Surface Expression of the Bam Fault Zone in Southeastern Iran: Causative Fault of the 26 December 2003 Bam Earthquake

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ABSTRACT: *The Bam fault zone is a major active fault zone in southeastern Iran. Geomorphic evidence indicates that it has been responsible for repeated faulting events since late Pleistocene. The December 26, 2003 Bam earthquake was associated with two fresh surface ruptures 5 km apart trending north-south and a 2 km wide zone of hairline fractures developed between the two main ruptures in north Bam. The amount of slip along the surface ruptures ranges between 0.5-5.5 cm across the zone. The whole system of fresh ruptures associated with the Bam earthquake is not direct manifestations of the earthquake fault but are secondary structures such as synthetic shears (Reidel shears), mole tracks and oblique grabens which are strongly indicative of right-lateral motion along principal displacement zone in the earthquake source. This is compatible with the focal mechanism solutions of the Bam earthquake and fault displacements during the late Pleistocene.*

Keywords: Bam; Active fault; Strike-slip fault; Geomorphology; Bam Fault

1. Introduction

On the early morning of Friday, December 26, 2003 the southeastern part of Iran was shaken by one of the worst earthquakes in Iranian history. The earthquake which was located south of Bam caused catastrophic damage in the Bam city. Preliminary estimates placed the death toll at 26,500 and 85 percent of buildings damaged or destroyed in the Bam area. International Institute of Earthquake Engineering and Seismology (*IIEES*) placed the epicenter at 29.02°*N*, 58.30°*E* with a focal depth of 8 kilometers, and assigned a surface wave magnitude (*Ms*) of 6.5 to the earthquake.

The fault segment responsible for the December 26 earthquake is difficult to locate as there is no direct surface faulting associated with this earthquake. The only fault which can be related to the earthquake, the Bam fault zone, is not clearly expressed at the surface along its large extent as a result of rapid sedimentation. However, aerial photographs and field observations along some of its sections show geomorphic evidence for repeated surface faulting events. The objective of this paper is to describe the main geomorphic features of the Bam fault zone and fresh ground fractures associated with the earthquake. Based on surface ruptures and fault displacements during the late Pleistocene, the fault zone responsible for the Bam earthquake is recognized.

2. Geological Setting

The Bam earthquake of December 26, 2003 occurred in the low plateau region of southeastern Iran, (see inset in Figure (1)). This region of Lut block constitutes a continental basin environment and is

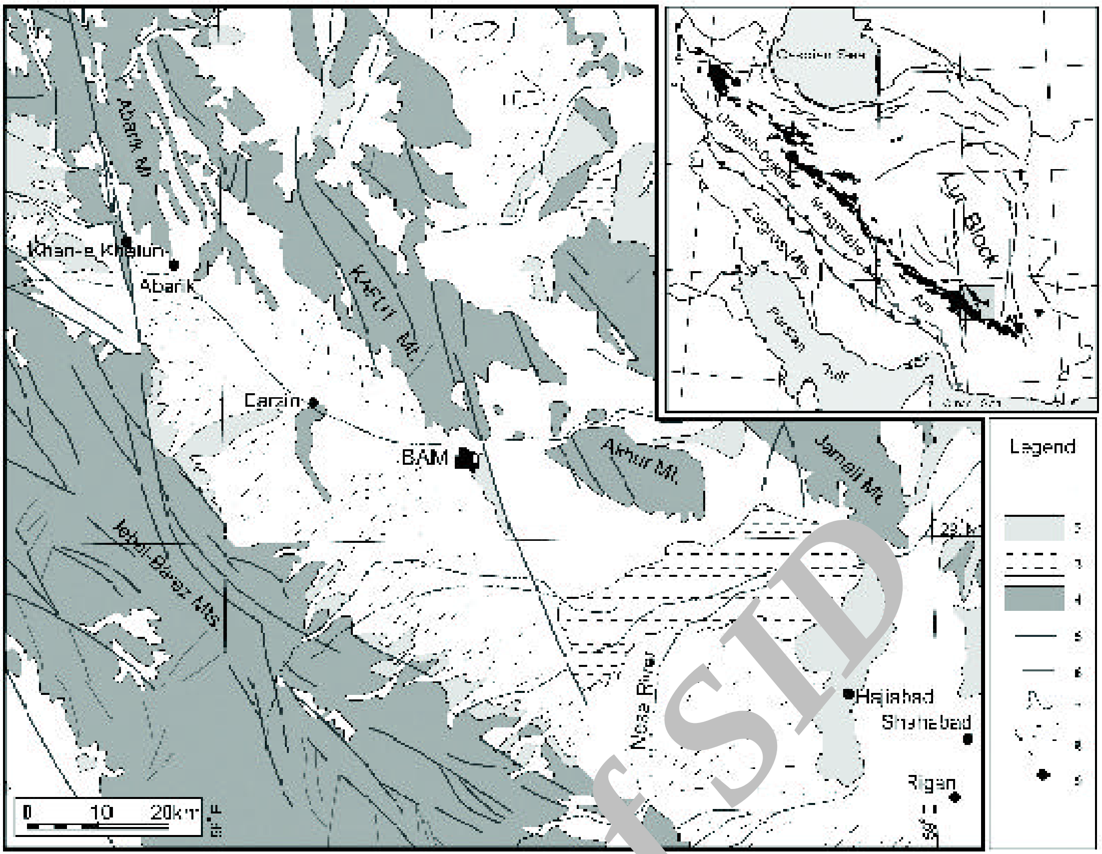

Figure 1. Simplified map of geology-geomorphology of the Bam area, modified after National Iranian Oil Company (1977). The upper right inset shows location of the map, Urmieh-Dokhtar magmatic arc (in black) and the Lut block. 1. Recent fluvial and alluvial deposits, 2. Low terraces and the edge of Dasht, 3. Lake deposits, 4. Volcanic rocks, 5. Major fault, 6. Minor fault, 7. River, 8. Alluvial fan, 9. Town.

tectonically very active compared to the central parts of the block. Cretaceous to Recent continental deposits are found throughout the region.

The Bam area is about 1067 m above sea level and located between two NW-trending mountain ranges (Figure (1)). To the north, the Kafut mountain with an elevation of 242[illegible] *m* represents the highest summit among the many mountains in the north of Bam. Jebal-Barez mountains to the south is the southeastern continuation of the Urmieh-Dokhtar magmatic arc, (see inset in Figure (1)). This arc represents a thin elongated zone of great tectonic movement and manifests itself as an area of intense eruptive and volcanic extrusives of Eocene age. The rivers drain northwestern flank of the Jebal-Barez mountain range and, to less extent, the southwestern flank of the Kafut mountain feed into the main NW-trending drainage system occupying the broad valley between the two ranges. This process is resulted in about 150 meters alluvial deposits overlying the volcanic rocks exposed a few *km* north of Bam.

The Quaternary deposits in the Bam area can be seen as three stratigraphic units. Lake deposits exposed at some 25 *km* to the south, as well as 40 *km* north of Bam, are lower Quaternary in age. The upper Quaternary is represented by low terraces and the edge of Dasht and mainly composed of silt, marl, sand and fine gravels. This unit is overlain by coarse gravels of fluvial and alluvial origin (Figure (1)).

3. Active Tectonics

The active faults of Iran result from active crustal deformation due to the on-going continental convergence between Arabia and Eurasia. Earthquake focal mechanisms suggest that this convergence has been accommodated mainly through *NNW*-trending right-lateral strike-slip faults in eastern Iran (Figure (2)). These strike-slip faults consist of several discontinuous fault segments which are arranged in an en-echelon pattern. Some of these segments ruptured during several earthquakes: the along Kuh-Banan fault zone in 1933 and 1977 [1], and along the Gowk fault zone in 1981, 1989 and 1998 [3]. The Bam fault zone, however, has been seismically inactive during the last two millennia [1].

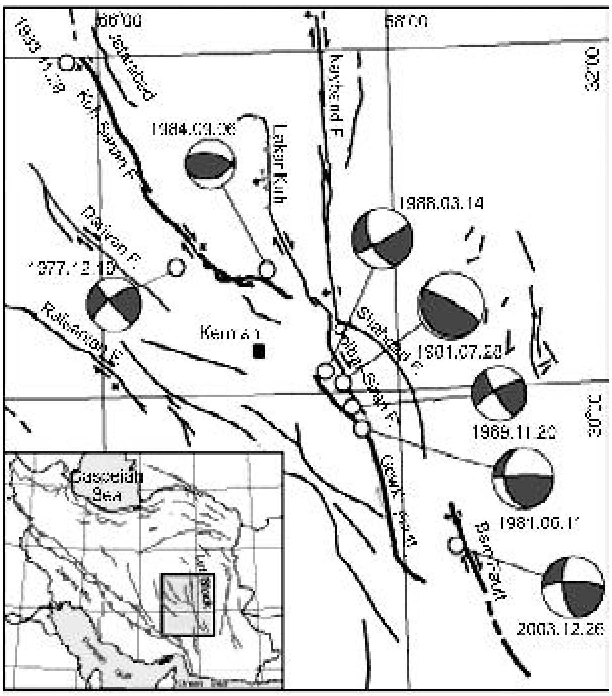

Figure 2. Major faults with CMT solutions of some of the large earthquakes in Eastern Iran. Seismicity occurs along the NNW-trending right-lateral transpressional faults shown by thicker lines.

4. The Bam Fault Zone

The Bam fault zone is considered as one of the active zones in southeastern Iran, (Figure (3)). Offset streams and scarps in alluvium outline this previously mapped fault and indicate that it has been active in Recent times [2, 7]. It has an average strike of *N-NW* over a length of about 50 *km* and dipping west (Figure (3)). Three major fault segments can be recognized along the Bam fault zone namely southern, eastern and northern segments. The geomorphic evidence indicating the late Pleistocene displacements along the Bam fault zone is well preserved along the eastern and northern segments compared to the southern segment. This is because rate of sedimentation along the Bam fault zone generally decreases from south to north as the distance between the Jebal-Barez mountains and the Bam fault zone increases northward.

4.1. The Southern Segment

The southern segment is some 33 *km* long and strikes *N* 18°*W* (Figure (3)). This segment of the Bam fault zone is not directly expressed at the surface along its great extent as a result of rapid sedimentation. Although, the fault zone along this segment is buried by the alluvial and fluvial deposits, it can be mapped on aerial photographs. The lower Pleistocene lake deposits to the east are juxtaposed across this fault segment against the upper Pleistocene deposits of fluvial origin (Figures (1) and (3)). Young alluvial fans and stream beds drain north-western flank of the Jebal-Barez mountains are truncated by this section of the Bam fault zone. A topographic profile across the southern segment is shown in Figure (4a). This profile as well as field observation (Figure (5)) indicates that this segment of the Bam fault forms an uplifted area elongated *NNW* which may represent an incipient fault-propagation fold incised by recent channels. The recent channels are locally displaced right-laterally along the crest of this uplifted area but it is not clearly evident everywhere.

4.2. The Eastern Segment

Some 5 *km* south of the town of Baravat, the southern segment steps left and continues generally northward in the direction of Baravat (Figure (3)). This segment of the Bam fault is about 10 *km* long, trends almost *N-S* and is clearly visible in the geomorphology.

The eastern segment forms a prominent fault scarp whose east side is downthrown relative to the west side. The vertical displacement varies from place to place between 15 and 25 meters. This scarp is a fault-propagation fold verging east as a result of slip along a buried thrust dipping west (Figure (6a)). However, the thrust has reached to the surface across one of its sections in north Baravat (Figure (6b)).

A topographic profile across the eastern Bam fault segment is shown in Figure (4b). As it can be seen a shorter scarp is formed 200 m to the west of the thrust front on the main uplifted surface. Along this shorter scarp channels are systematically displaced right-laterally (Figures (7a) and (7b)). The most spectacular feature among them is two lines of Qanats (underground water tunnels, marked by lines of access shafts) displaced right-laterally for about 11 ± 1 *m* (Figure (7b)). Offsets of several stream beds elsewhere along this section of the fault contain evidence for cumulative displacements by several individual offset events, however, these offsets are difficult to interpret. The vertical component of displacement along this shorter scarp varies between 2 and 3 meters, but in any case, the dip-slip component is subsidiary to the main right-lateral strike-slip movement. The existence of parallel

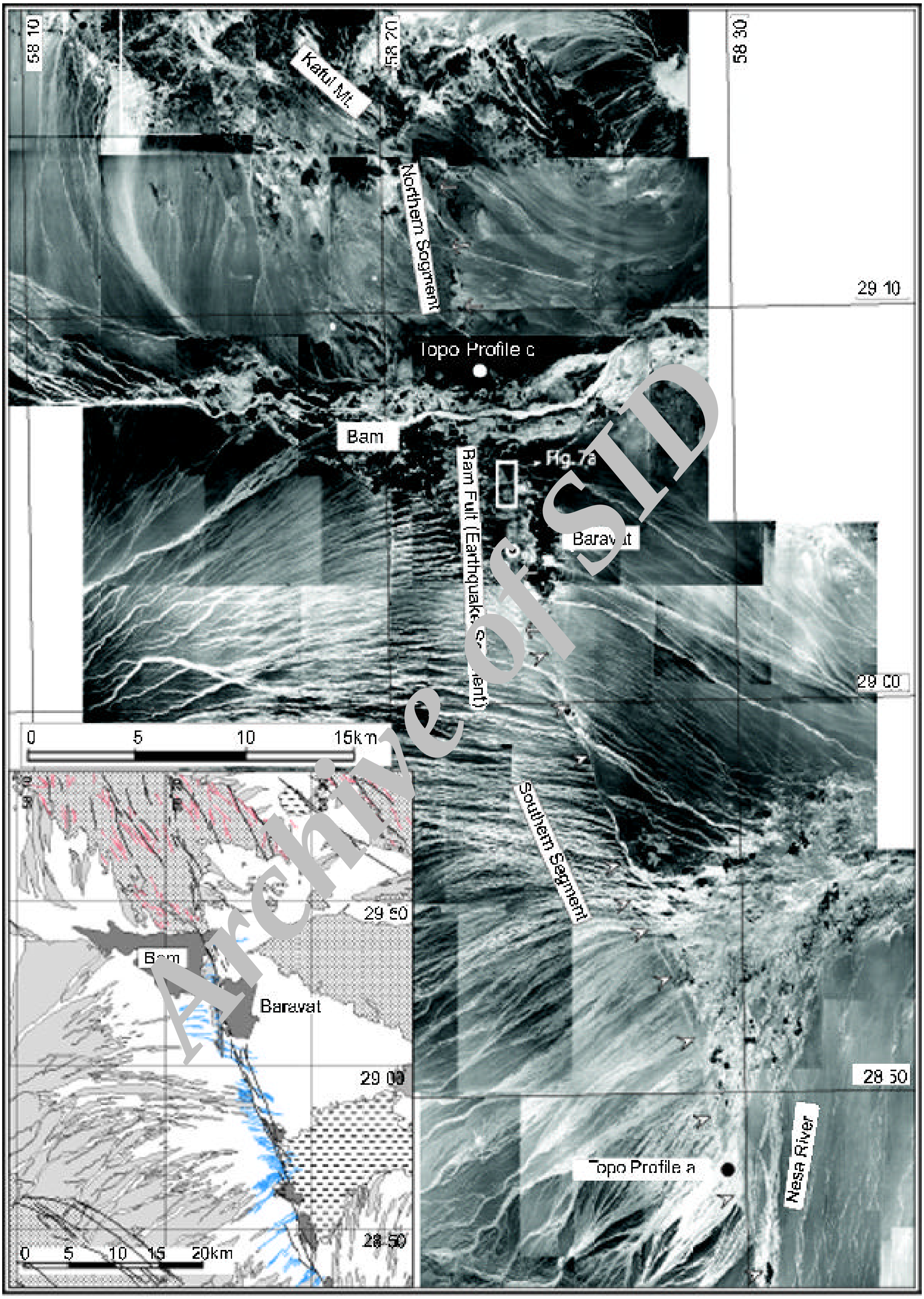

Figure 3. Aerial photomosaic of the Bam region. Bam lies between the Kafut mountains to the north and Jebal-Barez mountains to the south (see the lower left inset). The southern, eastern and northern segments of the Bam fault zone are discussed in the text. Filled circles show the location of topographic profiles in Figure (4). The rectangle encloses Figure (7a).

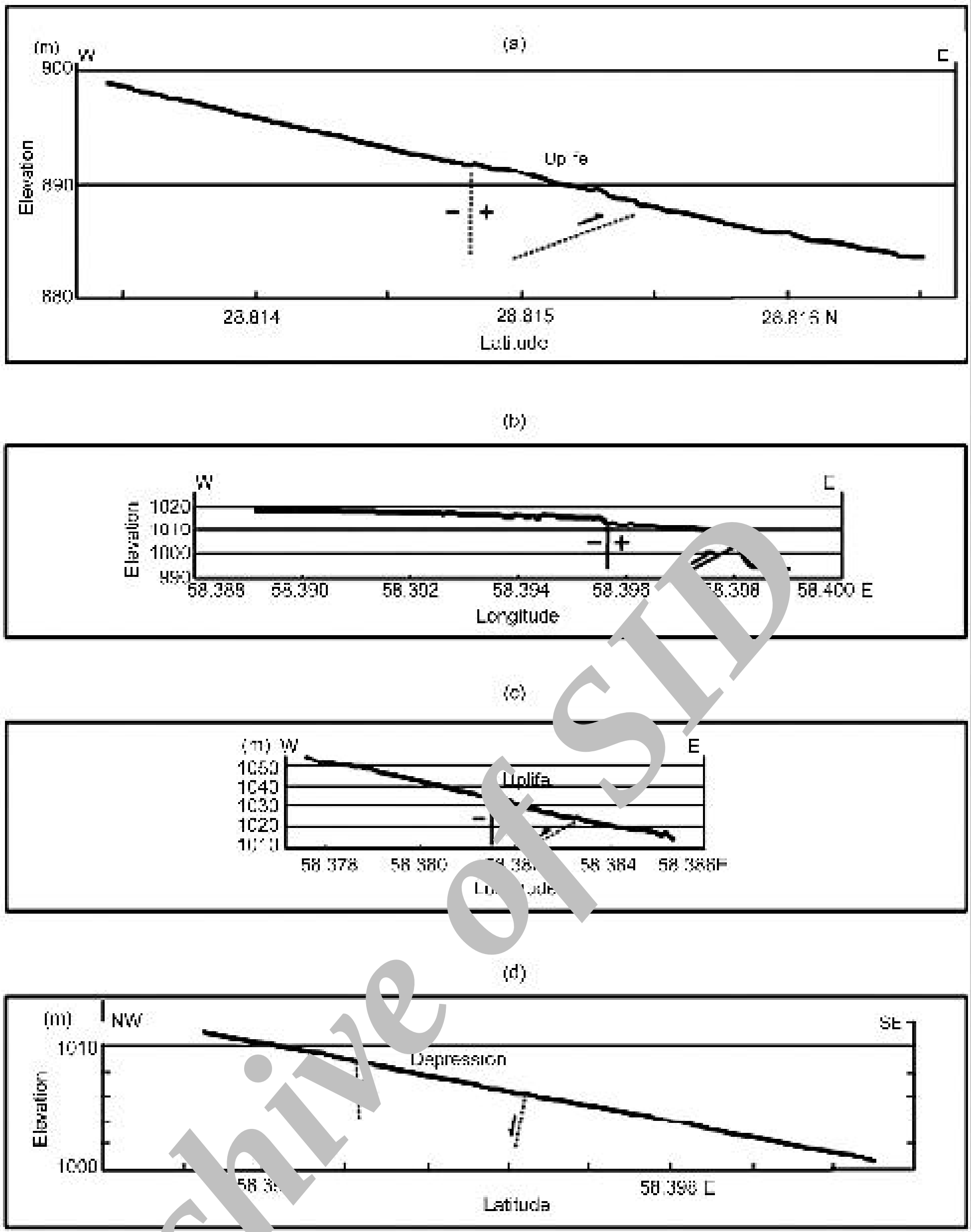

Figure 4. Topographic profiles across the Bam fault zone at several locations surveyed by two System 500 Leica receivers, see Figure (3) for location of the profiles. a, b and c indicate total vertical displacement across the fault scarps. Solid line with sense of motion indicates that the fault is exposed at the surface. Dashed line shows inferred fault. d, topographic profile across coseismic graben structure formed following the Bam earthquake.

Figure 5. Eroded surface and incised channels across the southern segment of the Bam fault zone forming an elongated uplift. Looking southeast.

active thrust and strike-slip faults along this segment of the Bam fault zone may indicate strain partitioning in this region.

The only direct estimate of the horizontal slip rate along this section of the Bam fault is based on the offset Qanats (Figure (7b)). The maximum age of the Qanat line is 3000 years [5, 6, 8, 11]; because it is horizontally offset for 11±1 *m*, it implies a minimum horizontal slip rate of 3-4 *mm/yr*. These rates are two times larger than the rates of 1-2 *mm/yr* suggested by Walker and Jackson [13] for the northern continuation of the Bam fault (i.e. along the Nayband-Gowk-Sabzevaran fault system).

Figure 6. a. Fault-propagation fold verging east, looking north-east. b. Thrust fault exposed at the front of the Bam scarp, looking southeast.

Age of the uplifted surface is not known, however, by making some assumptions on the age of the uplifted surface, we can estimate long-term slip rates of this fault segment. The uppermost layers of the upper Pleistocene sediments incised by drainages that show a 25 *m* vertical displacement could be attributed to the last important post-glacial deposition following the last glacial peak (10 - 10 *ka*). If this assumption is correct, the minimum vertical slip rate is 1.4-2.5 *mm/yr*.

4.3. The Northern Segment

The northern segment trends *N* 10º *W*. Here stream beds and gullies are systematically offset along the fault trace (Figure (8)). Right-lateral offsets of some stream beds along this section of the fault contain evidence for cumulative displacements by several individual offset events. Channels incised within the upper Pleistocene (maximum 125 *ka*) sediments are right-laterally offset for about 320 meters, indicating a minimum slip rate of about 2.6 *mm/yr*. This value is close to the slip rate along the eastern segment.

5. Co-Seismic Ground Ruptures

The geological effect of the Bam earthquake consists of two fresh surface ruptures that trend *N-S* and are 5 *km* apart, south and east of Bam (Figure (8b)).

The fresh surface rupture to the east of Bam developed along the eastern and northern segments of the Bam fault zone and extended discontinuously from south (south of Baravat) to the north for about 11 *km* (Figure (8)). On the eastern segment, the deformation zone consists of numerous tension cracks and fractures along which very small right-lateral motion (0.5-1 *cm*) can be seen (Figure (9)). This indicates that much of the right-lateral motion of the ground surface is distributed over a wide area in east Bam. The most spectacular feature along this segment is two normal faults 12 m apart forming an oblique graben on the crest of the fold on the main road connecting Baravat to Bam (Figures (4d) and (10)). The *N10°* trending normal faults at this locality suggest right-lateral movement along the principal displacement zone. On the northern segment, however, deformation is distributed over a 2 *km* wide zone in the northern Bam vicinity where numerous hairline ruptures trending *N* 20º*W* were evident (Figure (8)). The amount of displacement on individual fractures is as small as 0.5-1 *cm* right-lateral motion. The eastern side of this rupture zone follows exactly the previously mapped fault trace (i.e. the northern segment). The most characteristic deformational structure along the northern segment is mole tracks (Figure (11)). The size of mole tracks varies from 4 to 8 *cm* high, 10 to 50 *cm* wide and 1 to 1.5 *m* long. Mole tracks are typical push-up structures along the strike-slip rupture zones [4].

Following the Bam earthquake, an en-echelon rupture pattern stepping left developed in alluvium deposits in south of Bam, where no fault trace is visible in the geomorphology (Figure (8)). Each of individual ruptures trend *N*30º*E* and represent synthetic shear fractures (Reidel shears) which have developed along a *N-S* trending principal right-lateral fault zone in the basement. The maximum amount of right-lateral displacement observed along the fresh synthetic shears was about 5.5 *cm* (Figure (12)). This rupture zone which has been also revealed by *InSAR*, is considered as the main strike-slip fault responsible for the Bam earthquake [12]. However, on the northern and eastern segments of the Bam fault the same amount of co-seismic displacement or more is distributed over a wide fracture zone but, it is not delineated by *InSAR*. This is because, using

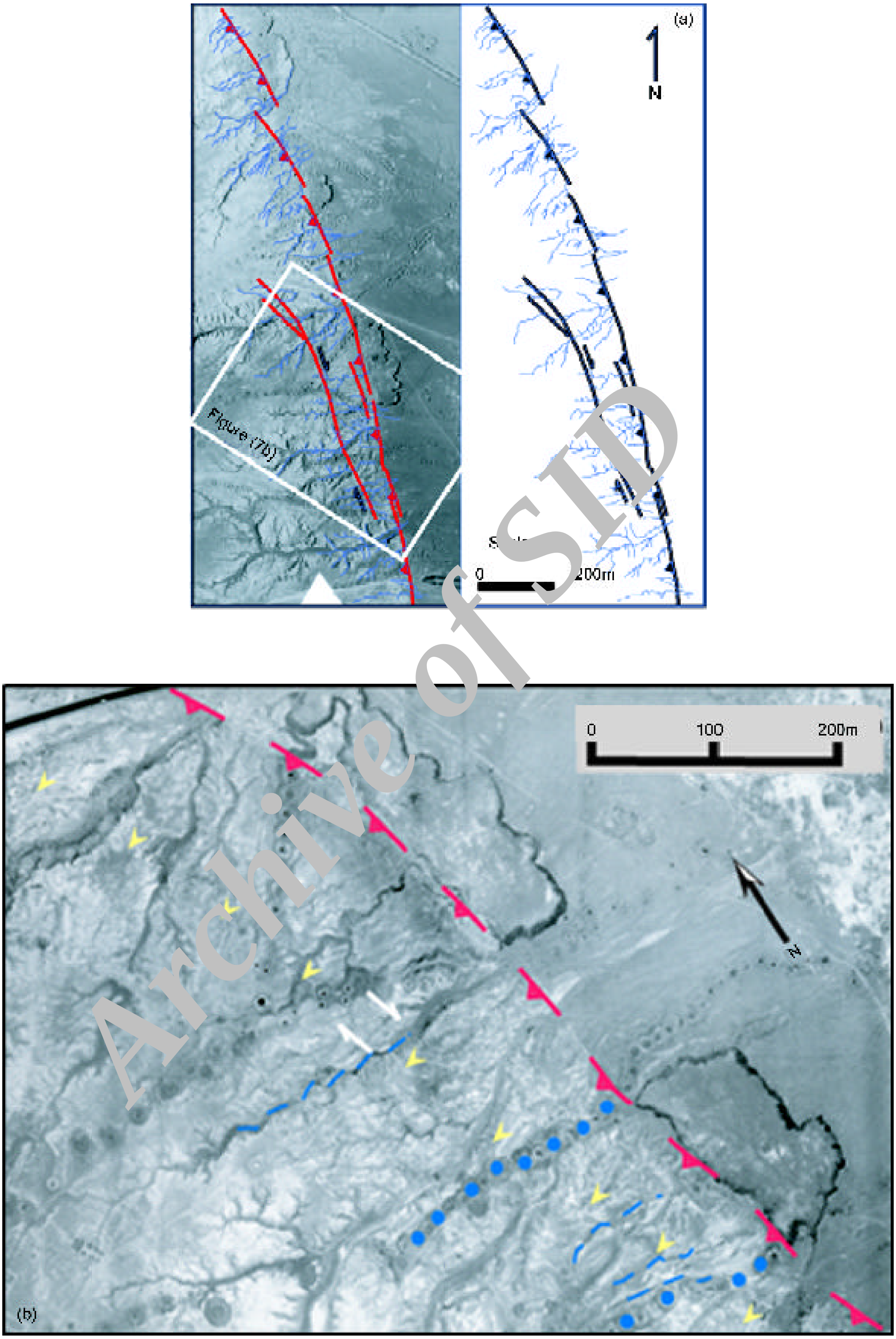

Figure 7. Aerial photographs of the eastern segment of the Bam fault zone. a. shows parallel active thrust and strike-slip faults forming this segment of the Bam fault zone. The rectangle encloses Figure (7b). b. stream beds and lines of Qanats are systematically offset along the fault trace. Red dashed line shows the Bam thrust forming the Bam scarp east of Bam, yellow arrowheads mark the strike-slip fault trace, blue circles mark the Qanat's shafts displaced right-laterally.

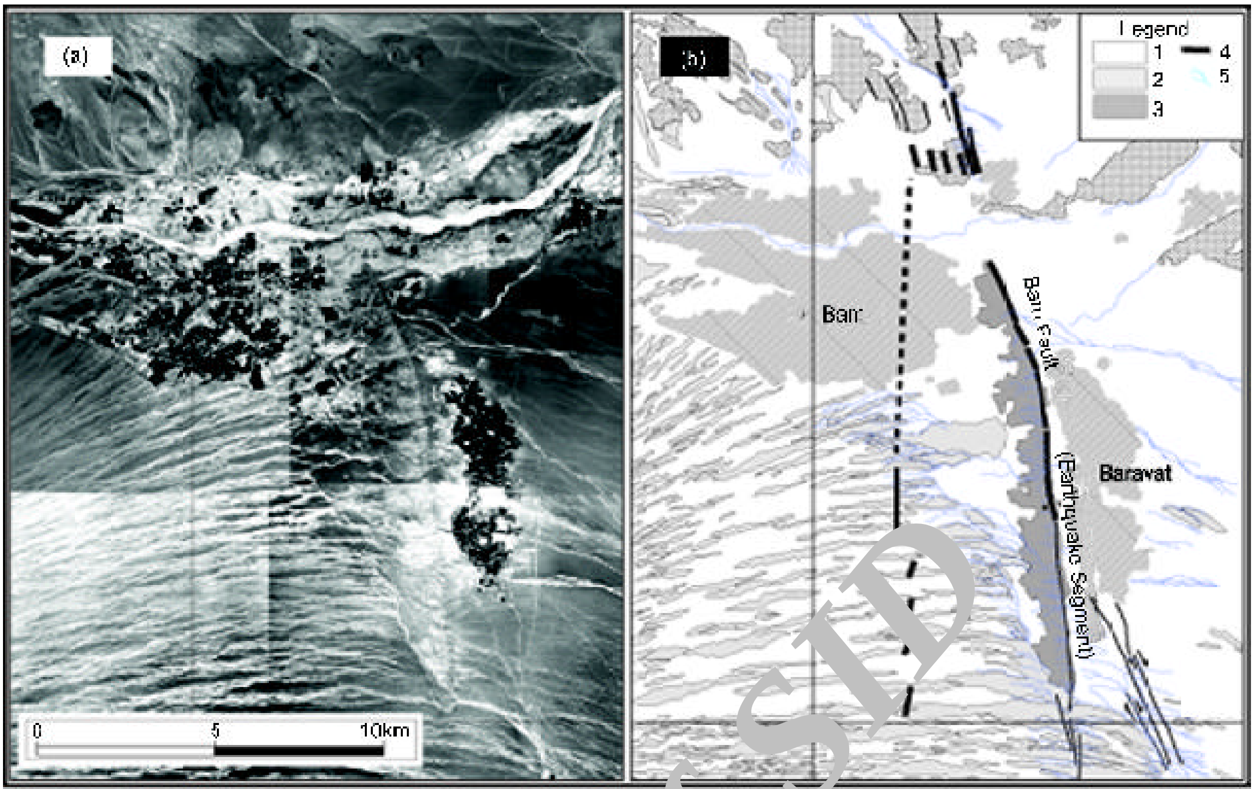

Figure 8. a. Aerial photomosaic of the Bam area. b. Line drawing showing surface ruptures associated with the Bam earthquake. Note 2km wide co-seismic hairline ruptures in the northern Bam vicinity. 1. Alluvial deposits 2. Fluvial deposits 3. Low terraces 4. Co-seismic rupture 5. Draiage channels.

interferometery, it is not easy to define displacements of 0.5-1 *cm* or less [9].

Finally, fresh ground displacements along co-seismic surface ruptures are not representative of total amount of slip along the principal earthquake fault which was not exposed at the surface. However, direction and sense of motion along co-seismic ruptures (synthetic shears, mole tracks and grabens) in the Bam area indicates right-lateral motion on a

Figure 9. Tension cracks with 0.5 cm lateral displacement west of Baravat.

Figure 10. Two different views of the oblique graben structure on the crest of the fold on the main road connecting Bam to Baravat.

Figure 11. Two different views of mole tracks north of Bam. Upper photograph looking south, the lower one looking north.

wide strike-slip fault zone whose eastern side is marked by the right-lateral Bam fault. In other words, the co-seismic ruptures in east, northeast and south Bam were related structures in a right-lateral zone 5 *km* wide. This is compatible with the *CMT* solution which corresponds to right-lateral strike-slip motion on a fault striking *N172 E* (Figure (2)).

Figure 12. Maximum 5.5 cm lateral displacement measured south of Bam.

6. Conclusions

The Bam fault zone is composed of sub-parallel strike-slip and thrust faults which have clear expression in the geomorphology. The December 26, 2003 Bam earthquake was an example for a good correlation between long-term cumulative deformation along an active fault zone and source parameters of an earthquake. The fault responsible for the Bam earthquake was not exposed directly at the ground surface. However, surface ruptures associated with the earthquake at Bam imply that the earthquake occurred along right-lateral segments of the Bam fault zone. This is compatible with the focal mechanism solution of the earthquake and fault displacements during the late Pleistocene.

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