Coseismic fault–related folding during the South Golbaf earthquake of November 20, 1989, in southeast Iran

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ABSTRACT
The South Golbaf earthquake of November 20, 1989 (m_s 5.7, m_b 5.6, I VII), in southeast Iran, was associated with coseismic surface faulting and folding. Surface faults 11 km (west-dipping) and 8 km (east-dipping) long with oblique reverse mechanisms developed on both sides of a small Holocene playa. Apparently, repeated coseismic fault–related folding was responsible for the Holocene 20° tilting of the playa deposits above the active fault tip at the ground surface. This study provided the first evidence of earthquake folding of Holocene playa deposits in Iran.

INTRODUCTION

The amount of displacement on a seismic fault at the surface during an earthquake (slip per event) and the fault slip rate (net tectonic displacement on a fault during a measurable period of time) reflect the rate of strain-energy release, which can be expressed as seismic moment and stress drop. The true amount of displacement per event and slip rates of faults, especially reverse faults, are difficult to determine because (1) the slip may diminish from the seismic source at depth toward the ground surface, (2) part of the motion may be accommodated by coseismic folding growth associated with, if not caused by, coseismic faulting, and (3) much of the faulting may be distributed over wide areas near the surface. Therefore, basic fault parameters are probably underestimated at the surface. Thus, the reverse-fault earthquakes in compressional tectonic regimes leave an incomplete displacement record at the ground surface, and shallow faulting is not necessarily a direct reflection of fault displacement at depth (King et al., 1981; Stein and King, 1984; Berberian et al., 1984; Namson and Davis, 1988; Davis et al., 1989).

The South Golbaf earthquake of November 20, 1989 (m_s 5.7, m_b 5.6, I VII), in the Kerman province of southeast Iran, provides the first evidence of coseismic surface faulting and folding of the playa deposits in the country. As with the two events of June 11 (m_s 6.7) and July 28 (m_s 7.1), 1981, to the north of the present meizoseismal area (see Berberian et al., 1984, for more information), the November 20, 1989, earthquake was associated with surface deformation that followed the mapped traces of the southern Gowk active fault system (Fig. 1). Because few people lived in the region of the epicenter of the 1989 earthquake, casualties were few and damage was minimal.

The November 20, 1989, earthquake, which took place at 14:19 GMT (07:51 local time), killed four people and injured 45. Most of the walls and objects in Golbaf fell down or were thrown to the east. All four casualties were killed by collapsing walls. Window panes broke in Golbaf, and several buildings were damaged, including the newly built mosque at Shahrak-e-Sodughi (built to the west of the town after the Golbaf-Sirch earthquakes of June 11 and July 28, 1981). Cracks developed in the shallowest part of the Golbaf depression south of Golbaf (called "darya" [sea]), and its water became muddy. Water flow in the Kushk qanat (underground water canal) in the northeastern part of Golbaf doubled, but the Tirgan qanat in the area south of the Golbaf sand pit (south of the town) dried up after the earthquake. Sand blows and mud volcanoes formed along the Golbaf river bed, especially in the area south of Golbaf.

Cracks developed in the buildings at Zamanabad, Fandoqa, Jowshan, and Chahar Farsakh, situated 5, 16, 29, and 60 km, respectively, north of Golbaf. The shock caused some minor damage in Kerman, the capital city of the province, 80 km to the northwest of the 1989 meizoseismal area. The earthquake was followed by

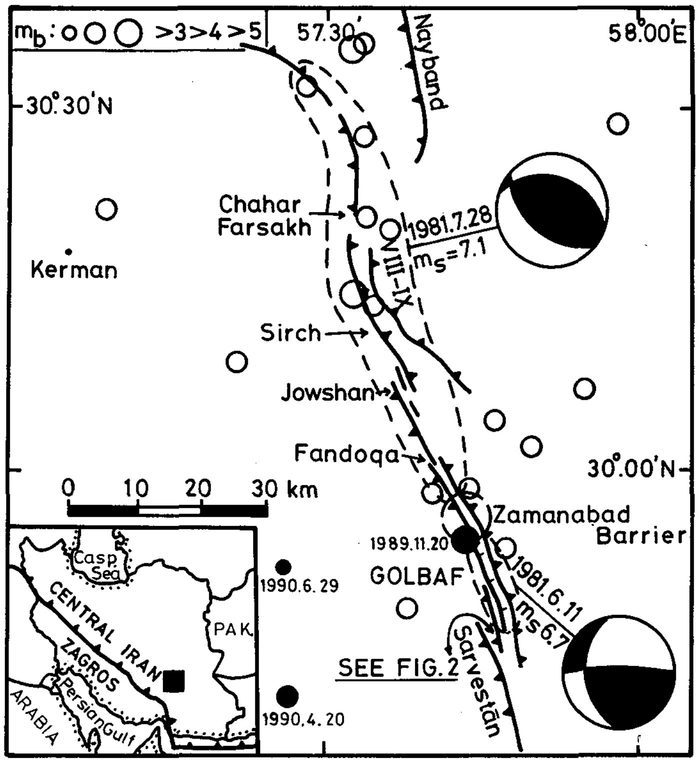

Figure 1. Seismicity (National Earthquake Information Center [NEIC], U.S. Geological Survey) on Gowk fault system since June 1982. (For historical and teleseismic data prior to June 1982, see Figs. 1, 4, and 7 with Table 1 in Berberian et al. [1984].) Solid circle indicates epicenter of November 11, 1989 (m_s 5.6), earthquake with its two poorly located aftershocks (NEIC). Faults (high-angle thrusts; sawteeth on hanging wall) and fault-plane solutions are after Berberian et al. (1984). Dashed-line ellipses indicate areas within which intensity was >VIII–IX (MMI) for July 28, 1981, Sirch and VII (MMI) for June 11, 1981, Golbaf earthquakes. Large open circle between two dashed ellipses indicates Zamanabad "barrier" proposed by Berberian et al. (1984).

several aftershocks that were felt in Kerman, but only two of them were recorded by the teleseismic network (Fig. 1).

It is worth noting here that teleseismic epicentral locations of earthquakes in Iran have large errors. Therefore, detailed correlation between seismicity and tectonics, as may be done for earthquakes in the United States and Japan, should not be expected in Iran (Berberian, 1978).

COSEISMIC SURFACE DEFORMATION

Surface Faulting

The November 20, 1989, earthquake rupture occurred in the southern part of the 1981 meizoseismal region. It had been predicted that the next event after the 1981 earthquakes would take place to the north (along the active Nayband fault system) or to the south (along the active Sarvestan fault segment of the Gowk fault system) of the 1981 fault breaks (Fig. 1), where the seismicity had been low (Berberian et al., 1984). However, the 1989 earthquake occurred along a short segment of the Gowk fault system whose southern part had not moved during the 1981 earthquake sequence. The whole Gowk fault system, except the Sarvestan segment to the south, moved during the 1981 and 1989 earthquakes (Fig. 1). Therefore, the Sarvestan segment should be considered to pose a serious seismic risk in the future.

We briefly visited the area a week after the November 20, 1989, earthquake. Two fresh surface ruptures had developed along the Gowk fault system, south and southeast of Golbaf (Fig. 2). As in the Golbaf and Sirch earthquakes of 1981 (Berberian et al., 1984), two faults on both sides of the South Golbaf depression were reactivated (Fig. 2). The surface rupture on the western side of the depression extended for 11 km, and the one on the eastern side for 8 km.

The western fault is a short fault segment of the Gowk fault system (Figs. 1 and 2). Its northern and southern ends die out in the Golbaf and South Golbaf depressions, respectively (Fig. 2). The Quaternary fault scarp along the western fault is about 5 m high; it was created by previous earthquakes. The height of the Quaternary fault scarp diminishes from 5 m in the north to 1 m and less in the south, where the fault enters the playa and shows surface folding (Fig. 3). To our surprise, the 1989 surface displacements and the pre-earthquake escarpment diminish toward the south. The western reverse fault, which dips 60° west at the surface, showed vertical (high-angle thrusts; western side upthrust toward the depression) and right-lateral slips. The amount of slip on individual faults at the ground surface was very small (1 cm vertical vs. 4 mm right-lateral motion; see Fig. 2). It is plausible that an earthquake of this size (m_s 5.7) might not be able to produce significant surface faulting. However, we note that the deformed zone along the western fault was up to 11 m wide and was composed of at least eight parallel hairline faults. In addition, the faulting was accompanied by coseismic folding.

Fresh, 8-km-long hairline ruptures along the eastern high-angle thrust fault dipping east (Fig. 2) cut the Holocene alluvial deposits. The fault had moved during the June 11, 1981, earthquake (Berberian et al., 1984). The hairline surface ruptures of the eastern fault looked more eroded than those of the western fault, when we saw them a week after the 1989 main shock. However, a day after the November 20, 1989, earthquake, it rained in the epicentral area.

The centroid-moment tensor solution corresponds to right-lateral strike-slip motion on a fault striking N148°E, dipping 81°SW, and having a rake of 165° (Fig. 2). The centroid depth was fixed at 15 km, and the seismic moment was 8.2×10^{17} Nm (Dziewonski et al., 1990). This mechanism does not account for all the surface faulting, which was also seen on the east-dipping fault. As with the June 11, 1981, Golbaf earthquake of m_b 6.1, m_s 6.7, I VII, it is likely that

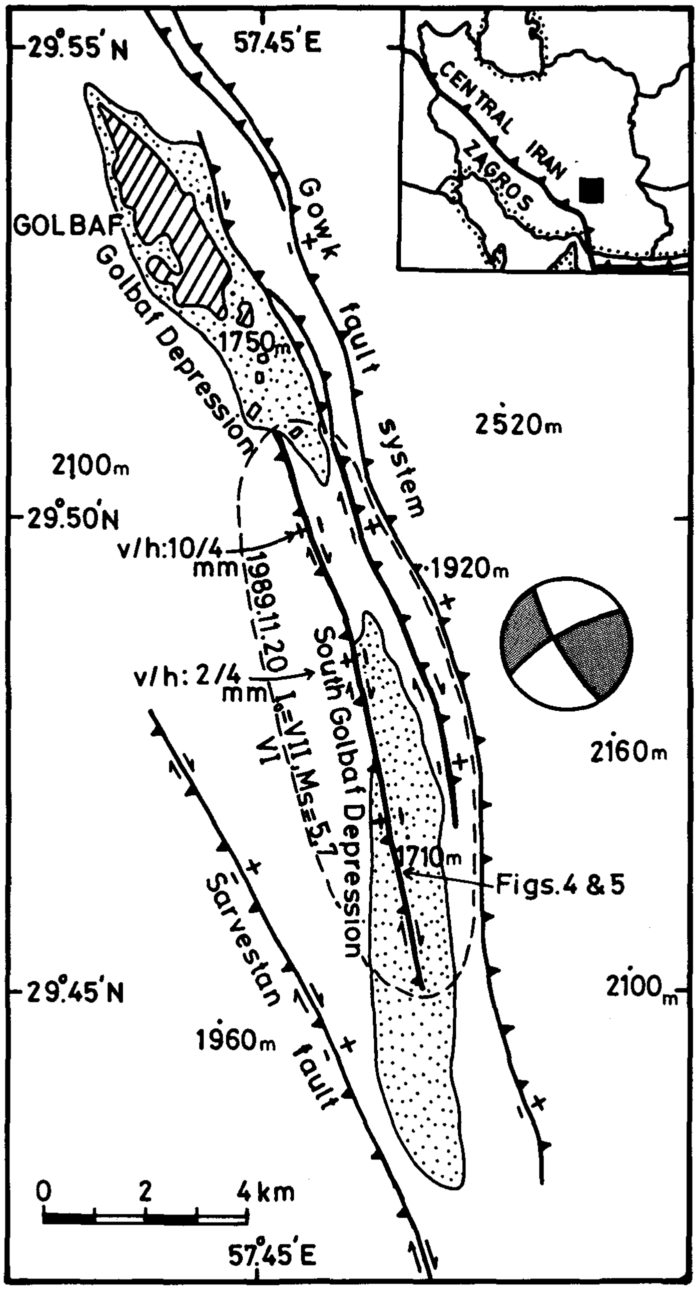

Figure 2. Surface ruptures (thick lines) associated with South Golbaf earthquake of November 20, 1989. Dashed-line ellipse indicates area within which intensity was VII (MMI) for 1989 event. Areas with dot pattern are Golbaf and South Golbaf compressional depressions. Vertical and horizontal displacements are labeled v/h (in millimetres). Centroid-moment tensor solution is after Dziewonski et al. (1990). Four-digit numbers are elevations of a few selected points, in metres above sea level. Active Sarvestan fault is southern segment of active Gowk fault system. Also see Figure 3.

the earthquake was a multiple event, in which the first subevent occurred on the west-dipping fault and the second one on the east-dipping fault (see Berberian et al., 1984, for more discussion). Motion on both these faults caused subsidence of their foothills and formation of the South Golbaf depression (Fig. 3). The western fault at the surface strikes N165°E and dips 60° west-southwest (Fig. 2). If we take the fault length to be 11 km, the depth extent to be 15 km, and the rigidity to be 3×10^{11} dyne/cm^2, then the calculated seismic

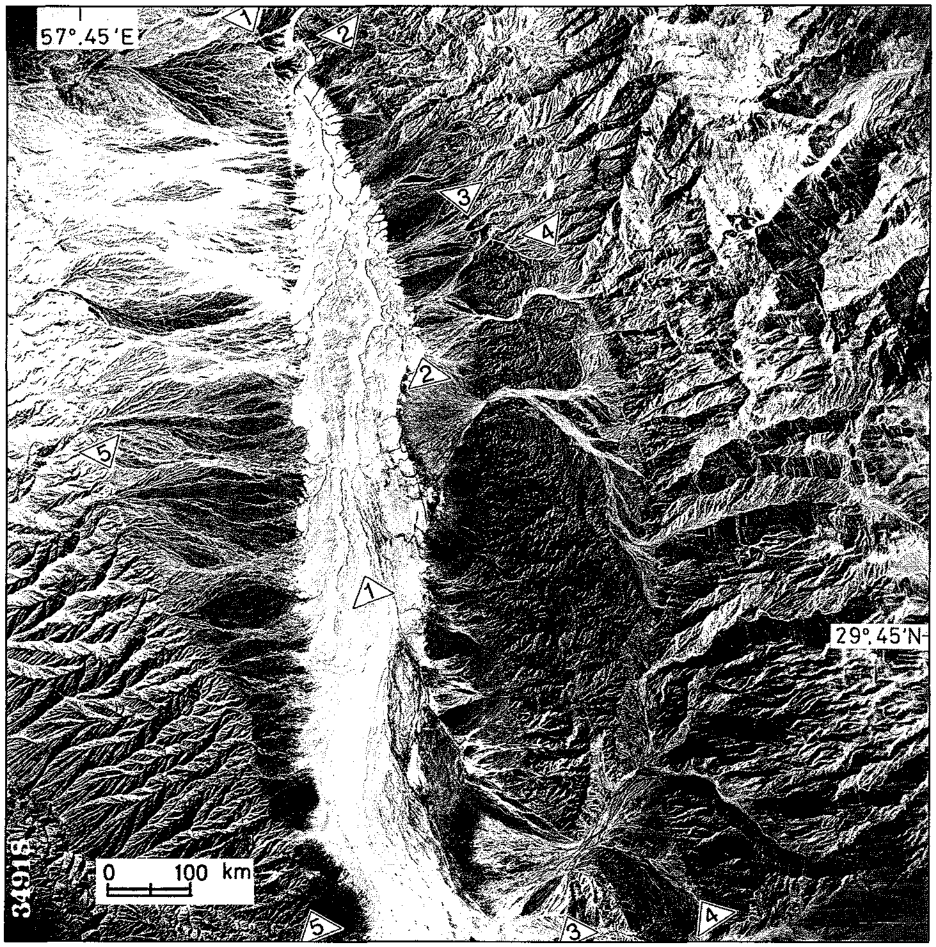

Figure 3. Central-valley west-dipping (1) and east-dipping (2) segments of active Gowk fault system (3 and 4) in South Golbaf depression. White patch is Holocene playa deposit cut by west-dipping fault (1) and river beds. Only faults in immediate vicinity of playa were reactivated (1 and 2). No activity was observed along faults farther east or west (3, 4, and 5). Apparently, South Golbaf depression was formed in two stages. During early stage (possibly early Quaternary), both east- and west-dipping mountain-bordering faults (4 and 5) were reactivated. During later stages (Holocene), central-valley faults (nos. 1 and 2; which slipped during 1989 earthquake) were reactivated. Also see Figure 2.

moment can account for an average slip of 16 cm. This amount is higher than the displacements observed in the field.

SURFACE FOLDING

During the field study of the 1989 earthquake faults, a natural exposure across the surface trace of the western oblique reverse fault was found in the Holocene playa deposits at the western edge of the South Golbaf depression. This exposure shows elastic folding of the horizontally bedded Holocene clay deposits in the earthquake fault zone (Figs. 2, 4, and 5). The exposure reveals both faulting (with splayed fresh ruptures and minimum surface displacement) and folding (flexural-slip faulting on bedding planes developed in the Holocene playa deposits above the active fault tip). The clay layers dip 15°–20°E (toward the playa) at the southern part of the western fault zone (Figs. 4 and 5). It is clear in this case that surface folding of the horizontal Holocene clay is intimately related to earthquake faulting and could be explained by repeated motions on the steeply dipping west Golbaf high-angle thrust fault during past (historic) earthquakes. Knowledge of the approximate times and extent of historic earthquakes would help in estimating the likelihood of future damaging and destructive earthquakes. However, because of lack of paleoseismic and geodetic data, the repeat time of the previous earthquakes, and rate of Quaternary or Holocene folding, tilting and uplifting are not known for this region.

The South Golbaf depression was apparently formed by earthquake faulting as well as coseismic folding, and its present topography is the result of these two types of elastic-brittle deformations. Although our observations here are restricted to the south Golbaf region of southeast Iran, similar mountain-bordering reverse faults in compressional tectonic regimes have developed earthquake-related folding.

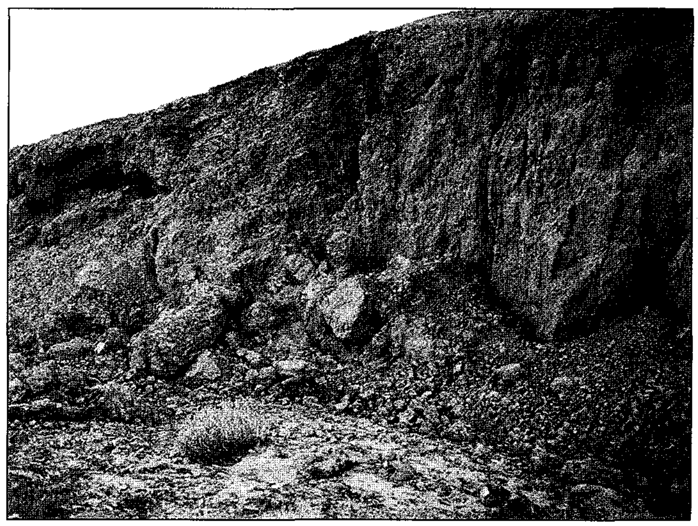

Figure 4. Surface deformation associated with Gowk high-angle thrust fault, south of Golbaf. Surface ruptures together with unknown amount of coseismic folding and flexural-slip faulting (bedding-plane slips with thrust mechanism) developed during South Golbaf earthquake of November 20, 1989. Looking south. See Figure 5.

The fold associated with the South Golbaf earthquake fault is not unique; similar folds are observed elsewhere. Work on the Tabas-e-Golshan (Iran) earthquake of September 16, 1978, m_s 7.4

Figure 5. Close-up view of Figure 4. Fold at active Gowk fault zone formed as consequence of diminished surface slip by repeated earthquakes. Recent horizontal deposits of playa (right) are tilted above fault tip and dip 20° toward east (left). Fresh coseismic splay ruptures (lower left, right, and top middle) together with coseismic flexural-slip faulting on bedding planes in Holocene playa deposits above active fault tip (marked by pens) developed during South Golbaf earthquake of November 20, 1989. Looking south.

(King et al., 1981), and the El-Asnam (Algeria) earthquake of October 10, 1980, m_s 7.3 (King and Vita-Finzi, 1981; Yielding et al., 1981), demonstrated that surface anticlines associated with active thrust faults increased in amplitude synchronously with fault motion at depth. The deformation was spread over wide zones at the surface, and much of it occurred within the hanging wall in the form of small fractures and flexural-slip faulting (bedding-plane slip). Thus, much of the observed surface displacement on the obvious fractures is less than that at depth, as estimated from seismic moment values. The Coalinga, California, earthquake of May 2, 1983, m_s 6.5 (Clark et al., 1983; Stein and King, 1984; Eaton, 1985; Rymer et al., 1985), and the Whittier Narrows, California, earthquake of October 1, 1987, m_l 5.9 (Hauksson and Stein, 1989; Lin and Stein, 1989), focused more attention on active folds and the relation among folds, faults, and earthquakes. Studies of these two California earthquakes showed that folds can grow suddenly, by means of repeated seismogenic ruptures, rather than by steady progressive deformation.

In the case of the November 11, 1989, South Golbaf earthquake, the earthquake fault slip was not fully accommodated by faulting and folding in the Holocene playa deposits above the fault tip. However, given the magnitude and depth of earthquake and the small amount of surface displacements on the faults, it is plausible that the earthquake fault slip progressively decreased toward the surface and that part of the shortening was transferred to surface folding.

SUMMARY AND CONCLUSIONS

The South Golbaf earthquake of 1989 along the active Gowk fault system in southeast Iran, together with the earthquake-related folding of the Holocene playa deposits above the fault tip, demonstrates that even in active regions with recognized seismogenic faults, much of the coseismic deformation is not manifested by large displacements on faults that break the ground surface. Faulting and folding of sediments could be coincident, and folds may grow episodically during earthquakes.

Further progress in (1) understanding the geometry and rate of deformation and (2) gathering evidence to support the repeated or single coseismic fault–related folding at the site requires information that we were not able to obtain during the very short time of the field visit.

ACKNOWLEDGMENTS

We thank Loqman Ne'mat, director of the Geological Survey of Iran Kerman office, for field work support, and Ross S. Stein and Martitia P. Tuttle for constructive comments and corrections.

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Manuscript received July 28, 1993
Revised manuscript received February 15, 1994
Manuscript accepted March 8, 1994