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Palaeoseismicity and pottery: Investigating earthquake and archaeological chronologies on the Hajiarab alluvial fan, Iran

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ABSTRACT

For millennia, humans have lived in locations that are highly vulnerable to large earthquakes, often out of strategic or cultural necessity and/or the proximity of these locations to resources necessary for survival. Despite the often catastrophic effects when large earthquakes occur, recent history reveals that human nature is to rebuild rather than relocate, implying that seismic activity is not a sufficient deterrent of population growth in tectonically vulnerable areas. In order to investigate whether this was the case for ancient civilisations, and thus perhaps a fundamental tenet of human behaviour, a palaeo-earthquake history was developed for the active Cheskin and Ipak Faults in northwestern Iran, and compared with the well-resolved archaeological history of the nearby 'Sagzabad cluster' settlements of Zagheh (7170–6300 BP), Ghabristan (6215–4950 BP) and Sagzabad (4050–2350 BP). Combining new geologic, geomorphic, and chronologic datasets revealed the presence of a fault-propagated anticline formed by large ($Mw \sim 6.5$–7.0) earthquakes on a blind thrust fault that projects to seismogenic depth directly beneath the Sagzabad cluster settlement sites. Large earthquakes with a return period of <1000 y occurred on the Cheskin and Ipak Faults during human occupation of the Sagzabad cluster. Gaussian cumulative distribution modelling indicates a >90% probability under most faulting scenarios that the energy release from these earthquakes would have been of sufficient magnitude to generate peak horizontal acceleration (PHA) values at the Sagzabad cluster in excess of likely threshold values for complete settlement destruction. Poisson modelling assuming a time–displacement repeating model for earthquake recurrence indicates a 66 (*42*) % probability of one (*two*) earthquakes that would generate PHA $\geq$ 0.25 g occurring during occupation of Zagheh, a 79 (*55*) % probability for Ghabristan, and an 88 (*65*) % probability for Sagzabad. Despite the near certainty that the residents of these Holocene settlements experienced large destructive earthquakes, the near-continuous history of occupation at this area suggests that early humans were not apt to relocate in response to earthquake activity. Environmental (e.g., alluviation, stream channel avulsion, climate change), cultural and/or political factors may have been more important drivers of settlement shifts and abandonment at the Sagzabad cluster of Iran.

1. Introduction

Human settlements throughout the Himalayan-Alpine mountain belt have grown from primitive mid-Holocene villages into cities and megacities despite being situated in close proximity to tectonically active, earthquake-prone fault systems (Jackson, 2006). A prime example is the Iranian capital megacity of Tehran (Fig. 1), with a modern population of almost 14 million people. The city is flanked to the north by the active North Tehran Thrust Fault (Berberian and Yeats, 1999) and resides above a network of active faults (e.g., Niavaran, Lavizan, and Tarasht faults) that have deformed the alluvial gravels supporting Tehran's infrastructure into a series of folds and fault scarps (Jackson, 2006; Abbassi and Farbod, 2009). The predecessors of modern Tehran were damaged or completely destroyed by earthquakes of probable moment magnitude (M_w 7) in the fourth century BC, 855, 958, 1177 and 1830

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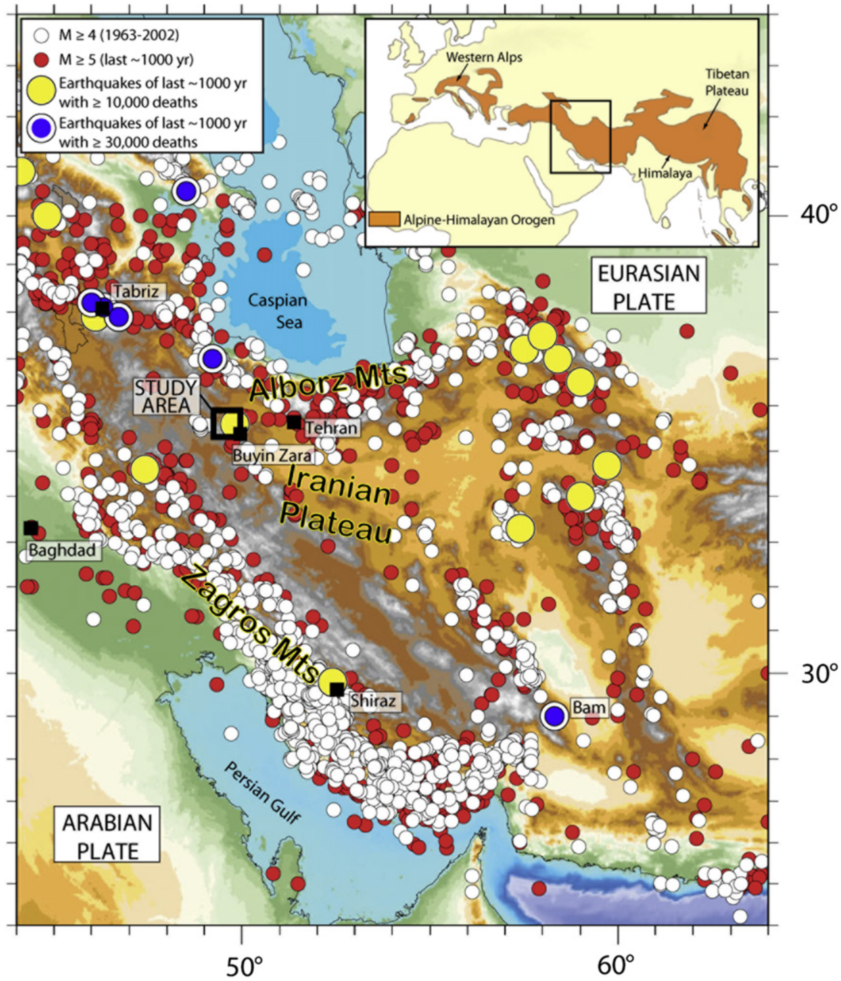

Fig. 1. (Inset) The Alpine-Himalayan Orogen, which results from the tectonic collision of the Eurasian plate with the African, Arabian and Indian plates to the south. (Main) Earthquakes in Iran and its surroundings, modified from Jackson (2006). White dots are well-located earthquakes of $M > 4$ during 1963–2002 from Engdahl et al. (2006). Red dots are earthquakes of the previous 1000 y, thought to be of $M > 5$, from Ambraseys and Melville (1982). Larger dots are earthquakes of the last 1000 y that have killed more than 10,000 people (yellow dots) and 30,000 people (blue dots). Note the close spatial relationship of several of these large earthquakes to major urban centres, the spatial overlap between zones of seismicity and edges of mountain ranges, and the relative paucity of earthquake activity in the low-lying desert regions. Location of study area (described in Fig. 2) as shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Ambraseys and Melville, 1982; Berberian and Yeats, 1999), with deaths likely on the order of hundreds or thousands (Jackson, 2006). However, the favourable location of this site on a major trade route encouraged rebuilding and growth rather than relocation, and Tehran grew to its modern size despite its seismic past. A M_w 7 earthquake centred in the city today would kill hundreds of thousands of people or more (Jackson, 2006). Perhaps driven by this potential loss of life, Iran's rulers are now contemplating the feasibility of moving the country's capital to a more tectonically stable setting and may be encouraging millions of its residents, via financial incentives, to relocate (Theodoulou and Sinaiee, 2010). The relocation of a capital city and many of its inhabitants to mitigate the impact of future earthquakes is globally unprecedented in the modern era, and if undertaken, would represent a major paradigm shift in contemporary human behaviour. One needs only to consider the recent rebuilding of cities destroyed during some of the largest earthquakes in the Himalayan-Alpine mountain belt over the last decade (e.g., 2008 M_w *7.9* Eastern Sichuan, China (~87,587 deaths), 2005 M_w *7.6* northern Pakistan (~86,000 deaths), 2003 M_w 6.6 Bam, Iran (~31,000 deaths), 2002 M_w *6.1* Hindu Kush, Afghanistan (~1000 deaths), and 1999 M_w *7.6* Turkey (~17,118 deaths)) to recognise that the historical precedent is to rebuild, rather than relocate, following catastrophic earthquakes.

This study poses the question, "*Did earthquakes influence the settlement behaviour of our ancient ancestors?*" Archaeological records from the Middle East suggest large earthquakes may have destroyed human settlements spanning back as far as 4000 a, although the human response to these earthquakes is unknown (Berberian and Yeats, 2001). A major earthquake in 747/748 AD has been considered to be responsible for the abandonment of the Decapolis region in Northern Jordan (Hoffmann and Kerner, 2002), although this is disputed (e.g., Lucke et al., 2005). Several authors have argued that earthquakes and related subsidence and/or tsunami-induced inundation caused the abandonment of ancient coastal settlements in western North America (Losey, 2005; Cole et al., 1996) and New Zealand (Goff and McFadgen, 2003). However, the authors are unaware of any irrefutable evidence that ancient human settlements in non-coastal settlements were abandoned due to the effects or, as has been proposed for modern Tehran, the threat of large earthquakes. The focus of this study is to determine whether the decisions to relocate and/or abandon Holocene 'tells' on the Hajiarab alluvial fan in central Iran (Figs. 1 and 2) were influenced by the occurrence of large earthquakes.

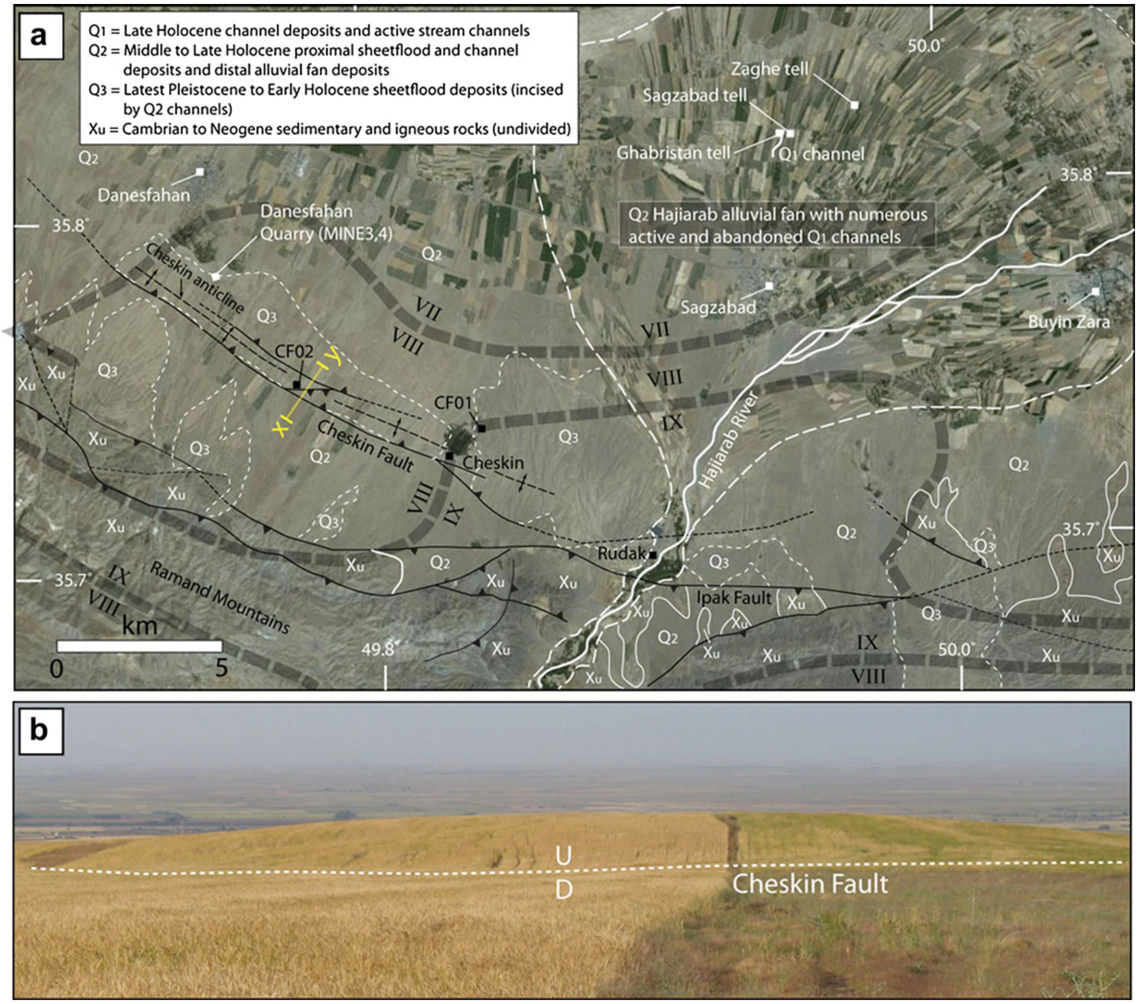

Fig. 2. (a). Geologic and geomorphic sketch map of the study area, showing locations of active faults and folds (Ipak Fault, Cheskin Fault, Cheskin anticline), bedrock outcrops, Late Pleistocene and Holocene alluvial sequences (Q_1–Q_3) and settlements, including the palaeo-settlements of the Sagzabad cluster. Locations of OSL samples and corresponding sample codes, and location of topographic cross-section *X*–*Y* (Fig. 3) as shown. Fault positions dashed where inferred. Position of Ipak Fault slightly modified from Berberian and Yeats (2001) and Ambraseys (1963) to adhere to topographic/geologic features. MMI contours from Ambraseys (1963). (b) View looking north from alluvial surface across the Cheskin anticline approximately parallel to section *X*–*Y*, showing prominent topographic expression associated with hangingwall folding and uplift. Inferred position of Cheskin fault shown.

This paper addresses this by developing and integrating new geologic, geomorphic and chronologic datasets to establish an earthquake chronology and seismic hazard analysis for the Holocene settlements of the Hajiarab fan. It then compares the earthquake history to the well-resolved archaeological history for the 'Sagzabad cluster' settlements of Zagheh (7170–6300 BP), Ghabristan (6215–4950 BP) and Sagzabad (4050–2350 BP). The results provide insights into the relationship amongst ancient humans and their natural environment, with relevance for understanding the fundamental development of human society (e.g. Boyer et al., 2006).

2. Archaeological context

The three tells of the 'Sagzabad Cluster' are situated on the Hajiarab alluvial fan, part of the Qazvin alluvial plain on the central Iranian Plateau of northwest Iran (Figs. 1 and 2). The Ramand Mountains lie ~15 km to the south (Fig. 2). The tells are located within a distance of 2.6 km of each other and form a settlement sequence, being established on successively aggraded fan surfaces (Schmidt and Fazeli, 2007). ^{14}C dating of organic samples and sealed contexts reveal that the oldest settlement, Zagheh, was occupied from 7170 BP (±156 at 2σ) to 6300 BP (±110 at 2σ) (Fazeli Nashli and Abbasnejad Sereshti, 2005). ^{14}C ages from the second site, Ghabristan, range from 6215 BP (±105 at 2σ) for sediments directly beneath the cultural material to ca. 4950 BP, when the site was abandoned (Fazeli Nashli and Abbasnejad Sereshti, 2005). There is a settlement gap of about 900 y in the archaeological record, from both the Hajiarab fan and much of the broader region with the exclusion of the Shizar Tepe, until the settlement of Sagzabad at ca. 4050 BP (Fazeli Nashli and Abbasnejad Sereshti, 2005). This settlement, located just 0.3 km east of Ghabristan, was inhabited until ca. 2350 BP (Malek Shahmirzadi, 1977a: p.79).

The reason for the settlement shifts and remarkably long settlement hiatus in the Early Bronze Age is unknown, and the subject of particular scientific interest (e.g., Schmidt et al., 2011). Although a disruption of the social fabric through the Kura-Araxes peoples has been considered (Fazeli Nashli and Abbasnejad Sereshti, 2005), several early observations from the tells suggest that large earthquakes may have occurred during their habitation and may even have influenced settlement patterns. Early archaeological investigations of the Sagzabad site (Negahban, 1971, 1973, 1974a,b, 1976, 1977) uncovered, "*complete but crushed skeletons of domesticated animals, lying side by side under collapsed walls, as* *though they had perished in a stable that had been destroyed by some natural calamity such as a flood, or more likely, an earthquake*". Subsequent Sagzabad archaeological investigations revealed the displacement of an undated charcoal layer and the rotation of blocks in alluvial deposits (Berberian et al. (1983, 1993)), and the collapse of a Late Bronze Age (c. 4000 ± 1600 BP) square brick column and tilting of a Late Bronze Age wall (Tala'j, 1998). Based on these observations, Berberian and Yeats (2001), speculated that a large earthquake on the Ipak Fault (Fig. 2) destroyed Sagzabad at ca. 4010–3510 BP. However, no palaeoseismic investigations of the Ipak Fault and broader region were undertaken to complement these archaeological observations.

3. Historical earthquakes: regional impacts of the 1962 M_S 7.2 Buyin-Zahra earthquake

Iran is part of a tectonically active, diffuse boundary zone between the Arabian and Eurasian tectonic plates (Fig. 1). The Iranian Plateau, although much less seismically active than the Zagros and Alborz mountainous regions (Fig. 1) hosts several active faults with slip rates of >1 mm y^{-1} (Bachmanov et al., 2004; Fattahi et al., 2006), and has experienced several destructive earthquakes in the last century, including the 1953 M_S 6.5 Torud, 1962 M_S 7.2 Buyin-Zahra and 2002 M_w 6.4 Changureh earthquakes (Walker et al., 2005)(Ambraseys and Melville, 1982). The epicentre of the September 1st, 1962 Buyin-Zahra earthquake was located ∼22 km SSE of the Sagzabad tells, and the natural response of the study site to this earthquake is instructive for understanding the potential impacts of palaeo-earthquakes on the tells. The Buyin-Zahra earthquake killed over 12,220 people, injured ∼2800, and damaged beyond repair ∼21,330 homes in 300 villages throughout the region (Ambraseys, 1963). More than 1800 aftershocks were recorded in the following months including two that were strong enough to cause further damage and collapse of houses (Ambraseys, 1963). The main earthquake occurred on the ESE-striking Ipak fault with a focal depth of ∼20 km (Berberian, 1976), centroid depth of ∼10 km (Priestley et al., 1994), M_w 7.0, and epicentre location ∼8 km south of the surface rupture along the eastern part of the Ipak fault surface trace (Fig. 2). The earthquake focal mechanism solution suggests almost pure thrusting on a 52°S dipping fault (Priestley et al., 1994). As expected, the epicentres of most aftershocks are located south of the Ipak Fault rupture trace, however there was at least one aftershock of M_S ∼ 5.0 (December 2, 1962) that was located ∼5 km NNE of Buyin-Zahra and ∼13 km N of the rupture trace (see Fig. 3 of Berberian and Yeats, 1999 for location), implying either stress triggering of a distinct fault or coeval rupturing of multiple faults during the Buyin-Zahra event. The Buyin-Zahra

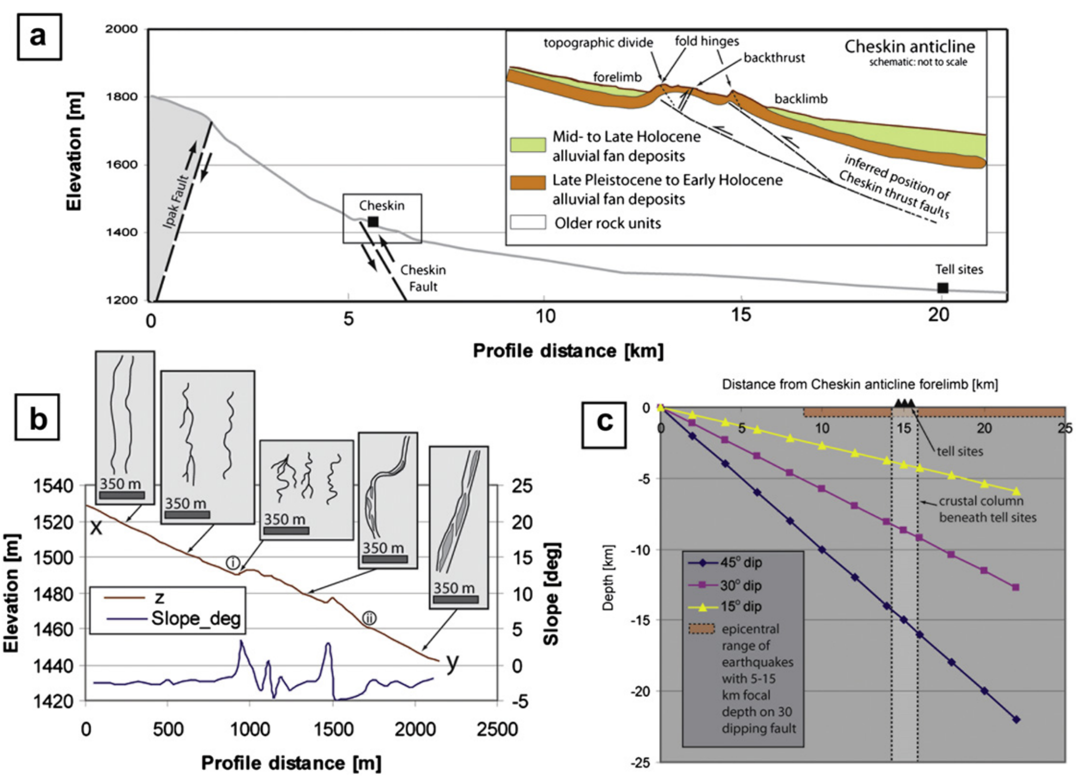

Fig. 3. (a) Tectonic geomorphology of the Cheskin anticline and underlying thrust fault. All sections oriented at an azimuth of ∼030° with a look direction to the WNW (a) SSW-NNE oriented topographic cross-section from Ipak Fault to the Sagzabad cluster tell sites, showing inferred dip of the Ipak and Cheskin faults. Location of inset as shown. (Inset) Schematic topographic and geological cross-section of the Cheskin anticline, showing inferred position of the Cheskin thrust faults and backthrust, major features of the fold (forelimb, hinge, backlimb) and distribution of alluvial fan deposits. See text for interpretation. (b) Total Station derived topographic profile and slope distributions across the Cheskin anticline, showing reversal of slope from NE dipping (negative slope) to SW dipping (positive slope) across the anticline. Slope changes and airphoto interpretation reveal topographic steps associated with the faults shown in (b). Slope data also shows the lack of a subsided region in the forelimb (i) and a slightly subsided region in the backlimb (ii) relative to mean fan slope (see text for interpretation). Changes in channel geometry shown for representative channels traced directly from remotely sensed imagery. Changes in sinuosity, channel width and character reflect changing slope and bedload flux related to folding (see text for interpretation). In general, ephemeral streams change from single, slightly incised channels with well defined banks to more numerous, highly sinuous streams directly upstream of the Cheskin Thrust, to fewer, straighter channels with terraces, braid bars, and steeper channel banks across the anticline, to less incised, straighter, wider braided channels with numerous point bars, consistent with observations of ephemeral stream responses to growing folds documented in other tectonically active settings (e.g., Pearce et al., 2004). (c) Estimated subsurface position of the Cheskin Fault for a range of possible fault dips plotted against distance from the anticlinal forelimb. Preferred fault dip of 30° based on anticline geometry results in fault depth of ∼8 km beneath Sagzabad tell sites, well within the 5–15 km depth range for typical earthquake centroid depths associated with Iranian earthquakes. See text for details.

earthquake generated a discontinuous series of surface ruptures with a total length of ~95 km. Ruptures were grouped into a sequence comprising a 56 km long, south-dipping eastern segment (the source of the hypocentre) and a 39 km long north-dipping western segment linked via a ~5–10 km wide deformation zone in the vicinity of Rudak (Ambraseys, 1963; Berberian and Yeats, 2001) (Fig. 2). Maximum recorded values of co-seismic displacements were 1.4 m vertically and 0.6 m left-laterally (Ambraseys, 1963; Berberian and Yeats, 2001). Modified Mercalli Scale seismic intensity (MMI) was estimated at VIII and IX in the ~15 km wide region bounding the fault and VII in the region encompassing the Zaghehh, Ghabristan and Sagzabad tell sites (Fig. 2) (Ambraseys, 1963; Berberian and Yeats, 2001). Numerous small landslides and rock-falls occurred on hillslopes throughout the region, liquefaction features such as mud and sand volcanoes as well as cracks developed on the banks of the Hajiarab River, and temporary reductions in discharge within underground water supplies (qanats) occurred during the earthquake (Ambraseys, 1963). New springs appeared in many places and old ones stopped flowing (Ambraseys, 1963), indicating the earthquake influenced subsurface water flow. Ambraseys (1963) suggested that a significant component of the main rupture did not propagate to the surface and was expressed by folding at the surface instead. A similar inference has been drawn for the 2002 M_w 6.4 Changureh (Avaj) earthquake (Walker et al., 2005). These so-called 'blind thrust fault' earthquakes are common in Iran (Berberian and Yeats, 2001; Bachmanov et al., 2004; Walker et al., 2005), and due to the absence of surface ruptures, are typically recognised by surface folding, springs and drainage diversions that are commonly observed on alluvial fans (Lettis et al., 1997; Walker et al., 2005; Jackson, 2006).

4. Structural and geomorphic evidence for pre-historic earthquakes in the study region

On the basis of the archaeological observations described above, Berberian and Yeats (2001) speculated that the Sagzabad settlement was destroyed by an earthquake of similar or greater magnitude to the 1962 Buyin-Zahra event at ca. 4010–3510 BP. They argued that a smaller earthquake resulting from a shorter rupture length event, even of the Ipak fault segment closest to the Sagzabad cluster, (i.e. the Rudak fault segment, ~14 km away with a length of ~18 km) would not have been capable of generating MMI intensities of VII and VIII at Sagzabad. The Ipak Fault was claimed as, "*the only one close enough to the Sagzabad cluster to be a candidate for the postulated earthquake destroying Sagzabad, and no geomorphic evidence of active folding above a blind thrust is present.*" Finally, these authors suggested that the 1962 Buyin-Zahra earthquake may be a repeat of the c. 4010 ± 1500 BP postulated earthquake, giving a 'maximum recurrence interval' of approximately 3500–4000 y for the Ipak Fault.

Bachmanov et al. (2004) reported vertical offsets of presumed lower and middle Pleistocene deposits of 2–3 m along a segment of the western Ipak fault on the north side of the Ramand Mountains. Bachmanov et al. (2004) also reported left-lateral separations of 85-90 m from the '*oldest generation of fans*' near the settlement of Ipak (35.623778°N, 50.308911°E), and offsets of 25 and 30 m of Late Pleistocene terraces across the eastern segment of the Ipak Fault (see also Ambraseys, 1963). The location of these sites was not disclosed and hence these interpretations could not be verified. The reconnaissance mapping and inspection of remotely sensed SPOT imagery did not reveal supporting evidence for the large scale lateral displacements proposed by Bachmanov et al. (2004), and accordingly caution is required in interpreting this data. Field mapping and remote sensing did allow refinement of the position and inferred dip direction of the western segment of the Ipak fault in the study area (Fig. 2). Three Late Pleistocene and Holocene alluvial sequences (Q_1–Q_3) are present. The Cheskin Fault is exposed on the Q_3, Latest Pleistocene to Early Holocene, surface.

Geological mapping of the alluvial plain between the northern piedmont of the Ramand Mountains and the Sagzabad Cluster revealed the presence of a NW-trending, >20 km long, ~0.75–1 km wide, elongate zone of anomalous, mildly elevated and steeply dissected topography that runs from south of the Danesfahan quarry, through the village of Cheskin, to the village of Rudak (Fig. 2). The linearity and apparent continuity of this feature with the Ipak fault near Rudak, and its surface-trace parallelism with strands of the Ipak fault, suggest that this uplifted feature is fault related. Cross-sectional profiles derived from a Total Station survey perpendicular to the uplift (Fig. 3) and SRTM data indicate that the upper surface of the alluvial plain southwest of the feature maintains a relatively uniform dip of ~2.5° NE from the range front until the feature is reached, where the fan surface slope changes to ~3.4° SE and the topography is elevated ~5 m relative to a best fit line of uniform slope derived from adjacent, unperturbed upstream and downstream reaches of the fan (Fig. 3a). A similar perturbation of ~3 m height is observed in the central part of the structure. The gross morphology of the land surface trending from SW to NE across the uplift thus consists of a relatively steeply SW dipping surface, a gently NE-dipping surface, a second, steeply SW dipping surface, and a gently NE-dipping back surface that ultimately rejoins the regional fan surface slope (Fig. 3a,b). Stream channels upstream of the uplift shows a transition from relatively straight, braided channels to more sinuous channels within ~300–500 m of the southern edge of the uplift, coincident with a decrease in channel slope (Fig. 3b). Similar changes from braided to meandering channel geometry have been replicated by decreasing channel slopes in stream table experiments (Schumm and Khan, 1972), implying that the changes in channel geometry reflect the uplift of the feature. Through the axis of the uplift, the channels are more steeply incised and flanked by small terraces, implying that the channels have cut down into the uplifting feature. Downstream of the uplift, the channels are wider and are bar braided, likely due to the increased sediment flux resulting from upstream incision into the uplift (Fig. 3b) (Ouchi, 1985). Collectively, the coincident changes in channel incision and fan slope across the uplift imply that a component of uplift has been synchronous with channel activity.

The uplifted feature is interpreted as an anticlinal fold, henceforth referred to as the Cheskin anticline, that has developed above a 'blind' thrust fault. The underlying fault appears to consist of at least two NE-dipping strands as indicated by the overall cross-sectional topographic asymmetry of the uplift and the sharp increases in slope on the SW-facing slopes of the SW edge and central part of the anticline (Figs. 2 and 3a). A small backthrust (Fig. 3a) in the vicinity of the topographic profile line (Fig. 2) is also apparent. The dip of the underlying fault(s) is unknown but is hypothesised using the geometry of the anticline. Elastic half-space models indicate that the dip of the fault underlying a growth anticline controls the position and relative magnitude of subsidence in the forelimb and backlimb regions (Ellis and Densmore, 2006). Analysis of the Cheskin anticline topographic profile and slope angle data (Fig. 3b) indicates the absence of a subsided region in the forelimb (i) relative to the mean fan slope, and a slightly subsided region in the backlimb (ii) relative to the mean fan slope. This morphology is best replicated by an underlying fault dip of ~30 ± 10° to the NNE (Ellis and Densmore, 2006). As no surface ruptures were observed in the field, it is suspected that the underlying fault is 'blind', i.e. does not reach the surface (e.g., Lettis

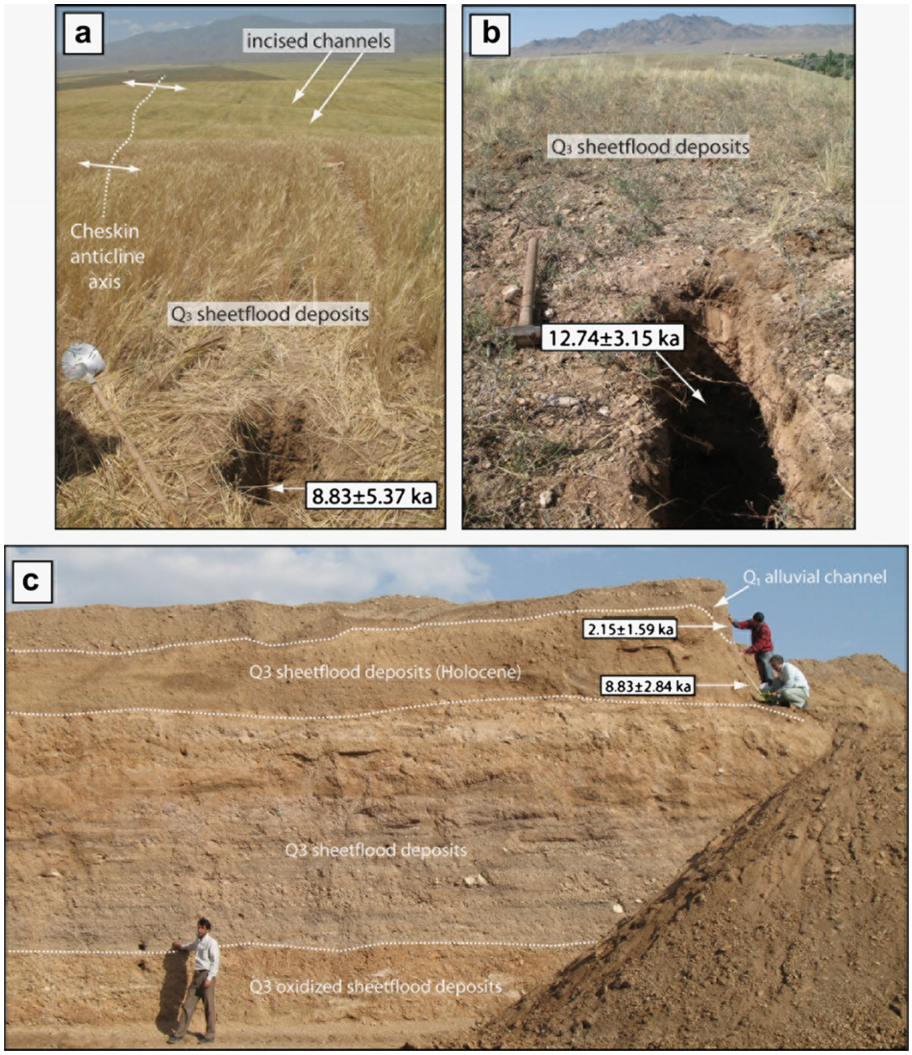

Fig. 4. (a) CF02 sampling pit site and OSL age from crest of Cheskin anticline (see text for details). (b) CF01 sampling pit site and OSL age from warped alluvial fan east of Cheskin. (c) MINE 03 and 04 sampling sites and OSL ages from Danesfahan quarry, and stratigraphic boundaries.

et al., 1997). Although there are no constraints on fault depth, the short distance ($\leq$150 m) from the forelimb to the topographic divide for both thrusts is favoured by models with shallow (i.e., $<$2 km depth) underlying fault tips (Ellis and Densmore, 2006).

This interpretation of the underlying fault geometry has important palaeoseismic implications for the nearby Sagzabad cluster settlements (Fig. 3c). Earthquake focal depths in Iran are generally restricted to the upper crust ($\leq$20 km depth) and most commonly occur in the 5–15 km depth range (Maggi et al., 2000). The Bam earthquake had a focal depth of $\sim 7 \pm 2$ km (Ramazi and Jigheh, 2006), although the extent to which this is representative of major Iranian palaeo-earthquakes is unclear, as this event only ruptured the upper half of the seismogenic crust (see Jackson, 2006). Southward projection of a range of possible Cheskin fault dips (15–45°) to a crustal column lying beneath the Sagzabad cluster reveals that the location of earthquake centroids associated with this fault are likely to have been in close proximity to the tell sites. For instance, the preferred fault dip (30°) based on anticline geometry places the fault at a depth of $\sim$8 km beneath the tell sites, which would have minimised the distance between likely regions of high moment release on the Cheskin fault and the tell sites, resulting in elevated peak ground acceleration and associated co-seismic damage at the surface.

5. Optically stimulated luminescence dating of fault-related alluvial deposits

5.1. Theory and methodology

In order to determine the chronology of earthquakes on the Ipak and Cheskin faults and assess whether these earthquakes occurred during the occupation of the Sagzabad tells, samples were obtained from deformed and undeformed alluvial deposits for dating by optically stimulated luminescence (OSL). When quartz and feldspar grains within a sedimentary sequence are buried, they begin to accumulate a trapped-charge electron population that increases in a measurable and predictable way in response to the ionising radiation dose to which the grains are exposed (Aitken, 1998). Exposure to sunlight releases the light sensitive trapped charge and resets the OSL signal. This process is commonly referred to as 'zeroing'. The time elapsed since quartz grains were last exposed to sunlight can be determined by measuring the OSL signal from a sample, determining the equivalent radioactive dose (*De*) and estimating the rate of exposure of the grains to ionising radiation since they were buried (the 'dose rate'; *Dr*) (Aitken, 1998). From these parameters, the burial age of well-bleached grains can be determined. OSL dating of alluvial sequences is presently used in

Table 1
Optically stimulated luminescence data and optical ages.

Sample	Lat. (°N)	Long. (°E)	Depth (cm)	K%	Th (ppm)	U (ppm)	*De* (Gy)[a]	±	Dose (Gy/ka)[b]	±	Optical age (ka)	±	From (BP)	To (BP)
MINE 03	35°46′50″	49°44′34″	178	2.26 ± 0.01	10.2 ± 0.1	2.72 ± 0.1	32.92	10.44	3.73	0.17	8.83	2.84	11670	5990
MINE 04	35°46′50″	49°44′34″	80	2.67 ± 0.01	12.5 ± 0.1	3.02 ± 0.1	9.23	6.81	4.30	0.17	2.15	1.59	3740	560
CF-01	35°44′11″	49°50′14″	60	2.04 ± 0.01	8.4 ± 0.1	2.53 ± 0.1	41.83	10.06	3.28	0.16	12.74	3.15	15890	9590
CF-02	35°45′06″	49°46′24″	62	2.44 ± 0.01	6.7 ± 0.1	2.07 ± 0.1	30.31	18.34	3.43	0.17	8.84	5.37	14210	3470

[a] Equivalent dose.
[b] Total dose rate.

a variety of contexts, including constraining the timing of palaeoseismic events (e.g. Fattahi et al., 2006; Quigley et al., 2006), flood events, and facies changes resulting from climate change (e.g. Quigley et al., 2007).

A total of 14 samples were obtained for OSL dating from 6 sites as part of an ongoing multi-disciplinary research program on the palaeo-environmental history of the Sagzabad cluster region (Schmidt et al., 2011). Here, discussion focuses on the samples that provide temporal constraints on the earthquake history. These include (a) fine-grained, sandy sheetflood alluvial sediments beneath abandoned alluviation surfaces on the crest of the Cheskin anticline (CF01, Figs. 2 and 4a) and a gently warped alluvial fan near Cheskin (CF02; Figs. 2 and 4b), and (b) a sandy-gravel channel fill deposit that correlates with channels associated with the topographic breaching of the anticline (MINE04; Fig. 4c) and overlies a sheetflood deposit (MINE03; Fig. 4c). It is hypothesised that the age of the Q3 anticlinal crest and Q3 warped fan sediments will provide temporal constraints on the abandonment of these alluviation surfaces and on fold growth subsequent to abandonment. The age of the Q1 channel is hypothesised to relate to the incision of the anticline and re-deposition of incised sediment in an aggradational channel downstream of the anticline, thus post-dating at least some phase of anticlinal uplift (Fig. 4c).

Samples were collected by driving 50-mm-diameter opaque stainless-steel tubes into cleaned alluvial stratigraphic sections. All samples were collected from depths greater than 45–50 cm. Samples from the deformed alluvial fans near Cheskin were collected by digging ∼75 cm deep pits into the upper fan surface and sampling horizontally at the base of the pits. Dose rates were determined by ICP-MS measurement of U, Th and K concentrations from sediments obtained from within a 15 cm radius around the sample hole. All the experiments reported here were carried out using a Risø automated TL/OSL system. OSL was detected using an Electron Tubes bialkaline PMT. Luminescence was measured through 7 mm Hoya U-340 filters. The sample was processed under subdued red light. The potentially light-exposed sediments at both ends of the tubes were extracted, and the sediment remaining was used for equivalent dose determination. A portion of the sample was wet-sieved to separate the quartz grains and immersed for two days in 1 N HCl to remove carbonate, followed by two days immersion in H_2O_2 to remove organic material. The grains were treated with 48% Fluorosilicic acid for 50 min in order to remove feldspar. The quartz separates were mounted as a monolayer (approximately 5 mg/disc) on 10 mm diameter aluminium discs using a silicon spray as adhesive. *De* was obtained using the single aliquot regeneration method of Murray and Wintle (2000). Laboratory beta dose rate was applied following Armitage and Bailey (2005). Sample moisture contents were determined by drying the samples at 40 °C in the laboratory. The conversion factors for water contents of Aitken (1985) and Aitken and Xie (1985) were used for the calculation of alpha, beta and gamma dose rates. Alpha and beta dose rates were corrected for attenuation due to grain size using the factors of Bell (1980) and Mejdahl (1979). Dose rates and optical ages for each sample are presented in Table 1.

5.2. Results

OSL dating of the Q3 anticlinal crest sediments suggests that the abandonment of the surface comprising the core of the Cheskin anticline occurred at ca. 8830 ± 5370 BP ago, assuming minimal crestal erosion (Fig. 4a; Table 1). Q3 alluvial fan deposits near Cheskin indicate that the abandonment of this fan occurred at ca. 12,740 ± 3150 BP assuming minimal crestal erosion. Collectively, these results indicate that a minimum of ∼5 m of Holocene vertical uplift on the Cheskin anticline; equivalent to the height of the surfaces above the adjacent alluvial surface to the south. OSL dating of the Q1 channel suggests that the anticline was breached by incising streams in at least one location by at least 2150 ± 1590 BP. The relationships amongst alluviation and tectonic activity are likely to be complicated given Holocene climate change in this region (Schmidt et al., 2011). The geomorphic disruption of modern streams crossing the anticline suggests that anticlinal uplift is ongoing. Although there are considerable errors associated with the age chronology, and uncertainty associated with relationship of

Table 2a
Surface rupture length (SRL), maximum displacement (MD), and rupture area (RA) values and M_w estimates derived using the regression formulas of Wells and Coppersmith (1994).

Earthquake source	SRL (km)	MD (m)	RA (km^2)	SRL regression[a] (strike-slip)	SRL regression[b] (reverse)	MD regression[c] (strike-slip)	MD regression[d] (reverse)	RA regression[e] (strike-slip)	RA regression[f] (reverse)
IPAK FAULT – 1962 Bo'in Zahra	95	1.5	3014	7.4 ± 0.3	7.4 ± 0.6	6.6 ± 0.2	6.6 ± 0.2	7.5 ± 0.2	7.5 ± 0.3
IPAK FAULT – Western segment	39	–	1237	6.9 ± 0.3	6.9 ± 0.5	–	–	7.1 ± 0.2	7.1 ± 0.3
IPAK FAULT – Eastern segment	56	–	1777	7.1 ± 0.3	7.1 ± 0.5	–	–	7.3 ± 0.2	7.3 ± 0.3
CHESKIN FAULT (30° dip)	20	–	1000	6.6 ± 0.2	6.6 ± 0.4	–	–	7.0 ± 0.2	7.0 ± 0.3
CHESKIN FAULT (52° dip)	20	–	635	6.6 ± 0.2	6.6 ± 0.4	–	–	6.8 ± 0.2	6.8 ± 0.3
CHESKIN + EASTERN IPAK	76	–	2772	7.3 ± 0.3	7.3 ± 0.5	–	–	7.5 ± 0.2	7.4 ± 0.3

[a] $M_w = 5.16(0.13) + 1.12(0.08) \times \log(\mathrm{SRL})$.
[b] $M_w = 5.00(0.22) + 1.22(0.16) \times \log(\mathrm{SRL})$.
[c] $M_w = 6.81(0.05) + 0.78(0.06) \times \log(\mathrm{MD})$.
[d] $M_w = 6.52(0.11) + 0.44(0.26) \times \log(\mathrm{MD})$.
[e] $M_w = 3.98(0.07) + 1.02(0.03) \times \log(\mathrm{RA})$.
[f] $M_w = 4.33(0.12) + 0.90(0.05) \times \log(\mathrm{RA})$.

Table 2b
M_w estimates derived using the modified regression formulas of Wells and Coppersmith (1994) for MD and the Hanks and Kanamori (1979) regression for M_w.

Earthquake source	MD (m)[a]	AD (m)[b]	RA (km)	M_w[c]	M_w[d]
IPAK FAULT – 1962 Bo'in Zahra	1.5	0.4	3014	7.2 ± 0.3	**7**
IPAK FAULT – Western segment	1	0.3	1237	6.9 ± 0.2	**6.7**
IPAK FAULT – Eastern segment	1.2	0.3	1777	7.0 ± 0.2	**6.8**
CHESKIN FAULT (30° dip)	0.8	0.2	1000	6.9 ± 0.3	**6.7**
CHESKIN FAULT (52° dip)	0.8	0.2	635	6.7 ± 0.2	**6.5**
CHESKIN + EASTERN IPAK	1.4	0.4	2772	7.2 ± 0.3	**7**

[a] log (MD) = −0.655(0.34) + 0.42(0.23) × log (SRL); modified from Wells and Coppersmith (1994).
[b] AD = 0.27(MD) from best fit M_w.
[c] $M_w = 0.666 \times \log(Mo) - 10.7$ with AD = 0.5 ± 0.3 × MD.
[d] $M_w = 0.666 \times \log(Mo) - 10.7$ with best fit AD = 0.27 × MD.

sediment age to earthquake events, the data nonetheless indicate that earthquakes of sufficient magnitude to destroy the Sagzabad tells occurred on the Cheskin fault during the time interval (ca. 8830 to ≤2150 BP) that the tells were occupied (ca. 7170–2350 BP).

6. Palaeoseismicity of the Ipak and Cheskin faults

6.1. M_W determinations from fault source parameters

If the M_S 7.2 (M_w 7.0) 1962 Buyin-Zahra earthquake is a suitable analogue for large palaeo-earthquakes on the Ipak Fault, then the geometric and seismological characteristics of this historical rupture may provide insight into the moment magnitude M_w of palaeo-earthquakes for this area. In estimating M_w for palaeo-earthquakes, a commonly used methodology is to use established regressions from historical earthquakes that link fault source parameters (e.g., surface rupture length, displacement, rupture area) to seismologically determined values of M_w (Wells and Coppersmith, 1994). To test the suitability of these regressions for the study region, the Ipak Fault source parameters associated with Buyin-Zahra earthquake were input into the regressions of Wells and Coppersmith (1994) to derive a hypothetical M_w to compare to the seismologically recorded value. Surface rupture length (SRL) and rupture area (RA) were used as input parameters because these regressions show the strongest correlations and lowest standard deviations with M_w in the Wells and Coppersmith (1994) dataset (Table 2a). Maximum displacement (MD) was used to derive M_w, despite a confidence level of <95% in the Wells and Coppersmith (1994) dataset. MD was computed from vector sum of the maximum horizontal and vertical slip components (=1.5 m). To derive RA, the subsurface rupture length (∼119 km) was determined using the empirical relationship subsurface RL = 1.25 × SRL (Wells and Coppersmith, 1994). An average fault dip of 52° (as indicated from the seismology) was assumed, with a rupture depth extent equivalent to the hypocentral depth of 20 km (Berberian, 1976) on the basis that most mainshocks for large earthquakes are located at or near the base of the seismogenic zone (e.g., Sibson, 1987). Although the focal mechanism for the Buyin-Zahra earthquake indicates almost pure thrusting, M_w was derived using regression parameters for both reverse and strike-slip-dominated earthquakes given the possibility of strike-slip components of displacement on the Ipak Fault (Berberian, 1976). SRL-M_w and RA-M_w regressions systematically over-predict the M_w for the Buyin-Zahra earthquake while MD regressions systematically under-predict the M_w (Table 2a). From the Wells and Coppersmith (1994) datasets, the Buyin-Zahra earthquake appears to have had a relatively long SRL, large RA, and small MD for its M_w compared to the global dataset of historical earthquakes (although similar values have been recorded elsewhere)(Table 2a). Thus, while M_w estimates for the Ipak and Cheskin Faults were derived using these regressions, M_w was estimated according to Hanks and Kanamori (1979)

$$M_W = 2/3 \times \log(\mu \times \mathrm{AD} \times \mathrm{RA}) - 10.7 \quad (1)$$

using a crustal rigidity modulus (μ) of 3×10^{11} dyn/cm^2, an average displacement (AD) equivalent to 0.5 ± 0.3 × MD (maximum displacement) (Wells and Coppersmith, 1994), and the RA computed above. This method results in a value of M_w (7.2 ± 0.3) that is more consistent with the measured M_w (Table 2b). This formula was inverted using $M_w = 7.0$ to derive a 'best-fit' AD–MD ratio (AD = 0.27MD), and assumed that historical ruptures on both the Ipak and Cheskin Faults maintained a similar AD–MD ratio, realising that this is likely to be the biggest uncertainty in this calculation (Table 2b). The Hanks and Kanamori (1979) seismic moment relation was then to derive M_w estimates for various earthquake scenarios on the Ipak and Cheskin faults (Table 2b).

As the Buyin-Zahra earthquake ruptured across two fault segments of 56 km and 39 km length (Ambraseys, 1963), it is possible that these segments may have ruptured independently in the past. Assuming that the rupture geometry of these faults was similar to that exhibited during the Buyin-Zahra earthquake, Eq. (1) was used to derive M_w estimates for these faults if they ruptured separately. The same hypocentral depth, and fault dips were used as

Table 3
Estimates of PHA, MMI, and % probability of exceedance of 0.25 g PHA at Sagzabad cluster for different earthquake sources based on Gaussian cumulative distribution functions.

Rupture type	R	M_w	ln PHA (gals)	$\sigma_{\ln PHA}$	PHA (gals)	PHA (g)	MMI	z	CDF	P PHA > 0.25 g
Bu'in Zara earthquake	24	7	5.53	0.41	251.86	0.26	8.0	−0.07	0.47	53
Cheskin – East Ipak 15° dip	4	7	6.60	0.41	735.15	0.75	9.5	−2.71	0.00	99
Cheskin – East Ipak 30° dip	8	7	6.38	0.41	592.14	0.60	9.2	−2.17	0.02	98
Cheskin – East Ipak 45° dip	15	7	5.99	0.41	398.62	0.41	8.6	−1.20	0.12	88
Cheskin 15° dip – best fit M_w	4	6.7	6.59	0.43	728.80	0.74	9.5	−2.56	0.01	99
Cheskin 30° dip – best fit M_w	8	6.7	6.32	0.43	557.93	0.57	9.1	−1.93	0.03	97
Cheskin 45° dip – best fit M_w	15	6.7	5.85	0.43	347.76	0.35	8.4	−0.82	0.22	78
Cheskin 15° dip for lower M_w	4	6.5	6.58	0.44	720.77	0.74	9.5	−2.45	0.01	99
Cheskin 30° dip for lower M_w	8	6.5	6.27	0.44	529.78	0.54	9.0	−1.75	0.04	96
Cheskin 45° dip for lower M_w	15	6.5	5.75	0.44	313.42	0.32	8.3	−0.56	0.29	71

R = closest distance Sagzabad cluster to rupture in km.
M_w = best estimate earthquake moment magnitude from Table 2b for range in best fit M_w except where specified.
PHA = peak horizontal acceleration at Sagzabad cluster.
$\sigma_{\ln PHA}$ = uncertainty in value of ground motion parameter.
MMI = Modified Mercalli Index value.
z = standard normal variate.
CDF = value of cumulative distribution function of standard normal distribution.
P PHA > 0.25 g = % probability of PHA exceeding 0.25 g during earthquake.

for the Buyin-Zahra earthquake to calculate the RA for each segment. To determine the MD, the y-intercept of the Wells and Coppersmith MD-SRL reverse fault regression line was modified in order to derive a regression line with the same slope as their line, but passing through the SRL-MD intersection point from the Buyin-Zahra earthquake

$$\log(\mathrm{MD}) = -0.655 + 0.42 \times \log(\mathrm{SRL}) \tag{2}$$

This regression was used to derive the likely MD for 56 and 39 km length ruptures, estimated AD using the AD–MD relation described previously, and input this data into (1). Using this method, best fit M_w values for the western and eastern fault segments are 6.7 and 6.8 respectively (Table 2b).

Finally, three scenarios were considered for the Cheskin fault: an independent rupture associated with SRL of $\geq$20 km on a 30° dipping fault, an independent rupture associated with SRL of $\geq$20 km on a 52° dipping fault (same as the Ipak Fault), and a linked Cheskin – eastern Ipak fault rupture with a total SRL of $\geq$76 km on a fault with the dip weighted between the 30° dipping Cheskin and 52° dipping Ipak faults. The methods outlined above were used to determine RA (using a 20 km hypocentral depth and fault dips of 30° and 52° for the Cheskin Fault), MD and AD. Best fit M_w values for the Cheskin fault only are M_w 6.7 (30° dip) and M_w 6.5 (52° dip) and for the combined Cheskin-Ipak fault rupture is M_w 7.0 (Table 2a,b).

6.2. Fault-slip rates and recurrence intervals

Constraints on the uplift rate of the Cheskin anticline are confined to the ca. 8830 ± 5370 BP to $\leq$2150 ± 1590 BP interval captured by OSL dating of the sedimentary deposits. The crest of the anticline is uplifted ~5 m on the southern (frontal) thrust relative to a planar surface projected from the adjacent, undeformed fan and ~3 m across the northern thrust. On a 30° dipping fault, this cumulative uplift of ~8 m equates to ~16 m of purely dip-slip movement. If anticline growth has been confined to the ca. 8830 to ca. 2150 BP interval, this equates to a fault slip rate of 2.4 mm y^{-1} and anticline uplift rate of 1.2 mm y^{-1}. If anticline uplift is still ongoing, either co-seismically (e.g., during the Buyin-Zahra event) or aseismically, then the minimum fault-slip rate is 1.8 mm y^{-1} and minimum anticline uplift rate is 0.9 mm y^{-1}. Erosion of the anticlinal crest, sedimentation at the forelimb, a shallower fault dip, an oblique component of fault slip, and/or a tighter age bracket for the fault-related sediments would all result in a faster fault slip rate and shorter earthquake recurrence interval. Differential erosional lowering of the landscape adjacent to the anticline, a steeper fault dip, and/or broader age bracket for the fault-related sediments would result in a slower fault slip rate and longer earthquake recurrence interval.

Using the estimated MD value of 0.8 m for a Cheskin Fault-only rupture derived from Eq. (2) (Table 2a,b) and assuming a repeating-displacement earthquake model, the M_w ~6.7 Cheskin fault earthquake recurrence interval is estimated as ~441 y from ca. 8830 BP to present. Using the estimated MD value of 1.4 m for a coupled Cheskin-eastern Ipak fault rupture, the M_w ~7.0 earthquake recurrence interval is ~775 y from ca. 8830 BP to present. Although these recurrence intervals seem short relative to the ~3500–4000 y Ipak Fault 'maximum' recurrence interval proposed by Berberian and Yeats (2001), their estimate is somewhat unconstrained given the lack of fault based palaeoseismic data in their study. The lack of damage to a number of Safavid structures (c. AD 1600) in the region, such as bridges, carvanserai, and mausoleums that suffered minor damage during the Buyin-Zahra earthquake, suggests a minimum quiescent period of about 400 y (Berberian and Yeats, 2001) prior to the Buyin-Zahra earthquake, consistent with the estimated recurrence interval from the Cheskin Fault.

6.3. Palaeo-PHAs and MMIs at the Sagzabad cluster

Peak horizontal acceleration (PHA) is the most commonly used ground motion parameter for seismic hazard assessments. PHAs for the Sagzabad cluster were derived using the global attenuation relationship of Campbell and Bozorgnia (1994) derived from accelerogram data from historical earthquakes,

$$\begin{aligned}\ln \mathrm{PHA(gals)} = {} & 3.512 + 0.904\, M_w \\ & - 1.328 \ln\sqrt{R^2 + [0.149\exp(0.647\, M_w)]^2} \\ & + (1.125 - 0.112 \ln R - 0.0957\, M_w)\end{aligned} \tag{3}$$

where R is the closest distance to the fault rupture (in kilometres). MMI at the tell sites was estimated using the correlation formula of Trifunac and Brady (1975)

$$\log \mathrm{PHA}\left(\mathrm{cm\ s^{-2}}\right) = 0.014 + 0.30\ \mathrm{MMI} \tag{4}$$

The Sagzabad cluster lies ~22 km NNE of the 1962 Buyin-Zahra earthquake epicentre at a distance of ~24 km from the hypocentre. Ambraseys (1963) reported a MMI of VII at the tell sites following the 1962 Buyin-Zahra earthquake. Using the attenuation and PHA–MMI formulas above, a PHA of 0.26 g and MMI of VIII were derived for this event. While most villages within 3–8 km of the Ipak fault surface ruptures were completely destroyed by the 1962 Buyin-Zahra earthquake, most villages in the vicinity of the Sagzabad cluster were only partially damaged (Ambraseys, 1963), suggesting that one or both of the equations above may slightly over-estimate the PHA and MMI for the study site.

For the pre-historic earthquakes associated with a Cheskin Fault only or Cheskin Fault – eastern Ipak Fault rupture, a range of R was considered given the uncertainties in subsurface fault geometry. All PHA estimates are $\geq$ 0.3 g. It is likely that PHA's $\geq$ 0.25 (MMI $\geq$ VIII) would have caused complete destruction of weak materials such as the adobe huts of the Sagzabad cluster. Gaussian cumulative distribution functions for the Buyin-Zahra earthquake indicate a 53% probability that PHA's of $\geq$0.25 occurred at the Sagzabad cluster site during this event (Table 3). For earthquake ruptures involving the Cheskin fault, there is a $\geq$90% probability that PHA's of $\geq$0.25 would be reached, with the exclusion of a Cheskin Fault only rupture on a 45° dipping fault. Given the earthquake recurrence intervals developed above, 11 or more earthquakes of sufficient magnitude to destroy the Sagzabad settlements have occurred in the study region since ca. 8830 ± 5370 BP, equivalent to a mean annual rate (λ_m) of $\geq$0.001246 events per year. Using a Poisson distribution model

Table 4
Poisson model % probability of 0.25 g PHA exceedance during occupation of Zagheh, Ghabristan, and Sagzabad for one and two events.

λ_m	P_Z	P_G	P_S	$P_{Z\text{-}2\ \mathrm{events}}$	$P_{G\text{-}2\ \mathrm{events}}$	$P_{S\text{-}2\ \mathrm{events}}$
0.001245753	66.2	79.3	88	41.9	54.5	65.3

λ_m = Mean annual rate of earthquakes with exceedence 0.25 g PHA at Sagzabad tell sites.
P_Z = Poisson model for % probability of 1 event with $\geq$0.25 g PHA occurring during settlement occupation at Zaghe (7170–6300 y BP).
P_G = Poisson model for % probability of 1 event with $\geq$0.25 g PHA occurring during settlement occupation at Ghabristan (6215–4950 y BP).
P_S = Poisson model for % probability of 1 event with $\geq$0.25 g PHA occurring during settlement occupation at at Sagzabad (4050–2350 y BP).

$$P[N \geq 1] = 1 - e^{-\lambda_m t} \tag{5}$$

the minimum probability of at least one (*two*) events occurring during settlement occupation of Zagheh is 66% (*42%*), Ghabristan 79% (*55%*), and Sagzabad 88% (*65%*). Cheskin fault-only ruptures and Ipak fault-only ruptures would increase the mean annual rate and, particularly in for the Cheskin Fault, the probability of exceedence.

7. Discussion and conclusions

For many centuries, Persian civilisation has recognised that active, earthquake-prone faults provide opportunity despite the hazard (Jackson, 2006). Relatively less permeable fault gouge may form a subsurface barrier to the water table, thus elevating it and locally generating springs and/or lakes that create refuges in many otherwise inhospitable locations. This fault-controlled water supply determines where many of Iran's settlements were situated, and also why many of them (e.g., Bam, Sefidabeh) have been destroyed by earthquakes in recent times. Historically, the precedent is for such settlements to be rebuilt. The authors questioned whether a similar principle applied in the distant past (ca. 7170–2350 BP) using the geological and archaeological records from the 'Sagzabad cluster' settlements of Zaghehh, Ghabristan, and Sagzabad.

A previously undocumented fault-propagated anticline was identified, and a fault dip inferred (based on the anticline asymmetry) that places this fault beneath the Sagzabad cluster at seismogenic depths, thus providing a proximal source for large earthquakes. Analogous, north-dipping thrust faults are present elsewhere in the region (e.g., Eshtehard Thrust; see Fig. 3 of Berberian and Yeats, 1999) and the epicentres of some earthquakes following the Buyin-Zahra event occurred to the north of the Ipak Fault, suggesting the presence of seismically active north-dipping faults (Berberian and Yeats, 1999). Palaeoseismic investigation of the Cheskin Fault suggests that this fault presents a major hazard to the tell sites whether it ruptures independently, during M_w ~6.5–6.7 earthquakes with a recurrence interval of ca. 440 y, or with the Ipak Fault, during M_w ~7.0 earthquakes with a recurrence interval of ~775 y. Expected PHAs for Cheskin fault-only and coupled Cheskin-Ipak Fault ruptures are well in excess of likely threshold PHAs for complete destruction of type-D structures such as the adobe huts and walls that would have accommodated the peoples of the Sagzabad cluster. Gaussian cumulative distribution modelling indicates a >90% probability that earthquakes would have caused PHAs in excess of 0.25 g at the Sagzabad cluster for most scenarios of both Cheskin and coupled Cheskin-East Ipak fault ruptures. Poisson modelling assuming a time and displacement repeating model for earthquake recurrence indicates a ≥66–88% probability that one earthquake occurred during occupation of each of the tell sites, and a 42–65% probability that two earthquakes occurred during occupation of each site, indicating it is highly likely that these settlements were destroyed by at least one earthquake, and more likely than not that both the Ghabristan and Sagzabad settlements were destroyed by at least two earthquakes. This data supports the archaeological evidence from the Sagzabad tell for at least one palaeo-earthquake during settlement occupation (Berberian and Yeats, 2001).

It is difficult to resolve whether earthquakes may have caused the observed settlement shifts and/or abandonment at the Sagzabad cluster in the absence of a numerical earthquake chronology. However, both the proposed minimum number of large earthquakes (~11) and short earthquake recurrence intervals (<1000 y) throughout the Holocene strongly support the hypothesis that the people living in the Sagzabad cluster experienced large, settlement destroying earthquakes during their residence. With the exception of the 900-year settlement hiatus from ca. 4950 to 4050 BP, the Hajiarab alluvial fan was continuously occupied by these settlements from ca. 7170 to 2350 BP. It is unlikely that the shift from Zagheh to Ghabristan, a distance of only ~2.6 km was a result of an earthquake, as the people of Zagheh may have well have observed that effects of a large earthquake were evident beyond their immediate settlement site. The 1962 Buyin-Zahra earthquake provides a modern example of the effects (e.g., fault scarps, mass movements, liquefaction features, fractures) that might have been observed. It cannot be determined whether the abandonment of Ghabristan and/or Sagzabad was due to large earthquakes. However, the probability of multiple events during the residence time at the sites (Table 4) suggests that these settlements likely experienced at least one earthquake without site abandonment.

At this juncture, environmental factors such as alluviation, stream channel avulsion, and climate change (Schmidt et al., 2011), and political factors such as disruptions to trade and social fabric (Fazeli Nashli and Abbasnejad Sereshti, 2005) must also be considered as equally viable drivers for Holocene settlement patterns at the Sagzabad cluster of Iran.

Future palaeoseismic investigations of the Cheskin and Ipak faults will better constrain earthquake chronologies and provide a more robust test of the links between earthquakes and cultural evolution in this region. Specifically, fault trenching, geophysical investigations, and dating of alluvial sequences that are faulted and/or have 'ponded' upstream of the growing Cheskin anticline will provide more insight into the subsurface geometry of the Cheskin Fault and the timing of palaeo-earthquakes. At this stage, the derived fault slip rates and earthquake recurrence intervals should be viewed cautiously, in light of the reconnaissance-type nature of our field investigations and various limitations of our datasets. Future archaeological investigations may provide additional insights into the effects of palaeo-earthquakes on the Sagzabad cluster settlements.

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