released during very large but infrequent thrust earthquakes, with the subduction zone presently locked since the last such event, which could be the 1483 earthquake (Mokhtari et al. 2008); note that this situation is reminiscent of the uncertainty regarding the tectonic regime of the Cascadia subduction zone, in the Pacific Northwest province of the USA, which prevailed prior to the documentation of the 1700 mega-earthquake (Atwater et al. 2005). The latter model is preferred on account of Late Holocene marine terraces along both the Eastern and Western Makran, suggesting that the Western segment is also capable of producing large plate boundary earthquakes with tsunami potential (Byrne and Sykes 1992), and of significant residual GPS motion between Oman and coastal Iran (Masson et al. 2007). Under a worst case scenario inspired by Ando's (1975) paradigm for laterally fragmented subduction zones, Okal et al. (2015) have suggested that the coeval rupture of the whole Makran subduction zone along a 1000-km-long fault could release a magnitude 9 earthquake whose tsunami might conceivably penetrate the Gulf through the straits of Hormuz (Al-Salem and Al-Enezi 2018).

In addition, tsunamis originating in the Arabian Gulf have been documented, notably during the A.D. 978 and 1008 earthquakes in Siraf, Iran (Ambraseys and Melville 1982), and more recently in September 1871, an event which Bou-Rabee and VanMarcke (2001) have proposed to associate with an earthquake in the vicinity of Bushehr, Iran. In addition, we recall that a quantitative reinterpretation of the phenomenon observed by Nearchus of Greece in 325–324 B.C., based on the updated chronicle by Arrian of Nicomedia (1983), suggests that his fleet encountered a tsunami-like phenomenon in the vicinity of the straits of Hormuz, and quite possibly inside the Arabian Gulf (Okal et al. 2015). Finally, in the recent case of the Bandar Dayyer, Iran, tsunami of 19 March 2017, Salaree et al. (2018) have proposed a meteorological origin, which however may not be directly applicable at the Northern extremity of the Gulf.

Under such scenarios, tsunami waves sweeping the shores of the Gulf, including in Kuwait, could potentially lead to soil failure (including liquefaction) in inundated coastal areas, resulting in a significant loss of lives and property.

In conclusion, a review of documented local and regional seismic and tsunami sources suggests possible frameworks for soil liquefaction in Kuwait, triggered by either agent.

2 Paleo-liquefaction evidence found in Jal-Az-Zor

In order to strengthen the assessment of the seismic risk and vulnerability of Kuwait and other Arabian Gulf countries, and considering the lack of written records prior to the 1950s as well as the long return periods of great earthquakes, we must seek evidence of such major events in the geologic record. In this context, a search for paleo-liquefaction features in Kuwait was initiated in 2003, mainly in the Jal-Az-Zor escarpment area (see Fig. 2). In this area, as in most of Kuwait, the potential for liquefaction hazard is high because of shallow groundwater and sandy, poorly consolidated deposits (Al-Bakri et al. 1988).

Because of the high seismic shaking threshold required to induce liquefaction, paleo-liquefaction studies can help document the occurrence of historical events of high intensity for which no other evidence is available, and as such are of considerable interest to engineers and planners. Worldwide data on historic earthquakes show that liquefaction effects can develop at earthquake magnitudes as low as about 5, but that a magnitude of 5.5 to 6 is the lower limit at which they become relatively common (Ambraseys 1998). Liquefaction caused by earthquake shaking most commonly originates at a depth ranging from a few to about 10 m, in areas where the sediment is nearly fully saturated. The extent of the zone liquefying during shaking depends on the relationship between the cyclic shear stresses generated by the earthquake and the stress required to initiate liquefaction in the sediment.

Liquefaction can also result from excess pore water pressure induced in sedimentary material by transient loads, upon violent inundation caused by tsunami waves, which in the case of Kuwait, could emanate from either a mega earthquake in the Makran subduction zone or a large one in the Gulf itself; a review of wave-induced liquefaction can be found in Jeng (2003). Excess pore water pressure build-up, causing partial fluidization of the top soil at the end of a tsunami ebbing phase near the coastal region, has also been numerically demonstrated (Young et al. 2009, 2010; Xiao et al. 2010a; Xiao et al. 2010b; Olsen et al. 2012). In addition to tsunamis, the downdraw following an extreme storm surge can also cause liquefaction of coastal sandy deposits, as suggested by Robertson et al. (2007), Xiao et al. (2010a), Xiao et al. (2010b) and Young et al. (2009, 2010).

One of the most commonly observed manifestations of soil liquefaction is the occurrence of sand boils along the ground surface. These volcano-like features are typically associated with liquefaction caused by generation of excess pore water pressure within a nearly saturated soil deposit, induced by intense ground shaking or rapid decompression due to sudden changes in water level. The resultant flow of the pore water, apt to concentrate in channels of relatively higher permeability (due to soil inhomogeneity), eventually erupts to the surface in the form of a sand boil (El-Gamal et al. 1993). The outflowing water typically carries sediments from the liquefied overlying layers. It should be noted that similar volcano-like features of sand boils were found and documented in the context of the 2010 Chilean earthquake and tsunami (Olsen et al. 2012).

To assess the risk of large earthquakes and tsunamis in Kuwait, we began the search for paleo-liquefaction features in 2003, focusing on the Jal-Az-Zor escarpment area which lies a few kilometers inland from the northwest and north shore of Kuwait Bay (Fig. 2). The Jal-Az-Zor escarpment has a remarkably straight trend, and the maximum local relief is 145 m [e.g., Fig. 3 of Al-Sarawi (1995]. The escarpment is Oligocene to Holocene in age and appears to reflect subsurface structures. The straightness of the escarpment suggests an origin related to faulting (Al-Sarawi 1982; Bou-Rabee 1986). The structural map of the Jal-Az-Zor area presented by Al-Sarawi (1982) shows two *en-échelon* faults located beneath Kuwait Bay, with a downward movement of 50–70 m and interpreted as a growth fault.

The geologic section of the Jal-Az-Zor escarpment contains, from toe to top, sand, clays, limestone and gravels (Al-Bakri et al. 1988). The toe of the escarpment is covered by a thin mantle of colluvium. The scarp face, nearly vertical and sharp, has many horizontal and vertical fractures that can be traced behind the escarpment face, indicative of active erosional processes (Al-Sarawi 1995).

Virtually all the evidence we found for paleo-liquefaction is located and distributed on the eastern sector of the Jal-Az-Zor escarpment (see Fig. 5). The features, shown in Fig. 6, are cemented sand and gravel-filled dikes that are nearly vertical and connect to a sediment source at depth. This location is 12 km from, and 112 m above, the present shore line. Sediment has vented from the dikes at many places to form sand blows, but many of them have since been eroded. As shown in Fig. 6, the dikes are linear in plan view and exhibit strong parallel alignment in the NNE-SSW direction. The size and abundance of the dikes along the eastern sector of Jal-Az-Zor escarpment generally decrease with increasing distance from a central region of large dikes.

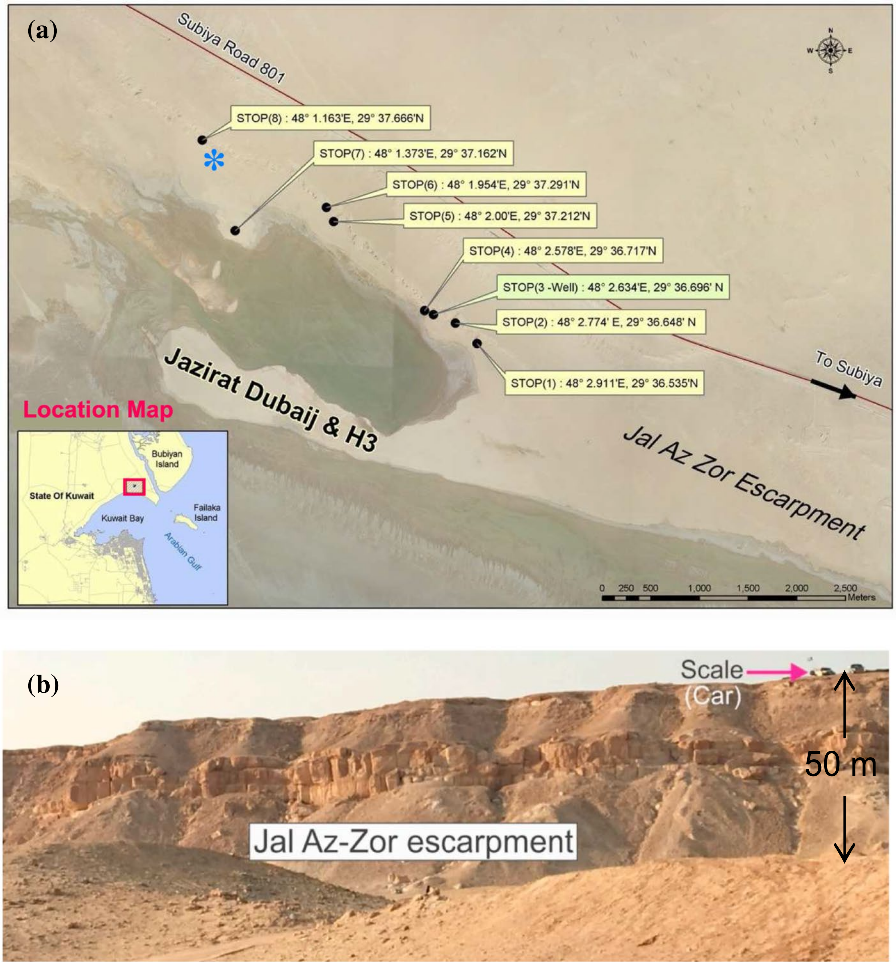

Fig. 5 **a** Map of paleo-liquefactions sites documented along the Jal-Az-Zor escarpment, Kuwait. The location of the trenches dug as part of this study is shown as the blue asterisk. The name H3 refers to one of the sites where the British Archeological Expedition to Kuwait identified archeological remains from *ca.* 7000 years ago [e.g., Al-Sarawi (1982)]. **b** View of Jal-Az-Zor escarpment [adapted from Behbehani et al. (2019)]. The cars on the top of the cliff provide a scale. The local height of the escarpment is approximately 50 m

Hand-dug trenches at two sites, distant ~ 5 m from each other, were excavated during March and April of 2007, at the location (29°37.614′ N; 48°01.217′ E) shown as an asterisk in Fig. 5. Samples from those trenches were collected at a depth of one meter. Each of the trenches exposed a fine- to medium-grained sand with some clay clasts. The surficial sand deposit was connected to numerous vertical sand dikes that range in diameter from a few centimeters to about one meter. These dikes seem to have been injected from the source sand that is in some places buried under a few meters of loose sand, while in other places it is exposed at the surface. Where the source sand is exposed, one can clearly see that the dikes were ejected from it.

Fig. 6 Photographs of sand boils found near the Jazirat Dubaij site, at the Jal-Az-Zor escarpment, Kuwait

Optically stimulated luminescence (OSL) dating was conducted on four samples from two locations in the study area, owing to the lack of organic material in the deposited sand. The application of this technique to geological problems has been reviewed, e.g., by Rhodes (2011). Two samples were collected from the cemented dikes and two from the loose sand surrounding the dikes. The main goal of this dating was to determine the difference in age, if any, between the dikes and the loose surrounding sand, in order to shed light on the mechanism that caused these features. Results from the OSL data are shown in Table 2. The average age of the loose sand (pipe samples) is about 125 kilo-annum (ka), while the average age of the cemented dikes (block samples) is 93 ka. A schematic vertical section of one of the sampled dikes is shown in Fig. 7. The older age of the loose sand suggests that the dikes intruded through the older loose sand from below, forming typical sand blows at the surface; this could not have happened without the generation of excessive pore water pressure.

We interpret the dikes and sand blows found in the eastern sector of Jal-Az-Zor as having been caused by a single large event of seismic origin because:

- This area, as most of Kuwait, has high liquefaction susceptibility due to the shallow ground water and the sandy, poorly consolidated deposits.
- The discovered dikes widen downward or have walls that are parallel to, and cut across, the layered sedimentary rocks. Some are concentric layered and others look like craters filled with sand finer in size than the surrounding rock.
- The dikes vented large quantities of sandy sediment to the surface as sand blows.
- The size and abundance of the dikes along the eastern sector of Jal-Az-Zor escarpment generally decrease with increasing distance from a central region hosting the large dikes.

Table 2 Quartz blue-light OSL ages for Samples 1 and 2 (Stop 8) at the slope of the cliff, close to the Northern end of the escarpment (Fig. 4; 29°37.614′ N; 48°01.217′ E)

Sample information	Sample 1, stop 8		Sample 2, stop 8	
	Loose sand	Cemented dikes	Loose sand	Cemented dikes
Water content (%)[a]	1 (31)	–	1 (25)	
Potassium, K (%)[b]	0.84 ± 0.01	–	0.96 ± 0.02	
Thorium, Th (ppm)[b]	1.71 ± 0.10	–	1.74 ± 0.10	
Uranium, U (ppm)[b]	0.50 ± 0.05	–	0.56 ± 0.04	
Cosmic dose[c] additions (Gy/ka)	0.183 ± 0.01	–	0.83 ± 0.01	–
Total dose[c] rate (Gy/ka)	1.11 ± 0.03	–	1.13 ± 0.03	–
Equivalent dose (Gy)	150 ± 11	110 ± 3	141 ± 5	109 ± 2
n^d	4 (5)	25 (30)	16 (18)	26 (29)
Age (ka)[e]	135 ± 10	98.7 ± 3	115 ± 5	88.3 ± 3

[a]Field moisture, with figures in parentheses indicating the complete sample saturation in percent. Ages calculated using 15–10% moisture value, halfway between the field and saturation moistures. Block moisture content estimated from loose sand due to later cementing.

[b]Analyses obtained using laboratory Gamma spectrometry (low-resolution NaI detector). Loose sand and block sediment mixed for sample.

[c]Cosmic doses and attenuation with depth were calculated using the methods of Prescott and Hutton (1994).

[d]Number of replicated equivalent dose (De) estimates used to calculate the mean. Figures in parentheses indicate total number of measurements made including failed runs with unusable data.

[e]Dose rate and age for fine-grained 250–180 µm quartz sand. Linear and exponential fit used on age; errors given as $1-\sigma$

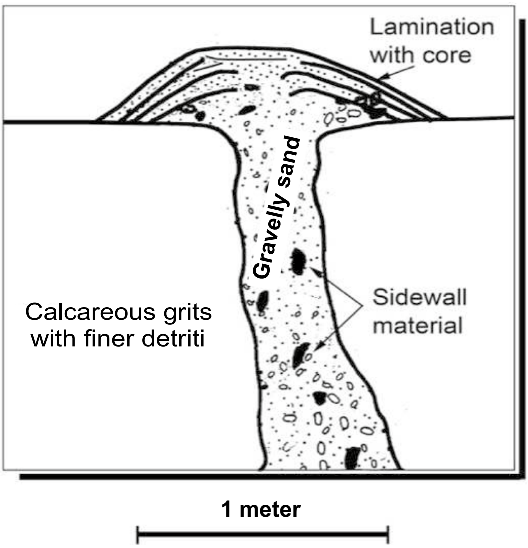

Fig. 7 Schematic vertical cross section of a typical sandboil formation in the eastern sector of the Jal-Az-Zor escarpment, showing the general characteristics of a subvertical gravelly sand dike. It is interpreted as having a seismically induced liquefaction origin

All of these features indicate that the groundwater setting of this area was suddenly affected by strong hydraulic forces of short duration; this could not reasonably be expected other than from earthquake-induced shaking or sudden decompression caused by rapid withdrawal of a large column of seawater due to tsunami downdraw or seiching of large tsunami-like waves (e.g., extreme storm surge) from the Arabian Gulf. In short, the presence, abundance, and spatial distribution of these paleo-liquefaction features (which include sand dikes, cylinders, and sand blows) indicate that they were caused by a single large event of seismic origin (strong earthquake shaking or an earthquake-induced tsunami) with high enough intensity to potentially damage man-made facilities.

At the liquefaction site, the thicknesses of the Calcareous grits and of the gravelly sands in the large dikes range between 1.4 and 1.6 m. Since the gravelly sand has a larger particle size, its permeability is expected to be higher than that of the Calcareous grit. Hence, a build-up of pore pressure in the Calcareous grit layer due to low permeability will push the gravelly sand layer up; this scenario will happen during the ebbing phase of a tsunami, following the large build-up of pore pressure from the runup, and the sudden decrease in overburden hydrostatic pressure during the downdraw (Young et al. 2009; Xiao et al. 2010b).

Given the large ages suggested by the OSL results, we caution that the interpretation of the documented liquefaction as due to a tsunami requires that this event take place during an episode of deglaciation. It is easily verified that at maximum glaciation, the world's oceans were as much as 200 m below their present level, several times the maximum depth of the Gulf, which therefore did not exist as a water mass (Lambeck 1996).

The observed paleo-liquefaction features in the eastern sector of Jal-Az-Zor are significant because they are at considerable distance from areas of presently recorded seismic activity. If the liquefaction features are indeed caused by earthquake-induced shaking, then the implications are serious as they require either a local earthquake source not previously recognized, or an earthquake in currently active zones (e.g., the Zagros belt), significantly larger than documented since the advent of instrumental seismology. On the other hand, if the liquefaction features are caused by wave activity (tsunami or seiche) in the Arabian Gulf, the implications are also serious since they point out to a form of hazard not recognized in this region, emanating from poorly understood sources (either a mega earthquake in the Western Makran subduction zone, or unsuspected major faults within the Gulf itself).

3 Archeological evidence of prehistoric settlement in Jal-Az-Zor

The discovery of liquefaction features at Jal-Az-Zor is intriguing, in the context of studies by the British Archaeological Expedition to Kuwait (BAEK), which suggest that a relatively advanced civilization existed in this region seven thousand years ago. Archeological remains were found by BAEK at a site known as H3 As-Sabiyah in the Jazirat Dubaij peninsula, separated from the present shoreline by a ~ 5-km sabkha, and shown in Fig. 5 (Carter et al. 1999; Carter and Crawford 2001, 2002). This location constitutes an ancient beach ridge, where marine mollusk samples have been dated to 5000–3500 yr b.p. (Reinink-Smith 2015). There is evidence of prehistoric boat travel between the Arabian Peninsula and Southern Mesopotamia, where people from the two regions met and traded exotic stone and painted ceramics (Lawler 2002). A stretch of the coastline of Kuwait, now deserted, supported a cosmopolitan and industrious community at this time. The people lived in villages and built houses using stones (Carter 2002). Today the site's surroundings appear empty and poor in vegetation, but there is evidence that the climate was wetter when the site was occupied (Sanlaville 1992), and fresh water wells can be found that are now abandoned. The demise of this community is unexplained, and one can reasonably speculate that it may have been precipitated by a major natural disaster.

While the seismicity map of Kuwait (Fig. 3) shows only moderate earthquake activity at the Jal-Az-Zor escarpment, our identification of paleo-liquefaction features in the same zone suggests prehistoric damage by large earthquakes or tsunami-like waves. Hence, it is a viable hypothesis that the civilization that existed in this region seven thousand years ago may have been destroyed by a large earthquake and/or tsunami. We note however an order of magnitude discrepancy between the age of the settlement at H3 and the OSL ages for samples recovered in the present study, which could conceivably be reconciled under the scenario of a much larger event giving rise to the liquefaction features, and a smaller one affecting the archeological sites.

In this context, the disappearance of the ancient civilization that lived in the same region where we document paleo-liquification features can be regarded as an indication of the continuity of catastrophic hazard, probably earthquake activity, in that area. There is no reason to believe that this activity should have stopped in the present era.

4 Implications for the future of Kuwait and the other Arabian Gulf Countries

Preliminary results from fieldwork, mapping, and hand-dug trenching in the Jal-Az-Zor escarpment in Kuwait have yielded important information, including the evidence of paleo-liquefaction attributable to large earthquake-induced ground motion or inundation by a tsunami, which itself would most probably have been generated by a large earthquake. Such features are distributed over the eastern sector of Jal-Az-Zor escarpment; they consist of cemented sand and gravel dikes that are nearly vertical and connected to a sediment source at depth. Additional research is needed to identify the exact source and sequence of events that led to these dike formations.

We recognize that our results may be meager, but we think that they should reawaken the question of seismic risk in Kuwait. In itself, our documentation of liquefaction events strongly suggests a significant undersampling of local or regional seismicity, and more generally of seismic hazard for Kuwait, not only by catalogues derived from the relatively recent operation of the KNSN, but also over the entire period of instrumental seismicity, amounting to the last 120 years.

While this result is in itself not totally surprising, such evidence documents the vulnerability of Kuwaiti coastal environments to natural hazards which had remained hitherto unsuspected. As such, the documentation of liquefaction features at Jal-Az-Zor becomes critical, as it mandates a reassessment of seismic risk for coastal Kuwait, in particular in the context of the City of Silk project, whose infrastructure would be directly threatened during a repetition of the natural agent (earthquake or tsunami) which triggered the liquefaction event identified in the present study. Incidentally, such hazard is not limited to Kuwait, but should also be extended to the neighboring Arabian Gulf countries.

Only through a program of natural-hazard risk assessment can we make informed decisions about protection, mitigation, or emergency response strategies aimed at reducing human suffering and the economical impact of future natural disasters. Additional paleo-deposit studies are also necessary to determine the cause—plausibly related to the geologic features described in this paper—of the disappearance of an ancient civilization that existed seven thousand years ago in Kuwait.

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