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Surface effects of the December 26th, 2003 Bam earthquake along the Bam fault in southeastern Iran

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Abstract

During the December 26th, 2003 Bam earthquake, continuous ruptures with a consistent right-lateral strike-slip of a few centimeters occurred north of Bam. A 3 km long strand of ruptures coincides exactly with the trace of the geologic Bam fault. These ruptures were possibly caused by the tectonic slip on the source fault of the 2003 earthquake. The Bam scarp south of the Zehedan highway might have grown during the earthquake. The extension of the area around the scarp indicated by the scarp-parallel fissures may represent the coseismic stretch of the surface. South of the Bam scarp, there was no systematic surface effect. The absence of significant tectonic offset at the surface is concordant with the intermediate magnitude of Mw 6.6. Only a small and deep portion of the Bam fault, or another adjacent blind fault plane was ruptured in 2003. The geologic evidence of the over 50 km long Bam fault suggests a large, probably M 7.5 or larger, event in the future, however, there is no historic and geologic data to quantify the risks.

Key words : surface rupture, Quaternary fault, fault scarp, Bam earthquake, southeastern Iran

1. Introduction

The Bam earthquake in southeastern Iran occurred at 01 : 56 UTC (05 : 26 local time) on December 26th, 2003. According to the U.S. Geological Survey (http : //neic.usgs.gov/neis/eq_depot/2003/eq_031226/), the hypocenter was located at 29.00°N, 58.34°E, and 10 km deep. The magnitude was Mw 6.6. Preliminary analyses of the rupture process based on the inversion of teleseismic data (e.g. Yamanaka, 2003) suggest a right-lateral oblique slip on a steeply west-dipping fault plane. Talebian *et al.* (2004) carried out SAR interferometry of the source area and inferred a blind source fault in south of the Bam town. The 20 km long inferred blind fault has a NS strike, and runs around 5 km west of a distinctive Quaternary fault. Suzuki *et al.* (2004) precisely located the aftershocks along the inferred blind fault. Although the magnitude was not very large, the area of intense shaking coincided with the densely inhabited town of Bam and caused more than 30,000 fatalities and 30,000 casualties (U.S. Geological Survey, http : //neic.usgs.gov/neis/eq_depot/2003 /eq_031226/).

The town of Bam lies directly above a Quaternary fault named the Bam fault, which has long been recognized [e.g. Bereberian (1976), Hessami *et al.* (2003)] for its distinctive flexure scarp just east outskirt of the city. The initial field reconnaissance after the 2003 Bam earthquake did not report any significant surface offset along the Bam fault, but minor cracks along the scarp. Thus, an absence of surface faulting was confirmed shortly after the earthquake. This absence is reasonable for the small magnitude of the earthquake. However, the fact that the existing Quaternary fault of the Bam fault did not rupture during the devastating event is an important problem for long-term forecasting of earthquake risks based on geologic evidence. Strong ground shaking and resulting severe damage from blind faults, such as

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during the 1994 Northridge earthquake in California or during the 2001 Bhuji earthquake in India, have been a critical challenge to the long-term evaluation of seismic risks. The authors accordingly studied the surface effects of the Bam earthquake, as well as the characteristics of the Bam fault, to understand the faulting and the surface deformation in a geologic context. The survey was carried out about a month after the Bam earthquake for a week from January 28th through February 3rd.

2. Tectonic background of the Bam fault and the Bam earthquake

Most of Iran is located on a highland between Zagros mountains to the south and Arborz Mountains to the north. The highland consists of the continental crust of the Eurasian plate overlying the underthrusting Arabian plate. The collision-type plate boundary is considered to run along the southwestern foot of the Zagros mountains northwest of the Hormuz strait and along the Makran coast down to the triple junction in southern Pakistan (Fig. 1). The oblique conversion of Eurasian and Arabian plates results in right-lateral and/or reverse slip on the intra-plate faults in southern Iran. The majority of the Quaternary and active faults here have a NW-SE to N-S strike, and show shortening with right-lateral slip (Hessami *et al.,* 2003). The Bam fault is one of the right-lateral compressional active faults surrounding the Dasht-e-lut basin to the east and north of Bam. In recent years, several surface faulting events have occurred in this region. Among them, the 1997 Qayen earthquake accompanied more than 110 km long right-lateral strike-slip surface faults (Ikeda *et al.,* 1998), and the 1981 Sirch and 1998 Fendoqa earthquakes ruptured the Gowk fault only 150 km north of Bam (Berberian *et al.,* 2001). The Bam fault on the other hand is believed to have been inactive at least

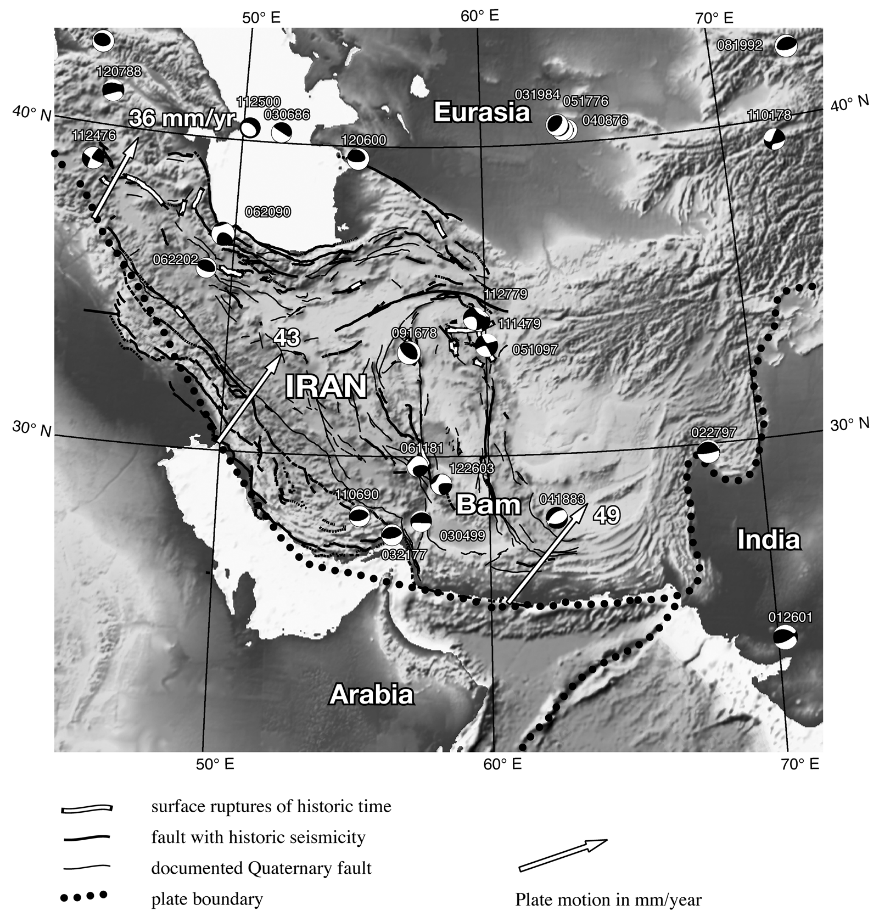

Fig. 1. Active tectonics and recent large earthquakes in Iran and adjacent areas. Harvard CMT (Mw > 6.5) 1976–2004. The numbers are in ddmmyy format. Fault traces are simplified from Hessami *et al.* (2003) and only the faults within Iran are shown. Plate motion indicated by arrows is in mm/year after http://sps.unavco.org/crustal_motion/dxdt/nnrcalc/.

for 700 years (Ambraseys and Melville, 1982). No earthquake that damaged Bam appears in the historic catalogs.

3. Surface effects of the 2003 earthquake along the Bam fault

During the post-earthquake investigation along the Bam fault around the city of Bam, we mapped minor surface ruptures associated with the 2003 earthquake at 2 localities and measured the fault topography of the Bam fault at 4 localities. At the time of our survey, there was no information on the ruptures reported by Talebian *et al.* (2004), so we did not conduct a survey south of Bam.

For mapping and profiling, we used a pair of Leica SR530 dual-frequency GPS receivers in real-time kinematic (RTK) mode using wireless modems at Locs. 4 and 6, in post-processing kinematic mode at Loc. 1, and in post-processing stop-and-go mode at Locs. 2 and 3. Post-processing was carried out using the SKI-pro application. For most records, errors for easting and northing were less than 10 mm and errors for height were less than 20 mm. Overall accuracy is sufficient for our purpose.

3. 1 2003 ruptures and the Bam fault north of Bam (Loc. 1)

On the north bank of Posht-e-Rud, 2 strands of continuous ruptures were formed on the surface during the earthquake. The west strand (N1 in Fig. 3) is about 3 km long and cuts the pediment surface. The ruptures of N1 around Loc. 1 are a continuous swarm of left-stepping en-echelon cracks (Fig. 4). Most ruptures show 1 to 2 cm openings with similar amount of right-lateral offsets. The N1 strand becomes less and less continuous toward the north and we could not follow it beyond 7 km north of Posht-e-Rud. There, minor surface cracks scatter all around the strand, however, they do not show any consistent orientation and continuity. The N1 strand, although discontinuous to the north, shows a series of ruptures.

The N1 strand exactly coincides with the trace of the Bam fault around Loc. 1. At Loc. 1 a gentle pediment slope is broken along the N1 rupture strand. As it is clear in Fig. 4, the east, lower side of the slope is higher than the west side. The saddles and knobs are aligned along the N1 strand and the streams are cutting down the higher slope on the east side. This lower-side-up topography is quite unusual on a pediment slope and only east-side-up faulting can create this topography (Fig. 3 profile). This topography is one of the clearest expressions of the Bam fault north of Posht-e-Rud. Here, the coseis-

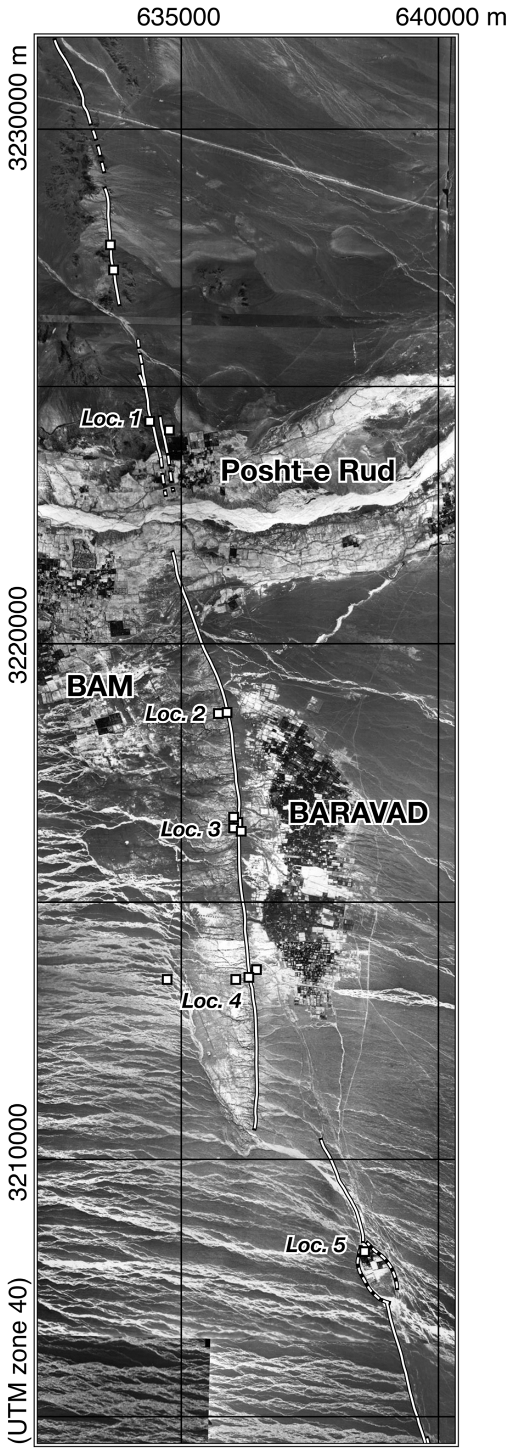

Fig. 2. The Bam fault and localities plotted on an originally 1 : 50,000 air-photo mosaic. White lines indicate the surface trace of the Bam fault. The UTM grid lines are every 5000 m.

mic ruptures appeared exactly on the Quaternary fault. This means the continuous N-S ruptures with small offsets occurred on the fault plane.

There are two ways to interpret the ruptures. One is that the coseismic slip decreasing toward the surface from an asperity beneath reached the surface and caused a minor but continuous slip. Judging from the consistent left-stepping en-echelon arrangement of the ruptures on a line, these strands may represent the upper end of the seismogenic fault plane of the Bam earthquake. The clusters of shallow aftershocks are deeper south of Bam and become shallower towards the north, and they almost reach the surface under this northern portion of the Bam fault (Suzuki *et al.,* 2004). Therefore, the ruptures here are possibly accounted for by the tectonic slip.

The other possibility is a slip triggered by shaking. In this case, the surface ruptures are isolated from the major slip around the hypocenter. The triggered surface slip as observed in Salton trough during the 1999 Hector Mine earthquake (Rymer *et al.* 2002) may explain the formation of ruptures on the N1 strand.

The easterly, N2 strand north of Posht-e-Rud

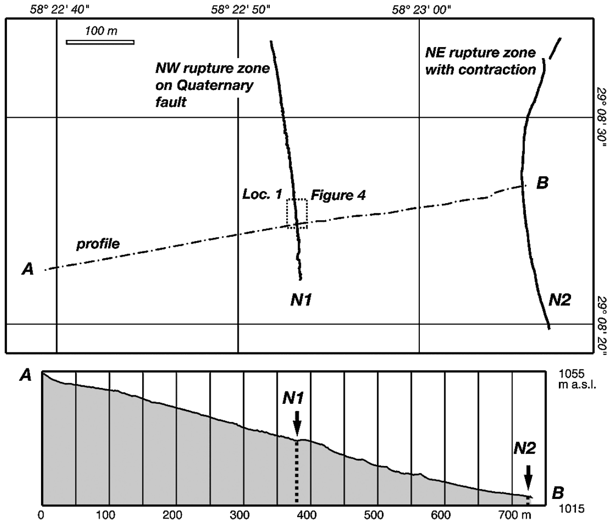

Fig. 3. A map of two rapture strands around Loc. 1 north of Bam (above) and profile of the faulted pediment slope across N1 and N2 ruptures.

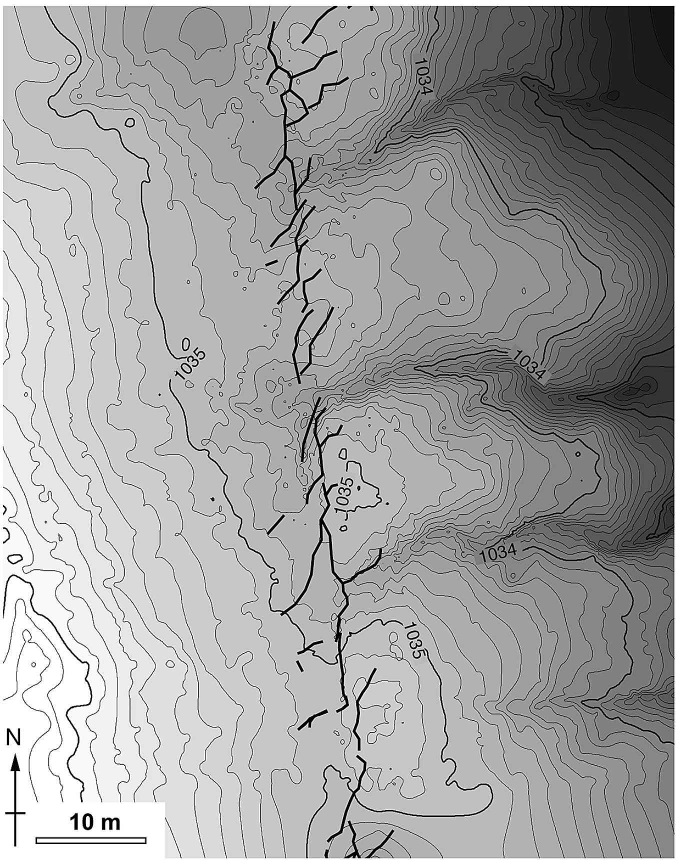

Fig. 4. At Loc. 1, coseismic left-stepping en-echelon ruptures (black solid line) were formed exactly following the fault saddles formed on an east-dipping pediment slope with east-side-up deformation by a Quaternary fault.

(Fig. 3) is cutting through almost flat pediment and alluvial surfaces for about 2 km. The N2 strand in Fig. 3 comprises continuous left-stepping en-echelon cracks with a small amount (probably 1 to 2 cm) of E-W shortening and around a 1 cm right-lateral strike slip. Along the cracks, small ridge-shaped push-up structures were formed due to the shortening. There is no evidence of repeated Quaternary faulting along this strand. On a small outcrop, a rupture follows a bedding plane within Paleogene sedimentary rocks.

3. 2 Quaternary activity of the Bam fault along the Bam scarp (Locs. 2 and 4)

The Bam fault has long been recognized by the scarp between Bam and Baravad. The around 20 m high scarp continues for about 12 km from the south bank of Posht-e-Rud. The scarp is very distinctive on the surrounding gentle and smooth alluvial fan surface and pediment slopes. The braided streams west of the scarp are deflected by the uplifted area along the scarp (Fig. 2). From aerial photographs, the Bam scarp and the uplifted west side look like an anticline.

However, the topographic profiles and deformed sediments (Fig. 5) show a flexure rather than an anticline. The bedding planes under the flexure scarp show concordant deformation with the scarp surface. This means the flexuring has formed both the scarp and the deformation. The sediments consisting of reddish silt and sand with gravel are finer than the alluvial fan gravels transported by the braided streams. The sediments look more like playa or over-bank deposit from large streams. There is no way to know the age of the sediment, but the low degree of weathering and of consolidation suggests the age to be Middle Pleistocene.

The west side of the flexure forms a flat upland on which the city of Bam is located. The inclination of the surface is almost level (Loc. 4), but dips toward the east. The modern alluvial fan deposits overlap the uplifted surface about 3 km west of the flexure scarp, and there is no evidence to indicate the entire area west of the Bam fault has been uplifted by flexuring. The flexure pushed up a zone less than 3 km wide on the west side of the scarp. This indicates that the geologic structure along the Bam scarp is an asymmetric anticline with a steep and tight east wing and a gentle west wing. A steeply west dipping blind fault with a reverse component is the most likely geologic structure creating the deformation.

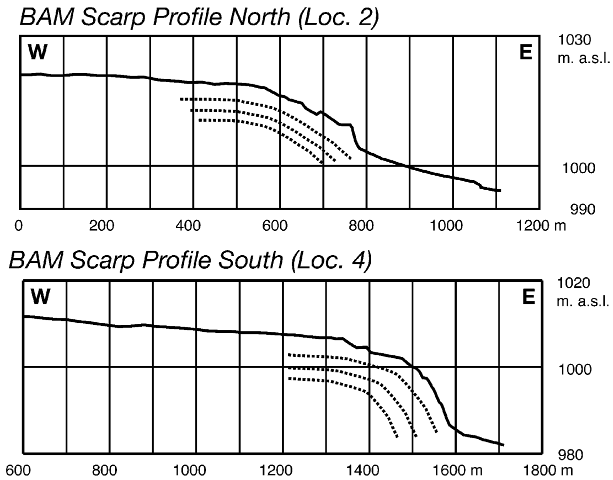

Fig. 5. Profiles of the Bam Scarp east of Bam (Loc. 2) and southwest of Baravad (Loc.4). Solid lines and dashed lines respectively indicate topographic profiles and deformed bedding planes (schematically).

3. 3 Deformation of the Zahedan highway on the Bam Scarp (Loc. 3)

Many minor surface ruptures appeared in the area south of the Zahedan highway southeast of Bam. The pavement of the highway was not severely damaged but several cracks cut through the road surface. We mapped a 40 to 50 m wide depression on the road surface (Fig. 6). The depression is only several centimeters deep, but both eastbound and westbound roads are deformed by a graben-like depression with NE-SW strike. The cause of the deformation is not clear, but gravitational failure of the scarp would not create a depression so oblique to the slope. This depression might be related to the coseismic growth of the flexure scarp.

3. 4 A Swarm of surface ruptures south of the Zahedan highway (Loc. 3)

The area 100 to 300 m south of the Zahedan highway showed the densest occurrence of discontinuous surface ruptures during the earthquake. We measured the strike, length, and the midpoint coordinates of each rupture in this area (Fig. 7). We carefully avoided measuring ruptures affected by gravitational failure on slopes. The measured ruptures are located either on the flat ground below the scarp, on the flat ground above the scarp away from scarps and irrigation tunnel (qanat) shafts, and on the stream bed along the dry river (wadi) cutting into the

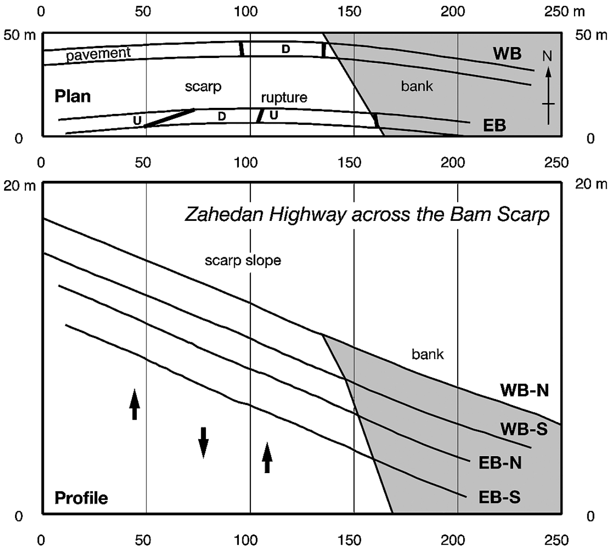

Fig. 6. Deformation appeared on the pavement of the Zahedan Highway across the Bam Scarp east of Bam city (Loc.3). D and U respectively indicate down-thrown and up-thrown road surface. A shallow depression bounded by linear ruptures (bold lines across the road) oblique to the Bam scarp was formed during the earthquake. The arrows in the profile show the vertical movement occurred along the ruptures across the roads. The lanes in the shaded areas are constructed on an artificial bank. WB : west-bound lane, EB : east-bound lane, N : north edge of the pavement, S : south edge of the pavement.

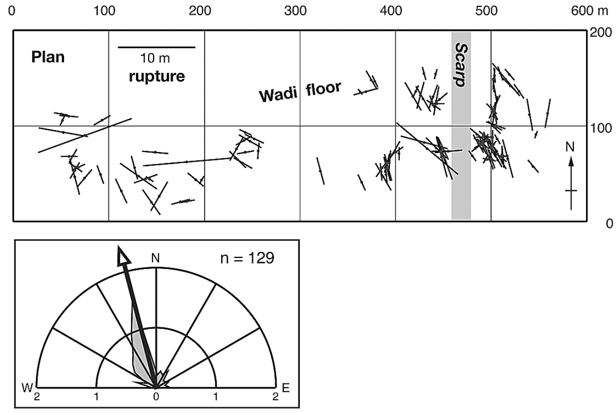

Fig. 7. A swarm of coseismic ruptures on the south side of the Zahedin highway across the Bam Scarp at Loc. 3. Distribution and individual length are plotted in a plan above. The rose diagram below shows the predominant strike of the ruptures around N15° W.

flexure scarp. The measurements below the scarp and on the stream bed are not affected by gravitational failures.

The majority of the ruptures have a N15° W strike (see rose diagram in Fig. 7), and show 1 to 10 cm openings. This shows that the surface length of the flexure scarp was stretched during the earthquake. The growth of the flexure scarp caused by the reverse faulting beneath may be the cause of this stretching. According to a local witness, a pipeline on the scarp slope was stretched and ruptured during the earthquake.

The long WSW-ENE rupture at 70 m in the plan is a south-dipping normal fault at the bottom of valley wall along the stream. This normal fault indicates a N-S extension existed in a shallow part 400 m west of the flexure structure. The pattern of rupture distribution in this part is different from the area close to the scarp. The N-S extension may be associated with E-W compression.

3. 5 Geologic evidence of recent activity of the Bam fault (Loc. 5 and further south)

Previous authors (Berberian, 1976 ; Hessami, 2003) did not hesitate to state the Bam fault continued over 50 km or more south of the Bam scarp. However, there is not clear evidence of faulting in this area. From the interpretation of aerial photographs, it is not clear if the lineament is erosional or tectonic because of the high activity of the streams.

There is no continuous coseismic rupture or any other clear feature south of Loc. 4. The southern area is mostly covered by two braided stream systems, one of which flows from the west and the other flows from the south. Between the east-flowing and north-flowing stream systems, there is a clear lineament dotted with island-like slightly high ground utilized for farming and housing. The lineament lies right on the southern extension of the general trend of the Bam fault around Bam city, although the southern part of the Bam scarp curves slightly westward and there is a gap between Loc. 4 and Loc. 5.

At Loc. 5 (Fig. 2), the elevated ground (shown as a vegetated area in the Fig. 2 is composed of reddish sand and gravels, which look similar to the old sediments forming the Bam scarp. The west side of the elevated ground is quite linear. South of Loc. 5, old sediments are not exposed, but east-flowing streams are terminated at a linear low (∼ 0.5 m) gravel scarp as shown in Fig. 2. The west-facing scarp is subtle, but the linear scarp does not seem to be an erosional

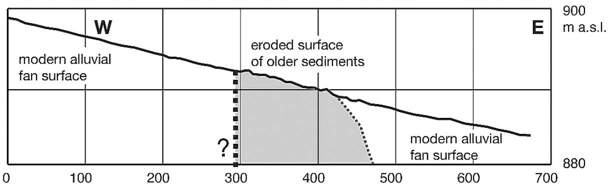

Fig. 8. Old Quaternary sediments exposed along the Bam fault south of Qotbabad (Loc. 6). The old Quaternary sediments seem to have been pushed up along the fault above the modern alluvial fan surface to be incised by a modern stream by a few meters.

feature caused by the streams.

The topography and geologic exposure at Loc. 6 (20 km SSE of Loc. 5) evidence the tectonic origin of the lineament (Fig. 8). At Loc. 6, the modern alluvial fan surface is juxtaposed against slightly higher ground by a linear scarp 0.5 to 1.0 m high. The higher ground on the east side is composed of reddish old sediments and is incised 2 to 3 m by the streams flowing across it. The profile shows slightly but definitely elevated ground on the east side of the lineament. Judging from the topography and the geology, the lineament is an active strand of a fault that uplifted the east side. The straight strand indicates the fault is steeply dipping. This trace of the southern Bam fault continues for another 20 km to the south.

4. Conclusion and discussion

The Bam fault is an active Quaternary fault that runs over 50 km. The segments north of Posht-e-Rud and south of Loc. 5 are high-angle faults with a small east-side-up component. There are possible offset streams that indicate a predominant right-lateral strike-slip. The Bam scarp represents an east dipping flexure or monocline on the east wing of an asymmetric anticline.

During the December 26, 2003 Bam earthquake, continuous ruptures with a consistent right-lateral strike-slip occurred north of Posht-e-Rud. The west strand extends about 3 km with a small extension. The west strand coincides with a trace of a Quaternary fault, namely, northern Bam fault. The east strand extends about 3 km with a small amount of compression. There is no evidence of precedent faulting along this east strand. These ruptures were possibly caused by the tectonic slip of the source fault of the 2003 earthquake. The offset is small, but the consistent en-echelon arrangement and coincidence of the west strand with the Quaternary fault support the possibility.

The Bam scarp south of the Zahedan highway might have grown during the earthquake. Most of the tension cracks have a N 15° W strike with openings of 1 to 10 cm. The extension of the area around the scarp may indicate the coseismic stretch of the surface. There is an E-W trending normal fault away from the scarp. The N-S extension may be correlated to the E-W compression.

South of the Bam scarp there was no systematic surface effect. The topography and geology suggest there is a southern extension of the Bam fault of over 30 km.

Geological and geomorphological evidence clearly indicate that the Bam fault has repeatedly ruptured over a 50 km long strand. The repeated faulting has created the Bam scarp and other surface features. However, the 2003 Bam earthquake did not create any significant fault topography on the surface. The absence of tectonic displacement at the surface is concordant with the small magnitude. This means the 2003 earthquake was not the largest earthquake expected from the geologic evidence. Only a small portion of the Bam fault plane was ruptured at depth, or another adjacent blind fault plane was ruptured in 2003. There is no way to forecast such a small blind earthquake by either seismological or geological research.

A devastating event at Bam has not occurred in the past 700 years or more, and did not occur in 2003, but it will occur in the future judging from the characteristics of the Bam fault. It is now possible to foresee a large, probably M 7.5 or larger event, but there is no historic and geologic data to quantify the risks. To reasonably reconstruct the city of Bam, we need much information about the earthquake cycle of the Bam fault.

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