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SURFACE RUPTURE AND MECHANISM OF THE BOB-TANGOL (SOUTHEASTERN IRAN) EARTHQUAKE OF 19 DECEMBER 1977

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The Bob-Tangol earthquake of magnitude 5.8 (M_S), occurred in southeastern Iran on 19 December 1977, not far from the region where the 1896 and 1933 earthquakes caused considerable damage and destruction. The shock was associated with a 19.5-km fault break at the surface with a maximum 20 cm right-lateral strike-slip movement along an Early Quaternary geological fault. Results of the field investigation together with the fault plane solution and epicentre location of the main shock are presented here in order to give a seismotectonic view of the event.

Surface rupture and fault plane solution of this medium-magnitude earthquake demonstrate a considerable amount of right-lateral movement along a major Early Quaternary high-angle reverse fault. This change in fault behaviour and slip vector may indicate that evidence of Early Quaternary movement cannot always provide a good clue to present-day crustal deformation.

1. Introduction

The Bob-Tangol (northeastern Zarand, Iran) destructive earthquake occurred at 23 : 34 : 34 GMT on 19 December 1977, along a segment of the Kuh Banan Fault [1–3], in the Kerman province of southeastern Iran, a region known to have been seismically active at least since 1896. The macroseismic epicentre of the main shock was located at 30.9°N, 56.6°E (Fig. 1).

The main shock destroyed or severely damaged about five villages, killed 551 and injured 247 people in a remote, desert area. The low casualty rate has been partly due to the fact that the stricken area was sparsely populated and partly because of the damaging foreshock of 9 November 1977, which made the Dehzu villagers live in tents. The maximum intensity of the shock just exceeded VII on the Modified Mercalli Intensity Scale (Fig. 2). A day after the main shock, heavy rain in the area washed away some parts of the earthquake faulting or covered it with debris, but nonetheless most of the features which did not cross alluvial fans were scarcely affected. Despite the obliteration of the original features in the fans by this storm, new features appeared which must have been associated either with aftershocks or with post-seismic creep.

2. Regional seismicity

Very few earthquakes from the Kuh Banan Fault zone have been documented because of remoteness,

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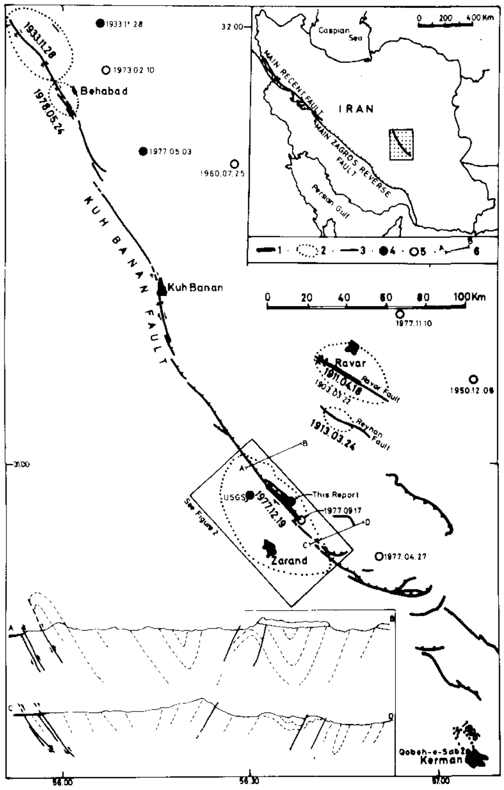

Fig. 1. Map of the Kuh Banan Fault in southeastern Iran. The epicentral regions of 1896, 1933 and the recent earthquakes of 19 December 1977 and 24 May 1978 are shown along the fault line. Two cross-sections (after Huckriede et al. [1]) of *A-B* and *C-D* are presented to emphasize the Early Quaternary high-angle reverse character of the fault in the investigated area. The Upper Precambrian–Lower Cambrian sediments (NE) are thrust over the Quaternary alluvial deposits (SW). The reactivated part of the fault during the recent Bob-Tangol earthquake, with a right-lateral movement of 20 cm, is shown by a thick line. Legend: 1 = documented earthquake fault; 2 = epicentral region; 3 = Early Quaternary fault; 4 = instrumental epicentre, $5 \leqslant m_b < 6$; $5 = m_b < 5$; 6 = geological cross-section.

low population and distance from the trade routes. We only know two destructive earthquakes along this fault; the Behabad earthquake of 1933.11.28 (with about 10 km of surface rupture associated with the earthquake), and the Qobeh-e-Sabz earthquake of 1896 in the north of the city of Kerman (Fig. 1). Three other destructive and damaging earthquakes took place about 60 km northeast of the Bob-Tangol 1977.12.19 earthquake region, in Ravar and Reyhan, in 1903, 1911 (with surface rupture along the Ravar Fault, shown in Fig. 1), and 1913. However, an interview with the people of the Bob-Tangol region showed that this segment of the Kuh Banan Fault was aseismic at least for three generations.

The location of the 20th century instrumentally recorded earthquakes in the investigated area, as well as the macroseismic regions of the major shocks, and surface ruptures associated with them, are presented in Fig. 1, which shows a very low recorded seismicity along the fault. For major shocks for which macroseismic data are available, the instrumental epicentres appear to be in error by tens of kilometres, therefore, the maximum damage zone of these earthquakes are given [4]. The error is about 50 km for the 1903.03.22 Zarand earthquake, 10 km for the 1911.04.18 Zarand earthquake, 20 km for the 1933.11.28 Behabad earthquake and finally 12 km for the recent destructive earthquake of 1977.12.19.

3. Foreshocks

The recent seismic activity along the Bob-Tangol segment of the Kuh Banan Fault started on 17 September 1977 when the area was strongly shaken by an earthquake. The second shock was felt on 15 October and the third one on 7 November. On 9 November, a rather strong shock (named here as the damaging foreshock) severely damaged Dehzu and Bob-Tangol villages (Fig. 2). No instrumental location is given for this shock, but its macroseismic epicentre is estimated at 30.9°N, 56.5°E, based on the field investigation. Two more shocks were felt by people in villages near the fault line on 10 and 13 November. Following this date no earth tremors were felt for 35 days between 13 November and 19 December. The main shock of 19 December 1977 occurred without any premonitoring foreshock which would have permitted people to wake up and escape from their houses.

The damaging foreshock of 9 November hit two villages (Dehzu and Bob-Tangol) on the northwestern segment of the Bob-Tangol Fault, and its macroseismic epicentre can be confidently located. During the main shock the centre of activity was shifted to the southeast, i.e., towards the Gisk region. Although the houses in the village of Dehzu were damaged and weakened by the damaging foreshock, they did not collapse

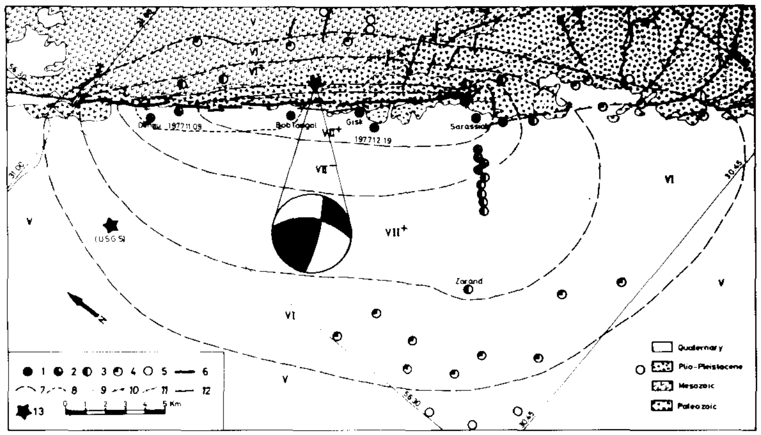

Fig. 2. Epicentral region, fault plane solution and map of the Earthquake Fault of the Bob-Tangol 19 December 1977 earthquake along the Kuh Banan high-angle reverse fault, northeast of Zarand. Despite the major reverse movement during the Early Quaternary (thrusting of Lower Paleozoic sediments over Quaternary alluvium), the earthquake faulting is right-lateral with a maximum offset of 20 cm. The earthquake fault is limited between two transversal tear faults. The asymmetric damage distribution may be because of the differences in foundation materials and in building type. Legend: 1 = houses completely destroyed; 2 = houses partly destroyed, badly damaged; 3 = houses damaged; 4 = houses fissured; 5 = the shock strongly felt; 6 = earthquake faulting; 7 = isoseismal line of the main destructive shock of 19 December 1977; 8 = isoseismal of the damaging foreshock of 9 November 1977; 9 = geological contact; 10 = synclinal axes; 11 = anticlinal axes; 12 = geological fault; 13 = instrumental epicentres of the main shock (U.S.G.S. and our locations).

completely during the main shock. The damaging foreshock made a pronounced distortion on the main shock macroseismic pattern and enlarged it northwestwards, covering the Dehzu region as well (Fig. 2).

4. Mainshock and surface faulting

The destructive earthquake of 19 December 1977 was associated with a right-lateral strike-slip surface rupture of 19.5 km long (the Earthquake Fault) caused by the reactivation of a high-angle reverse geological fault (the Kuh Banan Fault). The earthquake triggered several landslides.

The Kuh Banan high-angle reverse fault (Fig. 1) was first referred to as a recent major seismic fault by Huckriede et al. [1] and Berberian [2,3]. The fault is composed of several deep-seated en-échelon segments along which the Late Precambrian and Lower Paleozoic rocks thrust over the Quaternary alluvial deposits. The total length of the fault is more than 300 km and is clearly recognizable on the ground, especially in the sections where it separates hard rocks in the east from fanglomerates in the west. Pre-earthquake aerophotography do not indicate lateral motion along the Bob-Tangol segment of the Kuh Banan geological fault, along which the earthquake of 19 December 1977 took place. A subsequent field survey in the region along the faults given in Fig. 1, showed no evidence of reactivation of any other segments of the Kuh Banan and/or the nearby faults. However, it should be mentioned that the extreme northwestern segment of the Kuh Banan Fault was reactivated during the Behabad earthquake of 28 November 1933 ([1,2,5]; see Fig. 1).

The Bob-Tangol segment of the Kuh Banan Fault appears to be limited in the north and south by two minor transversal tear faults (Fig. 2). The segment has a gouge zone varying in width from a few metres to 30 m. The latest pre-earthquake movement along this segment (with a trend of N140°E and dip of 70°NE) produced new slickensides on the hanging wall with an average strike of N116°E and a plunge of 50°SE. Along this trend the Lower Paleozoic rocks (in the northeast) are thrust over the Quaternary alluvial deposits (in the southwest), thus the fault was an active reverse fault in the Early Quaternary. The area also shows several Late Precambrian–Early Cambrian Desu (Dehzu) Series (Hormoz Salt) deposits intruded into the Lower Paleozoic formations. The Kuh Banan Fault was a major facies divider during Late Pre-

Fig. 3. Right-lateral offset of a small stream bed along the earthquake fault at Gisk, looking west.

Fig. 4. Right-lateral offset of tractor wheel tracks along the branches of the earthquake fault, looking west.

cambrian–Early Cambrian time controlling the western part of the Hormoz Salt basin. No major Hormoz Salt is deposited in the western part of this deep-seated fault. It is therefore concluded that it is a very old feature.

Despite the fact that the Bob-Tangol segment acted as a major high-angle reverse fault during the Early Quaternary, earthquake faulting in the December 1977 shock is predominantly right-lateral strike-slip without any significant or detectable vertical movement at the surface. Several en-échelon tension openings with a strike of N-S to N20°E, indicative of right-lateral slip, were found along the fault line. Stream beds and wheel tracks of tractors were displaced right-laterally maximally 20 cm by the earthquake fault (Figs. 3 and 4). The 19.5-km pronounced surface break of this medium-magnitude earthquake may indicate that the northern segment of the present earthquake fault was activated during the damaging foreshock; a fact which we cannot prove, because nobody visited the fault line in the 35-day period between the damaging foreshock and the main shock.

The maximum 20-cm measured movement is observed southeast of the Gisk village in the southern part of the earthquake fault. Although the horizontal movement is changing inconsistently along the fault line, the displacements decrease and the fresh surface rupture gradually dies out as the earthquake fault approaches the extreme northwest and southeast ends of the fault segment, where the fault is cut by two minor tear faults (Fig. 5).

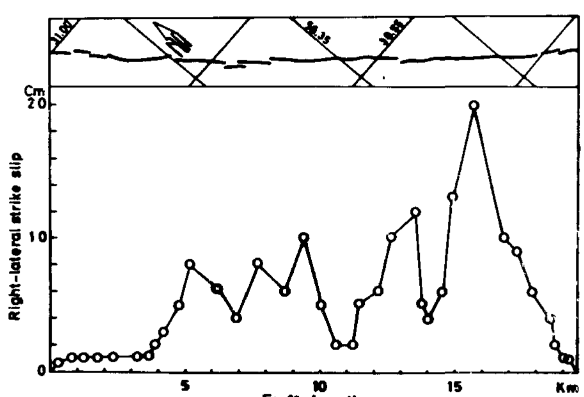

Fig. 5. Inconsistent horizontal displacement at the surface along the Bob-Tangol earthquake fault of 19 December 1977. Vertical axis is right-lateral displacement in centimetres and horizontal axis is fault length in kilometres.

5. Epicentre location

To locate the main shock the computer programme currently used by the Seismological Network of Ferdowsi University [6] has been used, in which a three-layer velocity model for P- and S-waves in the crust and upper mantle is assumed. The velocity model is taken from Asudeh [7], which is:

Layer	V_P	V_S	Thickness (km)
1	5.7	3.3	15
2	7.1	4.1	35
3	8.05	4.6	

P-readings from 12 regional seismic stations are used in the location programme. Since no S-readings were available and the nearest station is more than 300 km from epicentre, the control on depth of the event is poor. Our epicentral parameters and those of U.S.G.S. are as follows:

Origin time (GMT)	Location	m_b	M_S	Depth	N	Source
23 : 34 : 33.1	30.9°N, 56.6°E			9	12	present
23 : 34 : 34.2	30.954°N, 56.473°E	5.4	5.8	31	151	U.S.G.S.

in which N is the number of recording stations. A comparison of these two locations (Fig. 2) shows that the location given in this report is closer to the macroseismic epicentre than the U.S.G.S. location.

6. Fault plane solution

Based on the data collected from many seismological stations, a fault plane solution was made for the main shock. The polarities of the P-wave first motion (Fig. 6) show two nodal planes striking N148°E (dipping 58°NE) and N69°E (dipping 80°SE). Field investigation of the 20-cm right-lateral surface motion

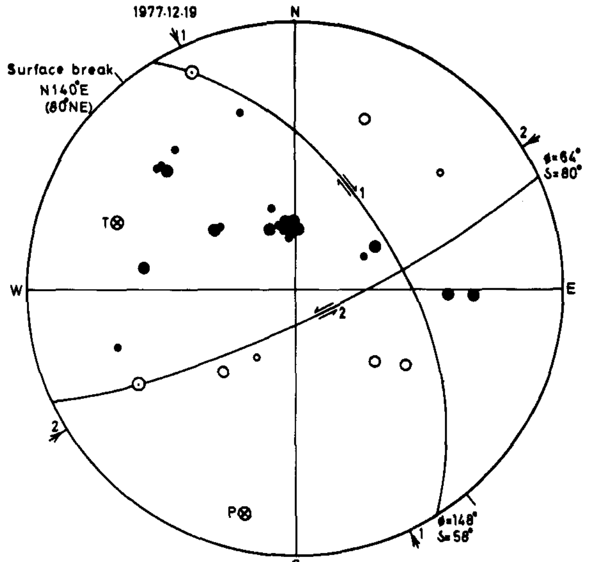

Fig. 6. Fault plane solution of the Bob-Tangol main shock of 19 December 1977. Equal area projection of the lower hemisphere of the focal sphere. Long-period polarity observations are shown as large circles and short-period data as small circles; open if the polarity was dilational, solid if it was compressional. T = tension axis, P = pressure axis. The focus is taken to be in the crust with a P-wave velocity of 6.8 km s^{-1}. The strike and dip of the surface break are also shown.

along the N140°E direction is consistent with the first plane being the fault plane. Although the solution shows a large lateral movement, there is a small component of thrusting which was not detectable on the surface during field work. The movement at the surface presented many strike-slip features; right-lateral offsets of stream beds, right-lateral en-échelon tension features, wheel track offsets, etc. (Figs. 3 and 4). Thus both the field observations and the fault plane solution suggest a change of fault behaviour, and hence of slip vector, in a relatively short geological period: the major amount of thrusting in the Early Quaternary changing to a predominantly right-lateral movement during the recent earthquake.

The average trend of the horizontal slip vector for Early Quaternary thrust movement along this fault, deduced from slickenside measurements (the only evidence available at present [8]) on the fault plane at the surface, is N116°E with a plunge of 50°SE, whereas the slip vector from the fault plane solution has a trend of N155°E. This change of slip vector trend, and hence the change of angle between the horizontal slip vector and fault trend, changed the horizontal to vertical displacement ratio of the fault.

Similar changes of slip vector have been found elsewhere in Iran. The Main Zagros Reverse Fault [2] behaved as a high-angle reverse fault during the Late Mesozoic–Early Quaternary orogenic movements (Zagros Orogeny or Wallachain), while in the same place the Main Recent Fault [9], which formed later, has shown right-lateral strike-slip movement during recent earthquakes (Fig. 1, inset). Another case of slip vector changing during Early and Late Quaternary time was noticed along the Buyin Zahra (Ipak) earthquake fault [2].

7. Damage to buildings

No major engineering structures were in the strongly shaken area, but the proximity of several mines, power plant installations, the town of Zarand, and the city of Kerman (which was partly destroyed during the Qobeh-e-Sabz earthquake of 1896), make the study of the Bob-Tangol earthquake important from the engineering as well as from geological and structural points of view. The earthquake had a restricted damage area in which the buildings were left in a highly unsafe and unstable condition. It is concluded that the motion in this region was intense and of short duration since continuing motion of even small amplitude would have destroyed the unstable structures. A few adobe mudstone houses which were built on the bedrock adjacent to the earthquake fault (e.g. the prayer house at Bob-Tangol) were damaged but did not collapse, while the same style of adobe houses were completely destroyed in the plain. A lower intensity in the immediate vicinity of the earthquake fault break than in the region at some distance from it was also observed by Ambraseys [10] during the Buyin Zahra earthquake of 1962 and by Berberian and Tchalenko [11] along the Salmas earthquake fault of 1930. The damage distribution is asymmetric with respect to the surface expression of faulting (Fig. 2). This is unlikely to be due to the seismic source (since the fault dips NE) and is probably associated with differences in the foundation material (bedrock to the northeast, alluvial deposits to the southwest of the earthquake fault), or the difference in building type.

8. Aftershock sequences

Aftershock activity during the first four months appeared to be concentrated along the Bob-Tangol segment of the Kuh Banan Fault and most aftershocks were felt by the inhabitants. On 24 December 1977 at 20.20 GMT the strongest aftershock caused some additional damage to the villages of the Bob-Tangol region and made people run outdoors. The last shock felt by the people in this region was the one of 2 April 1978 at 08.25 GMT.

Five months after the main destructive shock, the seismic activity shifted northwestwards along the Kuh Banan Fault and caused a damaging earthquake at Behabad, not far from the epicentral region of the 1933.11.28 destructive earthquake (Fig. 1). The seismic activity along this segment started two days before the Behabad damaging shock on 22 May 1978 with a minor tremor at 07.25 GMT. The second shock was strongly felt by the Behabad villagers on 23 May at 13.45 GMT. The damaging earthquake took place on 24 May 1978 at 05.10 GMT along the Behabad segment of the Kuh Banan Fault. During this shock 70 houses were badly damaged and the ceiling of the Behabad Polic Office collapsed.

9. Concluding remarks

The recent seismic activity of the Bob-Tangol segment of the Kuh Banan Fault started from its northwestern extremity on 17 September 1977 (91 days before the destructive shock) with a series of minor tremors and a damaging foreshock. After a 35-day gap in the "felt" seismic activity following the damaging foreshock, the seismicity migrated southeastwards along the same fault segment, creating the destructive earthquake of 19 December 1977. The damaging foreshock may have increased the stress field in the region of the mainshock.

Right-lateral ground displacements that accompanied the main shock coincided precisely with the pre-existing geological fault trace of high-angle reverse character. The earthquake clearly demonstrates that slip vectors on individual faults can change. Evidence of Early Quaternary movement cannot always be extrapolated to indicate present-day crustal deformation. This must be considered when geological data are used for recent-tectonic and seismic-risk evaluation studies. The Bob-Tangol earthquake (coupled with the Main Recent Fault data of Zagros) indicates that in a structurally complex and inhomogeneous collision region such as Iran, short-term behaviour is not obviously related to interplate slip vectors derived from time-averaged data.

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