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# Active faulting, earthquakes, and restraining bend development near Kerman city in southeastern Iran

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ABSTRACT

We provide descriptions of strike-slip and reverse faulting, active within the late Quaternary, in the vicinity of Kerman city in southeastern Iran. The faults accommodate north-south, right-lateral, shear between central Iran and the Dasht-e-Lut depression. The regions that we describe have been subject to numerous earthquakes in the historical and instrumental periods, and many of the faults that are documented in this paper constitute hazards for local populations, including the city of Kerman itself (population ∼200,000). Faults to the north and east of Kerman are associated with the transfer of slip from the Gowk to the Kuh Banan right-lateral faults across a 40 km-wide restraining bend. Faults south and west of the city are associated with oblique slip on the Mahan and Jorjafk systems. The patterns of faulting observed along the Mahan-Jorjafk system, the Gowk-Kuh Banan system, and also the Rafsanjan-Rayen system further to the south, appear to preserve different stages in the development of these oblique-slip fault systems. We suggest that the faulting evolves through time. Topography is initially generated on oblique slip faults (as is seen on the Jorjafk fault). The shortening component then migrates to reverse faults situated away from the high topography whereas strike-slip continues to be accommodated in the high, mountainous, regions (as is seen, for example, on the Rafsanjan fault). The reverse faults may then link together and eventually evolve into new, through-going, strike-slip faults in a process that appears to be occurring, at present, in the bend between the Gowk and Kuh Banan faults.


## 1. Introduction

We investigate the distribution of active faults around the city of Kerman in eastern Iran and the role that these active faults play in accommodating tectonic strain in the region. The faults occur in restraining bends along major strike-slip faults and are extremely well exposed due to the arid and sparsely vegetated environment of southeastern Iran. We are, therefore, able to describe the faults with a level of detail that is not possible in most actively deforming parts of the world: allowing us to investigate the general processes involved in the development of structures within restraining bends along major strike-slip fault systems.

The region around Kerman city (population ∼200,000) has a long record of destructive earthquakes, with historical accounts stretching back to ∼1850, and with numerous instrumentally-recorded events over the past ∼30 years including the 1981 Sirch and Golbaf earthquake sequence (e.g. Berberian et al., 1984), the 2003 Bam earthquake (e.g. Talebian et al., 2004; Jackson et al., 2006), and, most recently, the 2005 Zarand earthquake (Talebian et al., 2006). The city of Kerman, although shaken by many of the recent events, has not been subjected to heavy damage in the instrumental period. One of our aims in writing this paper is to aid future detailed studies of seismic hazard to Kerman city and its surroundings.

In addition to informing estimates of seismic hazard in Iran, our results also have general application in describing well-exposed examples of restraining bend development along major active strike-slip faults. Strike-slip faults are an important component of many active regions of continental shortening (e.g. Tapponnier and Molnar, 1979; Jackson and McKenzie, 1984; Baljinnyam et al., 1993).

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They accommodate this shortening either by translation (or expulsion) of material, by spatial separation (partitioning) of dip-slip and strike-slip components, or through a combination of strike-slip faulting and vertical axis rotation (e.g. Allen et al., 2006). Restraining bends, where a localised component of shortening is introduced due to changes in fault strike, are a common feature of strike-slip faults in regions of tectonic shortening. The faulting within these restraining bends is often very diffuse and may evolve rapidly (e.g. Cunningham and Mann, 2007; Mann, 2007).

In the following sections, we first briefly describe the tectonic and geological background of the study area. We then catalogue the many destructive earthquakes that have affected the Kerman region both historically and recently. In Section 4 we provide brief descriptions, made from both field and remote-sensing studies, of the active faults in the vicinity of Kerman city. Then, in Section 5, we describe how the population of active faults accommodate right-lateral strike-slip across eastern Iran and how they may have changed through time.

## 2. Geological and tectonic background

### 2.1. Active tectonics

The active tectonics of Iran are controlled by the northward motion of Arabia relative to Eurasia, which is at a rate of ∼25 mm/yr at longitude 56°E (Fig. 1a; Vernant et al., 2004). The GPS velocities relative to Eurasia decrease to zero at both the northern and eastern borders of Iran. This indicates that the major part of the continental shortening is confined within the political borders of the country, with the majority of the deformation concentrated in the Zagros mountains of southern Iran (*Z* in Fig. 1b), and in the Alborz and Kopeh Dagh mountains in the north (A and K in Fig. 1b).

The arid interior of Iran (Dasht-e-Kavir, Fig. 1a) is virtually aseismic and appears to not be deforming as rapidly as its surroundings. Central Iran is moving northwards relative to western Afghanistan at a rate of 16 ± 2 mm/yr at the present-day (Vernant et al., 2004). This northward motion introduces north-south, right-lateral, shear

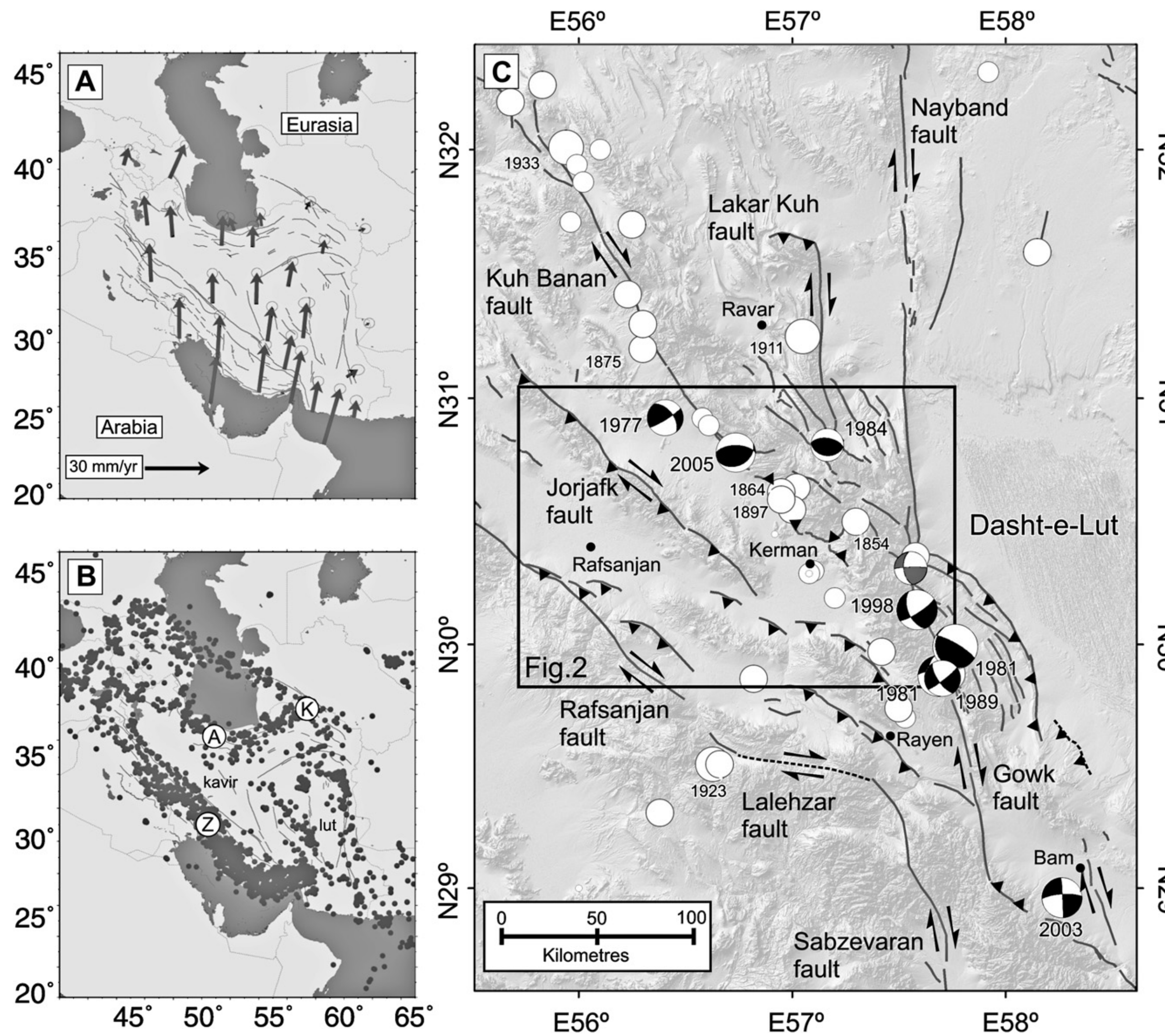


**Fig. 1.** (a) Map of Iran with GPS velocities of points relative to Eurasia from Vernant et al. (2004). (b) Map of Iran showing epicentres of earthquakes from the catalogue of Engdahl et al. (1998). Z = Zagros; A = Alborz; K = Kopeh Dagh. (c) Shaded-relief topographic map of the Kerman region (SRTM topography; Farr and Kobrick, 2000). Fault-plane solutions of major earthquakes are from waveform modelling (Jackson, 2001; Talebian et al., 2004; Talebian et al., 2006) and the Harvard CMT catalogue (http://www.globalcmt.org/). Epicentres of historical earthquakes are from the catalogue of Ambraseys and Melville (1982). The maps are in a Mercator projection.

across the eastern border of the country. South of latitude 34°N this shear is accommodated on north-south right-lateral faults that surround the Dasht-e-Lut (e.g. Walker and Jackson, 2004; Meyer and Le Dortz, 2007; Walker et al., 2009). North of latitude 34°N, however, the shear is accommodated by east-west, left-lateral, faults that are thought to rotate clockwise about a vertical axis (e.g. Jackson and McKenzie, 1984).

Our present study is concerned with the structures formed in the area surrounding Kerman city; in a region dominated by north-south right-lateral slip along the western margin of the Dasht-e-Lut (Fig. 2).

### 2.2. Geology

There is a northwest-southeast structural trend present across much of central and eastern Iran. This trend follows the orientation of the Iran-Arabian suture and of the Tertiary volcanic arc that parallels it (e.g. Berberian and King, 1981). This structural trend is oblique to the roughly north-south shortening and right-lateral faulting that typifies the active deformation and it is likely that the oblique northwest-southeast trending active structures that we describe in this paper result from this pre-existing trend. The pre-existing northwest-southeast structural trend is also thought to have influenced the trend of folding and faulting within the Zagros mountains of southwest Iran (e.g. Talebian et al., 2004).

The lithologies exposed in the study area are mostly Mesozoic and early Tertiary in age (GSI, 1992a, 1992b). Kuh-e-Jupar and Kuh-e-Sekonj (Fig. 2) expose a conformable Mesozoic and Tertiary sedimentary sequence. In the south of our study area, the Lalehzar and Rafsanjan faults run along the northern margin of the Sanadaj-Sirjan Tertiary volcanic belt, which consists of Eocene sediments and volcanic rocks, and which was formed during the closure of the Neo-Tethys Ocean (Dimitrijevic, 1973). The exposed rocks are likely to pre-date the onset of the late Cenozoic active tectonics, which might date from as little as 3.3 to 4.8 Ma (Walker et al., 2010).

## 3. Past earthquakes in the vicinity of Kerman

The region surrounding Kerman has an abundant record of earthquakes both historical and modern. The main sources in the discussion of historical seismicity are Berberian (1976), Ambraseys et al. (1979), Ambraseys and Melville (1982), Berberian and Yeats (1999), and Berberian (2005). Despite Kerman being an important marketing and production centre throughout the ancient and medieval periods, there is a complete absence in historical records of earthquakes up until ~150 years ago. This absence may, to some extent, be an artefact of its isolated location in the deserts of eastern Iran (Ambraseys and Melville, 1982; Berberian, 2005).

The earliest recorded earthquake to be felt in Kerman city was in November 1854 (Ambraseys et al., 1979; Berberian, 2005). The

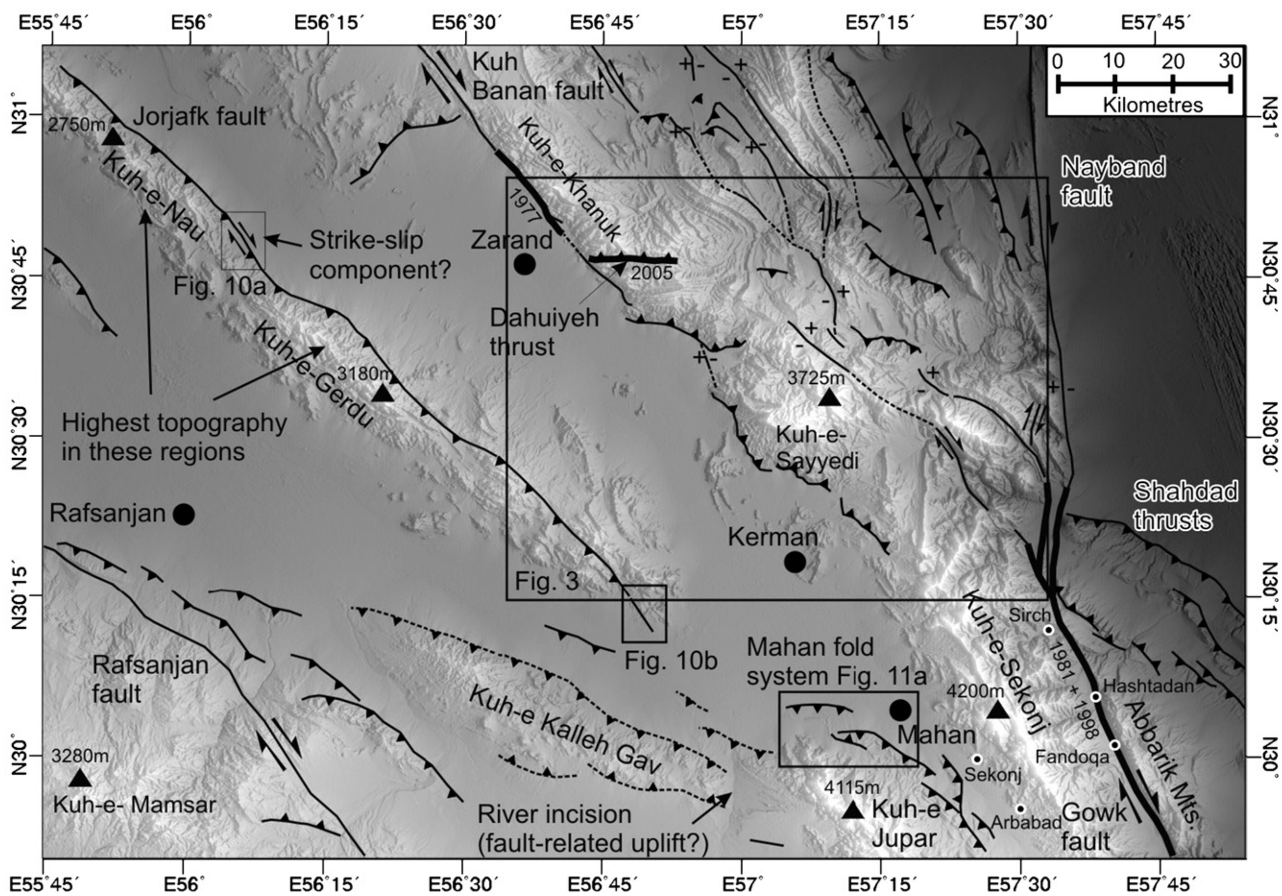


**Fig. 2.** Active fault map of Kerman city and surroundings overlain on shaded-relief SRTM topography (illuminated from the east) and with high elvations represented by lighter shades. Major peak heights are given in metres. Transfer of slip between the Gowk and Kuh Banan strike-slip faults occurs by distributed strike-slip, reverse faulting, and folding within the Kuh-e-Sayyedi mountains and by a series of thrust faults, linked by strike-slip segments, along the SE margin the mountainous topography. Additional distributed shortening is accommodated by fault-generated folds bounding ranges to the south of Kerman. The Jorjafk fault, which is situated west of Kerman, may have a strike-slip component in addition to shortening. Several of the faults are sited less than 20 km from Kerman and constitute a significant hazard to the city. Known earthquake ruptures are represented by thickened lines. Locations of later figures are shown by numbered boxes. This, and all later maps, are in a UTM40 projection.

epicentral region of this event was located in the mountainous regions northeast of Kuh-e-Sayyedi (Fig. 3), destroying the village of Hurjand, and badly damaging villages over a wide area including Deran (Dehran). An earthquake on January 17th 1864 caused considerable damage in Kerman city and destroyed the village of Chatrud (Fig. 2; also see Fig. 3) and 'settlements to the northeast of the plain' with the loss of much life. On the 14th August 1871 a second damaging earthquake occurred in the district of Chatrud. The next event, which was strongly felt in Kerman, was recorded in May 1875 (Ambraseys et al., 1979; Berberian, 2005). The distribution of damage from this earthquake suggests the Kuh Banan fault as the probable source (Fig. 1). In 1877 the villages of Sirch, Hasanabad, and Hashtadan, which are situated along the northern part of the Gowk fault (Fig. 2), were ruined by an earthquake, which also caused damage to Chatrud and Sarasiyab (Berberian et al., 2001; Berberian, 2005). Chatrud was totally destroyed, along with the village of Sarasiyab (Fig. 2; also see Fig. 3), by an event on May 27th 1897 (Berberian et al., 2001; Berberian, 2005). This earthquake caused several buildings in Kerman to fall down (many of which were already weakened by damage from the 1864 earthquake).

Several earthquakes are recorded from the first half of the twentieth century. In 1909 (27th October) an earthquake caused destruction in Hashtadan and Joshan on the northern Gowk fault (Fig. 2). The town of Ravar (∼110 km north of Kerman, Fig. 1) was badly damaged, with ∼700 casualties, by an earthquake that occurred either on the Lakar Kuh strike-slip fault (Ambraseys and Melville, 1982) or on an east-west thrust branching from it (Berberian, 2005). The Lalehzar earthquake of 1923 (Fig. 1; Berberian, 1976; Ambraseys and Melville, 1982) caused minor damage in Kerman. The epicentral region is centred on the Ab-e-Lalehzar valley to the south of Kerman (Fig. 1). The earthquake may have been on an eastward continuation of the Rafsanjan fault (Walker, 2006) and shows the potential for destructive events in southern parts of Kerman province (a region that has been virtually aseismic in the instrumental period). The North Behabad earthquake occurred on the afternoon of November 28 1933. This event totally destroyed villages to the northwest of Behabad on the Kuh Banan fault (Fig. 1). Ambraseys and Melville (1982) report possible remnants of the surface ruptures that would indicate components of both right-lateral and vertical (down to the west) slip. On 2nd January 1934 an earthquake occurred in the district of Mahan (Ambraseys et al., 1979) causing damage to the villages of Arbabad, Sekonj, Hojjabad, Aliabad and Langur (Arbabad and Sekonj are marked on Fig. 2). Reports of destruction to villages in the Gowk region point to the Gowk fault as

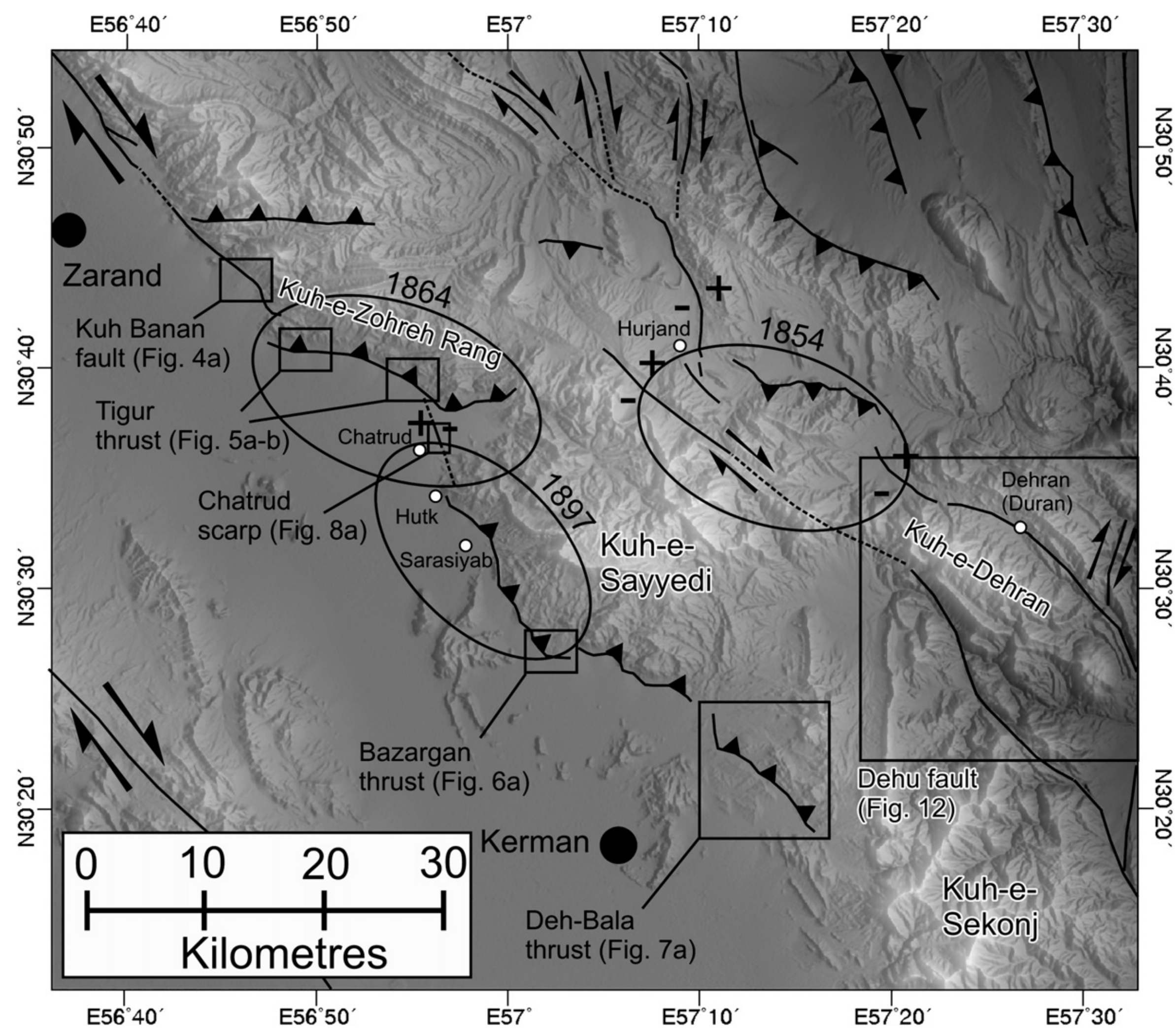


**Fig. 3.** Faulting in the regions north and east of Kerman city. NW-SE reverse faults are present along the base of mountainous topography. Our interpretation of the Bazargan and Deh-Bala faults as separate structures differs from the interpretation of Berberian (2005) who maps the Deh-Bala fault as a continuation of the Bazargan fault. Right-lateral strike-slip faulting, also with an NW-SE trend, occurs within the mountainous interior (Dehu and Dehran faults). The faults are likely to form a flower structure in cross-section. The epicentral regions of major historical earthquakes are from Berberian (2005). Boxes show the regions represented in later figures.

the probable cause of an event in 5 July 1948 (Ambraseys and Melville, 1982; Berberian et al., 2001; Berberian, 2005).

The instrumental period is marked by a series of destructive earthquakes in the Kerman region. The sequence started with the Mw 5.8 Gisk earthquake (19th December 1977), which produced surface ruptures along the Kuh Banan fault (Fig. 2), and which involved predominantly right-lateral strike-slip (Berberian et al., 1979). The sequence then continued with several destructive earthquakes on the Gowk fault, with two in 1981 (Mw 6.6 and 7.2), and another, of Mw 6.6, in 1998 (e.g. Berberian et al., 1984; Berberian et al., 2001; Fielding et al., 2004). The Bam fault, which is situated to the southeast of the Gowk fault (∼180 km southeast of Kerman, Fig. 1c), ruptured in a devastating earthquake in 2003 (e.g. Talebian et al., 2004; Berberian, 2005; Jackson et al., 2006). Most recently, the Dahuiyeh (Zarand) earthquake of 22 February 2005 caused serious damage to villages north of Kerman (Figs. 1 and 2; Talebian and Jackson, 2004). The fault-plane solutions of several other, less destructive, events in the Kerman region are also included on Fig. 1c.

## 4. Active faults of the Kerman region

The catalogue of destructive historical and instrumental earthquakes in the region surrounding Kerman city adequately demonstrates the overall present-day activity of the tectonic structures in the vicinity. Some of the earthquakes are assigned with certainty to individual faults as shown in Fig. 2 (e.g. Berberian et al., 2001; Berberian, 2005). Many of the causative faults are, however, still unknown. Given the relatively diffuse pattern of faulting that we will describe, and that the total summed rate of deformation across the Kerman region might be just a few millimetres per year (e.g. Vernant et al., 2004; Meyer and Le Dortz, 2007; Walker et al., 2009), the rates of slip on individual structures in the Kerman region is likely to be rather low. The repeat time between destructive

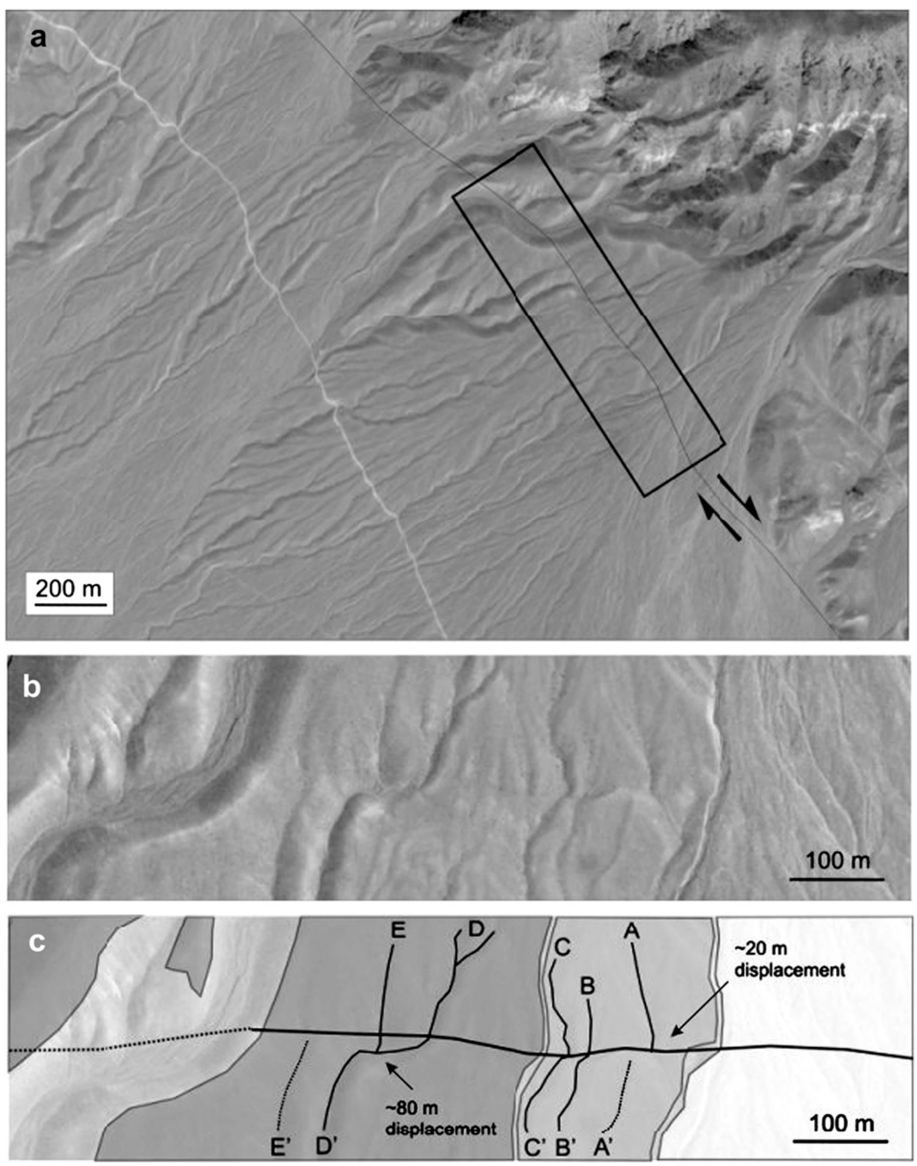


**Fig. 4.** (a) Quickbird image (from Google Earth) of the Kuh Banan fault as it cuts across a series of alluvial fans. Box shows the location of part b. (b) Close-up view along the fault line. Note the absence of vertical displacement across the fault. (c) Interpretation of the geomorphology. Three generations of fan deposition are identified. No clear lateral displacements are visible in the youngest fan (F1). Streams in F2 are displaced right-laterally by ∼20 m (correlating streams A, B and C with A′, B′ and C′ on the downstream side of the fault). Streams in F3 are displaced by ∼80 m (restoring the D–D′ stream to a linear course and correlating stream E with the beheaded stream E′).

earthquakes on individual active faults is, therefore, likely to be measured in the thousands of years and the record of historical seismicity, though unusually long and detailed in Iran (e.g. Ambraseys and Melville, 1982; Berberian and Yeats, 1999), will not provide a complete record of activity on all faults.

Several recent studies (e.g. Regard et al., 2005; Fattahi et al., 2006, 2007) have dated the abandonment of the most recent period of alluvial fans in eastern Iran to ~10 ka (±3 ka). These results, although still limited in number, suggest that fault scarps developed in young alluvial fan deposits in eastern Iran are likely to show activity within the last 10 ka (e.g. Meyer and Le Dortz, 2007). In the following survey of active faults we have taken those faults that have a clear expression in the geomorphology, and which have deformed young alluvial fan deposits, as being active at the present-day. Whether the faults are capable of producing destructive earthquakes can only be known with confidence after detailed palaeoseismic investigation. However, the maximum probable earthquake magnitude associated with any of the faults can be estimated from the fault length (Wells and Coppersmith, 1994). An earthquake that ruptures the entire length of a 15 km-long fault will have Mw ~6.4, a 30 km-long rupture will have Mw 6.8, and a fault 100 km in length could generate earthquakes of Mw ~7.4.

### *4.1. Faulting to the north and east of Kerman*

The active deformation north and east of Kerman city is dominated by the Gowk and Kuh Banan right-lateral strike-slip faults (Figs. 1 and 2). The Gowk fault, whose northern end is situated ~75 km east of Kerman city, has generated five destructive earthquakes in the past thirty years (e.g. Berberian et al., 2001) and is the probable cause of historical events in 1877 and 1948 (see Section 3). The Kuh Banan fault also has a long record of earthquakes with events in 1875, 1933 and 1977 (Berberian, 1976; Ambraseys and Melville, 1982). There is a left-step of ~40 km between the Gowk and Kuh Banan faults (Fig. 2). Slip that is transferred from the Gowk fault to the Kuh Banan fault crosses this restraining bend and has generated a wide zone of mountainous topography (Fig. 2). In the following Sections we first briefly describe the Gowk and Kuh Banan faults, and then describe the faulting that occurs in the restraining bend between them.

#### *4.1.1. Strike-slip faulting on the Gowk and Kuh Banan faults*

The Gowk fault is ~150 km long and trends ~155°. This orientation, which is oblique to the north-south orientation of right-lateral shear across eastern Iran (Vernant et al., 2004), has introduced an overall component of shortening across the fault. The

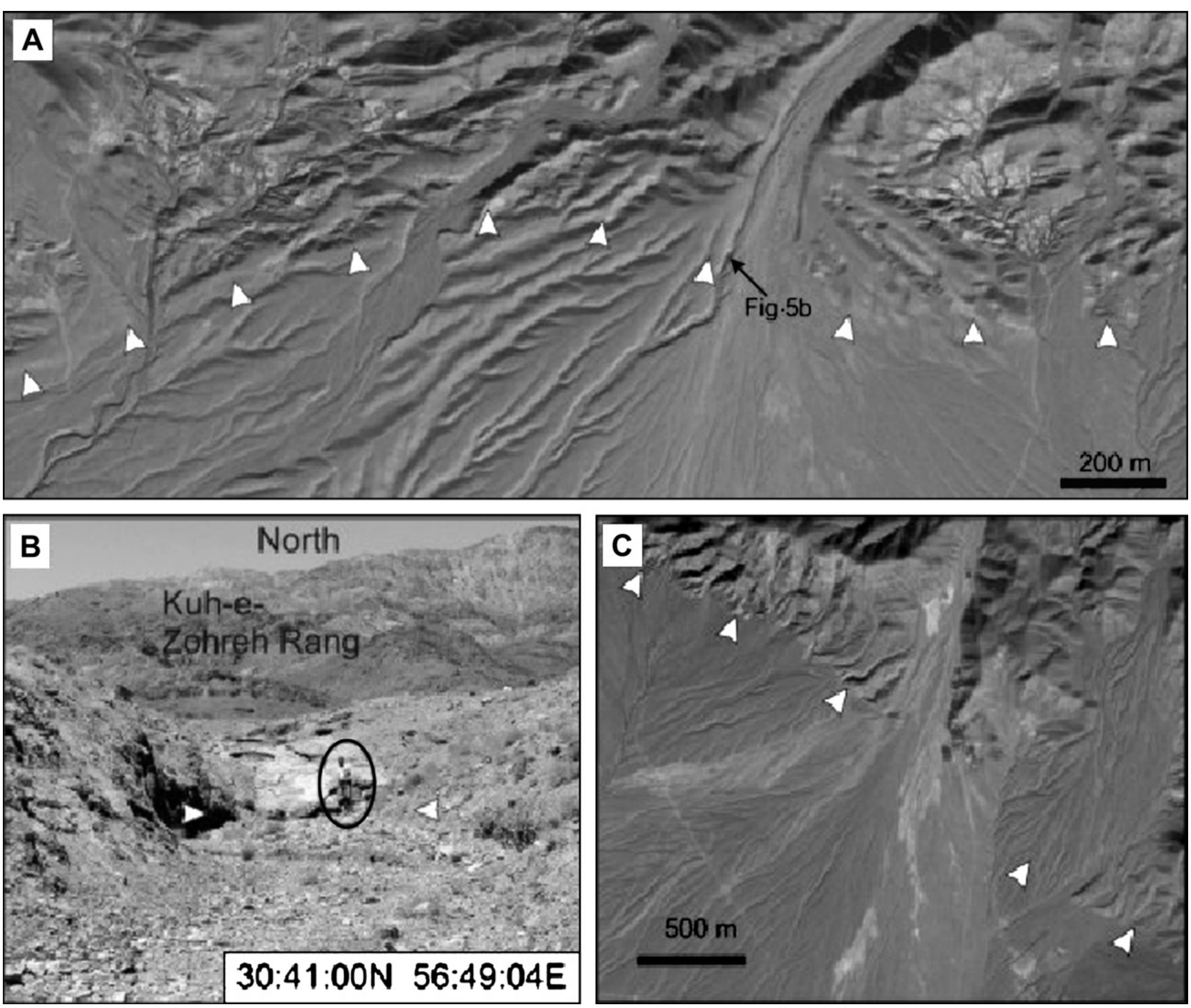


**Fig. 5.** (a) Quickbird satellite image (from GoogleEarth) of the NW-SE Tigur reverse fault scarp clearly expressed in alluvial fan material. (b) Quickbird image of the fault scarp at Garchuiyeh village. Faulting is less clear in this image. One fault strand runs along the margin of bedrock exposure. A 3 m scarp cuts through the middle of the alluvial fan. (c) Field photograph of 3 m vertical displacement of carbonate-cemented riverbed deposits at the southern fault scarp shown in 5b.

Gowk fault itself possesses an extensional component at the surface (as seen in the 1998 Fandoqa earthquake; Berberian et al., 2001). The shortening is instead accommodated across the Shahdad fold-and-thrust belt, which runs parallel to the Gowk fault, along the margin of the Dasht-e-Lut (Fig. 1; Walker and Jackson, 2004; Fielding et al., 2004). Walker et al. (2010) estimate a minimum Holocene slip-rate of 3.8 $\pm$ 0.7 mm/yr on the Gowk fault. The slip-rate on the Gowk fault should equal the cumulative slip-rates on the Kuh Banan, Ravar, Lakar Kuh and Nayband faults into which it breaks at its northern end.

The Kuh Banan fault runs for ~200 km along a NW-SE trend (Fig. 2). Its location at the base of a steep, and linear, range-front suggests that the fault has possessed a significant component of shortening during its history. The fault-plane solution of the 1977 Gisk (Bob-Tangol) earthquake, which occurred along the southern part of the Kuh Banan fault (see Fig. 2), instead indicates almost pure strike-slip motion on a NW-SE trending plane dipping to the northeast (Berberian et al., 1979). Fig. 4 shows the Kuh Banan fault cutting through several generations of late Quaternary alluvial fan deposits. The two older alluvial deposits are displaced laterally by ~20 m and ~80 m. Displacements across the youngest, and only slightly incised, surface are not visible in the imagery. If the 20 m lateral displacements represent cumulative slip over the last ~10 ka (e.g. Meyer and Le Dortz, 2007) the average slip rate will be ~2 mm/yr. There is little in the way of vertical displacement across the fault. The absence of vertical scarps in the fan deposits is also suggestive of a large component of strike-slip. It therefore appears that the sense of motion on the Kuh Banan fault may have changed through time, from reverse (or oblique reverse), to right-lateral slip (e.g. Berberian et al., 1979; Talebian et al., 2006). The importance of these observations for the evolution of faulting in the Kerman region will be discussed later.

#### 4.1.2. Reverse faulting between the Gowk and Kuh Banan faults

Numerous reverse faults are present along the margins – and within the interior of – the mountainous regions near the southern end of the Kuh Banan fault (Fig. 3). All of these range-bounding faults show a close spatial association with large-scale folding in bedrock (GSI, 1992a, 1992b) that indicates the total shortening across these structures may be of the order of several kilometres.

The northernmost of the known active structures between the Kuh Banan and Gowk faults is the steeply dipping, and east-west trending, Dahiuyeh reverse fault. This fault, which is situated within the Kuh-e-Khanuk range, was responsible for a destructive earthquake (Mw 6.4) on the 22 February 2005 (Talebian and Jackson, 2004; Fig. 2). The fault follows a mapped geological

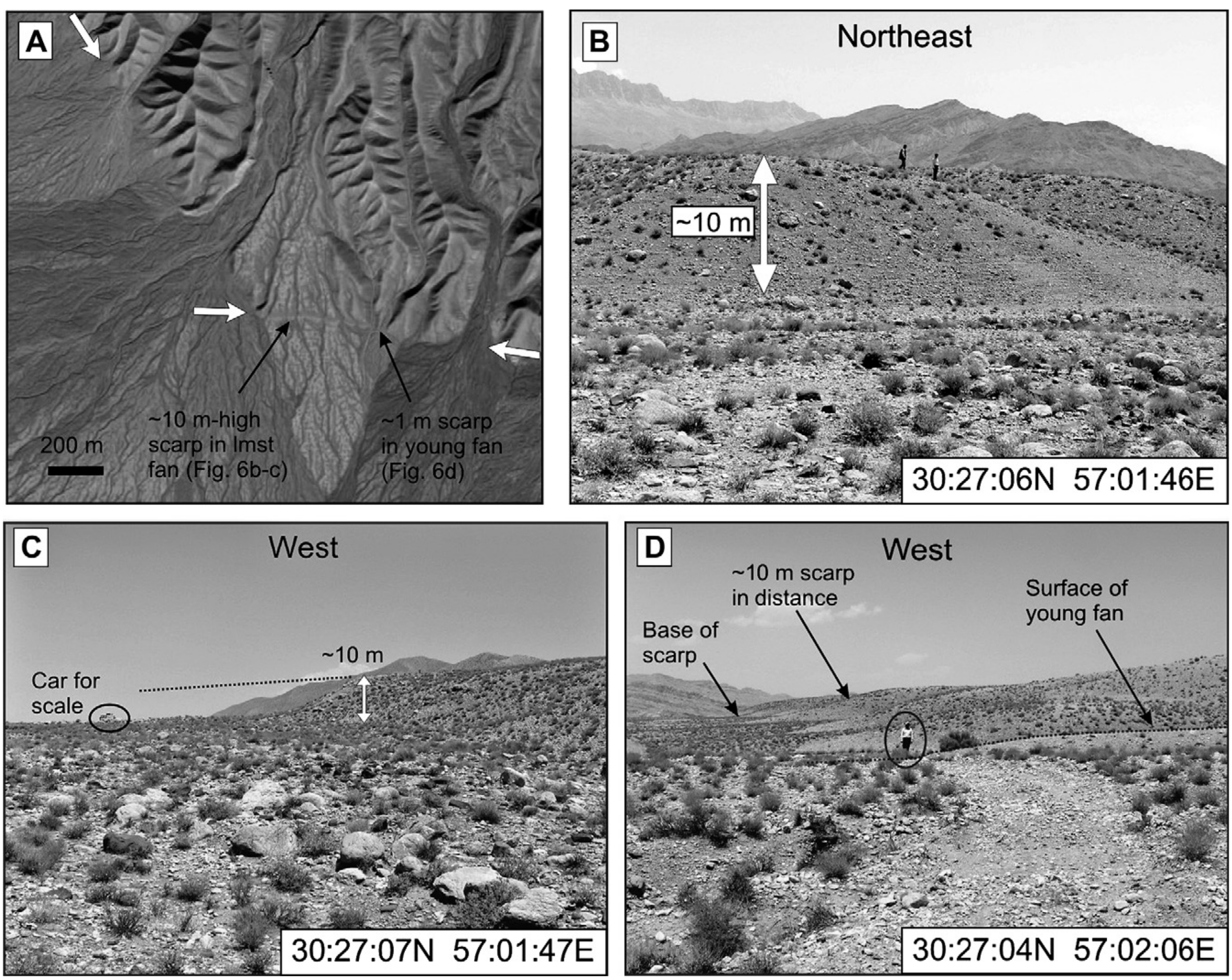


**Fig. 6.** (a) Quickbird satellite image (from GoogleEarth) of the Bazargan fault scarp north of Kerman city. A very clear E-W scarp is visible in the light-coloured (limestone) fan close to the centre of the image. (b) Field photograph, looking NE, of the ~10 m-high scarp in alluvial fan deposits. (c) Field photograph looking westwards at the 10 m scarp showing the clear displacement of the terrace surface across the fault. (d) Field photograph showing a sharp 1 m-high step in the youngest fan deposits.

structure but was not identified as active prior to the 2005 event. It is probable, therefore, that other active faults exist within the steep mountainous parts of the Kerman region.

The clearest evidence for late Quaternary reverse faulting is seen along the base of mountains in the regions between Zarand and Kerman (Fig. 3). This fault is named the Tigur fault by Berberian (2005). However, on Fig. 3 we only include the western half of the fault described by Berberian (2005) where it is visible in alluvial fan deposits along the base of Kuh-e-Zohreh Rang Range (e.g. Fig. 5). We did not find obvious evidence of late Quaternary movement on the eastern part of the fault. The fault separates deposits of the Chatrud basin on its southern side from Palaeozoic bedrock, folded into a tight anticline, on its northern, hanging-wall, side (GSI, 1992b). We visited the scarp close to the village of Garchuiyeh (Fig. 5a,b). Here, the fault consists of two parallel scarps, separated by ~50 m, that have deformed young alluvial fan deposits. The southern scarp is ~3 m high. The carbonate-cemented bed of a small stream, incised into the fan surface, is also displaced vertically by ~3 m at the scarp at location 30:41:03N 56:49:05E as shown in Fig. 5 (note that all our locations are given in the format degrees:minutes:-seconds). We estimate the dip at 20–30°N from trigonometry knowing the locations of the scarp in the fan surface and in the riverbed. The northern of the two scarps appears to place N-dipping bedrock over flat-lying gravels on a plane dipping 40–50°N (observed at 30:41:05N 56:49:01E). The scarp of the Tigur fault is extremely clear at its eastern end (e.g. Fig. 5c).

The Bazargan reverse fault also shows clear evidence of late Quaternary slip along the base of Kuh-e-Seyyedi south of the Chatrud valley (Fig. 3). The fault is ~30 km long, trends NNW-SSE along its northern half, and WNW-ESE along its southern half. Fig. 6a shows a Quickbird satellite image (from GoogleEarth) of the fault where it has displaced alluvial fans deposited from a river flowing southwards from Kuh-e-Seyyedi. Three generations of alluvial fan are visible in the image. The fault is marked by a sharp break in incision in the oldest, and most eroded, fan material. A very clear scarp, ~10 m-high, is developed in the second generation of fans. This scarp is shown in the photographs in Fig. 6b,c. A sharp ~1 m-high scarp is present in the youngest generation of fans (Fig. 6d). The hanging-wall of the Bazargan reverse fault is composed of an overturned anticline in Palaeozoic bedrock (GSI, 1992a).

The east-dipping Deh-Bala reverse fault follows the margin of bedrock exposure at the northern end of Kuh-e-Sekonj, and runs parallel to large-scale fold structures within the bedrock for a distance of ~12 km (Figs. 3 and 7a). Late Quaternary activity on the

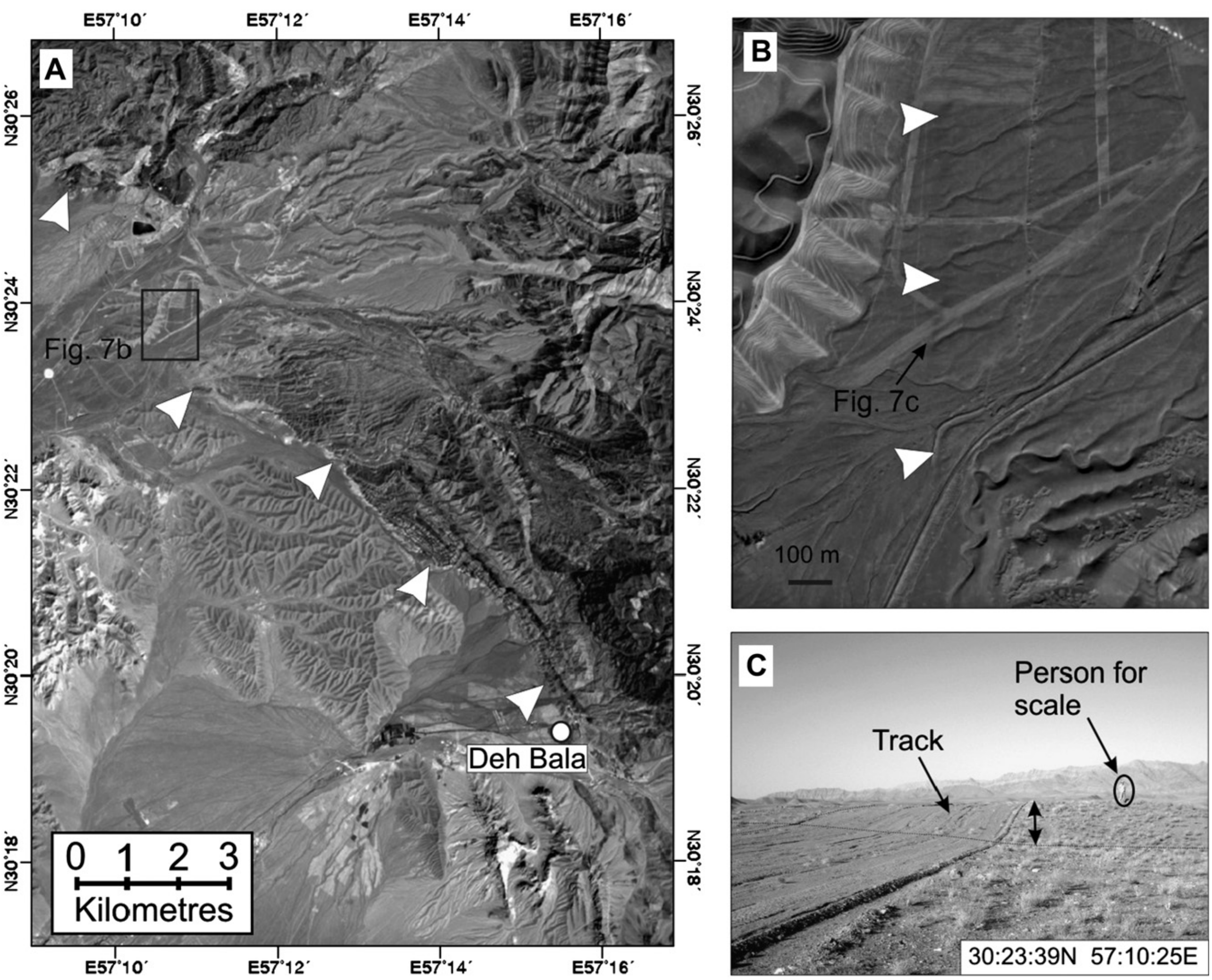


**Fig. 7.** (a) ASTER satellite image of the Deh-Bala fault scarp east of Kerman city. (b) Quickbird satellite image (from Google Earth) of the northern end of the Deh-Bala fault where it cuts alluvial fan deposits and forms a ~5 m-high, west-facing, scarp. We do not observe any late Quaternary scarps in the alluvial plain north of the area shown in Fig. 7b, indicating that the Deh-Bala fault is not connected at the surface with the Bazargan fault to the north. (c) Field photograph, looking east, at the ~5 m-high scarp in alluvial fan deposits.

Deh-Bala reverse fault is observed where it crosses a large alluvial plain close to its northern end. Here it forms a sharp ~5 m- high scarp in alluvium (Fig. 7b,c). The Deh-Bala fault is situated within 15 km of Kerman city and may be a potential cause of future damaging earthquakes in the city. Berberian (2005) interprets the Deh-Bala fault as a southern part of the Bazargan fault. We do not see any evidence for late Quaternary faulting within the wide alluvial plain that separates the two faults and we hence interpret them as two separate structures. If the two faults are linked the total fault length will be >40 km and the maximum possible earthquake magnitude will be increased (Wells and Coppersmith, 1994; Section 4).

*4.1.3. Faulting within the Chatrud valley*

In this section we identify a north-south scarp situated just to the east of Chatrud village (Fig. 3). We visited a short section of the scarp adjacent to a small bedrock hill (Fig. 8). The scarp is in alluvial material, faces to the east, and is 1 m high. Minor westward-draining streams, running along small runnels in the alluvial fan surface, are blocked by the scarp and have deposited fine-grained sediments against the fault scarp (e.g. Fig. 8b). These fine-grained deposits may be suitable for palaeoseismic trenching.

The Chatrud fault scarp is situated in a wide plain covered in alluvium from rivers draining southwest out of Kuh-e-Sayyedi. The alluvial fan surface has a well-formed desert armour with clasts showing a prominent desert varnish. The surface is, therefore, unlikely to have been reset by recent fluvial action. The vertical rate of displacement is therefore probably rather low (~0.1 mm/yr if the fan surface is ~10 ka old). However, the combination of well-preserved scarps, the north-south orientation, and the fact that the up-to-the-west vertical component on the Chatrud scarp is opposite to the overall sense of uplift in the area are all consistent with the major component of slip being right-lateral strike-slip (though we have no direct evidence, in the form of unambiguous lateral displacement of landform features, that the Chatrud fault involves strike-slip motion).

The Chatrud fault trends southwards towards the northern end of the Bazargan reverse fault, and nothwards towards the southeast end of the Tigur reverse fault (Fig. 3). The Chatrud fault appears, therefore, to be important in interpreting the regional structure, as its presence indicates that the structures along the base of the mountains northeast of Kerman, rather than being independent faults, are linked. We address the importance of this issue in the discussion.

*4.2. Active faults to the south and west of Kerman*

Another prominent band of active deformation is present to the south and west of Kerman city and comprises the Jorjafk fault (Berberian, 1976, 2005) and the Mahan fold belt (Walker, 2006). These structures are described, in turn, below.

*4.2.1. The Jorjafk fault*

The Jorjafk fault was first identified by Berberian (1976). It has an overall NW-SE trend although some sections trend closer to NNW-SSE. It is ~180 km long and follows the NE margin of Kuh-e-Gerdu. There is no record of historical seismicity in the Jorjafk region but the fault appears to be active in the late Quaternary, with clear scarps visible in young alluvial fan deposits along its entire length, and a fault trace marked by a line of small springs and oases (Fig. 9).

Fault scarps, several tens of metres high, are developed in fan deposits along the length of the fault (Fig. 9a,b). Folded basin deposits, of probable Neogene age (GSI, 1992b), are often exposed in the upthrown southwestern side of the fault (Fig. 9a), in a style often associated with active reverse faulting in Iran (e.g. Walker, 2006). A road cutting through a ~20 m-high fault scarp near Jorjafk village is shown in Fig. 9c,d. Alluvial fan deposits, which overlie Mesozoic purple shales, have been deformed by faulting. Close to the scarp, the gravel deposits have been rotated to dip almost vertically, and have been cut through by a series of low-angle thrust faults. The folding and thrust faults clearly indicate a component of shortening. Movement on the thrusts has led to the development, and subsequent deformation, of colluvial wedge deposits. The colluvial wedges, which are typified by red colouration and overall lack of clear bedding, may contain information on the record of past earthquakes that can be unravelling from palaeoseismological investigation.

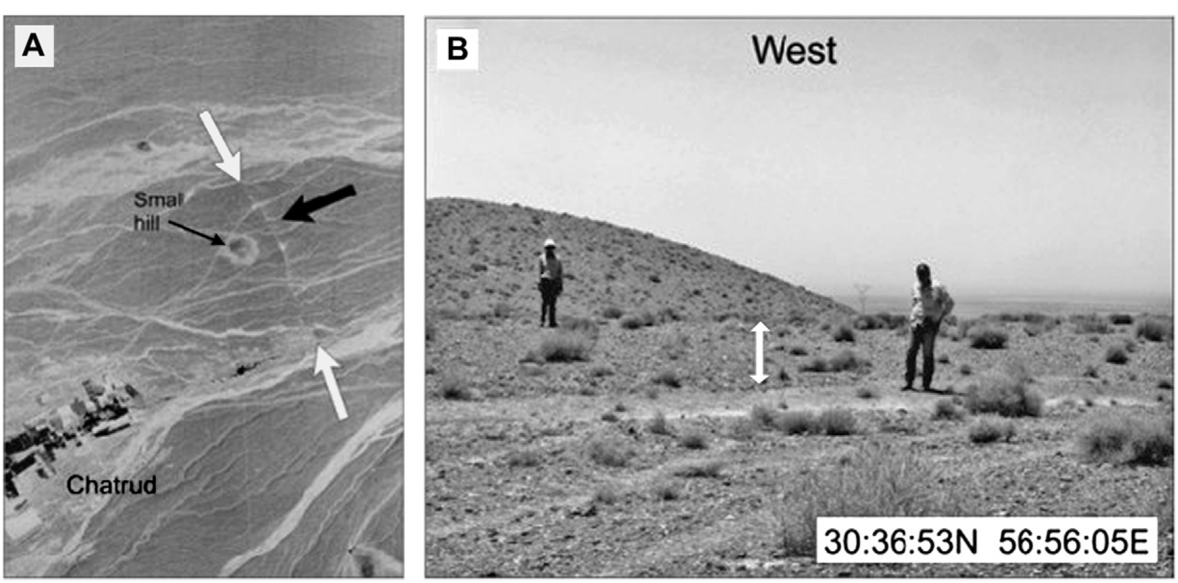


**Fig. 8.** (a) Aerial photograph (taken in 1956) showing a N–S scarp (between the white arrows) cutting alluvial fan deposits near Chatrud. An up-to-the-west vertical component of slip has impeded the westward flow of small streams causing ponding and the deposition of fine-grained, light-coloured, sediments along the scarp. The black arrow marks the location, and view direction, of Fig. 5b. (b) Field photograph, looking west, of the ~1 m-high scarp. Light-coloured, fine-grained, deposits are present at the base of the scarp. The small hill in the background is visible on the aerial photograph.

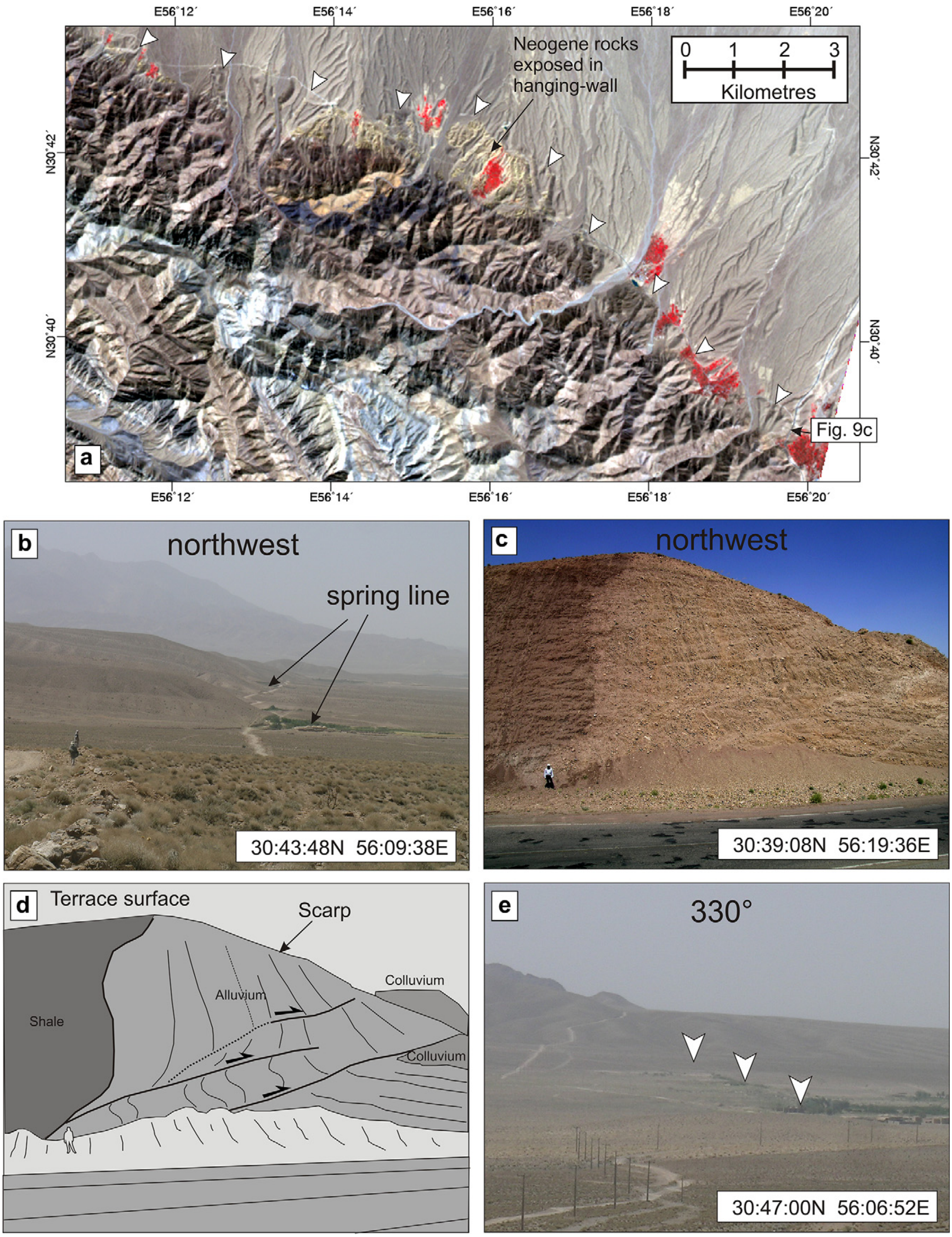


**Fig. 9.** Field photographs of the Jorjafk fault. (a) ASTER satellite image of northeast-facing scarps of the Jorjafk fault. (b) View northwest along the Jorjafk fault. East-facing scarps are clearly visible in alluvial fans along the length of the fault. Oases along the fault are fed by spring waters. (c) Section through the fault near Jorjafk village (d is an interpretation). The base of an ~20 m-high scarp is cut by a series of gently dipping thrust faults. Fan deposits on the hanging-wall of the faults have been tilted to almost vertical suggesting that much of the surface deformation occurs by folding. Colluvial deposits are present in the footwalls of the faults. Person for scale. (e) View north of the Jorjafk fault as it cross a broad alluvial plain (fault trace marked by white arrows). The extremely linear trace, combined with the subdued topography in this region, is suggestive of a strike-slip component (also see Fig. 10a).

Our observations show that the Jorjafk fault is active and possesses a large component of shortening. From the overall NW-SE trend of the Jorjafk fault, which is similar to the trends of the nearby Kuh Banan, Anar, and Rafsanjan right-lateral strike-slip faults (e.g. Fig. 1), we might also suspect a component of right-lateral strike-slip. We have not been able to find conclusive evidence of strike-slip along the Jorjafk fault. There are, however, a few locations where a strike-slip component may be inferred. As the fault exits Kuh-e-Gerdu near Baghain it crosses a series of old alluvial fans (Fig. 10a). The fans, and deeply incised rivers within them, appear to be displaced right-laterally by at least 100 m. At latitude ~30°45′N the fault moves away from the range-front and forms an extremely straight east-facing and ~10 m-high scarp – typical of the morphology associated with strike-slip faulting - as it cuts across a wide plain (Figs. 9e and 10b). In all the locations where strike-slip is apparent the fault trends NNW-SSE and the adjacent mountains are lower than in areas where the fault trends NW-SE (Fig. 2). It appears that the strike-slip component increases where the fault trends closer to north-south, i.e. where it trends closer to the regional direction of north-south right-lateral shear measured by GPS across eastern Iran (Vernant et al., 2004).

### 4.2.2. The Mahan fault-related folds

The folds trend NW-SE along the northern margin of Kuh-e-Jupar (Fig. 2) and are clearly visible in satellite imagery from exposures of light-coloured Neogene marls in their cores (Fig. 11; Walker, 2006). The folds are situated close to the town of Mahan (Fig. 2) and extend northwards to beyond the village of Jupar. An historical earthquake on 2nd January 1934 damaged villages along the Kuh-e-Sekonj range-front to the southeast of Mahan (Ambraseys et al., 1979; Berberian, 2005; Fig. 2). It is possible that this earthquake was associated with unidentified faults within Kuh-e-Sekonj, but it is more likely to have been generated by the Mahan fold system (e.g. Berberian, 2005). We compliment the remote-sensing study of Walker (2006) with field observations from the Mahan folds.

Fig. 11a shows a satellite image and field photographs from the Mahan folds. Growth within alluvial gravel beds exposed in the northern limb suggests continued folding through the late Quaternary and has tilted the older gravel units to dip steeply southwards (i.e. slightly overturned; see Fig. 11b). There is no evidence of a major fault displacing beds exposed in any of the deeply incised river cuttings. Gravel beds exposed at the southern fold margin also display rather steep dips of ~70°N, but overall the fold displays a vergeance to the north, from which we interpret the fold structures to be underlain by southward-dipping blind thrust faults. Dips on the southern fold margin may be locally steepened by north-dipping antithetic thrust faults (as can be seen on satellite imagery in some places, Fig. 11). Low fault scarps (1–2 m-high) are visible on the fold margins in a few locations (e.g. at 30:02:16N 57:14:23E). These scarps are too small to be visible in the satellite imagery. As we saw no evidence in the river cuttings for major faults at the surface we interpret these minor fault scarps at the surface to result from secondary faulting caused by fold growth.

## 5. Discussion

We have presented numerous indications of late Quaternary activity on faults surrounding the city of Kerman in eastern Iran; each of which should be considered as a potential source of destructive earthquakes in estimates of seismic hazard. We note, for instance, that the faults we describe in the Chatrud region are possible sources for the destructive earthquakes in the 19th

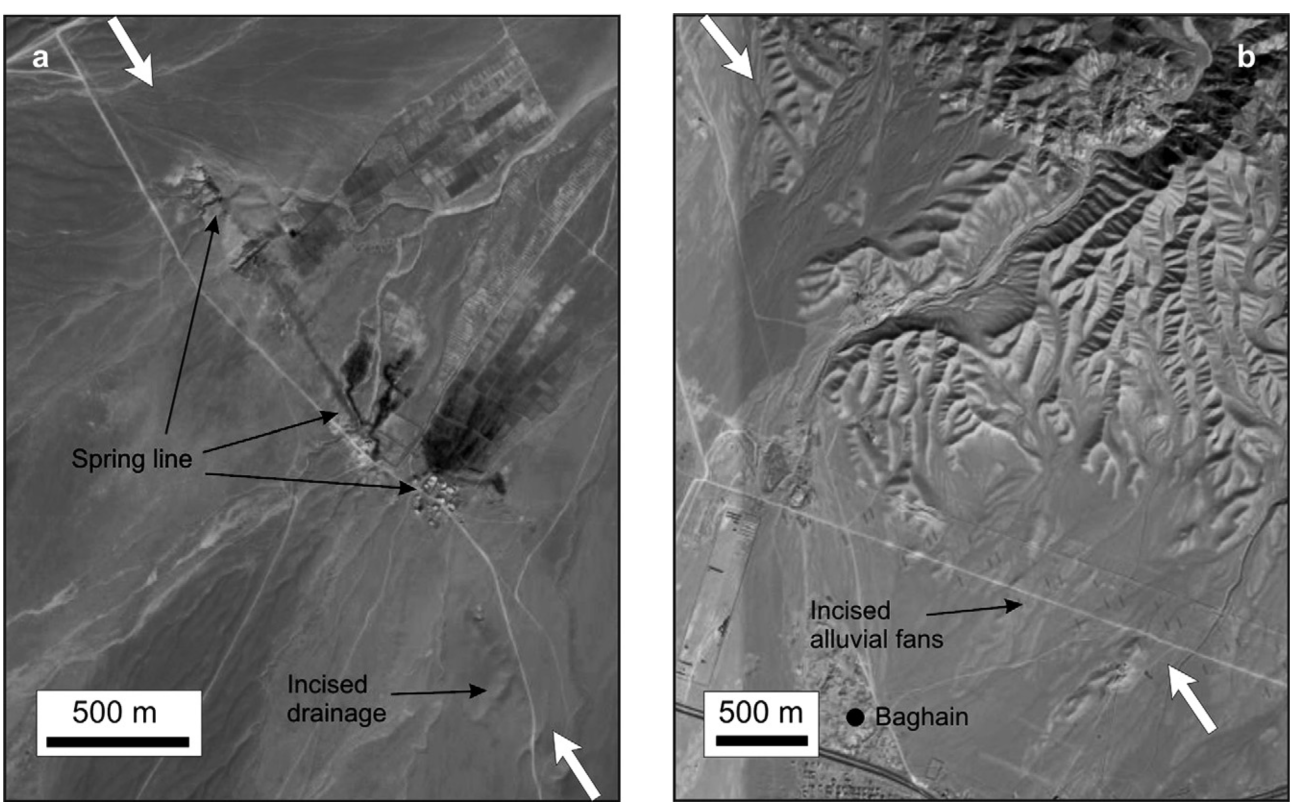


**Fig. 10.** Quickbird imagery (from Google Earth) of places on the Jorjafk fault where a right-lateral strike-slip component is inferred. (a) Extremely linear fault trace with spring line (also see Fig. 9e). The scarp is ~10 m high and faces to the ENE. (b) Apparent ~100 m right-lateral displacement of stream courses and old alluvial deposits close to the southern end of the Jorjafk fault near Baghain (in bottom left of the image). Younger alluvial deposits are incised on the western, downstream, side of the fault.

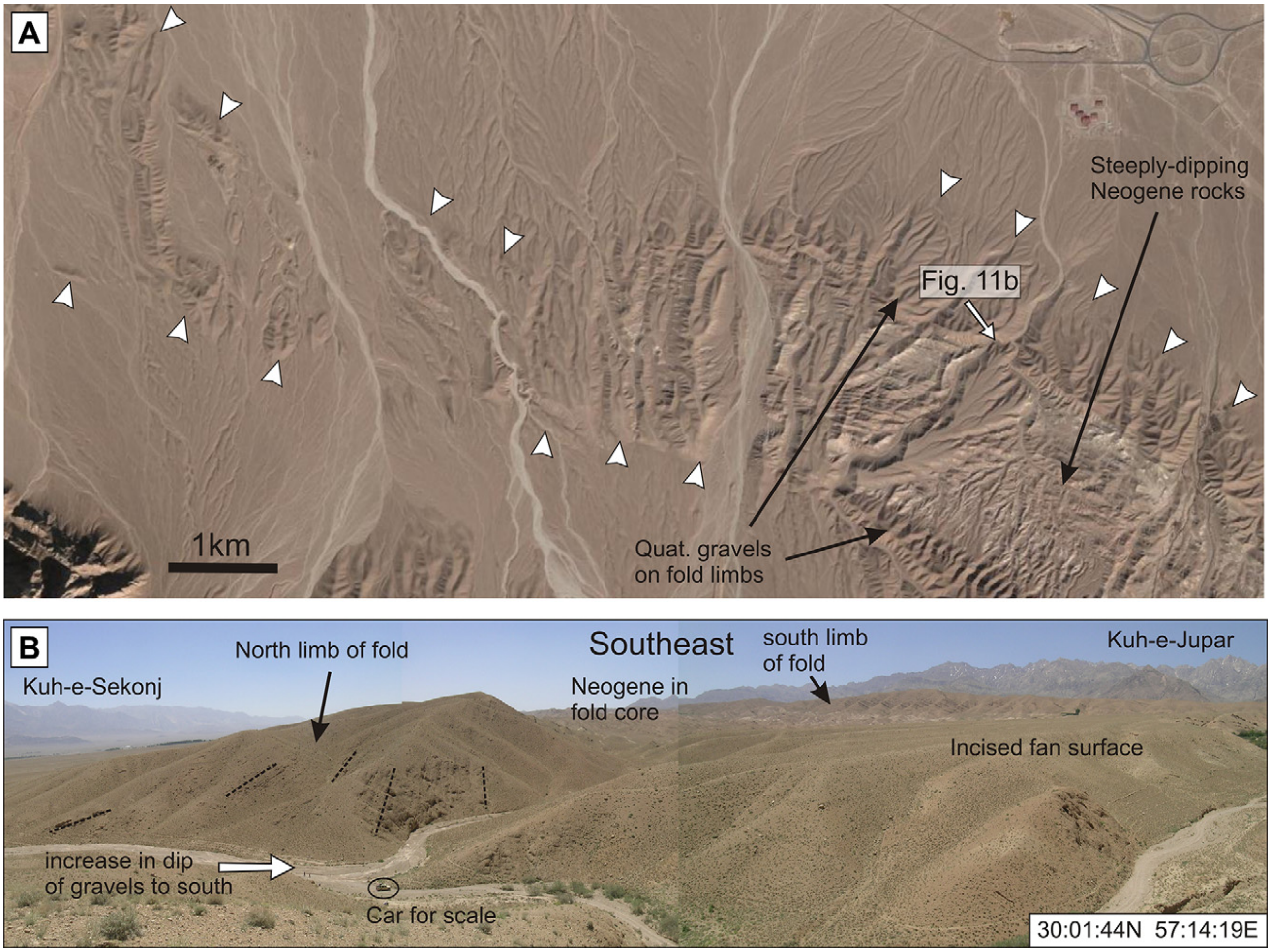


**Fig. 11.** Quickbird imagery (from Google Earth) of the northern part of the Mahan fold system. No sharp scarps are visible suggesting that faulting does not reach the surface (e.g. Walker, 2006). (b) Field photograph looking southeast at growth in folded gravels in the fold limb. The fold limb is not cut by major surface faulting again suggesting that any underlying thrust fault does not reach the surface.

Century. The sharp ~1 m-high scarps at Chatrud and Bazargan, in particular, and possibly the 3 m scarp at Garchuiyeh, may represent the ruptures from individual earthquake events. We anticipate that future detailed palaeoseismic studies will provide chronologies of past earthquakes on the faults. We also suggest that Quaternary dating of alluvial fans displaced by the faults will provide time-averaged slip-rates, and hence estimates of the average interval between earthquakes, on each individual fault. One of our aims in providing detailed descriptions of scarps in young deposits is to help guide these future studies.

The faults we describe are also important for understanding how tectonic strain is accommodated by faults, both at a local scale, and in oblique fault zones in general. We see that the city of Kerman is situated between two major fault zones: both of which approach to within 30 km of the city. In the north and east, a series of short strike-slip and reverse faults accommodate the transfer of slip between the Gowk and Kuh Banan faults. The Mahan and Jorjafk faults, sited to the south and west of Kerman, appear to be dominantly dip-slip. A right-lateral component is, however, apparent at several points along the Jorjafk fault and we suggest that the overall motion is likely to be oblique reverse and right-lateral. The northwestern tip of the Mahan fold system, and the southeastern tip of the Jorjafk fault, trend towards one another and are separated by only ~10 km (Fig. 2). This arrangement suggests that the Jorjafk fault may branch northwards from the Mahan faults, thus implying that the Mahan faults may also possess a component of strike-slip. Further studies are required on the Mahan and Jorjafk faults to determine both the sense, and the potential for earthquakes to occur, on these historically quiet, though clearly active, faults.

We have also uncovered new details of the active faults that border the mountains northeast of Kerman. The identification of the Chatrud scarp, whose morphology suggests it to be dominantly strike-slip in nature, indicates that the reverse faults are in the process of linking together and, furthermore, are likely to accommodate oblique slip. This observation has important implications for the evolution of faulting.

The faults that occur along the range-fronts northeast of Kerman are not the only active faults within the restraining bend between the Gowk and Kuh Banan faults. Many additional faults, all of which may be capable of producing earthquakes, are shown on Figs. 2 and 3. The faults in these figures all possess clear scarps in alluvium. The Dehu fault, which trends northwest-southeast through the centre of the mountainous interior of the restraining bend (Fig. 12), shows, in addition to scarps in alluvium, strike-slip displacements in bedrock of several kilometres (GSI 1992a). Widespread shortening, along with right-lateral strike-slip, is present at lower elevations near the town of Ravar and in the areas between the Kuh Banan, Lakar Kuh, and Nayband strike-slip faults (Figs. 2 and 3).

The faults that we describe are all elements in the accommodation of north-south right-lateral shear across this part of eastern

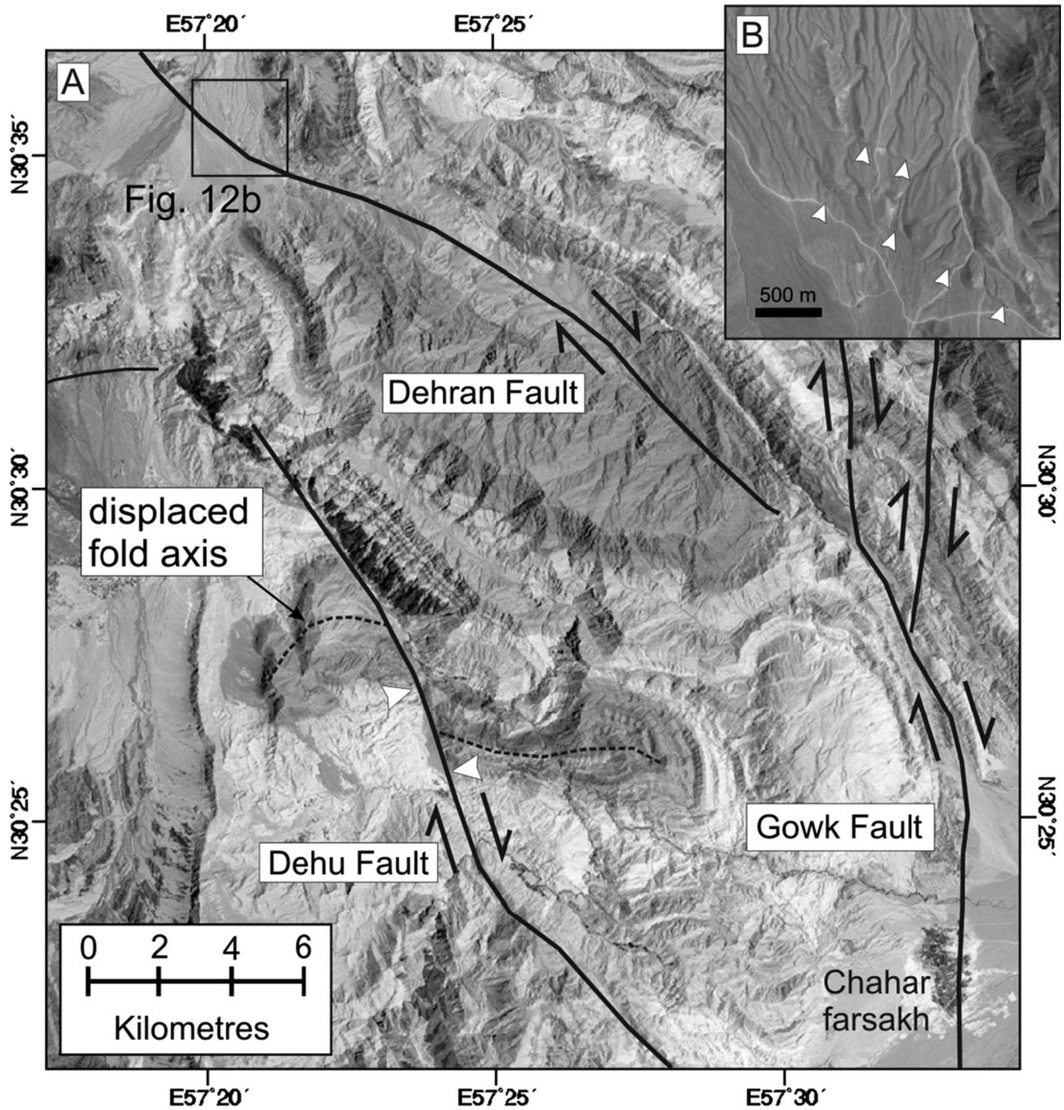


**Fig. 12.** ASTER satellite image of the Dehu fault within the high topography between the Gowk and Kuh Banan faults (see Fig. 3 for location). Folded Mesozoic rocks are displaced right-laterally by ~2–3 km. Inset is a Quickbird image (from Google Earth) showing scarps of the Dehran fault in late Quaternary alluvial fans.

Iran. We see that the region around Kerman city is part of a broad system of restraining bends along the right-lateral faults that occupy the western margin of the Dasht-e-Lut desert. The maturity of the fault systems appears to vary across the region.

Oblique slip on the Jorjafk fault is likely to represent the initial stage (Fig. 13a). Stresses generated by the elevated topography eventually result in a migration of the dip-slip component onto reverse faults in the adjacent lowlands whereas the strike-slip movement continues to occur along the original oblique slip fault.

This second stage in the evolution is represented in the almost total separation of strike-slip and dip-slip components of motion onto the parallel Rafsanjan and Rayen faults (Fig. 13b). It seems reasonable to suppose that the Rafsanjan fault system has also changed through time, with an initial stage of oblique slip forming the elevated topography, followed by a spatial separation of slip components as shortening migrates to lower elevations.

The restraining bend between the Gowk and Kuh Banan fault appears to represent an even more evolved stage in the evolution of faulting within a restraining bend (Fig. 13c). There is still a spatial separation (or partitioning) of components of slip onto parallel structures, with strike-slip within the high mountains and shortening on parallel faults at both the southwest, and northeast, margins of the high topography, but it does not appear as though this arrangement of faulting has persisted throughout the history of faulting. The Dehu strike-slip fault cuts through tightly folded strata within the centre of the mountains (Fig. 12). The reverse faults along the southwest margin of the topography appear to be in the process of linking together to potentially form a new through-going strike-slip fault. This scenario of broadening of the deformation zone through the generation of new thrust faults that then link up to form new through-going strike-slip faults has also been proposed for the Gobi-Altay of Mongolia (Bayasgalan et al., 1999) and may be a relatively common feature in regions of oblique shortening leading to the origin of flower structures in cross-section (e.g. Sylvester, 1988; Woodcock and Schubert, 1994).

A final implication of our study is in the extent to which the topography of eastern Iran results from late Cenozoic tectonics. The faults that we describe are closely associated with the existing topography, with reverse faults sited along the margins of mountains, and strike-slip faults situated either at the margins of the mountains or within their interiors. The existing topography appears, therefore, to result from the late Cenozoic tectonics. The only large mountain

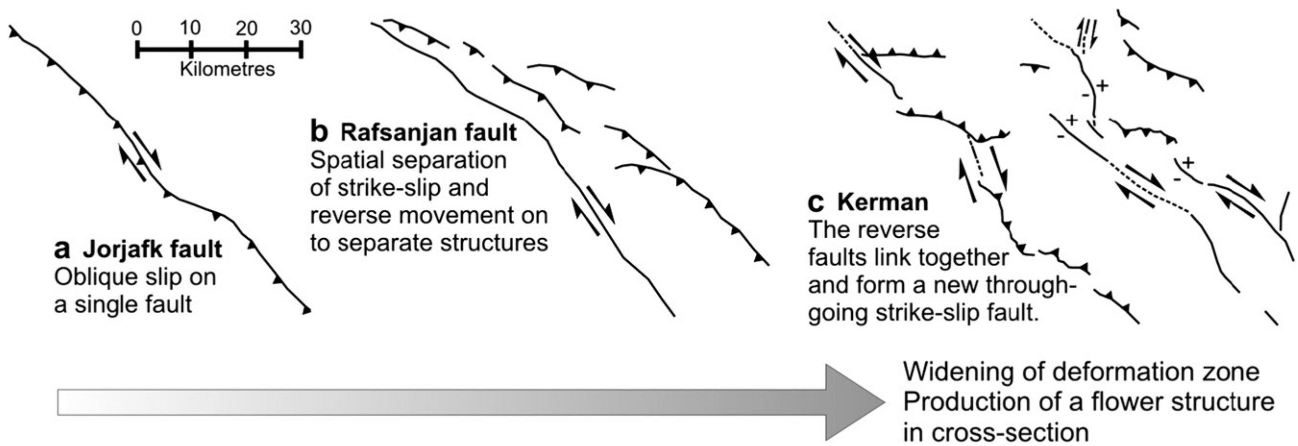


**Fig. 13.** Examples of faults in the Kerman region that show the three stages in fault evolution described in the text. (a) The Jorjafk fault shows the initial stage with shortening and strike-slip components of motion accommodated on a single northwest-southeast trending oblique slip fault. (b) The Rafsanjan fault shows a more mature stage of fault development, with a spatial separation (or partitioning), of strike-slip and dip-slip onto two parallel structures. The strike-slip fault remains within the high mountainous ground and the new reverse faults form in the adjacent lowlands. (c) Faulting in the restraining bend between the Kuh-Banan and Gowk faults near Kerman city show the most mature stage. The reverse faults have acquired a strike-slip component of motion and are in the process of linking together to form a new through-going oblique-slip fault. The evolution of faulting suggested by these three examples results in a broadening of the deformation zone and will resemble a flower structure in cross-section.

within our study area that does not show a clear relationship with mapped active faults is Kuh-e-Sekonj (Fig. 2). The Gowk fault runs along the eastern margin of Kuh-e-Sekonj, but it is the eastern side of the Gowk fault that is uplifting (e.g. Berberian et al., 2001; Walker and Jackson, 2002). Although it is possible that all the topography of Kuh-e-Sekonj is a relict of much earlier mountain building not related to the present tectonics, it is also possible that a rearrangement of faulting in the late Cenozoic has occurred around Kuh-e-Sekonj.

## 6. Conclusion

The faults around Kerman are an extremely clear demonstration of how oblique strike-slip and shortening is accommodated at a restraining bend along a major continental strike-slip fault. Our study was motivated by the abundance of destructive earthquakes recorded in the Kerman region over the last 150 years. We find that it is the siting of Kerman at a restraining bend along the major Gowk fault system, where the faults are rapidly evolving and highly segmented, that has contributed to the widespread occurrence of potential earthquake sources. Although the historical record may account for rupture of some of the faults near to Kerman is does not account for rupture on them all. We note, for instance, that the Deh-Bala thrust is located within 15 km of the city but in an area with no historical earthquake record.

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