The structure and late Quaternary slip rate of the Rafsanjan strike-slip fault, SE Iran

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Abstract

The Rafsanjan right-lateral strike-slip fault in SE Iran has a clear expression in the geomorphology, is sited close to several large population centers, and yet it role in the regional tectonics, its rate of activity, and its potential to generate destructive earthquakes are unknown. We use high-resolution satellite imagery and field investigation to identify the active strands of the fault system and show that the overall north-south right-lateral shearing across the region is spatially separated into almost pure strike slip on the NW-SE-trending Rafsanjan fault and an orthogonal component of shortening on parallel thrust faults in the lowlands. Possible remnants of ruptures, involving right-lateral slip of ~3 m, from an earthquake of ~Mw >7 are identified along the eastern part of the Rafsanjan fault. We speculate that these ruptures result from the destructive 1923 Lalehzar event. An alluvial fan displaced right laterally by 48 ± 4 m and tentatively dated at ~120 ka yields an average slip-rate estimate of ~0.4 mm/yr. Our slip-rate estimate is consistent with known estimates of late Quaternary slip rate on other faults within eastern Iran and with global positioning system (GPS) measurements of present-day deformation in this part of the country. Our results therefore suggest that the slip rates of faults in eastern Iran do not vary substantially through the late Quaternary: a result that is important for the interpretation of geodetic and late Quaternary measurements of slip rate in regions of distributed strike-slip faulting.

Introduction

Southeastern Iran is a region of rapid active deformation, with widespread evidence for active faulting (e.g., Berberian, 1976; Walker and Jackson, 2004; Meyer and Le Dortz, 2007; Fig. 1A), and which has a long record of destructive earthquakes (e.g., Berberian, 1976; Ambraseys and Melville, 1982; Jackson et al., 2006; Fig. 1B). The active faulting in this part of Iran accommodates north-south right-lateral shear between Iran and western Afghanistan, which occurs at a rate of ~15 mm/yr (Vernant et al., 2004), and is accommodated across a number of right-lateral strike-slip faults that surround the aseismic Dasht-e-Lut desert (Fig. 1C).

The distributed strike-slip faults surrounding the Dasht-e-Lut constitute a major, and largely unquantified, hazard to nearby population centers. Furthermore, the presence of multiple active faults presents an opportunity to investigate long-term interactions between the faults. Millennial-scale variations in the rate of slip have been proposed for the fault systems surrounding the Dasht-e-Lut in eastern Iran (e.g., Meyer and Le Dortz, 2007), in a similar manner to the variations suggested across the distributed right-lateral faults of the Los Angeles basin and eastern California shear zone in California (e.g., Dolan et al., 2007). In order to determine whether rates of faulting are constant over the late Quaternary, it is necessary to compare slip rates averaged over geodetic timescales to the long-term Holocene and late Quaternary slip rates that are averaged over many earthquake cycles.

Long-term slip-rate estimates now exist on some of the major faults in eastern Iran (e.g., Meyer and Le Dortz, 2007; Le Dortz et al., 2009; Walker et al., 2009; Walker et al., 2010a) and are summarized on Figure 1C. The data are not yet sufficient to fully understand the distribution of strain across eastern Iran or to determine whether the distribution of slip on the population of faults remains constant through time (e.g., Meyer and Le Dortz, 2007; Walker et al., 2010a).

The ~200-km-long Rafsanjan strike-slip fault is one of the major faults of southeast Iran (Fig. 2). It has a clear expression in the geomorphology, suggesting that it may have a high slip rate, with obvious implications both for local seismic hazard and for understanding the regional tectonics. It is, however, situated in a part of southeastern Iran that has little in the way of recorded earthquakes and in which GPS measurements do not show rapid deformation (Figs. 1 and 2).

This apparent discrepancy between long-term and short-term behavior raises the question of whether variations in the rate of activity might occur on the Rafsanjan fault, perhaps as part of a regional switching of activity between the various major faults of eastern and central Iran (Meyer and Le Dortz, 2007).

In the following sections, we first summarize what is already known, and add further observations from fieldwork and remote sensing, of the structure of the Rafsanjan fault. We then describe evidence, from analysis of high-resolution satellite imagery and fieldwork, for a previously unknown earthquake rupture on the eastern section of the fault. Finally, we estimate the late Quaternary slip rate at one site where the fault has displaced the surface of an alluvial fan. The constraints on structure, past earthquakes, and slip rate are then brought together in order for permission to copy, contact editing@geosociety.org
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to assess the importance and role of the Rafsanjan fault in the accommodation of regional tectonic strain, and to determine whether it is likely to have experienced significant changes in its rate of activity over the late Quaternary.

**STRUCTURE OF THE RAFSANJAN FAULT**

The northwest-southeast–trending Rafsanjan fault is ~200 km long and has a clear expression in the geomorphology along most of its length (e.g., Berberian, 1976; Walker, 2006). There are no constraints on its total cumulative displacement. It is likely to transfer some of the right-lateral slip on the north-south right-lateral Sabzevaran fault onto distributed strike-slip faults of central Iran such as the Anar fault. As the Rafsanjan fault is oriented at an angle of ~45° to the Sabzevaran fault, roughly equal components of strike slip and shortening are expected across it. This large component of shortening is expressed in the high elevations of the mountains bounding the southern side of the fault (Fig. 2).

At its northern end the fault links through the Kuh-e-Mosahem Mountains to the north-south right-lateral Anar fault (e.g., Walker, 2006). To the southeast, it runs along the range front of Kuh-e-Mamsar, where it is visible in Quaternary alluvial deposits. Berberian (1976) describes the Rafsanjan fault as an oblique right-lateral fault and notes a clear expression of the fault at the village of Kansabz (Fig. 2), where it forms a southwest-facing scarp, several meters high, in alluvial gravels (we observed particularly clear southwest-facing scarps at 30°13′42″N, 55°57′05″E). The component of vertical displacement is hence opposite to the regional topography at this site. Clear lateral displacements of alluvial fans are observed elsewhere along the fault, such as in the sections south of Bardsir (Fig. 3).

Figure 1. (A) Global positioning system (GPS) velocities of points measured relative to stable Eurasia (Vernant et al., 2004). The velocities reduce to zero at both the northern and eastern margins of Iran, indicating that the tectonic shortening is accommodated within the political borders of the country, and resulting in a north-south right-lateral shear of ~15 mm/yr across eastern Iran. (B) Epicenters of earthquakes from the catalogue of Engdahl et al. (1998). Seismicity is concentrated in the Zagros Mountains (labeled Z) in the south of the country, and the Alborz and Kopeh Dagh (A and K) in the north. The Kavir and Lut deserts are largely aseismic. (C) Map of eastern Iran showing the locations and estimated slip rates (in mm/yr) of the major strike-slip faults (from Regard et al., 2005; Meyer et al., 2006; Meyer and Le Dortz, 2007; Le Dortz et al., 2009; Walker et al., 2009; Walker et al., 2010a). The Rafsanjan and Lalehzar faults are shown in bold. The velocities of GPS stations KERM and ZABO, which together show ~15 mm/yr of right-lateral shear across eastern Iran, are shown relative to stable Eurasia (Vernant et al., 2004).
Walker (2006) identified an eastward continuation of the Rafsanjan fault within the east-west Lalehzar valley at the village of Chaman Rang (Figs. 2 and 4). This part of the fault is visible in the field as a continuous south-facing scarp ~1 m high (Fig. 4B). A spring at the scarp provides water for the village. A near vertical fault zone is exposed beneath the scarp in a river cutting west of Chaman Rang (Fig. 4C), and hot springs come to the surface in the riverbed adjacent to Figure 4C. Active faulting east of Chaman Rang within the ~50-km-long Lalehzar valley is difficult to follow in satellite imagery. This may be a consequence of rapid erosion within the steep and narrow valley (Walker, 2006). A large component of shortening is expected across the Lalehzar fault due to its east-west orientation and the tightly folded Paleogene volcanic rocks outcropping along the northern margin of the valley (Geological Survey of Iran, 1993). The south-facing scarp at Chaman Rang could, therefore, indicate a component of shortening across the fault at this location.

Despite its northwest-southeast trend, which is inclined at ~45° to the regional north-south right-lateral shearing across this part of Iran (e.g., Vernant et al., 2004), the absence of high scarps along much of the length of the Rafsanjan fault indicates that it is predominantly strike slip for much of its length (e.g., Berberian, 1976). Where vertical scarps are present, they often face toward the high mountains of Kuh-e-Mamsar, and the dip slip does not, therefore, appear to be simply a consequence of uplift along an oblique reverse fault at the range front. The dominantly strike-slip nature of the fault is particularly clear immediately west of Bagh Bazm (Fig. 5). At this locality, the fault breaks into two parallel strands with scarps that face toward one another. A strike-slip component is evident in the lateral displacement of drainage channels incised into the abandoned surfaces of alluvial fans. The drainage channels, and the top of the risers between the channel and fan surface, are restored to their original linear courses by ~50 m of right-lateral slip (Figs. 5B and 5C).

A quarry exposure through the southern fault strand reveals a steeply north-dipping normal fault (Figs. 5D and 5E). The overall structure of the fault at this location hence appears to be a graben with two parallel fault strands, each possessing normal components of slip, and which dip toward one another. Predominantly right-lateral slip on the Rafsanjan fault is also indicated in small-scale stream displacements (see Evidence for a Past Earthquake on the Rafsanjan Fault section), and in the right-lateral displacement of an alluvial fan surface (see Late Quaternary Slip-Rate Estimate section), south of Bardsir on the road to Baft (Fig. 3). The observations show that, despite its northwest-southeast trace, the expected component of shortening appears to be mostly absent along the sections of the fault that we have studied in detail. This might not be the case along the entire length of the fault, as range-front scarps are visible along some sections, particularly in the region north of Kansabz (Fig. 2).

Figure 2. Shuttle Radar Topography Mission (SRTM) digital topographic map of the Rafsanjan and Lalehzar fault traces showing the major active faults and the fault-plane solutions of instrumentally recorded earthquakes (Jackson, 2001; Talebian et al., 2004). White circles represent epicenters of historic earthquakes (Ambraseys and Melville, 1982). Red dots denote villages damaged by the 1923 Lalehzar earthquake from Berberian (1976). The red ellipse represents the epicentral zone from Ambraseys and Melville (1982). The parts of the Rafsanjan fault where potential earthquake ruptures are observed are marked in red (see Evidence for a Past Earthquake on the Rafsanjan Fault section).
Figure 3. Landsat satellite image (displaying bands 4, 3, 1 as R, G, B) showing the main field study sites described in this paper. Active fault strands are drawn as black lines, dotted where activity is inferred and red where the fault trace displays features indicative of slip in a single earthquake event. The main Rafsanjan strike-slip fault runs along the base of the Kuh-e-Mamsar Mountains. A second zone of active strike-slip faulting cuts across the alluvial plains southwest of Bardsir.
The component of shortening that is expected across the Rafsanjan fault appears, instead, to be accommodated on a series of active structures in the plains north of the main Rafsanjan fault trace (e.g., Walker, 2006; Walker et al., 2010b; Figs. 2 and 3). The majority of these structures are northwest-southeast–trending anticlines with Neogene marls exposed in their cores. The anticlines are underlain by southward-dipping thrust faults that reach the surface and form north-facing scarps in alluvial fan deposits (Walker, 2006). The folds and thrusts are present along most of the length of the Rafsanjan fault (Fig. 2).

We identify an additional series of northwest-southeast scarps running through the plains south of Bardsir (Fig. 3). The faults are clearly visible in the landscape and yet there is little topographic expression across them for much of their length. Along some short sections of the fault, such as that shown in Figure 6, there

Figure 4. (A) High-resolution Quickbird image (from Google Earth) of the Lalehzar fault scarp at Chaman Rang village. The fault runs between the white arrows. In the center of the image, it cuts across a wide river terrace and forms an ~1 m south-facing scarp. (B) View NNE at the 1 m fault scarp in the surface of a river terrace west of Chaman Rang. (C) Photograph looking east at vertically dipping fault rocks exposed in a river cutting west of Chaman Rang. The fault exposure is along strike of the scarp shown in Figure 4B.
Colluvial deposits

~50 m of restoration

under-restored

over-restored

NW

Colluvial deposits

SE

Colluvial deposits
is a height change across the fault. The southern side of the fault is uplifted by ~3 m where it is crossed by the Bardsir to Baft highway (Fig. 6B). Near the center of Figure 6A, the fault bends more to the west and the scarp height increases. A man-made structure has been built across the fault scarp at this high point (Fig. 6). The multiple concentric walls of the structure are not visibly displaced across the fault, either laterally or vertically, which suggests that no large slip events have occurred since its construction. The size and shape of the square inner structure suggest that the structure may be a fire temple, in which case it could date from the Parthian period (in the third century B.C.) or later (Dr. Ruth Young, University of Leicester, 2011, personal commun.). Farther to the northwest of Figure 6, the fault scarp is traced on satellite imagery through flat-lying agricultural regions to link with folds west of Bardsir (Figs. 2 and 3). We infer from the above observations that the faults are mainly strike slip in nature and locally accommodate shortening at small restraining bends.

**EVIDENCE FOR A PAST EARTHQUAKE ON THE RAFSANJAN FAULT**

We now describe evidence for rupturing of the ground surface, which we interpret to be the result of a single earthquake event, along the eastern part of the Rafsanjan fault (Fig. 3). This section of the fault cuts through sandstones that are cemented by calcite precipitated from a line of hot springs that run parallel to the active fault trace (Fig. 7A). A number of small northward-flowing streams have incised through the calcite-cemented sandstones to occupy gullies several meters deep (Figs. 7B and 7C). The active streambeds are also cemented by calcite.

Fissuring of the ground over a distance of ~1.5 km is visible both in high-resolution satellite imagery and in the field (Figs. 7 and 8). In the northern part of the zone, the fault is manifested as a series of short fractures aligned along the fault trend (Figs. 7B, 7C, and 8D). In the middle section, the fault widens into a zone of left-stepping en echelon fissures indicative of right-lateral slip (Figs. 7B and 7C). In the south of the zone, the fault is represented by a series of small pressure ridges (Figs. 7B, 7C, 8E, and 8F). These pressure ridges stand proud of the surrounding land surface by ~2 m (Fig. 8F).

A number of stream displacements are shown in Figures 7B and 7C. The northern margin of stream X is displaced right laterally by 3.2 m (measured to the nearest 0.1 m with a tape measure, Figs. 8A and 8B). The southern margin of stream X is less distinct than the northern margin, and, although it does appear to be right-laterally displaced, we do not attempt to estimate the amount of displacement. Both margins of stream Y are displaced by 2.8 ± 0.1 m (Fig. 8C). The fault trace, with a vertical displacement of ~0.5 m, is visible in the carbonate-cemented bed of the stream. Farther south, the surface expression of the fault widens to a zone of fissuring and push-ups ~40 m wide, such that sharp displacements of the stream channels are not seen (Figs. 7B and 7C).

The scale and the level of preservation of the structures described above are compatible with them arising during a single earthquake event. Assuming that the average surface displacement in the earthquake was 3 m (the average of our 2.8 m and 3.2 measured stream displacements), and applying the scaling relationship between...
average displacement and moment magnitude for strike-slip faults (Wells and Coppersmith, 1994), yields a moment magnitude of ~7.5. If we instead take the maximum stream displacement of 3.2 m and use the scaling relationship for maximum surface displacement, the moment magnitude is estimated at 7.2. We can also use scaling relationships to estimate the probable length of rupture in the earthquake. From the 7.2 to 7.5 range of moment magnitude, and applying the moment-magnitude and rupture-length relationship of Wells and Coppersmith (1994), yields a rupture length of ~65 km to 125 km.

The southern part of Kerman province, in which the Rafsanjan and Lalehzar faults are situated, is notable for the low rates of seismicity in comparison to more northerly parts of the province (Fig. 2; Walker, 2006; Walker et al., 2010b). The only recorded destructive event in the region, with roughly 200 deaths, is the Lalehzar earthquake of 22 September 1923 (Berberian, 1976; Ambraseys and Melville, 1982; Walker, 2006). There is some uncertainty about the extent of the epicentral zone. Ambraseys and Melville (1982) state that the earthquake destroyed the villages of Lalehzar, Gughar, Khatib, and Qaleh Askar (Fig. 2). The features that we interpret as preserved earthquake ruptures lie to the northwest of this epicentral region. Destruction may, however, have extended northeast to Dishkan, Bagh-Bazm, and Gowd-e-Ahmar (Fig. 2; Berberian, 1976), delineating an epicentral zone that is parallel to the Rafsanjan fault and ~100 km in length. Because the ~3 m right-lateral stream displacements that we identify are consistent with a rupture length of 65–125 km, it is possible that the ruptures result from slip in the 1923 earthquake, though paleoseismic trenching is required to validate this suggestion. The unusually well preserved ruptures in this one short section may result from the hard, cemented, sediments that form the land surface. We did not find clear evidence of rupturing of the ground surface resulting from an earthquake along other sections of the fault, although the sharp 1-m-high scarp at the village of Chaman Rang (Fig. 4B), which was damaged in the 1923 earthquake, is of an appropriate scale to result from a single event.

LATE QUATERNARY SLIP-RATE ESTIMATE

We have shown that the Rafsanjan fault, together with a parallel system of southwest-dipping thrust faults, accommodates oblique right-lateral strike slip (see Structure of the

![Figure 7](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/7/5/1159/3340837/1159.pdf)
Figure 8. Field photographs of proposed earthquake ruptures on the Rafsanjan fault. (A) View west toward stream X (Fig. 7C). Fractures are visible in the streambed. The figures are standing by the stream margin displaced right laterally by 3.2 m. (B) View of the 3.2 m right-lateral displacement in the margin of stream X (Fig. 7C). (C) View of stream Y (Fig. 7C) showing the 2.8 m right-lateral displacement of the channel margin and ~0.5 m vertical displacement. (D) View south along the fault trace. In the foreground, the surface expression is of small, aligned fractures. A pressure ridge is visible in the far distance. (E) View southeast at a series of aligned pressure ridges. (F) Photograph showing the ~2 m of relief between the summit of a pressure ridge and the surrounding land surface.
Rafsanjan Fault section). We have also provided evidence that the fault has generated earthquakes in the recent past (see Evidence for a Past Earthquake on the Rafsanjan Fault section). In order to characterize the hazard that the faults pose to local populations, and to determine their importance in the regional tectonics, we now estimate the slip rate of the Rafsanjan fault averaged over the late Quaternary.

**Site Description**

Our study site is situated close to the eastern end of the Rafsanjan fault segment close to where it enters the Lalehzar valley (Fig. 9). Two generations of alluvial fans have been deposited across the northwest-southeast–trending fault trace. The surface of the older alluvial fan (highlighted in orange on Fig. 9A) has been deeply incised by a series of minor streams. Two parallel, NW-SE–trending fault

![Figure 9](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/7/5/1159/3340837/1159.pdf)

**Figure 9.** (A) Georeferenced aerial photograph of the Rafsanjan fault in alluvial fan deposits west of the Bardsir-Baft highway (see Fig. 3 for location). Two parallel fault strands displace a heavily incised alluvial fan (in orange). A subtle fault scarp is visible in a younger generation of fan (in yellow; see Fig. 10A). A fault along the range front, which is marked by travertines deposited along aligned springs, does not appear to have displaced the fan surface (see Fig. 10B). (B) Close-up of right-laterally displaced incised drainage. A minor vertical component across both fault strands has produced ~10 m west-facing scarps. The locations of the two sampling pits (labeled A and B) and the field photographs in Figure 11 are shown. (C) The same view with 48 m of right-lateral displacement restored. The incised streams are now realigned to their original linear courses.
The Rafsanjan strike-slip fault, SE Iran

scarps are visible in the older fan surface. The continuation of the scarps in the younger surface (yellow in Fig. 9A) is less clear, though subtle west-facing scarps are still visible in high-resolution satellite imagery (e.g., Fig. 10A). There is no measureable lateral displacement of the riser between the older and younger fan surfaces (Fig. 10A). Both fault scarps show uplift of ~10 m to the east in the older fan surface (Figs. 11A and 11B). Drainage channels incised into the surface of the fan are displaced right laterally by 14 ± 2 m across the western scarp, and 34 ± 2 m across the eastern scarp (Figs. 9B and 9C), giving a total of 48 ± 4 m of right-lateral displacement since incision of the alluvial fan surface.

A range-front fault, marked by a series of springs and travertine deposition (Figs. 9A and 10B), does not appear to displace the surface of either of the two generations of alluvial fans (Fig. 10B). The observations from high-resolution satellite imagery are supported by our own field observations, because we were unable to find any evidence of disruption of the older fan surface as it crossed the range-front fault. We therefore assume that this fault records an earlier phase of faulting that has been inactive since abandonment of the older alluvial fan surface. The two active fault strands are oblique to the overall NW-SE trend of the fault by 10°–15°, and from their orientation relative to the main strike-slip fault trend, we infer that the west-facing scarps result from a minor component of extension.

We excavated two pits into the fan surface (Figs. 9A, 11C, and 11D). The exposed stratigraphy consisted of coarse gravels overlain by ~25 cm of a red soil layer. No homogeneous silt or sand layers were found, and instead we collected two samples for luminescence dating from each pit by hammering steel tubes into the sediment at sites of relatively fine-grained alluvium. The ends of the tubes were packed tightly with paper and aluminum foil and then sealed with several layers of duct tape. The sealed tubes were then individually packed in opaque black plastic bags. In both pits, the samples were collected from depths of 50–60 cm and 80–90 cm.

**IRSL Dating Methods**

The fan material was predominantly composed of basic igneous and volcanic rocks derived from Kuh-e-Mamsar to the south (Fig. 2), and insufficient quartz was found for optically stimulated luminescence (OSL) dating. Instead, we isolated potassium feldspar grains and dated the grains using infrared stimulated luminescence (IRSL). The potentially light-exposed sediments at both ends of the metal tubes were extracted, and the sediment remaining was used for equivalent dose determination.

Figure 10. High-resolution Geoeye satellite imagery (from Google Earth) showing details of the displaced alluvial fans in Figure 9. (A) The white arrows point to north-south scarps in the younger fan generation, demonstrating that slip has occurred since abandonment of these younger surfaces. The dashed black line marks the riser between the older and younger fans. The riser is not laterally displaced by a measurable amount, suggesting that the amount of slip since abandonment of the younger fan surface has been small. (B) Close-up image showing the older of the two fan surfaces as it crosses the range-front fault (running between the white arrows). Dashed black lines mark the edges of the fan surface. No displacement of the fan surface is visible across this fault. An apparent right-lateral deflection of the fan is caused by deflection around the southern side of a bedrock ridge.
The sample was wet sieved to separate the 90–250 µm size fractions and immersed for two days in 1 N HCl to remove carbonate, followed by two days immersion in 35% H2O2 to remove organic material. A K-feldspar-enriched extract was then separated using a heavy liquid solution (density <2.58 g/cm³) and etched for 10 min with 48% HF to remove the outer alpha-irradiated layer from the grains. After etching, any contaminating fluorides were dissolved using HCl. A second stage of dry sieving through a 90 mm sieve was undertaken to obtain the final feldspar concentrate used for experiments. At each stage of the separation procedure, samples were generously rinsed with distilled water.

Medium (~5 mm) aliquots were mounted on 10-mm-diameter aluminum discs using silicone oil for the single-aliquot analyses. All the experiments reported here were carried out using a Riso (Model TL/OSL-DA-15) automated TL/OSL system equipped with an IR laser diode (λ = 830 nm) as a stimulation source. Infrared stimulated luminescence was detected using an Electron Tubes bialkaline photomultiplier tube (PMT). Luminescence was measured through 7 mm Hoya U-340 filters. The equivalent dose (Dₑ) was obtained using single-aliquot regeneration methods (Table 1A). The equivalent dose distribution for each sample is given in Figure 12.

Dose rates for each sample were calculated using radioisotope concentrations, burial depth, and present-day moisture content, following the same procedures as reported by Fattahi et al. (2007). Uranium, thorium, and potassium concentrations were measured using inductively coupled plasma (ICP)–mass spectrometry. Present-day moisture contents were determined by drying at 40 °C in the laboratory. Alpha, beta, and gamma dose rates were calculated from radioisotope and water contents.

Sample pit A:
29:45:41.1N 56:31:29.9E

Sample pit B:
29:43:58.8N 56:32:57.8E

C
D
Soil (25 cm)
Ra1
(55 cm)
Ra2
(85 cm)

Sample pit A:
29:45:41.1N 56:31:29.9E

Sample pit B:
29:43:58.8N 56:32:57.8E

Figure 11. Field photographs of the displaced alluvial fan shown in Figure 8 and our infrared stimulated luminescence (IRSL) sampling sites. (A) View northeast down a stream incised into the fan surface. The right-lateral stream displacement (labeled X-Y; see Fig. 9B) is ~34 m. The fault trace is marked by a black line. There is ~10 m uplift of the eastern side of the fault. Lateral displacement of topography caused a higher scarp immediately north of the drainage channel. Figure (circled) for scale. (B) View north along the eastern fault scarp. The scarp, which is ~10 m high, is interrupted by incised drainage channels. The horizons are highlighted for clarity by black lines. Figure (circled) for scale. (C) Sample pit RA showing the stratigraphy and locations of samples RA1 and RA2. (D) Sample pit RB showing the stratigraphy and locations of samples RB1 and RB2.
The preheat and cut heat treatments used for the calculation of internal dose rate follow Aitken (1998) and Aitken (1985), respectively. Alpha and beta dose rates were corrected for attenuation due to grain size using the factors of Bell (1980) and Mejdahl (1979). An alpha efficiency of 0.04 ± 0.02 percent. The derived age estimates are shown in Table 2.

Several authors have shown that the feldspar signal intensity increases with temperature (e.g., Duller and Bøtter-Jensen, 1993; Poolton et al., 2002; Li and Li, 2010). Some studies (e.g., Thomsen et al., 2008; Buylaert et al., 2009; Schmidt et al., 2010) show that at the high temperature (say 290 °C) the post-IR signal does indeed show a reduced anomalous fading rate in comparison to the IRSL signal measured at 50 °C. To account for such temperature-dependent effects, Li and Li (2010) introduce a multielevated-temperature, post-infrared (IR) IRSL in which the fading rate decreases as the sample temperature increases from 100 to 250 °C.

We applied the post-IR blue signal (ultraviolet detection) using a preheat of 220 °C and post-IR sample temperature at 125 °C for samples RA1, RA2, and RB1 (Table 1B), the post-IR, elevated-temperature IR signal (blue detection) (Table 1C), and multielevated-temperature, post-IR IRSL for samples RA1 and RB1 (Table 1D). For the samples we examined, none of the additional methods showed significantly higher D\textsubscript{\text{d}} than the D\textsubscript{\text{d}} produced from the IRSL signal measured using the sequence presented in Table 1A. We therefore use the method presented in Table 1A to generate the ages shown in Table 2.

**Interpretation of Age Data**

The four IRSL ages from the uppermost 1 m of the fan deposits range between 128.37 ± 9.6 ka and 197.79 ± 15.4 ka. In both sample pits, the younger ages are obtained from the stratigraphically lower sample showing that the variation in age is not reflecting slow rates of deposition within the alluvial fan. The variation in age could, alternatively, be caused by uncertainty in the dose rates calculated from ICP–MS measurements of U, Th, and 40K, which is a valid concern in the coarse and relatively inhomogeneous alluvial setting of the sediments (e.g., Duller, 2008).

We cannot exclude variability in dose rate within the inhomogeneous sediment as a cause of the variation in ages. However, assuming that at least some of the range of ages from 128.37 ± 9.6 ka and 197.79 ± 15.4 ka is caused by incomplete resetting of the luminescence signal on deposition, we tentatively suggest that the fan dates from the younger end of the age range suggested by the OSL results, at the transition from a glacial to interglacial environment at ~120 ka.

From the stable isotope composition of carbonate cements in fluvial sandstones, Parsons et al. (2006) showed that conditions of enhanced wetness relative to today existed at ~120 ka. In addition, a number of studies show an abandonment of alluvial fan surfaces in the early Holocene following the end of the most recent glacial period (e.g., Regard et al., 2005; Fattahi et al., 2007; Fattahi et al., 2007; Le Dortz et al., 2009), from which we might infer a similar history of deposition and incision during earlier glacial-interglacial transitions.

If we are correct in attributing the abandonment and incision of the alluvial fan in Figure 9A to a regional change in environment at 120 ka, we would expect to see the remnants of alluvial fans of the same age adjacent to other catchments along the Kuh-e-Mamsar range. Deeply incised fan surfaces are indeed present along the mountain front (e.g., Fig. 3). At the only other site where the amount of displacement of the fan surface can be quantified (Fig. 5C), a restoration of ~50 m of right-lateral slip restores the drainage channels—and also the tops of the channel margins—to their original linear courses (Fig. 5D). Because the two alluvial fans shown in Figures 5C and 9A are morphologically similar, and have been displaced by similar amounts of 48 ± 4 m and 50 m, it is likely that their abandonment occurred at the same time and hence that their abandonment was caused by a regional change in the environment.

**Slip-Rate Estimate**

As described in the IRSL Dating Methods section, drainage incised into the alluvial fan surface in Figure 9A is displaced right laterally by 48 ± 4 m. When combined with an assumed age of 120 ka for abandonment of the fan...
Figure 12. Equivalent dose distribution diagrams for the four infrared stimulated luminescence (IRSL) samples (sample names are given in the lower-left corner of each plot). The x-axis represents the dose (in grays) required to reproduce the natural luminescence signal. Blue triangles represent the equivalent dose ($D_e$) for each individual aliquot displayed in rank order. A probability density function is displayed along the x-axis. The red triangle represents the $D_e$ assigned using a central age model.

### Table 2. Infrared Stimulated Luminescence Dates from the Displaced Alluvial Fan Shown in Figure 8

<table>
<thead>
<tr>
<th>Sample</th>
<th>Latitude (°N)</th>
<th>Longitude (°E)</th>
<th>Depth (m)</th>
<th>Water (%)</th>
<th>K (%)</th>
<th>U (%)</th>
<th>Th (%)</th>
<th>Equivalent dose (Gy)</th>
<th>Annual dose rate (Gy/ka)</th>
<th>Age (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA 1</td>
<td>29.45411</td>
<td>56.31299</td>
<td>0.55</td>
<td>2.0</td>
<td>0.53 ± 0.05</td>
<td>0.69 ± 0.13</td>
<td>2.3 ± 0.4</td>
<td>308.2 ± 18.4</td>
<td>1.56 ± 0.08</td>
<td>197.8 ± 15.4</td>
</tr>
<tr>
<td>RA 2</td>
<td>29.45411</td>
<td>56.31299</td>
<td>0.85</td>
<td>2.0</td>
<td>0.84 ± 0.05</td>
<td>1.23 ± 0.13</td>
<td>4.1 ± 0.4</td>
<td>289.0 ± 17.8</td>
<td>2.09 ± 0.08</td>
<td>138.0 ± 10.1</td>
</tr>
<tr>
<td>RB 1</td>
<td>29.45345</td>
<td>56.31317</td>
<td>0.9</td>
<td>2.0</td>
<td>0.38 ± 0.05</td>
<td>1.01 ± 0.13</td>
<td>2.9 ± 0.4</td>
<td>261.6 ± 11.2</td>
<td>1.53 ± 0.08</td>
<td>171.06 ± 9.3</td>
</tr>
<tr>
<td>RB 2</td>
<td>29.45345</td>
<td>56.31317</td>
<td>0.9</td>
<td>2.0</td>
<td>0.95 ± 0.05</td>
<td>1.37 ± 0.13</td>
<td>3.8 ± 0.4</td>
<td>283.2 ± 18.2</td>
<td>2.21 ± 0.09</td>
<td>128.37 ± 9.6</td>
</tr>
</tbody>
</table>

Note: All processing steps are described in the IRSL Dating Methods section. The equivalent dose is determined using a central age model (CAM; Galbraith et al., 1999).
The Rafsanjan strike-slip fault, SE Iran

our aim in writing this paper was to inves-
tigate the late Quaternary importance of the
Rafsanjan fault given that it has a very clear
expression in the geomorphology, and yet is not
at all prominent in terms of present-day defor-
mation measured with GPS (e.g., Vernant et al.,
2004), or in the occurrence of earthquakes both
ancient and modern (e.g., Ambraseys and Mel-
ville, 1982; Engdahl et al., 1998). This appar-
et discrepancy may point to variations in slip
rate on the Rafsanjan fault through time, such
that it is currently less active than its long-term
average rate, as has been suggested regionally
crossing eastern Iran by Meyer and Le Dortz
(2007). Validating whether changes in fault-slip
rate occur has profound importance for the use
of both geodetic and late Quaternary measure-
ments for seismic hazard and tectonic studies,
and the existence of slip-rate variations might
also be used to constrain the rheological proper-
ties of the continental lithosphere (e.g., Dolan
et al., 2007).

We have found that the fault is actually slip-
pling relatively slowly, averaged over the late
Quaternary, when compared to other structures
in the region (e.g., Fig. 1C). Although the Raf-
sanjan fault is visible in the geomorphology, we
see that it is only in the older landforms, such as the
~120 ka alluvial fans shown in Figure 9A, that the
fault is clearly visible. The expression of the
fault in the younger alluvial fan surfaces is
actually very subtle (Fig. 10A). This is probably
because insufficient displacement has occurred
since abandonment of the youngest fan sur-
face to be quantifiable in satellite imagery. The
youngest generation of alluvial fan deposits has
been dated to ~10 ka at sites across eastern Iran
(e.g., Regard et al., 2005; Fattahi et al., 2007; Le
Dortz et al., 2009). If the younger fan deposits,
highlighted in yellow in Figure 9A and shown in
detail in Figure 10A, also date to 10 ka, we
would expect only ~4 m of lateral displacement
since their abandonment. If the riser between
the older and younger fan surfaces was reset by
fluvial erosion during deposition of the younger
fan surface, it would also explain why we can-
not see a lateral displacement of the riser (Fig.
10A), because the maximum lateral riser dis-
placement should be only 4 m.

Our estimate of slip rate on the Rafsanjan
fault, when combined with slip-rate estimates
on other faults in southeast Iran (Fig. 1C),
helps explain the distribution of tectonic strain
east of Iran. The right-lateral strike-slip rate of
~0.4 mm/yr that we estimate should, when
combined with an equivalent amount of short-
ening across the parallel thrusts, accommodate
~0.55 mm/yr of north-south right-lateral shear
(e.g., Slip-Rate Estimate section). This suggests
that only a small proportion of the 4.0–7.4 mm/yr
of right-lateral slip estimated on the Sabzevaran
fault (Regard et al., 2005) is transferred across
the Rafsanjan fault to the Anar fault in central
Iran. The majority is instead transferred north-
wards onto the Gowk fault, whose Holocene
slip rate is estimated at 3.1–4.7 mm/yr (Walker
et al., 2010a). However, the north-south right-
lateral rate of ~0.55 mm/yr that we estimate is
slightly less than the ~0.8 mm/yr of right-lateral
slip estimated for the right-lateral Anar fault by
Le Dortz et al. (2009). The discrepancy could be
caused by an overestimation of the abandon-
ment age of the alluvial fan in Figure 9, though
we are confident that the fans were abandoned at
~120 ka due to the reasons outlined in the Inter-
pretation of Age Data section.

The relatively slow slip rate that we have
estimated might instead indicate that the range-front fault in Figures 9A and 10B is
active and that we have not accounted for the
slip across it. We were, however, unable to
find evidence of disruption of the fan surface,
either in the field or in aerial photography,
where it crosses the range-front fault (e.g., Fig.
10B). Also, the close agreement between the
measured displacement of 48 ± 4 m in Fig-
ure 9A, and of ~50 m at the only other site
where drainage incised into an abandoned fan
surface can be clearly reconstructed, indicates
that the displacement is correct.

A third option is that the establishment of the
incised stream network, which we have used to
estimate the lateral displacement of the aban-
donated fan surface, actually postdates the surface
abandonment by a significant amount. If this
is the case, the true lateral displacement since
abandonment of the fan surface could be much
larger than the ~50 m measured from stream
displacements. This scenario is unlikely, how-
ever, because if the stream network was estab-
lished after significant amounts of displacement
had already accumulated on the abandoned
fan surface, the eastward-flowing streams would
have been blocked by east-facing scarps along
the two fault strands. Only if the stream network
became established very soon after surface
abandonment would the streams be able to keep
pace with uplift across the faults.

An alternative cause for the relatively slow
slip rate measured on the Rafsanjan fault is that
the remainder is accommodated on structures
within the Rafsanjan plain such as those iden-
tified in Figures 3 and 6. Right-lateral slip on
these faults at a rate of only ~0.2 mm/yr accounts
for any remaining discrepancy between the slip
rates on the Rafsanjan and Anar faults. Because
the faults are sited far from the mountain range
front, where the alluvial fans are not deeply dis-
sected by incised drainage, there are no obvious
drainage displacements from which the rate of
activity can be quantified.

CONCLUSIONS

We have presented observations of activity
on the Rafsanjan fault ranging from slip in a
single earthquake to the cumulative displace-
ments accumulated over the late Quaternary.
We have shown that it is slipping at an aver-
age rate of ~0.4 mm/yr that is consistent with
what is known of the distribution of tectonic
strain in the part of Iran, and it is likely to
transfer a proportion of the right-lateral slip
on the Sabzevaran fault to the Anar fault of
central Iran. Our results help to constrain the
hazard posed by the Rafsanjan fault to nearby
population centers and, furthermore, indicate
that the rate of slip is likely to be near con-
stant over the late Quaternary—a result that is
of importance in studies of active strike-slip
faulting in general.
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