# Tectonic and climatic controls on fan systems: the Kohrud mountain belt, Central Iran

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**Abstract**

Late Pleistocene to Holocene fans of the Kohrud mountain belt (Central Iran) illustrate the problems of differentiating tectonic and climatic drivers for the sedimentary signatures of alluvial fan successions. It is widely recognised that tectonic processes create the topography that causes fan development. The existence and position of fans along the Kohrud mountain belt, NE of Esfahan, are controlled by faulting along the Qom-Zefreh fault system and associated fault zones. These faults display moderate amounts of historical and instrumental seismicity, and so may be considered to be tectonically active. However, fluvial systems on the fans are currently incising in response to low Gavkhoni playa lake levels since the mid-Holocene, producing incised gullies on the fans up to 30 m deep. These gullies expose an interdigitation of lake deposits (dominated by fine-grained silts and clays with evaporites) and coarse gravels that characterise the alluvial fan sediments. The boundaries of each facies are mostly sharp, with fan sediments superimposed on lake sediments with little to no evidence of reworking. In turn, anhydrite-glauberite, mirabilite and halite crusts drape over the gravels, recording a rapid return to still water, shallow ephemeral saline lake sedimentation. Neither transition can be explained by adjustment of the hinterland drainage system after tectonic uplift. The potential influence in central Iran of enhanced monsoons, the northward drift of the Intertopical Convergence Zone (ITCZ) and Mediterranean climates for the early Holocene (~6–10 ka) point to episodic rainfall (during winter months) associated with discrete high magnitude floods on the fan surfaces. The fan sediments were deposited under the general influence of a highstand

playa lake whose level was fluctuating in response to climate. This study demonstates that although tectonism can induce fan development, it is the sensitive balance between aridity and humidity resulting from changes in the climate regime of central Iran that influences the nature of fan sequences and how they interrelate to associated facies.

Keywords: alluvial fans, climate, tectonism, central Iran, playa lakes, ITCZ

## 1. Introduction

The association between active faults and alluvial fans is well established in the research literature (e.g., Allen and Hovius, 1998; Jones, 2004; Harvey 2012; Bahrami, 2013). Moreover, fluvial-fans (megafans), alluvial fans and fan deltas have been widely documented from the margins of many ancient and recent depositional basins in extensional (Gawthorpe and Leeder, 2000; Leeder and Mack, 2001), transtensional (Dorsey, 2002; Sözbilir et al., 2011; Le Dortz et al., 2011) and compressional tectonic settings (Jones, 2004; Leleu et al., 2009; Waters et al., 2010). In many modern structurally active areas it is very tempting to interpret any cyclical or episodic sedimentation as tectonically controlled. In such settings an important question is whether or not the character of the alluvial fan sediments and sequences can be used to assess the degree and rate of fault activity (e.g., Ford et al., 1997; Quigley et al., 2007).

It is clear that tectonism provides the opportunity for alluvial fan development through creation of topography, increasing gradients of river systems supplying sediments, and creating accommodation space for storage of sediment. Tectonic activity has a fundamental control on fan development, of any size (Blair and McPherson, 1994; Allen and Hovius, 1998; Jones, 2004). However, the influx of coarse clastic sediment alone cannot be taken as direct evidence of fault activity and rejuvenation of a drainage basin.

Our hypothesis is that climatically controlled events can produce sedimentary signatures similar to those created by tectonism and individual fault activity (Pope and Wilkinson, 2005; Waters et al., 2010). In fact it is well known in arid zones that small changes in rainfall can have pronounced and even devastating effects on river discharge, and therefore sediment supply and lake levels within intermontane basins (Vázquez-Urbez et al., 2013). In addition there are low frequency/high magnitude flood events associated with enhanced monsoon and seasonal winter rainfall due to ITCZ migration that lead to substantial runoff (e.g., Frostick and Jones 2002). All of these affect the development and character of sediments on alluvial fans (e.g. Walker and Fattahi, 2011; Arzani, 2012).

This paper will firstly summarise the general geology and geomorphology of the study area based on satellite imagery, digital topography, geology maps and our own detailed fieldwork observations. We then describe the alluvial fan sedimentology, proximal fan hot–spring intercalated travertines and distal intercalated playa lake sediments which are all part of the distal alluvial fan system. Finally, we use a variety of published age constraints from periods of Late Pleistocene and early Holocene fan abandonment from central and eastern Iran, to contrain the timing and controls on the alluvial fans draining the southwestern side of the Kohrud Mountain belt of central Iran, an area never previously studied in detail.

## 2. Geological Setting

The Iranian Plateau is a relatively flat area whose morphology strongly contrasts to that of the mountains to the south (Zagros) and to the north (Alborz and Kopet Dagh). Mean elevations in the plateau region are typically 1500 – 2000 m asl, in contrast with the desert lowlands of the Dasht-e Kavir and Dasht-e Lut to the east (Fig. 1), which are <1000 m asl. The plateau includes regions with more pronounced topography such as the NW-SE trending Urumieh-Dokhtar Zone, which is largely formed by an Eocene magmatic arc. The Iranian Plateau is a sector of the larger Turkish-Iranian Plateau, that covers ~1.5 million $km^2$ in area (Fig. 1).

Iran has a complex tectonic history that involves closure of minor ocean basins (Berberian, 1981), which originally separated microcontinental blocks. Precambrian to Carboniferous strata of these microcontinents are very similar, indicating that they once formed part of a broad platform on the eastern margin of Gondwana (Scotese and McKerrow, 1990; Heydari et al., 2003). Permian rifting was responsible for the separation and northward motion of the Iranian microcontinents away from Arabia. Collision with Eurasia took place during Middle-Late Triassic time (Berberian, 1981; Davoudzadeh, 1997; Stampfli et al., 1991). By the Jurassic a subduction zone developed along the western edge of the Sanandaj-Sirjan Zone (Fig. 1), and the Urumieh-Dokhtar magmatic arc began to form (Alavi, 1994; Berberian, 1981). Initial collision of Arabia and Eurasia took place at ~35 Ma, in the late Eocene (Allen and Armstrong, 2008), and convergence has continued to the present (Agard et al., 2005).

A major tectonic re-organisation at ~5 Ma led to the end of or reduction in slip on many faults within the Turkish-Iranian Plateau, and the onset of the present configuration of deformation across a vast area from western Turkey to eastern Iran (Allen et al., 2004). The precise reason for this re-organisation is not clear, but crustal thickening and shortening across an orogenic plateau tends to cease once a critical elevation threshold is reached (Allen et al., 2013). Seismogenic thrusts within the Zagros are very rare above elevations of 1250 m (Nissen et al., 2011), although the rise in elevations above this level indicates that another process must operate to produce the plateau. Mantle support of central Iran, linked to the scattered Pliocene-Quaternary magmatism, is possible (Maggi and Priestley, 2005). Other factors linked to the present high elevations of the plateau may be underthrusting of the Arabian plate beneath Iran (Paul et al., 2010).

At present, limited plate convergence takes place within the Iranian plateau: the GPS-derived velocity field indicates internal deformation on the scale of 2 mm/yr or less (Vernant et al., 2004). In contrast, ~20 mm/yr of north-south Arabia-Eurasia convergence takes place at longitude 51° E (roughly Tehran), but most of this is achieved within the Zagros to the south of the plateau and the Alborz/Kopet Dagh ranges and the South Caspian Basin to its north.

The study area is located along the central portion of the Urumieh-Dokhtar Zone, known as the Kohrud mountain belt and the northeastern margin of the Meymeh-

Esfahan basin (MEB) of central Iran (Fig. 2). The MEB occupies the northwestern portion of the larger Gavkhoni-Abarkoh-Sirjan depression (Fig. 1). This depression is more than 600 km long. The Urumieh-Dokhtar Zone is sliced obliquely by NW-SE or NNW-SSE trending right-lateral strike-slips faults such as the Qom-Zefreh (Kashan) and Deh Shir (Meyer et al., 2006; Allen et al., 2011). Offset on these faults is typically tens of kilometres, and possibly up to 40 km for the Qom-Zefreh Fault (Allen et al., 2011). These faults may have acted to help accommodate plate convergence by rotating anti-clockwise about vertical axes, at the same time as lengthening the collision zone along strike.

These faults do not appear to be particularly active compared with many other structures in Iran: they are not typically associated with instrumental records of earthquakes of *Mw* ~5 or above (Jackson et al., 1995; Fig. 1) and, as noted above, they do not perturb the GPS-derived velocity field. However, nor are they completely inactive: an earthquake in AD 1344 near the southeast end of the Qom-Zefreh Fault was an estimated *M* ~5.7 (Ambraseys and Melville, 1982), while numerous smaller earthquakes have been recorded instrumentally (Nadimi and Konon, 2012). Jamali et al. (2011) recorded offset streams and historical drainage channels (qanats) along the line of the Qom-Zefreh Fault.

## 3. Stratigraphy

The alluvial fans along the northwestern side of the Gavkhoni-Abarkoh-Sirjan depression have drainage basins carved into the Kohrud mountain belt. These can be separated into two broad terranes divided by the Qom-Zefreh Fault (Fig. 2). In the northwest fans are sourced largely from drainage basins with Devonian sandstones, Triassic dolomites, Lower Jurassic sandstones and Lower Cretaceous *Orbitolina* limestones. This contrasts to fans in the southeast of the study area that have drainage basins within Middle to Upper Eocene granodiorites, gabbros and volcanics (basaltic-andesites). Tectonic activity since the mid Tertiary has thrusted and uplifted the successions (Berberian, 1981; Aghanabati, 2004).

Late Pliocene to Recent alluvial sediments are found along the margins of the Kohrud Mountain belt and create an important link between the mountain drainage and playa lake, as recognised in many other parts of Iran (e.g., Arzani, 2005, 2012; Walker and Fattahi, 2011; Fig. 3). However, from field observations and drilling in the Gavkhoni playa, a similar drainage pattern to other playas in central Iran has probably existed since earlier times (Nadimi and Konon, 2012): Pliocene marls underlie Quaternary marls and conglomerate intercalations adjacent to the modern lake. The total Quaternary succession is recorded as >300 m in these places (Nadimi and Konon, 2012). In contrast, the fan sediments are of unknown thickness, but assumed to thicken closer to the mountain fronts and grade basinwards into evaporites and fine-grained sediments of the Gavkhoni playa lake (Fig. 3). There is presently ~500 m elevation difference between the apices of the fans and their toes.

## 4. Hydrology

*Rivers*

Modern drainage patterns in central Iran have probably existed very broadly since the deposition of the Early Miocene Upper Red Formation and its equivalents (Morley et al., 2009; Ballato et al., 2011). Rivers draining the northern and southern sides of the MEB have predominately transverse patterns that cut across several basin-bounding faults and have built large alluvial fans. The fans on the northern side of the basin form the subject of this study. The Zayandeh Rud (rud = river) flows along the basin axis. In many places this river cuts the toes of the alluvial fans or captures any associated drainage (Fig. 2).

The present climate of the area is arid to semi-arid with average rainfall ranging between 50 and 200 mm in the basin, and up to 350 mm in the headwaters of many rivers of the Kohrud Mountain belt (Alijani et al., 2008). Because of this, all rivers except the Zayandeh Rud are ephemeral, and most flows occur during the late winter months and Spring (December to April). A rainfall gradient from the headwaters to the middle/lower reaches of many streams exists and flow is more likely in the upper reaches of the rivers.

*Gavkhoni playa lake*

Along the axis of the Gavkhoni-Abarkoh-Sirjan depression (Figs. 1, 2) are several playa lakes, the floors of which can occur as high as 1500 m asl. Gavkhoni playa lake itself is at 1450 m asl. All of the playa lakes are hypersaline and at the present day do not contain any water within them for much of the year. High salt concentrations arise partly from high evaporation rates in this enclosed arid basin. However, significant recharge comes from the alluvial fan drainage systems that drain Eocene alkali volcanic terranes, and from relatively high solute loads of the present day axial Zayandeh Rud.

It has been widely documented that lake levels of intermontane rift basins are highly variable (Cross et al., 2000; Magee et al., 2004) and have a considerable influence over sedimentation and architecture of contemporaneous basin fills (Owen and Renaut, 1986; Frostick, 1997; Lin et al., 2001). Lake Zeribar and Mirabad in the Zagros Mountains and Lake Urmia in NW Iran provide lake core records of climate changes during the Holocene and corresponding lake level changes (e.g. Steven et al., 2006; Wasylikowa et al., 2006; Djamali et al., 2010). The Gavkhoni playa lake (Fig. 2) will have experienced several rises and falls of the lake levels and had an important impact on both erosional modification and progradation of the fan systems.

## 5. The Esfahan fluvial fan systems

Along the southern side of the Kohrud Mountain belt, between Soh and southeast of Varzaneh in the MEB (Fig. 2), there are at least 35 fluvial fans of different sizes that build out from the edge of the mountain front. Some of these fans are sited against faults at the mountain front (e.g., Zefreh), and may be an indicator of at least some present fault activity. Others are at places where the mountain front is abrupt, but no active fault is recognised (e.g., Soh); topography may be relict from late Cenozoic, when the faulting was more prevalent within the area of the present day plateau.

According to the restricted classification of alluvial fans by Blair and McPherson (1994), the Esfahan fans would be described as fluvial depositional systems. However, the application of such a rigid classification seems inappropriate with such well-defined fan geometries (Fig. 2) and the recognition that fans are controlled by many allocyclic and autocyclic processes (Frostick and Jones, 2002; Jones, 2004). In this paper the term fluvial fan is used (or *megafan*, as named first by Gohain and Parkash, 1990) to describe a large ($10^2$-$10^3$ km$^2$) and gentle low gradient, fan-shaped sedimentary accumulation formed mostly by fluvial deposits. Usually, fluvial fans generate from large catchments developed in mountain ranges (Fig. 4); the majority of the 35 fluvial fans in our study area have catchment areas of 10-$10^2$ km$^2$. By contrast, alluvial fans are typically smaller in size than fluvial fans, have local catchments and steeper slopes, with a greater predominance of gravity driven sedimentary deposits (*sensu* Blair and McPherson, 1994).

Of the 35 fluvial fans that build from the flank of the Kohrud towards the Gavkhoni-Abarkoh-Sirjan depression, three large and by inference long-lived fans were selected for study. They are (from northeast to southwest): Soh; Zefreh; and Feshark (Figs. 4 - 6). The Soh fan is the largest with an area of 537 km$^2$ (Table 1). It also illustrates some of the best exposures of the fanglomerates. The Soh fan is comparable to other similar sized fluvial fans along the margin of the basin (e.g., Arzani, 2005, 2012). The Zefreh and Feshark fans are slightly smaller is size with fan areas of 309 km$^2$ and 179 km$^2$ respectively (Table 1). The toe of the Soh fan is at 1750 m asl; the toes of the Zefreh and Feshark fans are at ~1500 m, and on the edge of the Gavkhoni playa (Fig. 2). The fluvial fans in this study provide a useful reference for patterns of sedimentation and sequential fan development, but are also of use in providing information about fan evolution in areas of differing catchment geology and, potentially, base level change (Fig. 2).

Like most fan systems worldwide, precise dating of the Esfahan fans is problematic because of the lack of diagnostic fossils or other material typically used for radiometric dating. A variety of techniques using cosmogenic nuclide exposure dating, luminescence dating and uranium series dating has been widely applied to date fan surfaces and associated cross-cutting faults across central and eastern Iran (Table 2). The dating of Holocene and Late Pleistocene fan development in the central Iranian plateau region has allowed the Esfahan fans and landscape development to be constrained (e.g., Le Dortz et al., 2009; Talebian et al., 2010). The widespread landscape evolution during the Holcene for the Iranian plateau region sees an abandonment phase of most of the fan surfaces at ~11 - 9 ka (Walker and Fattahi, 2011; Table 2). Records of lake and playa highstand sedimentation indicate corresponding wetter conditions for the Gavkhoni playa at ~9.6 +/- 2.4 ka and for the South Golbah, SE Iran at 7.9 +/- 0.1 ka (Table 2). These periods of fan activity reflect increased moisture from the early to mid Holocene, supported by speleothem analysis in Oman recording a continental pluvial event for the early to middle Holocene at 10.5 - 6 ka (Burns et al., 2001). Increased aridification since ~6 ka is widely supported across central Iran from archaeological data (Schmidt et al., 2011) and multi proxy climate data from several lakes (Stevens et al., 2001; Wasylikowa, 2006; Kehl, 2009). The

Esfahan fans appear to have been relatively stable since the onset of increased aridity in the region with no directly attributable fan activity.

*Fluvial fan geomorphology*

The long profiles of each of the fans are an important element of understanding catchment and fan area evolution in that, together with the channel networks, they fix the boundary conditions for slope processes (Fig. 7). River long profiles show an approximately graded profile for each fan and its bedrock catchment area, with a localised knickpoint at the apex of the Soh fan. The general geometry of the fans conforms to the classical models of a fan with a conical radiating form (e.g., Bull, 1977; Stainstreet and McCarthy, 1993). The Soh fan is deeply incised (Fig. 5), which is probably the result of a combination of tectonic uplift and playa lake level fall. The Zefreh and Feshark fans are more elongate in plan view than the Soh fan, and lack the incision of the latter (Fig. 6). In cross-section all of the fans are wedge-shaped and the latest phase of fan development is also incised. Ayoubi (2002) has dated paleosols from the margin of the Gavkhoni Playa, that intercalate with the younger alluvial fans sediments at Zefreh, by optically stimulated luminescence (OSL) as c. 9.6 ka BP (Table 2). Since then a further 10 - 12 m of incision has taken place.

Incision of the Soh fan has produced near-vertical cliffs of up to ~30 m in height (Fig. 8). Individual beds that can be traced over distances > 1 km provide an opportunity for detailed sections to be studied, allowing for a comprehensive understanding of fan evolution, architecture and interaction with playa sediments. In general, fans at the northwest end of the MEB tend to be more incised than those to the southeast. Possibly, their higher elevations make them more prone to incision during lake level lowstands. The Soh fan is particularly incised, and perhaps effectively abandoned/beheaded during lowstand phases: the main channel in the vicinity currently passes immediately to the east of the Soh fan, feeding a newer fan to its east that has prograded farther into the basin interior (Fig. 5).

*Fan sediments*

The fan sediments are characterized by sheets of polymict, clast- or matrix-supported conglomerates. The sheets of conglomerate are laterally competent and extend up to 750 m in section, and individual beds range in thickness from 30 cm – 1 m (Fig. 8). The conglomerates predominantly show a bimodal grain size with predominantly cobble-grade clasts and a medium-grained to granular sand-grade matrix (Fig. 9). Clasts tend to be subangular to subrounded. A variety of sedimentary structures is observed throughout. Large scale planar cross stratification (<1 m) is found in thicker beds whereas imbrication, incorporated with pebble clustering on bedding surfaces and in cross section, erosive bases and fining-upward packages are common in most of the succession (Figs. 8, 9).

The fan lithologies strongly reflect their drainage basin geology with the Soh fan dominated by Devonian, Triassic and Cretaceous limestones and sandstones. This contrasts to the Zefreh and Feshark fans whose drainage basin geology is located with in the Urmieh–Dokhtar volcanic belt consisting of volcaniclastics, basaltic and andesitic volcanics (Ghasemi and Talbot, 2006). The predominance of the volcaniclastic clasts for the Zefreh and Feshark fans (Fig. 9; Table 1), is what provides their characteristic black colour on Landsat images (Fig. 6).

Conglomerates and coarse grained clastics make up approximately 90% of the observable fan sediments in the proximal regions close to the fault scarp (Fig. 8), but within ~20 km down fan this has decreased to < 45% (Fig. 10). The remainder of the sequence is composed of fine-grained playa lake sediments and evaporites. An exception to the general pattern is the proximal to medial part of the Soh fan. It consists of predominantly coarse-grained clastics derived from incision of precursor Plio-Pleistocene fan sediments that prograded at previous playa lake levels. The only fine-grained playa lake sediments occur as either laterally truncated lens or as thin veneers. They indicate lacustrine transgressions, but are largely truncated and eroded by successive later fan flood events.

In proximal reaches of the Soh fan and to a lesser extent the Zefreh and Feshark fans, intercalated hot-spring travertines and travertine-cemented fanglomerates are a common associated facies (Fig. 8, 11). The travertines can reach ~3 m thick (Fig. 8) and extend laterally up to ~450 m. The intercalated travertines tend to be layered mats composed of alternating layers of porous and dense carbonate horizons (Fig. 11A). The dense horizons are composed of fine-grained micrite. Thicker micrite horizons commonly contain angular to sub-rounded clasts of fine to medium-grained detrital quartz and even small pebbles from the alluvial fan drainage basin lithologies. Examples of layered mat travertines preserving rim pool structures (or microterrace textures) that occurred on the margins of an ancient travertine mound are less common and only found in proximal regions of the fans, in close proximity to a fault (Fig. 11B). Cobble to pebble size conglomerates are frequently cemented by travertine and usually contain blocks of angular layered mat (Arzani, 2012). Many of the hot-spring travertine locations along the Urmieh–Dokhtar volcanic belt of the central Iranian plateau are associated with important Paleolithic sites (Heydari-Guran et al., 2009).

*Playa lake sediments*

The playa lake sediments are commonly red-brown clays with discrete layers of anhydrite-glauberite, mirabilite and halite, although in the most recent sediments there are abundant gypsum crystals occurring as layers and within the fine-grained detritus. The fine grained sediments are derived from the distal parts of the fans that represent the suspended fraction and downstream fining of high magnitude-low frequency flash flood events that prograde out into the playa lake (Figs. 12, 13). In addition suspended sediment carried by the rivers provides an alternative source (Fig. 2). Observations from the modern playa lake illustrates that the gypsum tends to form as patches and as a white crust on the surface of the playa during drying out, with no lake level identifiable (Fig. 14). It is suggested that the evaporites were deposited in quiet, very shallow water conditions, perhaps where water was pooled at the margins of the playa and evaporites are intercalated with clastic sediments.

Other lesser components of the playa, are polygonal desiccation cracks, mud curls and thin (maximum of 0.4 m thick) medium-grained sandy stringers. These features are always found in the distal part of the fans.

Gypsiferous marls drape fans at places along the northern side of the MEB at a consistent elevation of 1600 m asl. A section of these sediments shows as a pale blue stripe along the Landsat mosaic in Fig. 6, aligned NW-SE. At the same elevation, there is a 30 m high scarp ~6 km to the east of the modern shoreline of Gavakhoni playa, likewise draped by a veneer of pale sediments. We interpret these features as the collective record of a lake highstand, perhaps of early Holocene age, 150 m above the present playa surface. Walker and Fattahi (2011) recorded relatively wet conditions in central and eastern Iran about 8 ka BP or younger. Gavkhoni playa lake is about 600 km from the lacustrine strata dated by Walker and Fattahi (2011), and at a similar latitude, and comparable present-day climate.

## 6. Discussion

*Tectonic activity*

As discussed in section 2, the faults and mountains ranges in the study area are apparently less active during the Pliocene – Quaternary than earlier times, but they are not completely inert. It is therefore tempting to speculate that many of the coarse beds represent tectonically-induced erosion and sediment flux from the hinterland catchments (e.g., Blair and McPherson 1994; Mack and Leeder, 1999; Viseras et al., 2003; Allen et al., 2013). An alternative interpretation is that progradation of the fan deposits over the playa lake sediments was caused by a increase in basin subsidence rate. This process would create coarsening upward successions, but this motif is absent from the Esfahan fans. The fan deposits mostly have sharp contacts above playa lake sediments, while conversely the playa lake sediments abruptly drape the fanglomerates and finer-grained fan sediments (Figs. 10, 11).

However, from satellite images (Figs. 5, 6), field observations and geological mapping it is evident that tectonics is very important in controlling the gross location of the fans, including their outlet positioning from the Kohrud mountain front. Several studies have highlighted the importance of drainage basin scale and fault locations/orientations in controlling drainage patterns and hence outlet spacing into a depositional basin (e.g., Hovius, 1996; Jones et al., 2001; Jones, 2004). In this sense, the Soh, Zefreh and Feshark fan positions are all clearly controlled by tectonism, with major faults or fault intersections located at or near the apex of the fans (Allen et al., 2011; Le Dortz et al., 2011; Figs. 2, 5, 6). A landscape dominated by tectonics, rather than sediment availability and changes in precipitation, will show fluvial incision in regions of uplift often located close to a fault. It is also obvious that fault activity along the basin margin controlled hot-spring travertine deposition along fault lines and at intersections between adjacent fault segments, which locally contributed to fan deposition. Fault activity may have promoted an increase in hydrothermal groundwater discharge rates with rapid degassing of $CO_2$ at or near the surface leading to phases of travertine precipitation. In many locations up to 20 m of incision has occurred through hot-spring travertines especially in the proximal portion of the Soh fan (Arzani, 2012;

Figs. 5, 8). Tectonic signals may be overprinted by climatic events with higher frequency and shorter response times (Humphrey and Heller, 1995; Allen and Densmore, 2000; Allen et al., 2013). Unless tectonic activity manifests itself in prolonged and drastic landscape modification, climate perturbations will most likely overprint local or small scale tectonic signals as for the Esfahan fans. Periods of higher rainfall and infiltration of runoff could have enhanced the hydrothermal circulation and led to the several phases of travertine precipitation as intercalated amongst the fan sediments (Fig. 8). We find little geomorphic evidence for the numerous active faults depicted by Nadimi and Konon (2012) around the present margins of Gavkhoni playa lake, and suggest these features should be the target of further study.

*Climatic control on sedimentation*

The recognition of climatic signals in sedimentary successions is more difficult than tectonic signatures due to the timescales over which climate influences sedimentation and the number of overlapping geomorphic processes that operate with climate (Frostick and Jones, 2002). However, it is inevitable that any fluctuations in climate within a drainage system will have a consequent effect on sediment delivery to the depositional basin (e.g., Huisink, 1997, 1999; Fryirs and Brierley, 1998; Jones et al., 1999). This is most evident in the Esfahan fans where superposition of coarse-grained clastics on playa lake sediments, and a recognisable cyclicity in sedimentation, are not readily attributable to tectonism (Fig. 11).

An increase in precipitation in the early Holocene is reflected in playa lake levels of the Gavkhoni that were at least 150 m above present lake levels (Ayoubi, 2002; Arzani, 2012; Fig. 6). This is consistent with lake deposition in other areas of the Middle East (Bar-Matthews et al., 2003) and North Africa where the Dead Sea experienced elevated lake levels in the early Holocene (Frostick and Reid 1989; Frumkin, 1997; Klinger et al., 2003). Interestingly, the occurrence of a pluvial or a wetter phase during the early Holocene is not present in lake cores from lake Zeribar and the nearby lake Mirabad in the Zagros Mountains, and the lake Urmia record from the NW (Stevens et al., 2006). From oak pollen records a sharp rise is recognized around ~6 ka that may reflect an increase in moisture content in the mid-Holocene (Stevens et al., 2006; Wasylikowa et al., 2006 ). However, cave speleothem records from northern Oman show enhanced monsoonal rainfall from ~10.6 ka with a return of arid conditions by 6.3 ka (e.g. Burns et al., 2001; Fleitmann et al., 2007), and it is possible that central and southeastern parts of Iran were also subject to monsoonal rains during the early Holocene (e.g., Regard et al., 2006). The early Holocene wetter period with fluctuations in playa lake levels (mostly fed by the Zayandeh Rud) accounts for the transgressive events of lacustrine sediments, but does not necessarily explain why coarser-grained clastics are interbedded in the playa succession.

The simplest and most plausible explanation is that the coarse-grained fan sediments were laid down by low-frequency, high-magnitude flood events. Temporal and spatial rainfall variations in arid zones is likely to give rise to infrequent large floods (Schick and Lekach, 1987) and the high sediment flux resulting from rainfall-runoff processes will supply large amounts of sediment to the alluvial fans (Frostick et al., 1983; Frostick and Jones, 2002). High magnitude flood events will account for abrupt contacts with the underlying playa lake sediments and the coarse alluvial sediments would have been laid down quickly, i.e., one bed per flash flood. However, perhaps more significantly it accounts for the abrupt change to the unadulterated playa sediments and finite thickness of each alluvial bed (Figs. 8, 10). There are no interspersed alluvial fan sediments in the playa lake sediments, or a general fining tendency that would be expected if the system as a whole were trying to adjust itself to tectonic rejuvenation.

The current semi-arid to arid setting of the central Iranian plateau is located in the transition zone of the eastern extensions of the winter depressions from the Mediterranean (Northwesterlies), dominated by winter storm tracks and the north-western extension of the strong seasonal reversal of the arid winter-NE and the humid summer-SW (Asian) monsoon (see Fig. 3 in Kober et al., 2013). Any northward shift in the Intertropical Convergence Zone (ITCZ) during an interglacial period would imply an enhanced influence of monsoonal rainfall and prevailing pluvial conditions (Fleitman et al., 2007; Preusser, 2009; Kehl, 2009; Djamali et al., 2010). An alternative moisture source is by the Mediterranean Northerwesterlies winter rainfall that directs moisture from the Middle East and Western Asia (Bar-Matthews et al., 1997; Kober et al., 2013).

The potential influence in central Iran of both the Monsoonal and Mediterranean climates for the early Holocene (~6 – 10 ka) points to episodic rainfall (during winter months) associated with variable magnitude flash floods on the fan surfaces. This increased episodic rainfall is also likely to be accountable for the hot-spring travertine deposition seen in the proximal portions of the Esfahan fans (Heydari-Guran et al., 2009; Arzani, 2012) and for similar age late Pleistocene to early Holocene travertines of Turkey (e.g., Vermoere et al., 1999).

The sensitive balance between aridity and humidity from the interaction between the Mediterranean, Indian Monsoonal and northward shift of the ITCZ during the early Holocene pluvial event will have resulted in highly erosive flood events on the Esfahan fans, liberating significant amounts of sediment that were deposited under the general influence of a highstand playa lake whose level was fluctuating in response to climate (rainfall). The consequence was periodic drowning of the fan toes and accumulation of lake sediments, most of which was derived from a suspended load of low-magnitude flash floods, but also from evaporite precipitation in the Gavkhoni playa lake. Sporadically throughout the fan sequence, high magnitude flash floods crossed out onto the playa lake. The structure and fabric of these sediments is reminiscent of braided stream deposits of the present day fans. These changes reflect changing patterns of discharge and sediment availability, in response to early Holocene climatic fluctuations within the drainage network of the Kohrud Mountain belt.

## 7. Conclusions

Although it has been widely recognised that fault movement, fault geometries and subsidence create a topography that induces fan development, climate exerts a more discrete control on sediments of alluvial fan sequences. This is perhaps too easily overlooked in both modern and ancient basin settings but, as recognised in this study, climate is a more important control of alluvial fan sequences once an outlet has been sited along the mountain front. Tectonic activity tends to be located along major faults that may dissect fans but do not directly influence the sedimentation.

This raises an important question of interpretation of similar deposits in more ancient successions. Since the sedimentary signature of a climatically driven high-magnitude flood is the same as that supposed to characterise a post-tectonic flood, there can be little justification for an automatic assumption that either climate or tectonism had a greater responsibility for the deposit without corroborating evidence. In fact in recent years there is a growing number of measurements of the sedimentary effects of large floods on alluvial fans, and climate is argued as the more important control on sediment flux and fan evolution (e.g., Quigley et al., 2007; Walker and Fattahi, 2011).

This study has demonstrated that although tectonism can induce fan development, it is the sensitive balance between aridity and humidity resulting from changes in the climate regime of a region that influences the nature of fan sequences and how they interrelate to associated facies. This is easily overlooked in the need to identify tectonic events and interpret ancient basin history.

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**Table and Figure Captions**

Table 1

Summary morphometric characteristics of the studied fluvial fans along the Kohrud mountain belt, central Iran.

Table 2

Available age constraints from alluvial fan abandonment and playa lake sediments across the central Iranian plateau. Details of the age dating methods used can be found within the papers referenced.

Fig. 1. (a) Neotectonic map of Iran, after Allen et al. (2011). Q-Z = Qom-Zefreh Fault. (b) Location map for (a). Thick white line is the approximate boundary of the Turkish-Iranian plateau. Dashed lines mark basement block boundaries within Iran. CIM - Central Iranian Microcontinent; DSFS – Dead Sea Fault System; EAF – East Anatolian Fault; NAF – North Anatolian Fault. (c) Cenozoic tectonic units of Iran. The extent of Central Iran is shown by hatching between the Zagros suture and the southern side of the Alborz (solid lines).

Fig. 2. Geological map of the central part of the Kohrud mountain belt and the Meymeh-Esfahan basin. The active Qom-Zefreh and Deshir right lateral faults cut across the Kohrud mountain belt, juxtaposing Palaeozoic-Mesozoic sediments against Eocene volcanic rocks. Alluvial fans drain the Kohrud mountain belt into both the Zavareh and Gavkhoni playa lakes. The boxes outline the areas enlarged of Landsat

mosaics in figures 5 and 6. Alluvial fans identified with cross-hatching are those specifically included in this study and from the NW to SE they are the Soh, Zefreh and Feshark fans respectively.

Fig. 3. View north towards the apex of the Feshark fan showing the typical gradient of the fans draining the Kohrud mountain belt (see Table 1) and the margin of the Meymeh-Easfahan basin delimited by the Qom-Zefreh fault. Distance between pylons is 100 m.

Fig. 4. Catchment area versus fan area for 35 fans along the northern faulted margin of Meymeh-Esfahan basin.

Fig. 5. Landsat Mosaic of the Soh fluvial fan and smaller adjoining fans along the margin of the Meymeh-Esfahan basin. Dashed line refers to long profile as in Figure 7. Note the first fan phase, which is now characteristically deeply incised. The fan sediments are cemented with hot-spring travertines and incorporate large travertine clasts, that are considered to be late Pleistocene in age (Arzani, 2012).

Fig. 6. Landsat Mosaic of the Zefreh and Feshark fluvial fans. Dashed lines refer to long profiles as in Figure 7. Black arrows identify the former Govkhoni playa lake high stand. The catchment for both fans is within Eocene basic volcanics. Note the sharp contact between the fans and Eocene volcanics of the catchment area. This is delimited by the Qom-Zefreh fault.

Fig. 7. Long profiles of the Soh, Zefreh and Feshark fans draining the Kohrud mountain belt showing the position of the mountain front, marking the faulted boundary with the northern margin of the Meymeh-Esfahan basin (see Figs. 5, 6 for location of profiles).

In the case of the Zefreh and Feshark fans the mountain front is delimited by the Qom-Zefreh fault.

Fig. 8. Detailed sedimentary logs for the Soh fan. The position of the sedimentary logs is located on the inset map. Sedimentary logs 2 and 3 contain intercalated travertine deposits, recording episodes of fault activity that controlled deposition through $CO_2$-rich thermal mineral waters as the fan crosses a fault. Sedimentary logs 4, 5 and 6 record abrupt alternation of coarse fan and playa lake margin sediments in the distal reaches of the alluvial fan. This is also common to the Zefreh and Feshark fans.

Fig. 9. Field photographs of alluvial fan sediments. (A) View eastwards across the surface of the Zefreh fan. Bimodal distribution of cobble and pebble size clasts in the proximal portions. (B) Zefreh and Feshark fans dominated by Eocene alkali volcanic clasts, with minor Mesozoic limestone and sandstone clasts. Scale shown on ruler in centimetres. (C) Pebble to small cobble size clast supported gravels that fine upwards into coarse-grained sands. The fining upwards gravel occur as ~30cm repeating packages through a 2 m trench cut perpendicular to flow across the Feshark fan.

Fig. 10. Graph illustrating the relationship between the proportion of fan or playa lake sediments and the distance from the apex for the Soh, Zefreh and Feshark fans.

Fig. 11. Field photographs of hot-spring travertines. (A) Example of layered mat facies with some banded white veins, proximal portion of the Soh fan. Dense aragonite veins that are composed of bands of white crystals cut through the layered mats. These white banded veins mainly range in thickness from 5 cm to 50 cm and would have been precipitated from rapid degassing of $CO_2$ from highly agitated subsurface waters while

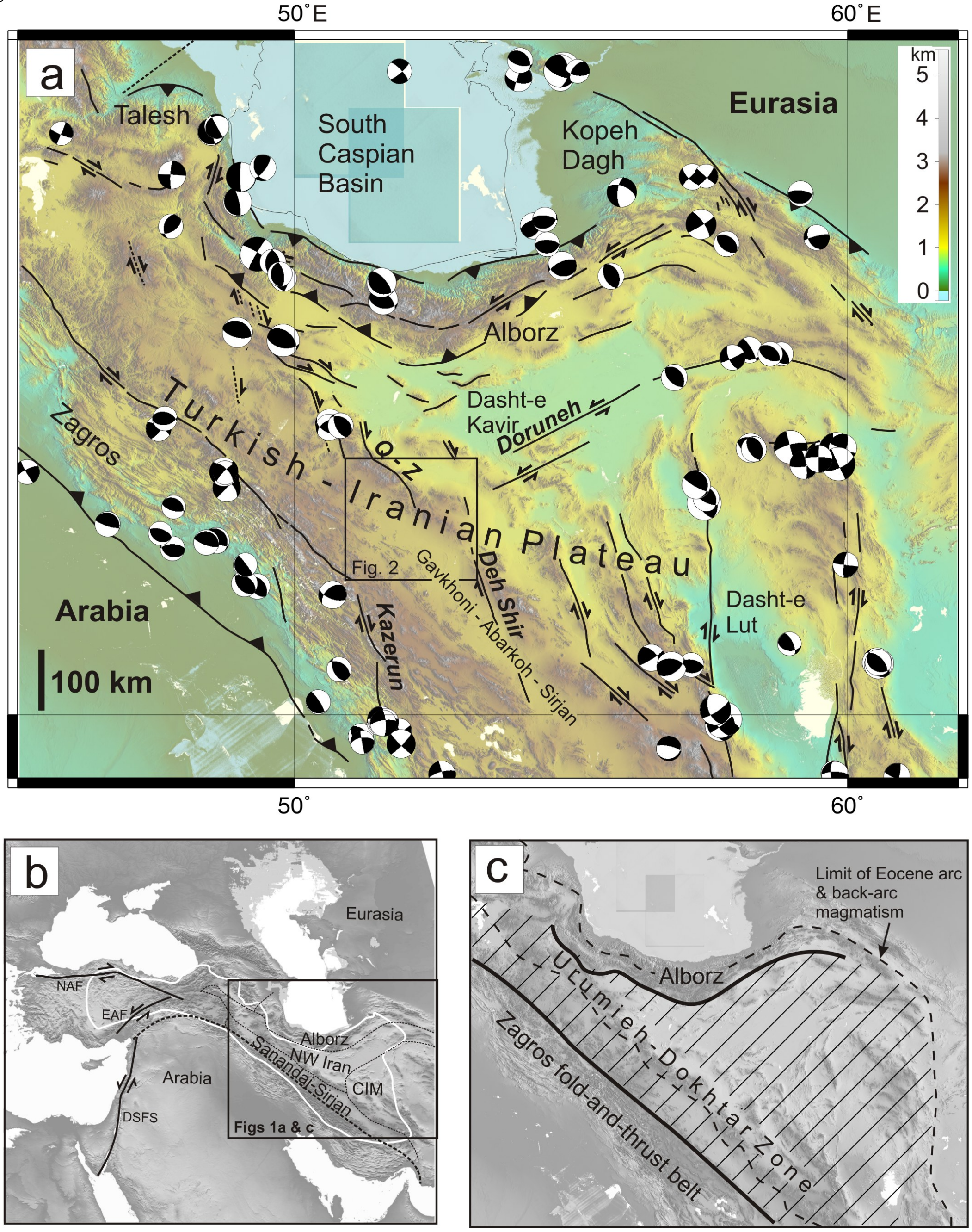
the travertines were still an *in-situ* mound. (B) Layered mat facies intercalated with conglomerates, proximal Zefreh fan. Well preserved pool and rim geometries of microterraces that once formed on the margin of an active travertine mound.

Fig. 12. Intercalated playa lake (P) and fan (F) sediments. Fine-grained lake sediments are often superimposed onto the coarser sands and gravels frequently with gypsum crusts. The lake sediments are often rippled with minor convoluted bedding. The coarser fan sediments exhibit horizontal stratification, with some low angle planar cross-bedding, pebble imbrication and erosional bases. The intercalation of sediments are found throughout the distal portion of the Zefreh and Feshark fans and can be identified along the Gavkhouni high stand strand line (See Fig. 6).

Fig. 13. Detailed sedimentary log of the distal portion of the Zefreh fan. See figures 2 and 6 for location. $D_{90}$ records the $90^{th}$ percentile of the coarsest grain size fraction.

Fig. 14. Field photograph of view southwards across the Gavkhoni playa. In the foreground, is a discrete patch of white anhydrite-glauberite surrounded by brown clay. This is a common occurrence across the modern Gavkhoni playa.

Figure 1



50˚E
60˚E
40˚ N
40˚
30˚ N
30˚
50˚
60˚
a
km
5
4
3
2
1
0
Talesh
South Caspian Basin
Kopeh Dagh
Eurasia
Alborz
Dasht-e Kavir
Doruneh
Turkish - Iranian Plateau
Zagros
Q-Z
Fig. 2
Deh Shir
Gavkhoni - Abarkoh - Sirjan
Kazerun
Arabia
Dasht-e Lut
100 km
b
Eurasia
NAF
EAF
Alborz
NW Iran
Sanandaj-Sirjan
CIM
Arabia
DSFS
Figs 1a & c
c
Limit of Eocene arc & back-arc magmatism
Alborz
Urumieh-Dokhtar Zone
Zagros fold-and-thrust belt

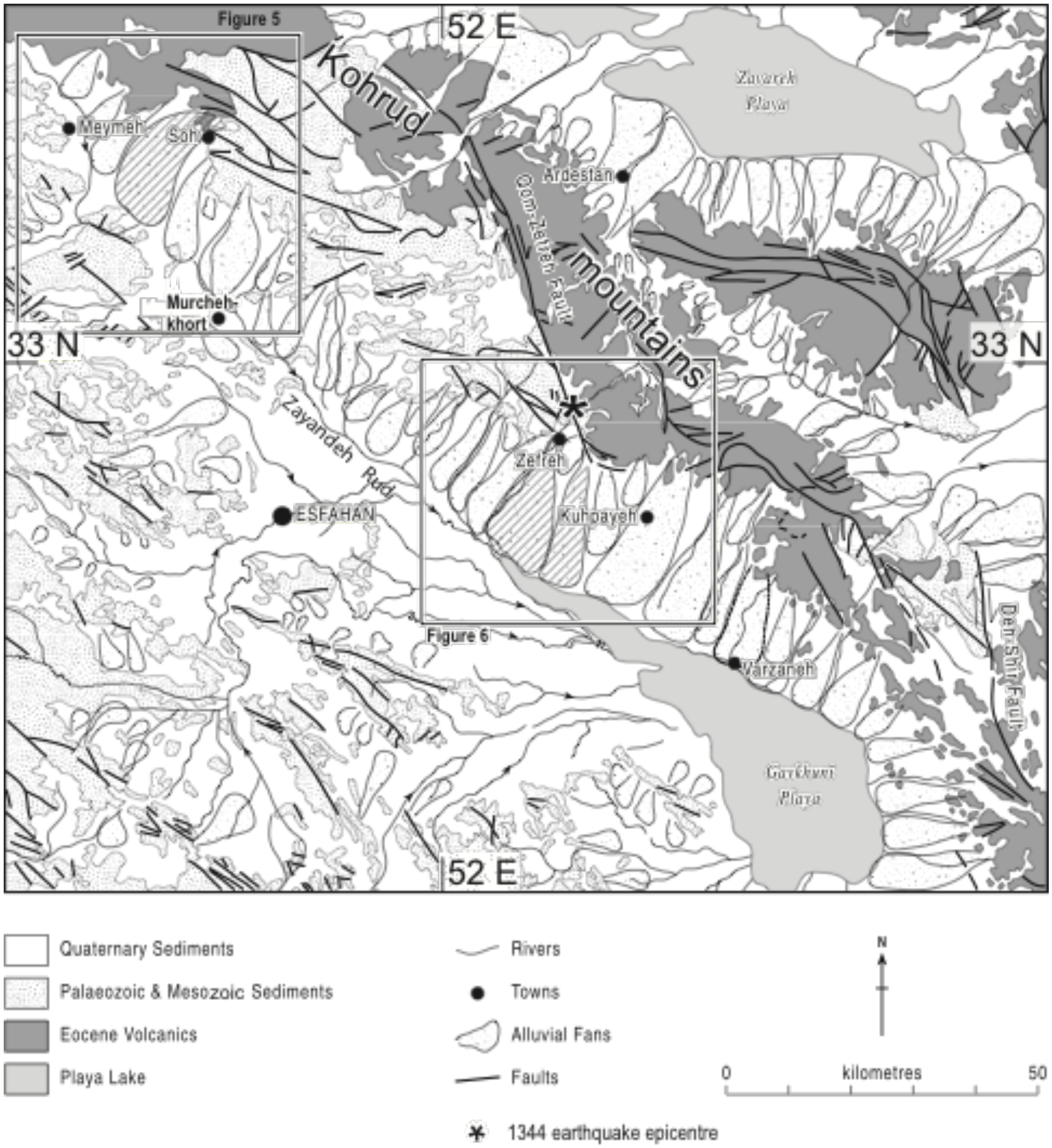


Figure 5
52 E
Kohrud
mountains
Qom-Zefreh Fault
Zavareh Playa
Ardestan
Meymeh
Soh
Murcheh-khort
33 N
33 N
Zayandeh Rud
ESFAHAN
Zefreh
Kuhpayeh
Figure 6
Varzaneh
Gavkhuni Playa
Deh Shir Fault
52 E
Quaternary Sediments
Palaeozoic & Mesozoic Sediments
Eocene Volcanics
Playa Lake
Rivers
Towns
Alluvial Fans
Faults
1344 earthquake epicentre
N
0
kilometres
50

Figure 2

Figure 3

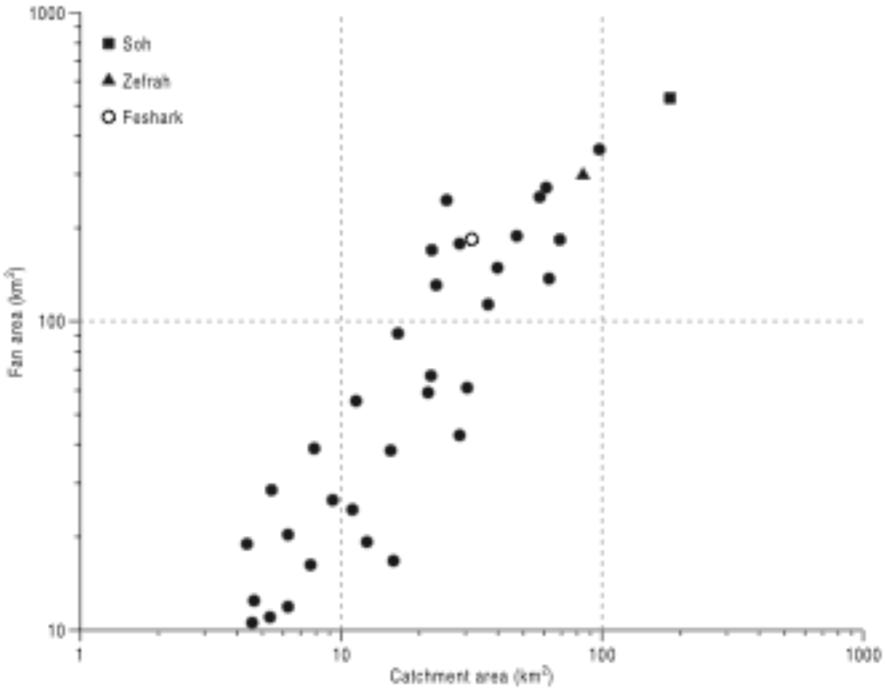

Soh
Zefrah
Feshark
1000
100
10
Fan area (km$^2$)
1
10
100
1000
Catchment area (km$^2$)

Figure 4

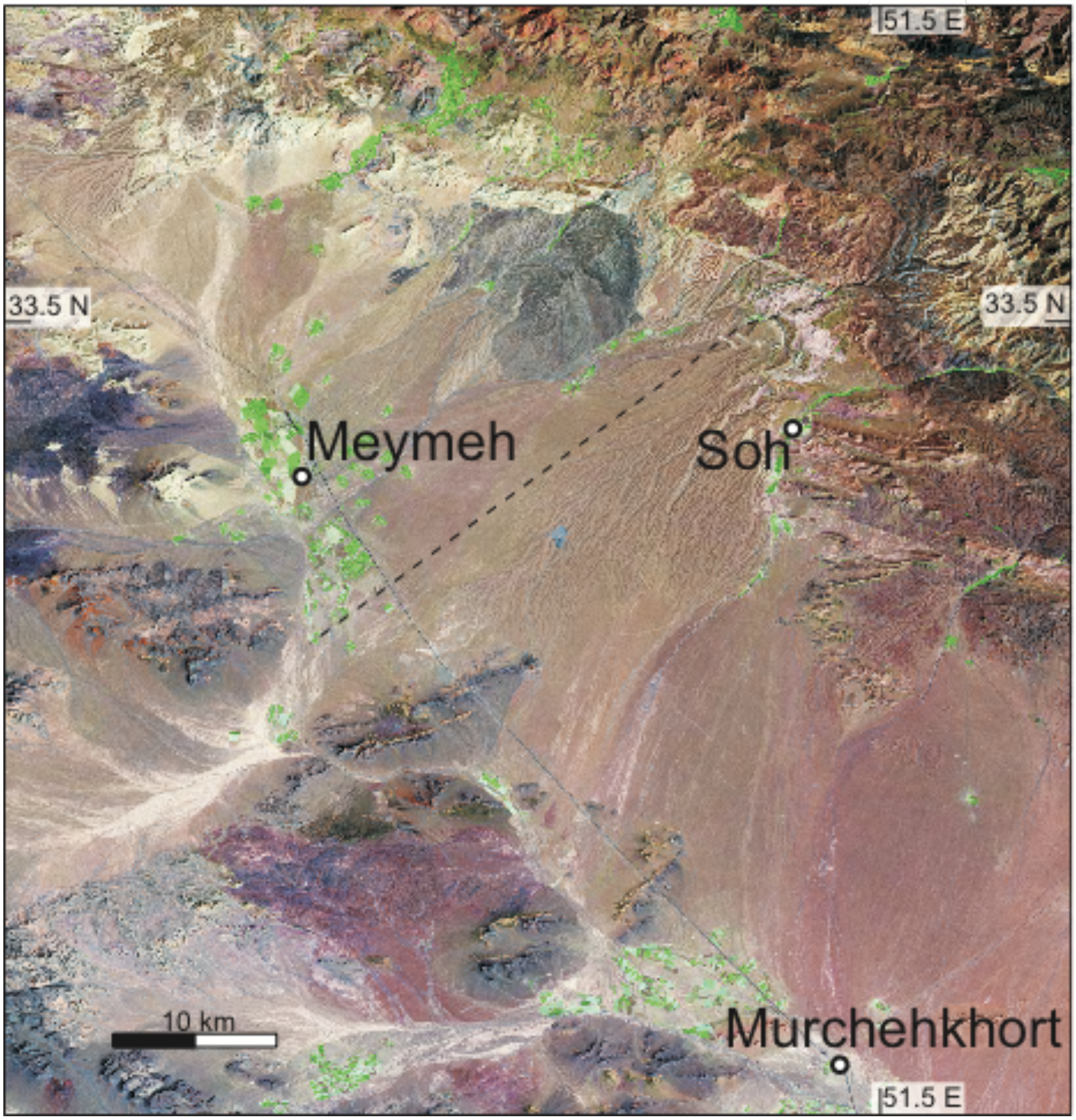



Figure 5

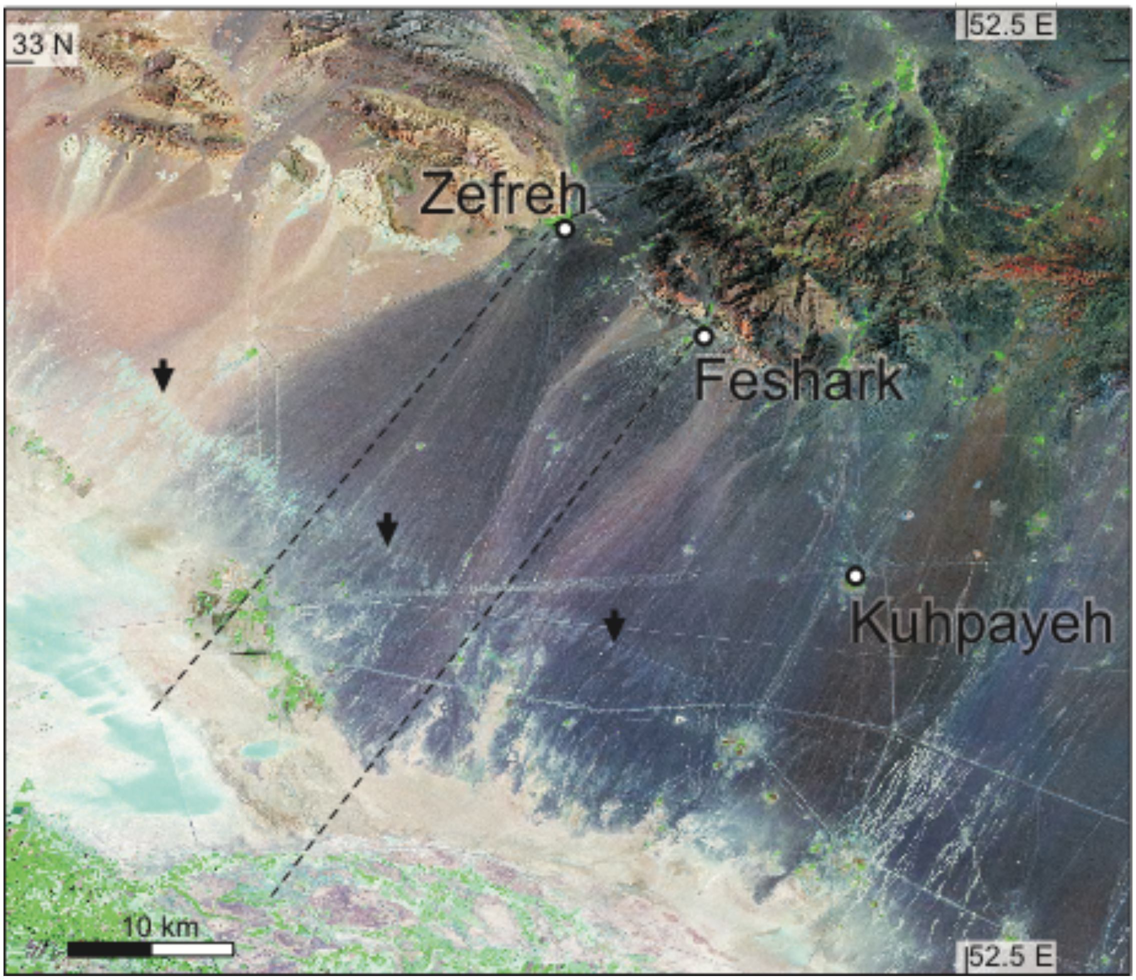
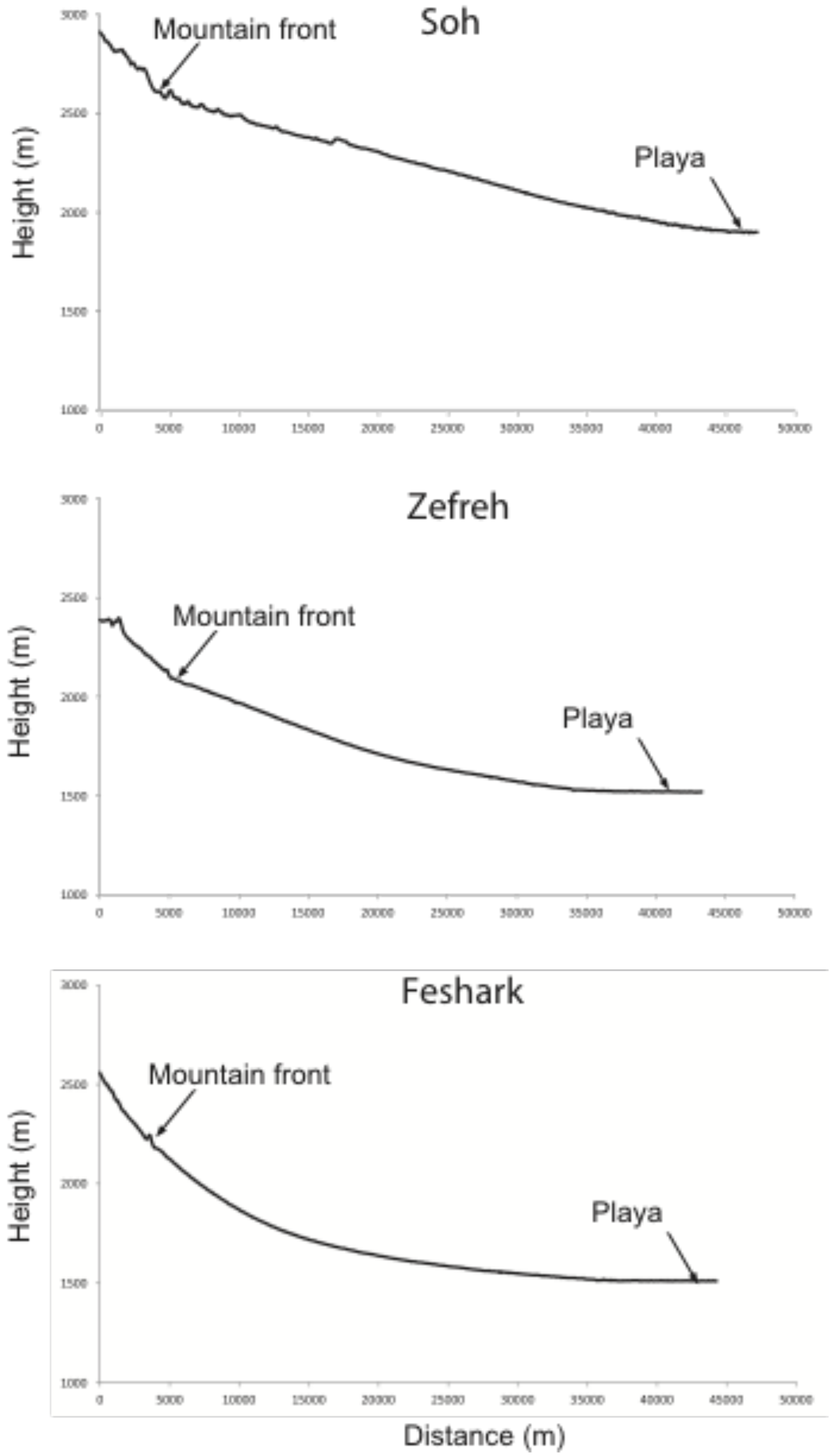
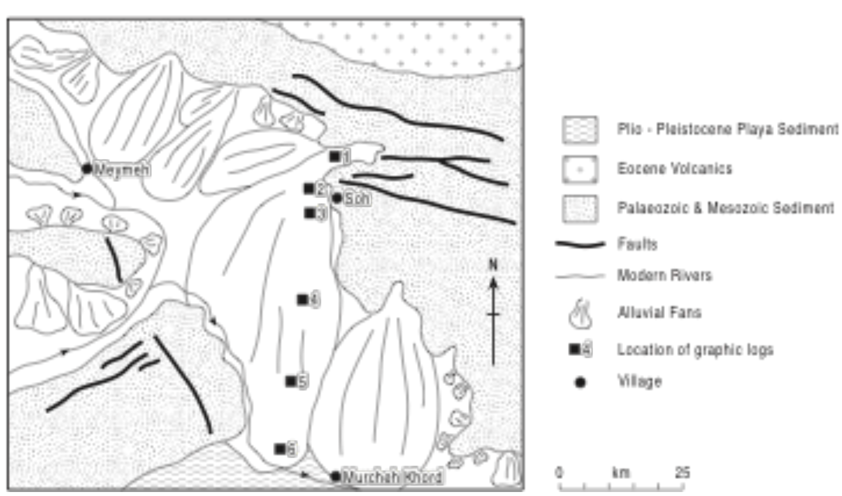



Figure 6


Soh
Mountain front
Playa
Height (m)
Zefreh
Mountain front
Playa
Height (m)
Feshark
Mountain front
Playa
Height (m)
Distance (m)


6
5
4
3
2
1
Metres
c fs ms
s cs congl
Conglomerate
Sandstone
Silt
Mud
Travertine
Gypsum
Vertical reed stems
Plant material
Planar cross bedding
Imbrication
Pebble cluster
Erosional scour
Horizontal bedding & lamination
Lens of sand
Anhydrite
Rhizoliths
Oncoids


Meymeh
Soh
Murcheh Khord
N
Plio - Pleistocene Playa Sediment
Eocene Volcanics
Palaeozoic & Mesozoic Sediment
Faults
Modern Rivers
Alluvial Fans
Location of graphic logs
Village
0 km 25

874


A
B
C
cm

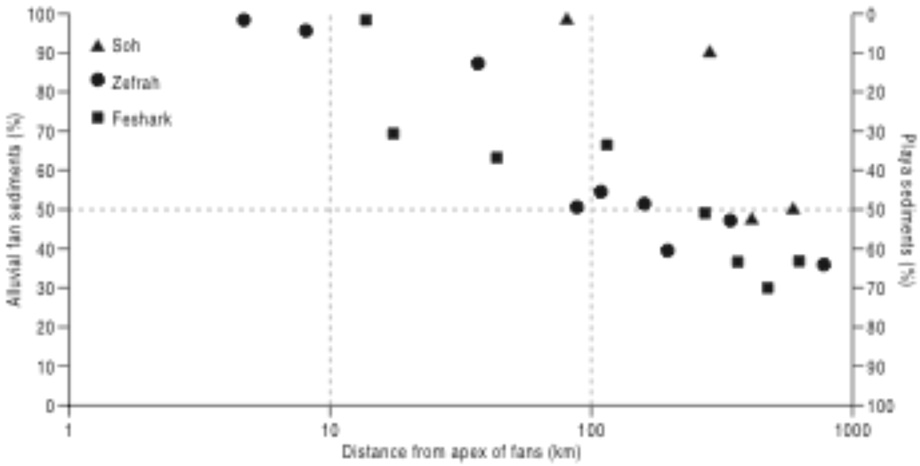
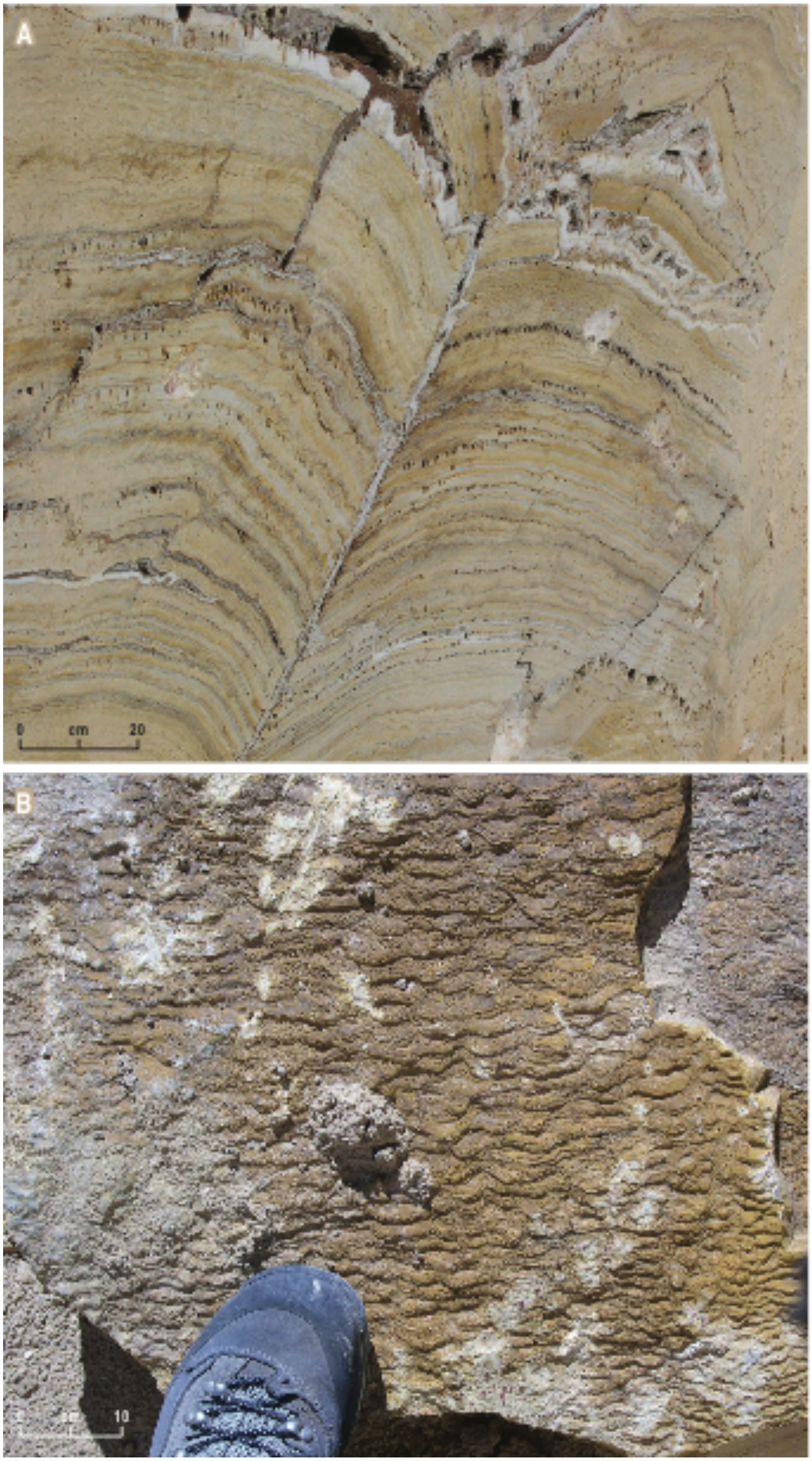

Soh
Zafrah
Feshark
Alluvial fan sediments (%)
Playa sediments (%)
Distance from apex of fans (km)

Figure 10


A
0 cm 20
B
0 cm 10

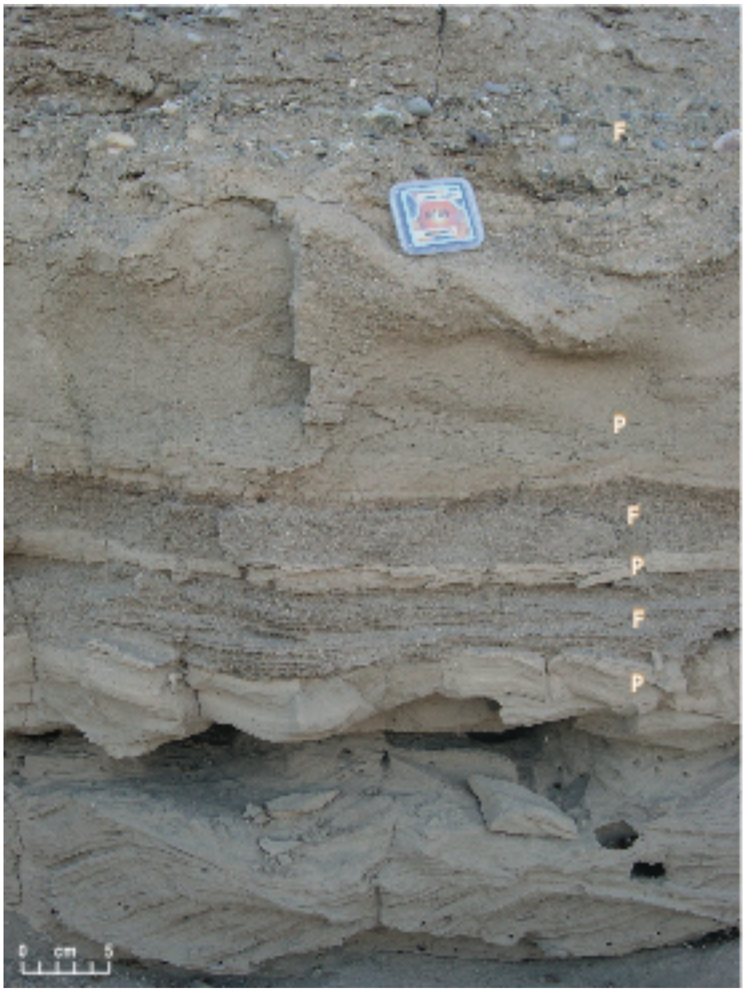



Figure 12

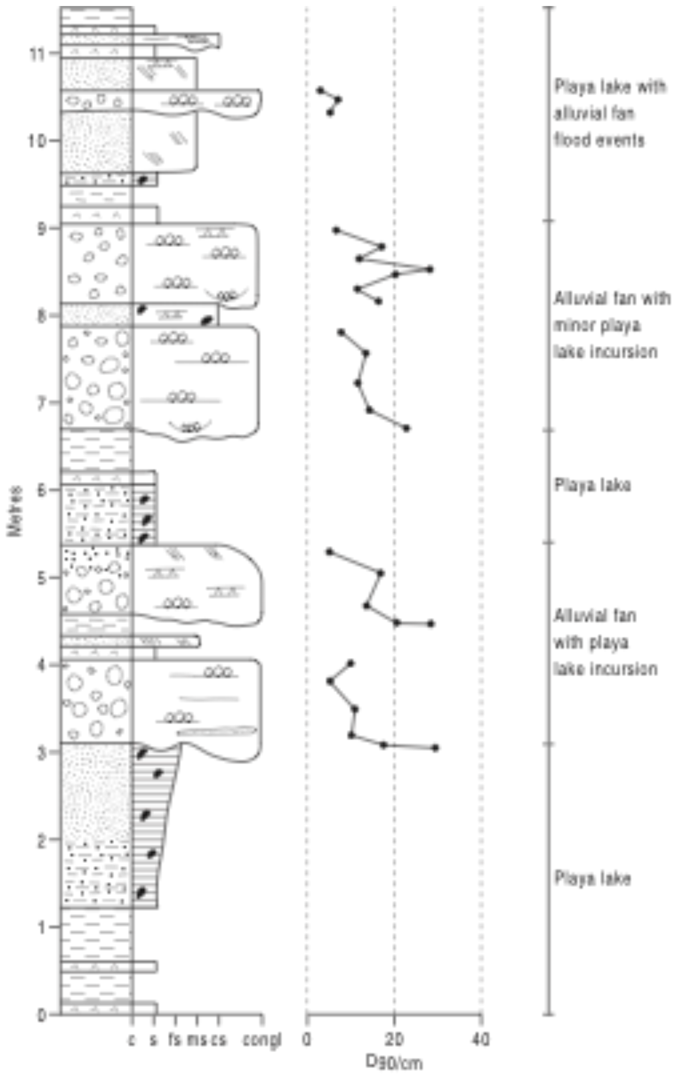

Playa lake with
alluvial fan
flood events
Alluvial fan with
minor playa
lake incursion
Playa lake
Alluvial fan
with playa
lake incursion
Playa lake
Metres
0
1
2
3
4
5
6
7
8
9
10
11
c s fs ms cs congl
0 20 40
D90/cm

Figure 13


Figure 14

| Parameters | Soh | Zefreh | Feshark |
| --- | --- | --- | --- |
| Fan area ($km^2$) | 537 | 309 | 179 |
| Average fan slope (degrees) | 0.01-0.15 | 0.04-0.2 | 0.06-0.23 |
| Average catchment slope (degrees) | 0.48 | 0.39 | 0.39 |
| Fan progradation distance (km) | 32.4 | 35.6 | 28.3 |
| Fan radius (km) | 8.1 | 6.3 | 3.7 |
| Catchment area ($km^2$) | 178 | 84.5 | 23.5 |
| Catchment length (km) | 23.6 | 15.7 | 8.7 |
| Catchment maximum elevation (m asl) | 3200 | 3250 | 3200 |
| Catchment basin relief (m) | 900 | 1250 | 1270 |
| Catchment lithology types | Devonian to Cretaceous sandstones, siltstones and carbonates. Hot spring Travertines | Predominantly Eocene andesitic volcanics. Some Hot spring travertines | Predominantly Eocene andesitic volcanics |
| Fan lithology types | Carbonate clasts (75%) sandstone and siltsone clasts (25%). Where fan intercalated with travertines, carbonates (30%), sandstones (15-20%), travertine clasts up to (50%) in proximal fan | Volcaniclastic clasts (75%) basaltic and andesitic clasts (~15%) dolomite clasts (~5%), travertine clasts only proximal fan (5%) | Volcaniclastic clasts (75%) basaltic and andesitic clasts (~15%) dolomite clasts (~5%), travertine clasts only proximal fan (5%) |

Table 1.

Table 2

| Site name | Method used | Sediment type | Age (ka) | Reference |
|---|---|---|---|---|
| South Golbah, Dasht-e-Lut, SE Iran | $^{14}C$ | Terrestrial wood in lake carbonates | 7.9 +/- 0.1 | Walker et al., 2010 |
| Anar, Central Iran | OSL/ $^{10}Be$ | Alluvial fan sediments | 11.8 +/- 6.5 | Le Dortz et al., 2009 |
| Dehshir and Marvast River, Central Iran | OSL/ $^{10}Be$ and $^{26}Cl$ | Alluvial fan sediments and river terraces | 412 (oldest terrace); 26.9+/-1.3; 21.9+/-1.5; 10.0+/-0.6 | Le Dortz et al., 2011 |
| Gavkhouni, Central Iran | OSL | Paleosols and playa sediments | 9.6 +/- 2.4 | Ayoubi, 2002 |
| Dehshir, Central Iran | OSL | Alluvial fan and fluvial | 2.8+/-1.4; older terraces 10-30 | Nazari et al., 2009 |
| Bam, Dasht-e-Lut, SE Iran | IRSL | Sands and silts of alluvial fan | 9.2 +/- 1.5 | Talebian et al., 2010 |
| Hajiarb Fan, NW Iran | OSL | Alluvial fan sediments | 8.83 +/- 2.84 | Schmidt et al., 2011 |
| Sefidabeh, Eastern Iran | U-series | Calcite cemented sandstones from fan sediments | 99 +30/-24 | Parsons et al., 2006 |