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Ground deformation study of M_w 7.7 Bhuj earthquake of 2001

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A preliminary study of ground deformation of the catastrophic Bhuj earthquake of 26 January 2001 is described. This earthquake of magnitude M_w 7.7, Ms 8 caused large-scale destruction including 20,000 deaths. Surface faulting has not been detected probably due to the 23 km focal depth. Reverse faulting is inferred along a steeply dipping fault that could be the westward extension of the northern boundary fault of the Wagad uplift. If extended upward it would meet the surface 25 km north of the Kutch Mainland Fault. As a result of this uplift, intense land deformations have been observed in a 40 km × 20 km area like lateral spreading, ground uplifts (about a meter at Budharmora extending for 300 m in length), ground slumping (at Chobari and Amarsar), and deep and wide cracks (N-S at Manfara but mainly E-W at other places). A NNW-trending 5-km long fracture between Manfara and Kharoi, interpreted as a right lateral strike slip fault by some could be a tensional fracture. Similar is a small fracture at Sikra. Strong shaking has caused liquefaction with ejection of a lot of water and some sand in Banni grassland, in saline areas of Great Rann and Little Rann of Kutch and in coastal areas up to 200 km distance from the epicenter. Stray incidences of liquefaction have occurred up to 275 km such as south of Ahmedabad and near Jambusar.

Introduction

The catastrophic Bhuj, Gujarat, India earthquake of 26 January 2001 (23.429˚N, 70.232˚E; 16-23 km focal depth) of magnitude M_w 7.7, Ms 8 and origin time 03:16:40.5 UTC caused large-scale destruction including 20,000 deaths. Salient results of our study of ground deformation for this earthquake are presented.

This earthquake is a great intraplate (Stable Continental Region—SCR) earthquake as the Herat-Chaman plate boundary in the west is about 400 km away and the Himalayan plate boundary in the north is more than 1000 km away (see inset map of Figure 1). It is enigmatic that such large earthquakes can occur away from plate boundary and in SCR. SCR earthquakes are anyway rare, with a total moment release of only 10^{26} dyne-cm per year, that is less than 0.5% of the annual strain energy released globally (Johnston, 1994) and a great earthquake in SCR is a rare happening. The great earthquakes in SCR have occurred only in New Madrid region of Missouri, USA (M8.3, 8.2 and 8.1 in 1811—1812) or in Kutch (previous one in 1819).

High stress accumulation in Kutch is attributed to the proximity of the triple junction and pivotal point for anticlockwise rotation of the Indian Plate. The isostatic imbalance caused by erosion of the younger sedimentary layers and the Deccan volcanics in the uplifted region gives an additional stress over the N-S compression due to plate tectonics (Gupta et al., 2001a).

The Kutch and surrounding region has been affected in the past by large damaging earthquakes (Figure 1). The Samaji town (25˚N, 68˚E) on the Indus delta in Pakistan with 30,000 houses, reportedly sank into the ground due to an earthquake of intensity X (MM scale) in May 1668 (Chandra, 1977). An earthquake of M_w 7.8, intensity XI occurred 100 km NW of Bhuj in the Great Rann of Kutch on 16 June 1819. It formed a 90-km long scarp with a maximum height of 6 m (and 3 m subsidence) that was named "Allah Bund" or "Wall of God". This earthquake took a death toll of 2,000 people in Kutch and 500 in Ahmedabad. On April 19, 1845 an earthquake of intensity VIII hit Lakhpat with 60 strong aftershocks followed by intensity VII earthquake on June 19, 1945. The last damaging earthquake in the region was M_w 6 (intensity IX) Anjar earthquake of 21 July 1956 that caused 115 deaths (Chung and Gao, 1995, Tandon, 1959). Damaging earthquakes occurred in 1864,1903, 1940 and 1950. Nevertheless, smaller earthquakes are fewer.

The rocks in the epicentral region comprise Mesozoic sediments (135–65 Ma) overlying an uplifted granite basement. The Deccan volcanics (60–65 Ma) are exposed in southern Kutch. The major tectonic features of the Kutch region are trending E-W. From north to south these are Nagar Parkar Fault (along Pakistan border), Allah Bund Fault (associated with the 1819 great earthquake), Island Belt Fault (associated with a few magnitude 5 earthquakes), Kutch Mainland Fault (KMF) and the Katrol fault along which the 1956 earthquake occurred. KMF extending for 125 km separates the hilly region of Mesozoic rocks in the south from the Quaternary sediments of Banni rift basin (grass land) and the Great Rann of Kutch (low lying saline-marshy area that gets flooded due to sea water during monsoons) in the north. This is a reverse fault and has a structural displacement of 2–3 km.

These faults might have been generated in different episodes of rifting when the Indian plate traversed over hot spots in its northward journey after its breakup from the Gondwanaland 120 Ma. Under the present-day compression stress field due to the northward movement of Indian plate, the pre-existing normal faults associated with the former rifting are reactivating in the reverse sense of motion as indicated by the focal mechanism of Kutch earthquakes like the 1956 Anjar earthquake (Chung and Gao, 1995), the 1819 Rann of Kutch earthquake and a few others.

The 2001 mainshock caused uplift of the southern side of the northern Wagad Fault. During the 1819 earthquake the northern side of Allah Bund fault uplifted (Gaur, 2001). This type of movement in the past has created low-lying area of the Great Rann of Kutch. Yagi and Kikuchi (2001) have modeled deformation along a reverse fault matching with the inferred fault along a 75 km × 35 km rupture plane. The maximum dislocation is 8.5 m at 23 km depth, reducing to about a meter near surface. However, the ground deformation pattern indicates that the rupture has ended at some depth. The source duration is 25 sec. The aftershocks indicate activity along a WNW-

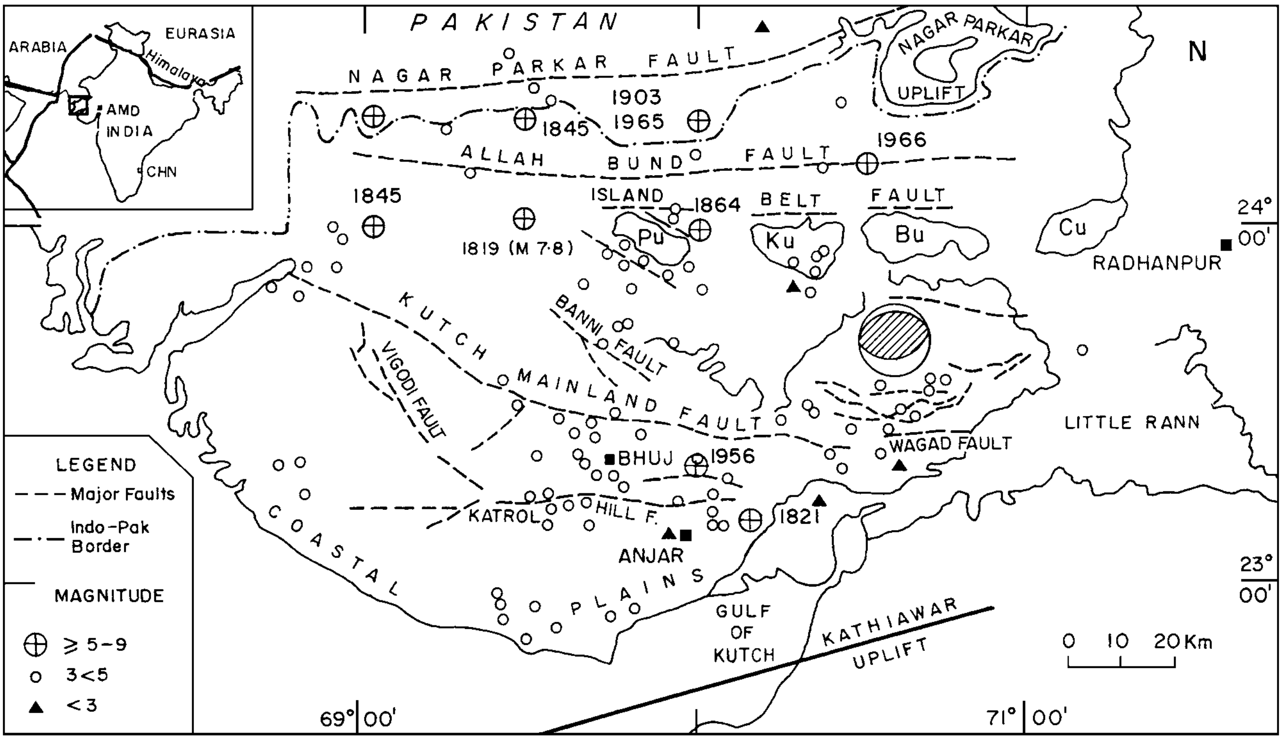


***Figure 1** Faults, past earthquakes and focal mechanism of the 2001 earthquake (modified after Malik et al., 1999; faults are from Biswas and Deshpande, 1970 and GSI, 2000). The Kutch Mainland Uplift is south of the Kutch Mainland Fault and Wagad Uplift is north of Wagad Fault. Other uplifts—PU: Pashham Uplift, KU: Khadir Uplift, BU: Bela Uplift, CU: Chorar Uplift.*
Inset: The Indian plate boundaries forming a triple junction northwest of the Kutch region. Cities shown: Ahmedabad (AMD), Chennai (CHN).

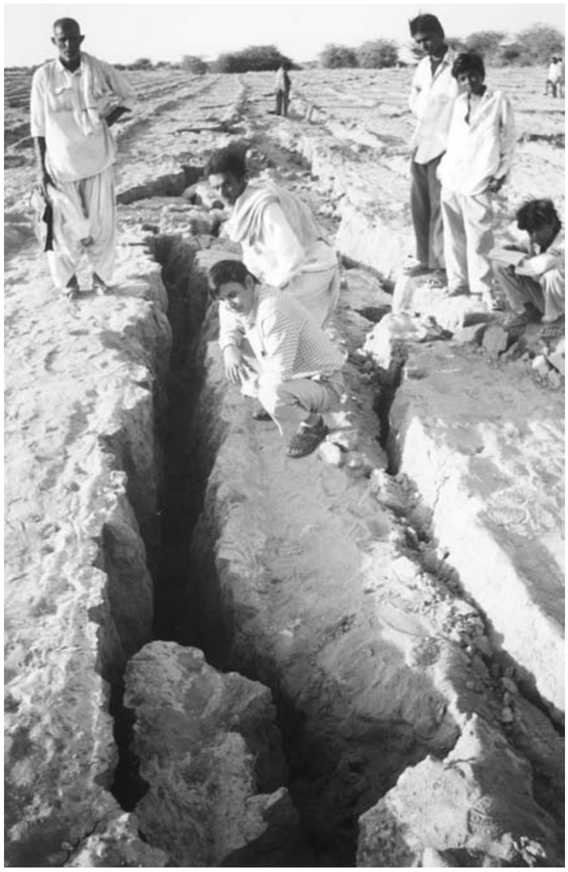
ESE trending and SW dipping fault (matching with the northern Wagad Fault) at depths of 10 – 40 km.

Ground deformations

The maximum damage due to the Bhuj earthquake is of intensity X + (MSK or MM scale) in a NE-SW trending area of 40 km × 20 km in Bhachau and to its north. Most of the houses collapsed in this area, many of which were reinforced and framed structures. The ground deformations include deep and wide cracks (N-S at Manfara as shown in Photograph 1, but mainly E-W at other places), ground uplifts of about a meter at Budharmora (Photographs 2 and 3) (extending for 300 m) and slumping at Amarsar. Railway line was slightly bent along a ground crack in Bhachau. The maximum estimated acceleration is 0.7 g from collapse of very small structures near Vondh and Bhachau.

As occurrence of ground deformations warrants assignment of intensity XI, earlier we assigned intensity XI to the meizoseismal area. However, it was realized that the ground deformations are mainly due to lateral spreading and not severe enough for intensity XI. Moreover, the damage to railway lines, roads and bridges are not intense enough for intensity XI. Hence, the maximum intensity is now limited to X+ and the other intensity areas are suitably modified.

Intensity IX+ is assigned in an area of 100 km × 60 km that encompasses Bhuj, Rapar, Anjar, Gandhidham and Navlakhi (Figure 2). In this area several reinforced buildings and most of the adobe houses have collapsed. Ground cracks of several cm in width have occurred and water pipelines have broken. There is severe lateral spreading at Navlakhi. As expected, the damage is much more severe in the thick-soil covered areas due to amplification as compared to hard rock areas. Deep cracks have formed near Manfara. Widespread liquefaction has occurred in the Great Rann (saline-



***Photograph 1** Deep cracks at Manfara formed due to lateral spreading in a field.*

Photograph 2 Land uplift by about a meter near Budharmora.

Photograph 3 Another view of the land uplift near Budharmora.

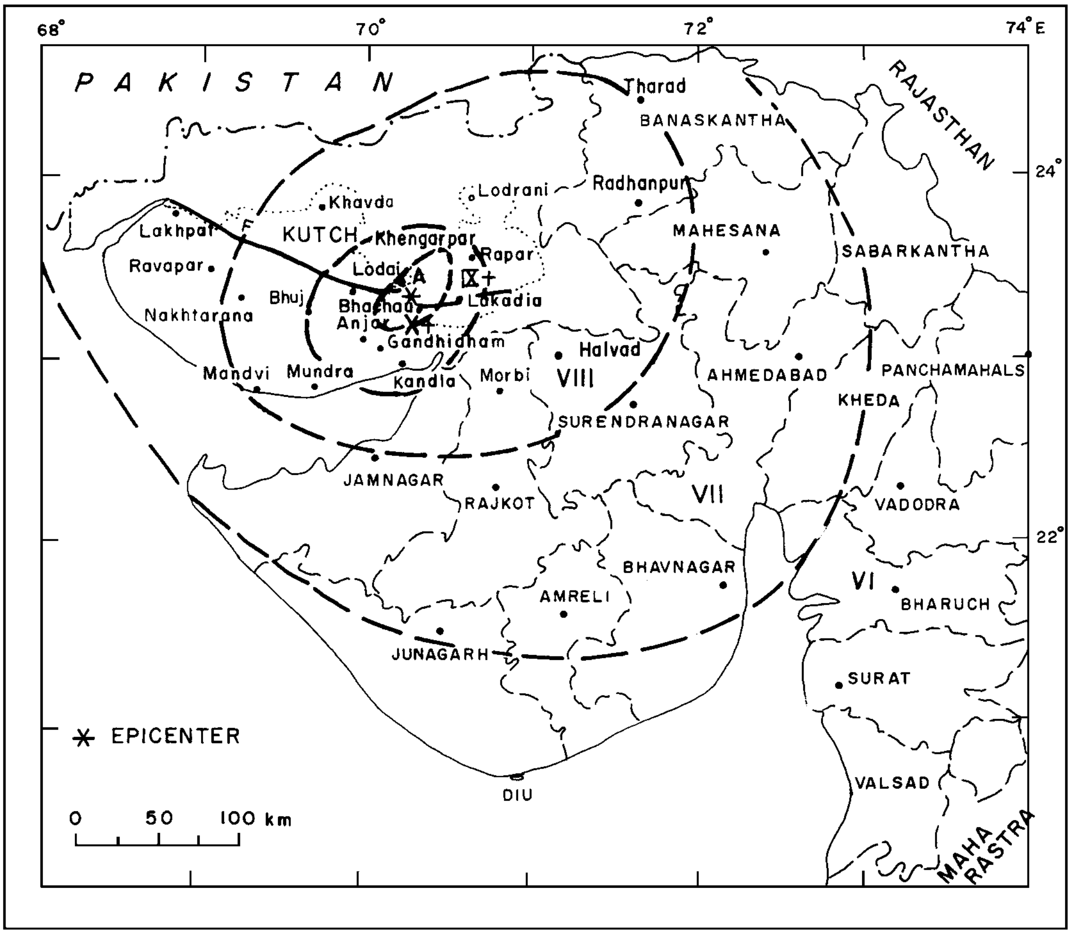


Figure 2 Isoseismal map for intensity X to VII.

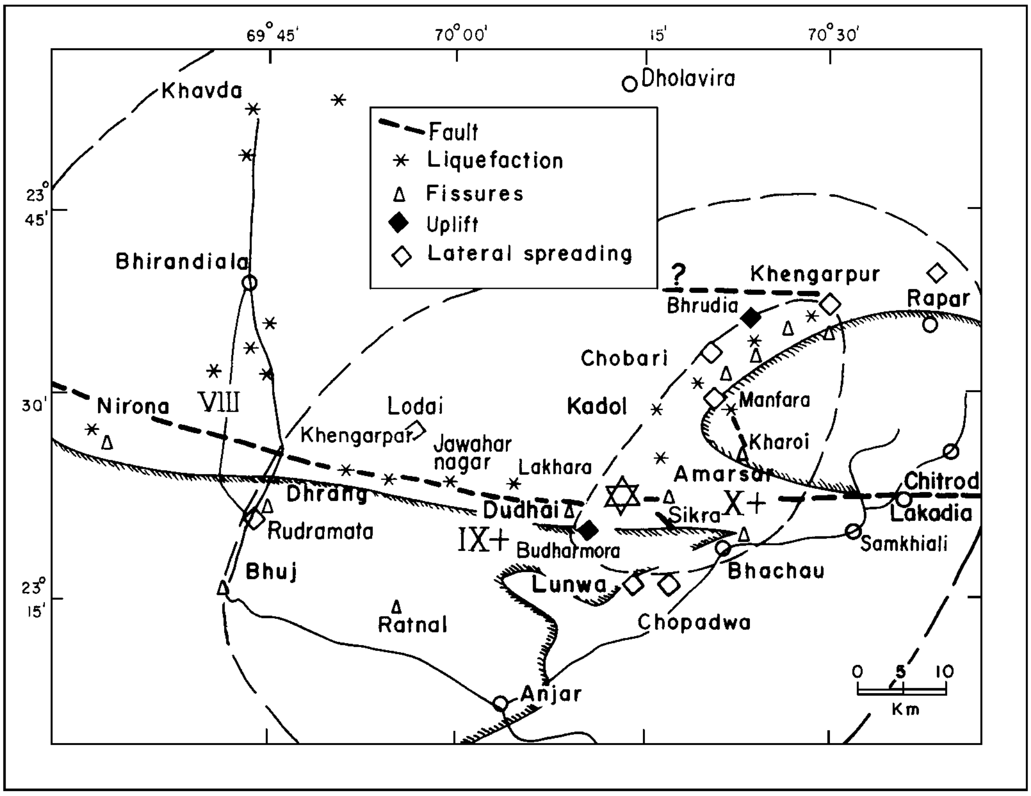


Figure 3 Isoseismal map for intensity X and IX and ground deformation features.

marshy lowlands) to the north, the Little Rann to the southeast and coastal areas. Some important sites of liquefaction include Lodai, Umedpar, Amarsar, Patri, Navlakhi, Kandla and the areas around Khadir. Due to soil liquefaction/subsidence, railway lines have been heavily damaged in Navlakhi and Dhrangadhra areas. Five medium and 15 small-sized dams near Bhachau, Bhuj and Rapar have also been badly damaged. These dams are of rockfill or embankment type and the damage is mostly due to lateral spreading of the dam body.

Ground uplift

Ground uplift was observed in Budharmora about 13 km west of the epicenter (Figure 3). Along a length of 300 m in E-W direction and a width of 2–3 m the south side was uplifted by over a meter on a nearly flat ground (Photograph 2). In a field near Bhrudia, a 80 m × 10 m zone is uplifted for 80 cm. Several NW trending ground cracks developed in the uplifted portion (Rajendran et al., 2001).

Lateral spreads, ground slumping and relative subsidence

The most intense lateral spreading has been observed in the area near Budharmora (Photographs 4 and 5), Chobari, Manfara, Kadol and Khengarpar villa occur in the fields situated along the boundary of Mesozoic and Holocene rocks. Near Manfara the area covered is over 300 m × 400 m. Cracks are about a meter wide, 5–10 m deep and mostly in N-S direction in this area (Photograph 1). However, the liquefaction cracks are in E-W direction. In other places the disturbed areas are of an order of 100 m × 100 m. At Amarsar ground slumping by about a meter has been observed along three elliptical patches of 200 m × 300 m.

At a few hundred meters west of Budharmora uplift, a zone of spectacular lateral spreading has been observed in the fields and along a kutchha road. This road is running N-S and at one place where it is sloping southward, step faulting occurs with south side always remaining up (Photograph 5).

Several instances of sand blows and fluidization have also occurred (Photographs 6 and 7). Lateral spreads and down slips have

Photograph 4 Step-like lateral spreading in a field a little east of the Budharmora.

Photograph 5 Step-like lateral spreading on a south sloping road east of the Budharmora uplift.

Photograph 6 Big sand craters of 3m diameter formed due to liquefaction near Lodai.

Photograph 7 Small sand craters formed due to liquefaction near Lodai (photo curtsey V. Kolvankar).

been prominently seen at the Rudramata reservoir basin and in a coastal region near Kandla and Navlakhi.

At Chopadwa, lateral spread is observed along an E-W running road where the south side ground has uplifted by about a meter (Photograph 8) and west-side sloping road shows lateral spread.

Lateral spreads are common in the epicentral regions where a large amount of liquefaction of underground sediments takes place.

Ground fissures

Most of the surface cracks with no slip or lateral spread are observed near KMF. Almost all the roads in the eastern Kutch district towards Bhuj, Bhachau and Rapar have suffered intensive cracks. The ground cracks have occurred around Bhuj, Dhrang and Lodai (Bhuj area), Bhachau, Dudhai, Jawaharnagar (in Bhachau area), Rapar, Bharudia (in Rapar area), Anjar, Ratnal and Tapar (in Anjar area) and Mandvi and Gandhidham (all in Kutch district). Cracks have also occurred at Deesa, Suigam (Banaskantha District) and Viramgam and Nal sarovar (Ahmedabad District) (Karanth et al., 2001).

A N55W trending coseismic fracture was reported by Geol. Sur. India that cuts a road near Sikra and shows a 2 cm left-lateral displacement. A 5 km-long N25W trending rupture with a right-lateral slip of 15–35 cm was reported by Seeber that extends southward from Manfara and cuts the Kharoi-Rapar road 5 km from Kharoi. It has opened up the hard rocks also but can be explained as a tensional fracture as no relative movement is observed on the road (Karanth et al., 2001).

Rock falls

Rock falls at low scale have been observed at several places around KMF. These places are Lodai, Kotai and Loria (near Kas Hills), Jawaharnagar, Desalpar, Dhrang, Khengerpar and Bhachau (Karanth et al. 2001).

Liquefaction and fluidization

The earthquake resulted into large-scale liquefaction and fluidization in an area of 300 km × 200 km covering the Great Rann, Little Rann, Banni Plain and coastal areas. Numerous hidden river channels show emergence of water in satellite imageries. Shallow ground water at these places provide most favorable environment for liquefaction in areas of intensity VIII or more. Manifestations of liquefaction are fluidization, sand blows or dykes, craters, ground fissures, subsidence and lateral spreads. Photograph 7 shows a series of typical sand craters formed near Lodai. Water that emerged is saline and was seen as wet ground or pools of water even after three months of the main earthquake. White patches are formed near craters due to salt deposition. The amount of fluidizaion

Photograph 8 About 80 cm uplift of the southern side of a road at Chopadwa.

is intense but ejection of sand is very less, maximum being 10 cm. The sand dykes are extremely narrow with maximum of a few cm and mostly less than a cm.

Isolated cases of liquefaction have been observed up to 275 km like Rupen River bed in Patan District, Tharad in Banaskantha District, Dholka in Sabarmati basin, Vataman and Nada village near Jambusar (22N–72.5E, Bharuch District) (Karanth et al., 2001). Mohanti et al. (2001) report observing water channels in satellite imagery of Rajasthan at 450 km distance from the epicenter. Liquefaction has occurred at border areas of Mesozoic and the Rann in Manfara, Chobari, Vejpar and Amarsar. The locations in Banni region are Lodai, Dhrang, Amrapar and Bhirandiala. The coastal regions where large amounts of liquefaction and lateral spread occurred include Mandvi, Mundra, Navlakhi and Maliya. At Navlakhi, a small portion of the railway track submerged in seawater. Further in alluvial areas of Halvad and Dhrangadhra railway tracks were damaged due to lateral spread.

Water fountains or sprouts along with sand were reported from Katwant, Desalpar, Lodai, Budharmora, Dhora, Khengarpar and Mandvi. For example Water fountains are reported as high as 2–10 m lasting for over 2 hr at Lodai and between Rapar and Dholavira.

Concluding remarks

The 2001 Bhuj earthquake occurred due to uplift of the southern side of the E-W trending and S dipping extension of northern Wagad Fault situated about 25 km north of the Kutch Mainland Fault. Severe ground deformations occurred in the area between these two faults in the form of lateral spreading, up to a meter uplift, and a meter wide and several meters deep ground cracks. However, clear surface break of the fault is not noticed. It may be because of a focal depth of 16–23 km. Wide spread liquefaction with up to 6 meter wide craters occurred in soil covered areas up to 275 km from the epicenter.

The detailed studies of ground deformation and liquefaction can be used for estimating the acceleration and hazard at different sites.

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