2. Surface Deformations and Active Faults

2.1 Surface Deformation around Budharmora

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Abstract

On the gentle north-facing warping surface extending E-W in the epicentral area around Budharmora and Morgar villages, extensive lateral spreading took place by the Bhuj earthquake. The deformation was generated in water saturated surface soil horizon resulting in numerous E-W striking extensional cracks or normal faults and rises to the surface forming the longitudinal pressure ridges. Deformational features identified during our field and aerial survey are mostly gravitational features caused by strong ground shaking over a gently sloping surface.

Introduction

An earthquake (Mw 7.6) occurred early in the morning of January 26, 2001, attacking an extensive area of Kachchh, Gujarat, West India. It is one of the largest earthquakes in the Peninsular India during the historical period. USGS located the hypocenter of the main shock to be 23.36°N and 70.34°E and 22km beneath the surface from teleseismic data (Fig 2.1). The magnitude is estimated Mw7.5 and Mw7.6 by the USGS and University of Tokyo, respectively. The earthquake broke out in the region where two large historical earthquakes, namely the 1819 Allah Bund earthquake (Mw7.8) and the 1956 Anjar earthquake (the Mw 6.0) occurred.

Field and aerial reconnaissance reveals that no primary surface fault rupture resulted from the Bhuj earthquake, in spite of the large magnitude of the earthquake. Deformational features identified during our field and aerial survey are secondary tectonic features caused by strong ground shaking over a gently sloping surface; they are mainly extensional cracking of near surface ground and liquefaction. These features are briefly described by Oyo Co. (2001) and NSF- SCEC Team (2001). We made a detailed observation on the intense lateral spreading in the vicinity of the epicentral area around Budharmora and Morgar to define their characteristics (Fig. 2.1), and dug trenches across the liner bulges to confirm their deformational structure.

Description of the ground deformation

Satellite photo around study area clearly shows that the intense ground deformation appeared along an E-W striking lineament north of Budharmora and Morgar. It is located on the eastern extension of the Kachchh Mainland fault that marks the northern margin of the hill in the west (Fig. 2.2). Along the Kachchh Mainland fault, domes and asymmetrical anticlines of the folded Mesozoic rocks are characterized by the uplift of southern block with gentle back-tilting due south and north facing steep forelimb (Biswas, 1980; Malik *et al.*, 2001). The folding in Middle Pleistocene Miliolite rocks along the south dipping reverse faults indicates that similar deformation has continued during Upper-Pleistocene to Holocene (Sohoni *et al.*, 1999, Malik *et al.*, 2001).

The lateral spreading in the study area was associated with numerous extensional cracks in the agricultural fields as well as linear bulge (Photo 2.1, Fig. 2.3). These

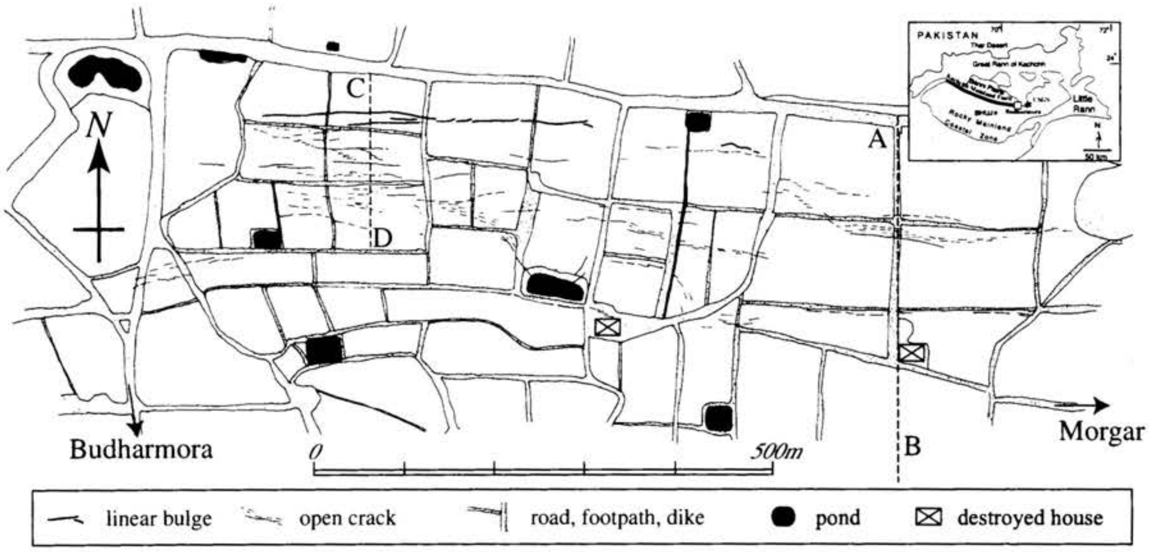

Figure 2.1. Ground deformations around Budharmora. Compiled by an aerial observation and field mapping. Open cracks are selectively mapped and many minor cracks are not shown in the figure. A-B and C-D indicate the location of profiles shown in Figure 2.4.

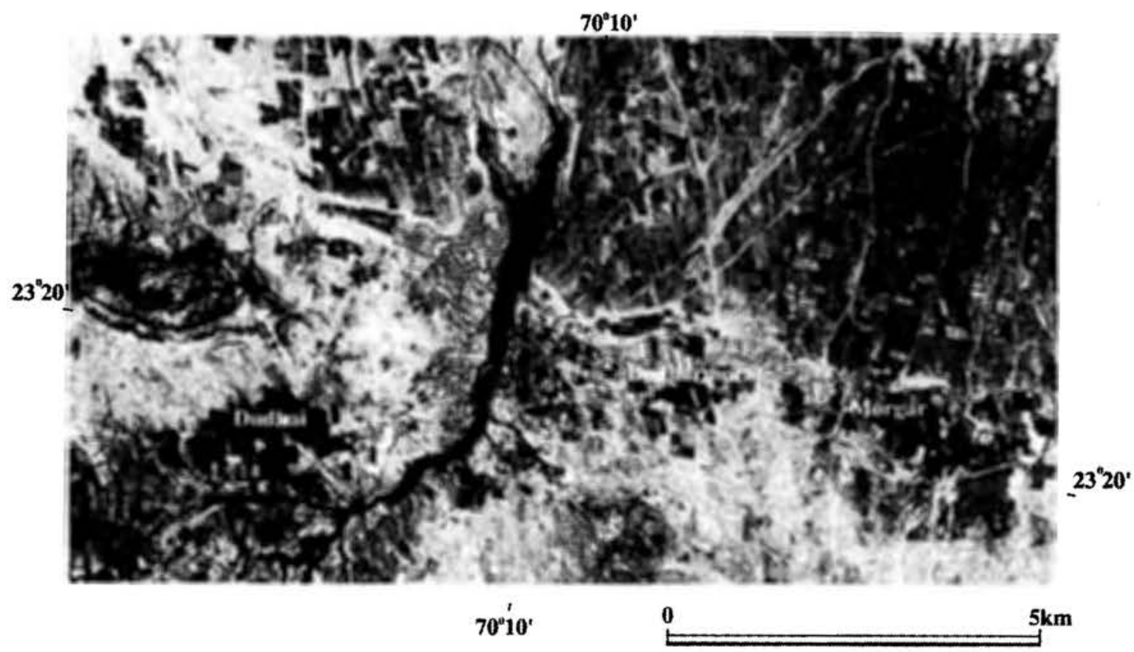

Figure 2.2. Satellite photo around study area. Note that an E-W striking lineament north of Budharmora and Morgar is located on the eastern extension of the tectonically controlled northern margin of the hill in the west. Ground deformations took place along the lineament.

cracks are confined in a zone of about 0.2 to 0.3 km wide, and extend E-W for about 1 km in length on the gently north dipping slope. Fig. 2.4 shows profiles across the slope where ground deformations took place. Profile A-B is an N-S cross-section across the zone of uplift where villages and fields are located as seen in Fig. 2.2. The north-facing slope dipping gently (2 % at steepest) may be originally a flexure scarp associated with faulting along the tectonic margin. Profile C-D is a typical section of ground deformation on the gentle slope (3 % at steepest) across the E-W striking lineament seen in Photo 2.1. A zone of extension consisting of open cracks on the upper slope and zone of compression consisting of pressure ridges (linear bulges) on the lower slope clearly indicate a lateral spreading.

Oyo Co. (2001) claims that the deformation zone extends farther west about 1 km with minor cracks, but we have not carried out field observation in that area because of their obscure features. Major cracks striking almost E-W are composed of normal faults down-thrown to north, and associated with the rotated blocks, which resulted in the formation of series of half-graben structures under the extensional regime. Scattered wet patches on the ground (light tone in Photo 2.1) indicate that the ground water was pored out with pressure during the strong shaking. E-W extending major cracks and linear bulges are almost parallel to each other and minor en-echelon cracks trending NW-SE oblique to the major ones are convex to down slope displacing the rows of agricultural field (Photo 2.1 and 2.2). Right-lateral offsets of field patterns along the linear cracks are also observed occasionally at places. Sand blow craters ranging in diameter from several 10's cm to 1.5 m were the common features found associated with the cracking (Photo 2.4).

Width between the cracks running parallel to each other varies from 20 to 30 cm along with some as wide as 60 to 70 cm apart. These cracks are associated with north-

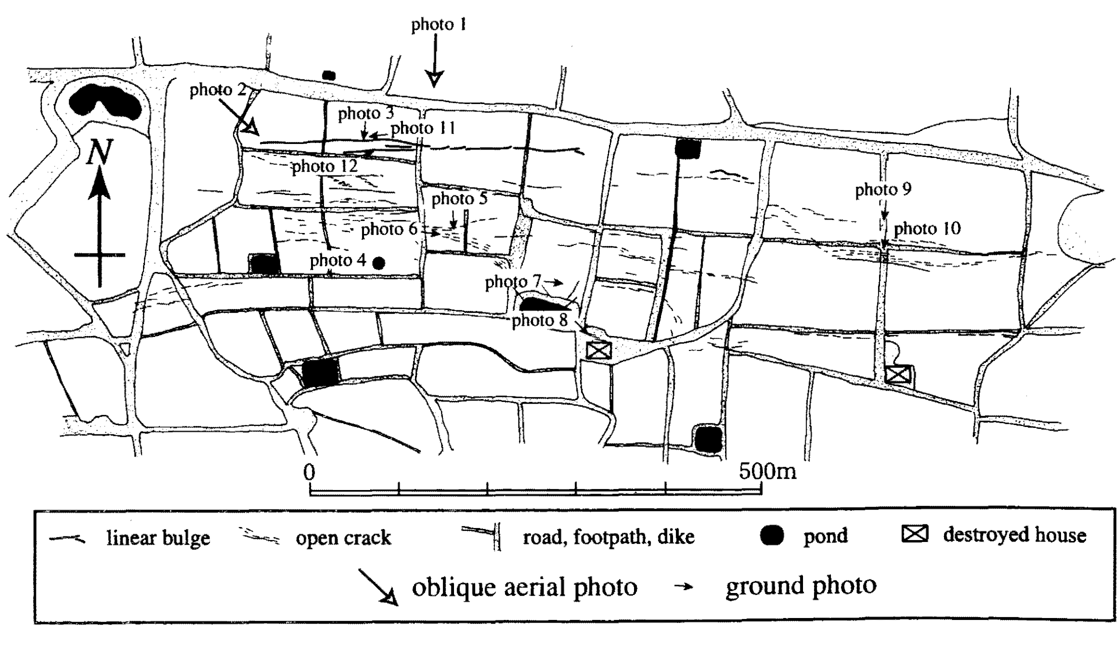

Figure 2.3. Index map of photographs. Direction of arrows indicates camera angle. Photo 1 here, for example, corresponds to Photo 2.1 in the text. Others follow the same abbreviation.

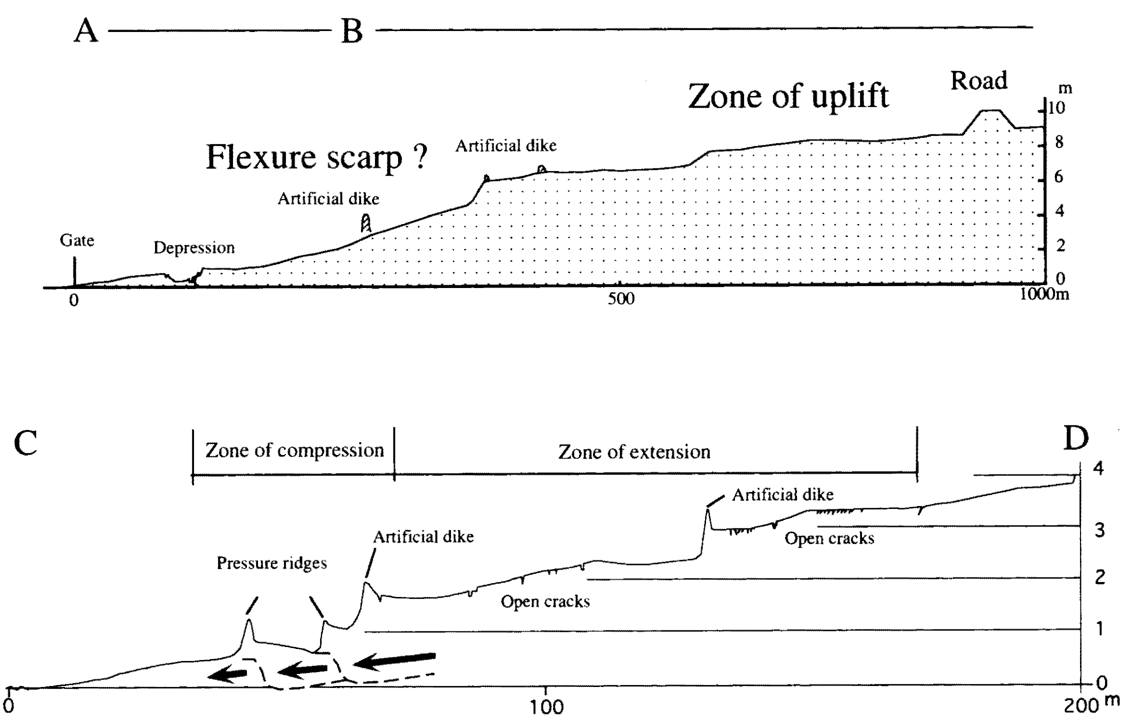

Figure 2.4. Profiles across the slope where ground deformations took place. Profile A-B is an N-S cross-section of the zone of uplift seen in Fig. 2.1. The north-facing slope where the ground deformation took place may be originally a flexure scarp associated with faulting along the tectonic margin. Profile C-D is a typical section of ground deformation seen in Photo 2.1. A zone of extension consisting of open cracks on the upper slope and zone of compression consisting of pressure ridges (linear bulges) on the lower slope clearly indicate a lateral spreading. Locations of the profiles are shown in Fig. 2.1.

facing steps about 10 cm high, and generally making descending step-pattern down north (Photo 2.5), with tilting of the ground by a few degrees toward south (Photo 2.6). In the study area the intensity of the extensional cracks increases from south to north, and finally dies out with two to three E-W striking longitudinal bulges (Profile C-D in Fig. 2.4). These bulges resemble the morphology of pressure ridge. Opening of the cracks varies from less than 1 cm to 25 cm wide, and total amount of expansion roughly matches to the amount of shortening revealed by trenching across the bulges.

The shortening of the near-surface soil layers developed asymmetric anticlines with sharp north-facing scarp and gently dipping back limb to the south. At some places the southern limb shows dip up to 12° to 15°. The height of the north-facing steep scarp varies between 30 and 50 cm. The axial crest surface or the hinge of the fold exhibits development of numerous extensional cracks occurring parallel to the strike of the bulge axis along with some showing conjugate pattern. These warps run parallel to each other in E-W direction and continue for about 400 m (Fig. 2.1, Photo 2.1). In some portions of the field, the deformation has waved-up the surface resulting into alternate pattern of bumps and depressions.

An apparent lateral offset along an N-S extending fracture is locally formed due to lateral spreading in a highly moist soil close to a pond in the upper slope (Photo 2.7) . An irrigation channel along the fracture is offset about 1.2 m right-laterally, but the rupture disappears quickly to the north. Most of the

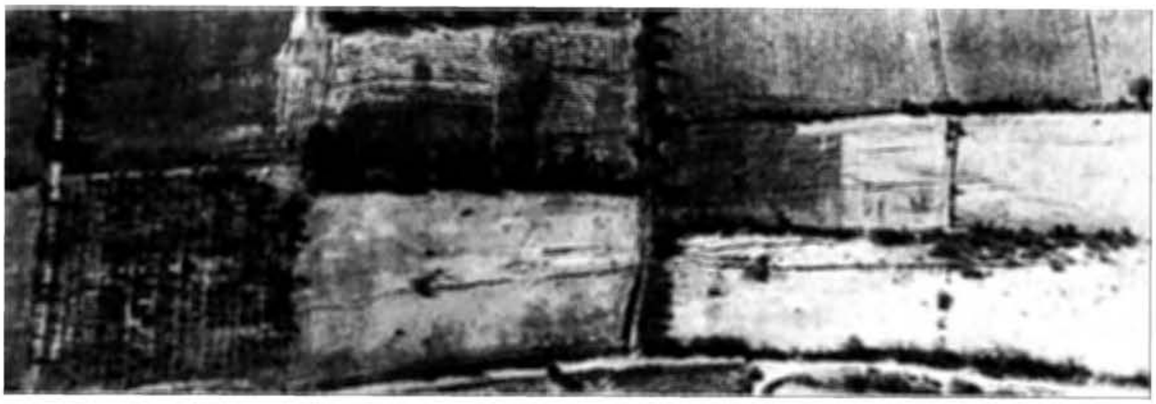

Photo 2.1. An aerial view of the cracks and linear bulges that appeared in the northwestern portion of the study area. Looking from north. E-W extending major cracks and linear bulges are almost parallel to each other and minor cracks oblique to the major ones are convex to down slope. Note consistent right-lateral offset of field patterns along the linear cracks. The linear bulges had already been dug by previous workers.

Photo 2.2. An oblique view of open cracks and bulges looking from northwest.

Photo 2.3. A close-up view of the linear bulges at the trench site. Looking south. Trench A was dug across the bulge far behind the standing person and trench B close behind him.

houses in the vicinity of the study area were destroyed by severe ground shaking, and some houses were destroyed because they were just on fractures as seen in Photo 2.8.

The cracks down-thrown to both north as well as south have resulted in a development of small depressions at places. A relatively large depression of this kind was observed in the Profile A-B in Fig. 2.4 (Photo 2.9). The depression is located in the lower slope in the profile A-B. Photo 2.10 is a close-up view of the north-facing steps in Photo 2.9. The ground across the fractures slumped about a meter to the north by densely spaced extensional faults, and fractured surfaces were rotated with dip to the south.

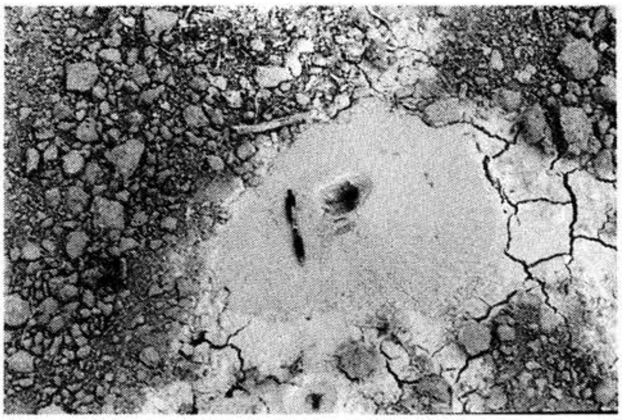

Photo 2.4. A small but typical sand blow in the field on the upper slope.

Photo 2.5. A view of typical fractures in an agricultural field. Looking south. Ruptures here are running parallel to each other and associated with north-facing steps about 10 cm high.

Photo 2.6. A parallel view of the ruptures in Fig. 2.5, looking east. The ground is fractured by extensional faults spaced by tens of centimeters to a meter and is tilted by a few degrees toward south.

Trench excavation across the bulges

We dug two trenches across the linear bulges in the northwestern part of the study area (Fig. 2.5). The trench walls are mainly composed of medium to coarse-grained sand layers with fine sand matrix. The layers are rather homogeneous and may be blown sand from Banni plains to the north. They are tentatively classified in Fig. 2.5 by the tone of brown in color that is probably due to difference in moisture content. Both trench walls demonstrate a typical thin-skinned tectonics. The sand layers partially cemented with calcareous material locally called as Miliolite is intercalated along the fault plane. Photo 2.11 shows simple fault-bend fold deformation at trench A, while trench B suggests over-thrusting surface layers

Photo 2.7. An apparent right-lateral offset of an irrigation channel along an N-S striking fracture in an agricultural field, looking east. The ground in front of the fracture is locally moved northward due to lateral spreading in a highly moist soil close to a pond in the upper slope to the south.

Photo 2.8. Right-stepping fractures causing total destruction of a farmer's house just on them. Looking southeast.

forming linear bulge with fluid deformation at the toe of hanging wall (Photo 2.12).

Amounts of shortening across these trenches are calculated from the length of base line, i.e. horizontal length of each figure, and the length of the original surface before the earthquake. As a result, a shortening of 1.16 m is estimated at trench A, and 1.32 m at trench B. Thus the total shortening across the zone of compression on profile C-D in Fig. 2.4 is about 2.5 m. This amount is more or less consistent to that of extension on the upper slope of the profile, if we consider the amount of wave-up deformation that is difficult to measure.

Thickness of the layer above the ramp, i.e., the steeper portion of the fault plane, is less than 1 m, suggesting that depth of low-angle fault plane is very shallow seated. Therefore, lateral spreading occurred on a gently sloping surface probably along the Miliolite that worked as an impermeable

Photo 2.9. A relatively large depression formed between extensional faults down to the north and those down to the south. The depression is located in the lower slope in the profile A-B in Fig. 2.4.

Photo 2.10. A close-up view of the north-facing steps in Photo 2.9. The fractured ground slumped about a meter to the north by densely spaced extensional faults.

layer, and about 1 m thick mass of the superficial soil has been slid down to the north in response to a rise in pore-water along Miliolite layer under seismic stress. The movement also caused complex ground deformation involving breaking, some slumping and some liquefaction and flow. This type of flows usually occurs over a very gently inclined ground surface, as gentle as 0.1 to 5 % (Obermeier, 1996).

Therefore, it is suggested that the lateral spreading in the study area is the result of increased pore-water pressure during strong ground shaking.

Discussion and conclusion

About 5 km north of Kachchh Mainland in Banni Plains near village Umedpur, located north of Lodai, distinctive fractures extending roughly in N-S direction were observed. These fractures are characterized by a vertical separation of 10 cm down to north, and show apparent right-stepping pattern along with 10 to 20 cm left-lateral movement (Photo 2.13). These fractures well resemble the Manfara fault NSF-SCEC Team (2001) mapped northeast of the USGS epicenter. Judging from the photographs and description in their web site (NSF-SCEC Team, 2001), the Manfara fault with right-lateral strike-slip is still dubious to be a tectonic feature because the fractures occurred close to the boundary between bedrock exposure and alluvium. Unconsolidated sediments with different thickness often result in ground rupturing under a strong shaking.

Regarding the cause of the extensive ground deformation in the vicinity of Budharmora, there has been Internet

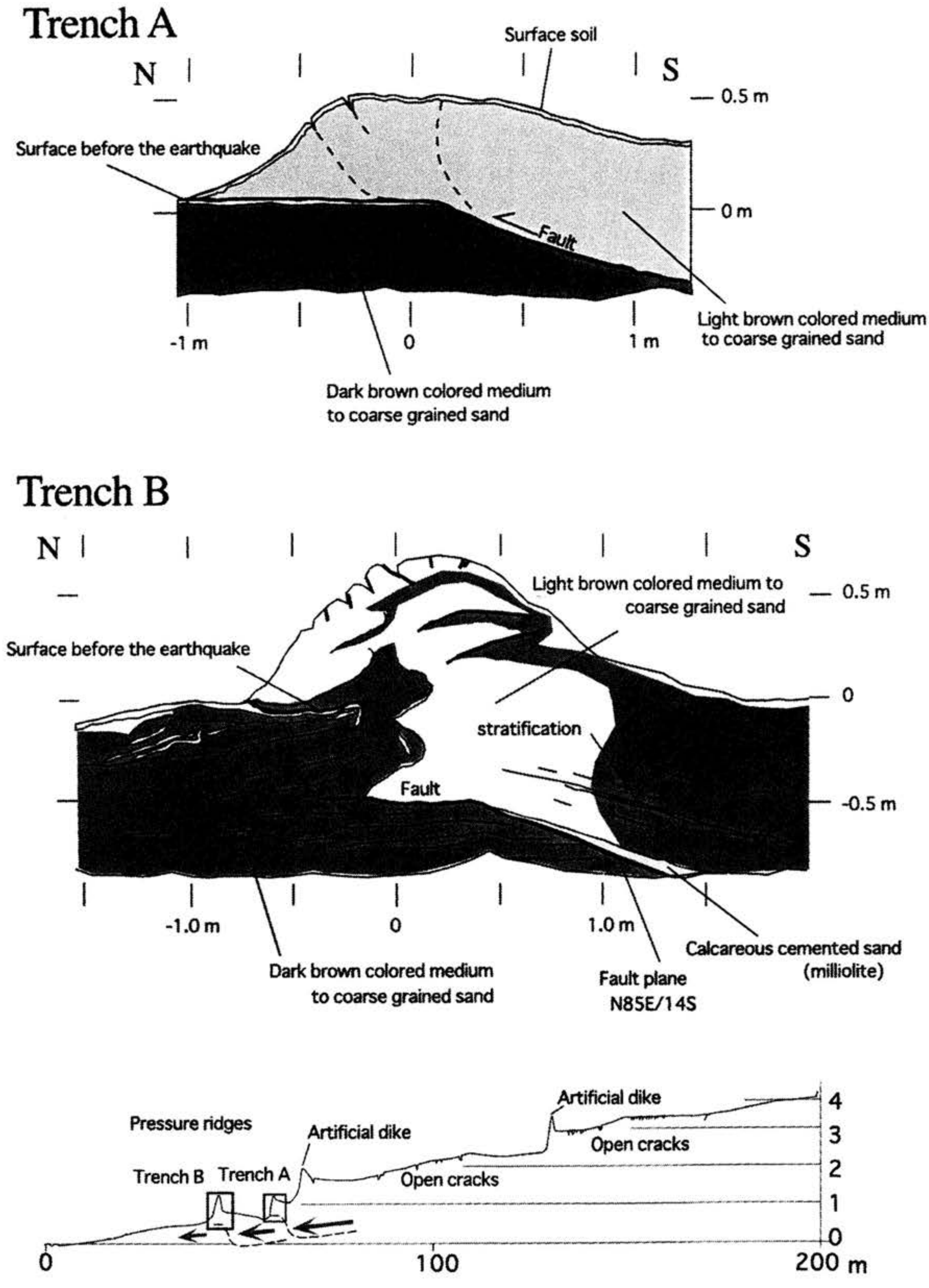

Figure 2.5. Logs at Trench A and B. The trench walls demonstrate typical thin-skinned tectonics. Trench A indicates a simple fault-bend fold, while trench B suggests fluid deformation at the toe of over-thrusting surface layers. Locations of the trenches are shown in the profile at the bottom.

Photo 2.11. Simple fault-bend fold deformation appeared in the trench A, looking east.

Photo 2.12. Over-thrusting surface layers forming linear bulge at trench B. A rather complicated structure on the trench wall may be due to fluid deformation.

Photo 2.13. Distinctive cracks near village Umedpur, located north of Lodai. These cracks are in N-S direction, and are characterized down to north and shows apparent right-stepping pattern.

discussion on some evidence of a thrust fault scarp. As we described above, we agree with NSF-SCEC Team (2001) that this deformation is the result of a lateral spreading. Aftershocks of the earthquake are distributed in a wide area north of Bhachau, and they suggest a south-dipping reverse faulting in a deeper part of the crust under Rann of Kachchh (Sato *et al.*, 2001). Therefore, we conclude that fault ruptures directly related to the earthquake did not appear on the surface associated with the earthquake.

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2.2 Active Faults

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Abstract

The Kachchh falls under seismically active zone-V outside the Himalayan seismic belt, and forms a part of Stable Continental Region (SCR). In the span of 50 years the Kachchh has experienced two large magnitude earthquakes, i.e. the July 21, 1956 Anjar with M_L 7 and the 2001 event with Mw 7.6. No coseismic surface rupture was associated with the Bhuj earthquake, suggests that movement along a blind thrust has resulted into extensive lateral spreading of water saturated near surface soil horizon giving rise to formation of numerous E-W striking extensional cracks or normal faults and the longitudinal pressure ridges in the epicentral area around Budharmora and Morgar villages. Liquefaction in the low-lying areas comprising fine sediments was the common phenomenon observed during this earthquake.

By satellite photo interpretation several traces of active faults were identified for the first time occurring in the pediment zones along the northern margins of Katrol Hill Range and Northern Hill Range, respectively. The active faults have displaced along them the Late Quaternary alluvial fan deposits and colluvial debris, resulting into formation of the north facing fault scarplets. Our field observations reveal that none of the active faults have moved this time. Thus, it is suggested that these faults still have high potential to break large magnitude earthquake in future.

Introduction

At 8:46 a.m. (IST) on January 26, 2001, when people of India were celebrating the Republic Day, a large earthquake of Mw 7.6 broke out in the western part of Gujarat, India, causing vast destruction and casualties. The event lasted for more than 30 seconds. Epicenter of the mainshock reported by the USGS to be 23.36°N and 70.34°E, Mw7.5, depth 22 km and the University of Tokyo, suggests Mw 7.6; 23.4°N and 70.3°E, depth 18 km. However, the Indian Meteorological Department located the epicenter 23.6°N and 69.8°E, in the Great Rann-Banni Plains, and measured a local magnitude M_L 6.9, depth 15 km (Fig. 2.6).

This is the most devastating earthquake in the history of India, in the sense of casualties and destruction. There are records of such large magnitude events which struck Kachchh in the recent past, the well known amongst them are of 1819 Allah Bund, M_L 8 and 1956 Anjar, M_L 7. Though these two events were of magnitude above M 7, number of casualties reported was much less, about 2000 killed during the 1819 and only 115 fatalities and hundreds were injured by the 1956 quake. The main reason for rising toll of the deaths and total destruction during the present earthquake is the rapid increase of population in the area. More than 19,000 people are reported to have been killed and over 160,000 injured by this earthquake (Jain *et al.*, 2001). However, according to the local people of Kachchh the toll of deaths is much higher than the figure declared officially. Many of them stated that, still the dead bodies are lying buried under the debris, which are not recovered, this was the situation almost after a month passed. News agencies have mentioned that about 600,000 people are left homeless due to this quake. The Gujarat State Government has estimated loss of about US $ 5 billion i.e. around Rs. 22,000 Crores (Jain *et al.*, 2001).

Numerous studies carried out after the

earthquake suggest that probably the movement took place on a blind thrust, and the rupture did not reached to the surface. Also it is not fully understood whether the earthquake was an interplate or intraplate type.

A short fieldwork and aerial survey was undertaken in Mainland Kachchh along Kachchh Mainland Fault Zone and Katrol Hill Fault Zone by our team between February 27 and March 5, 2001. Our prime emphases were: (1) to identify a surface rupture resulting from the present quake and to collect the ground truth of active fault traces (identified with help of satellite photo interpretation by Malik and Nakata, before this quake), (2) to verify whether any active fault was the source for this earthquake and (3) to record the magnitude of damage in and around the epicentral area.

Since the active faults identified were only the active tectonic features in the area, we presumed that one of them was probably the source of the Bhuj earthquake. However, our field observations revealed that none of the active faults moved during this earthquake. It is, however, difficult to yet pinpoint exactly which fault moved in sub-surface.

We present here a preliminary report on the field observations and aerial survey, highlighting active faults identified along the Kachchh Mainland Fault, surface deformation formed during this quake and

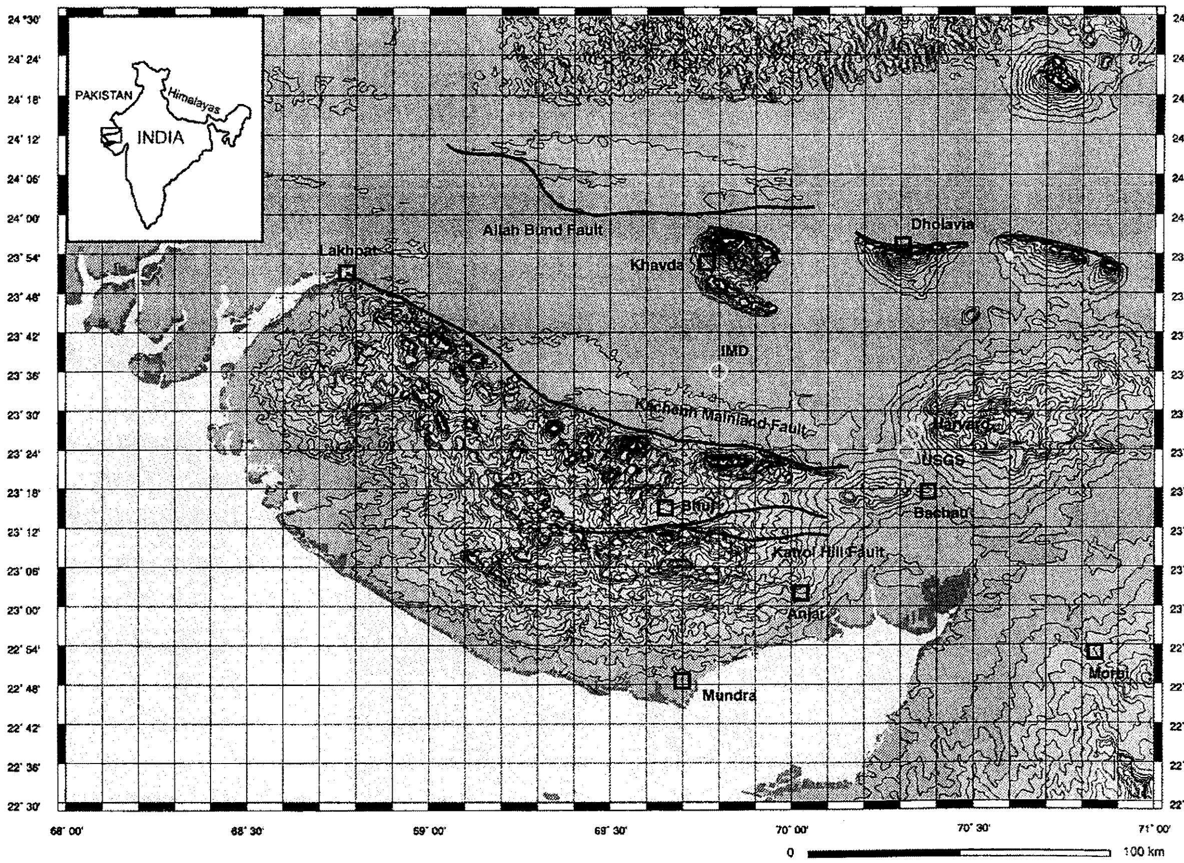

Figure. 2.6. Map showing locations of epicenters of the Bhuj earthquake according to various sources viz. Indian Meteorological Department, New Delhi; United State Geological Survey and Harvard. (Topographic map is prepared by Prof. Koji Okumura, Hiroshima University, Japan, and is based on DEM GTOPP30, GMT; contour interval 10 m).

degree of damage in the epicentral area and its vicinity. We expect that this information will be useful to evaluate the seismic hazard assessment for future and to understand the nature and pattern of faulting.

Geomorphic and Tectonic Setup

The Kachchh peninsula marks the western continental passive margin of northward drifting Indian plate (Fig.2.6). The basic structural framework of Kachchh represents a rift basin, which dates back to Late Triassic-Early Jurassic, exhibiting the longest record of the Mesozoic succession in the western India (Biswas, 1987). This rift basin is now under the influence of compressional stress regime resulting from the collision of Indian and Eurasian plates. The landscape of Kachchh shows a complex structural pattern marked by uplifts (Kachchh Mainland) and low-lying residual depression (Great Rann-Banni plains). Uplifts are confined along the major sub-parallel E-W striking longitudinal faults (Fig. 2.7), e.g. the Katrol Hill Fault, Kachchh Mainland Fault, Banni Fault, Island Belt Fault and Allah Bund Fault (Biswas and Deshpande, 1970; Biswas, 1980). The general form of deformation and uplifts are marked by domes and asymmetric anticlines exposing the folded Mesozoic rocks (Middle Jurassic-Lower Cretaceous) in the Kachchh Mainland (Biswas, 1980; Malik *et al.*, 2001). The uplifts, however, are not simple broad-topped upwarps, but are the manifestation of complicated flexures along the bounding faults and by secondary uplifts. Tertiary and Quaternary succession with mainly coastal plain and fluvial structures border these uplifts. Satellite photo interpretation as well as field studies suggest that the area has been experiencing intense folding and these

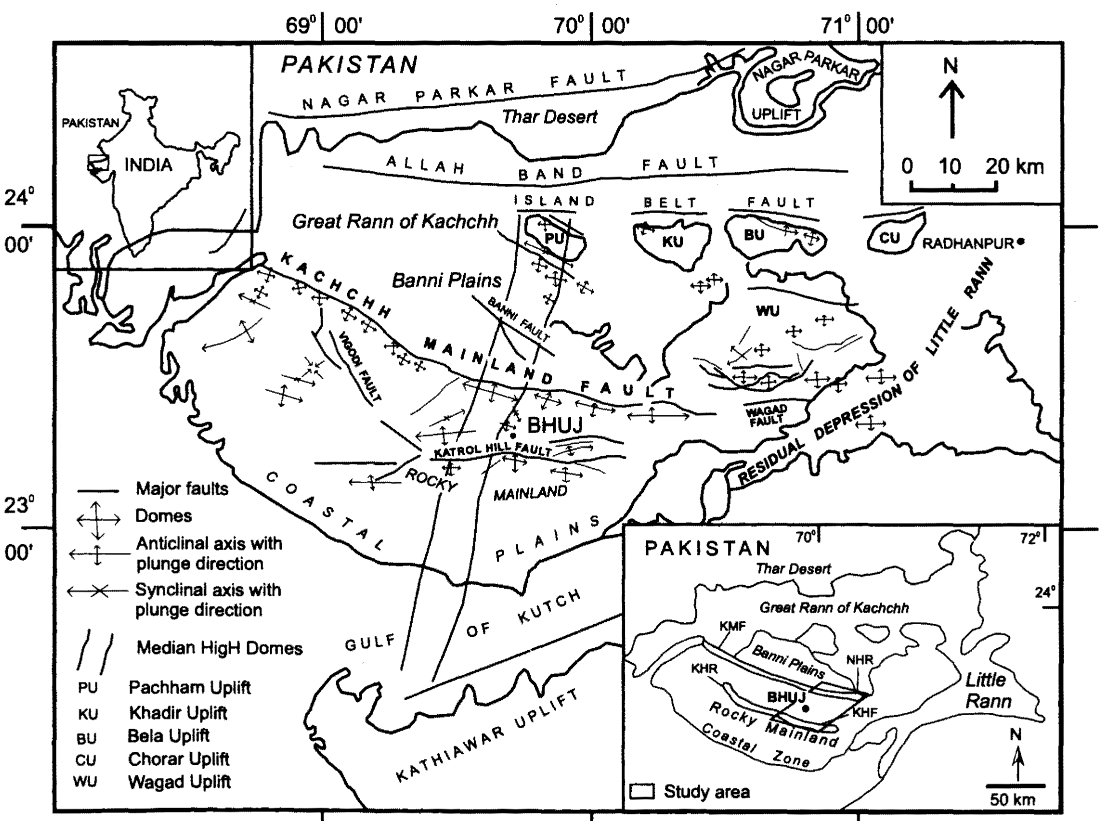

Figure 2.7. Structural map of Kachchh (after Biswas and Deshpande, 1970). Inset show generalized geomorphic zones of Kachchh peninsula. Box in the lower inset shows study area. NHR- Northern Hill Range, KHR- Katrol Hill Range, KMF- Kachchh Mainland Fault and KHF- Katrol Hill Fault.

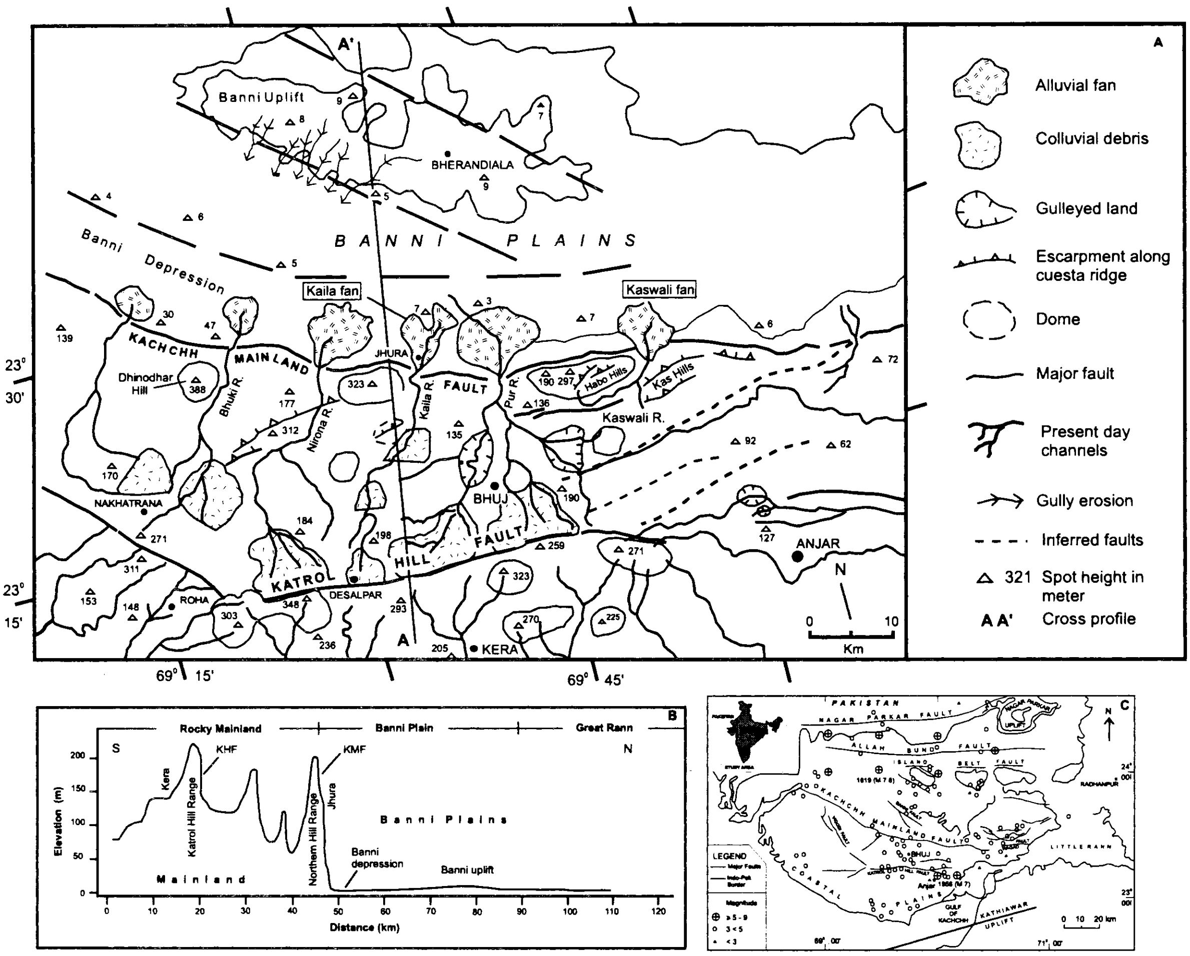

Figure 2.8. Geomorphic and tectonic setup of Kachchh Mainland. A: Tectonic geomorphology of Kachchh Mainland and Great Rann-Banni Plain, B: S-N cross profile along AA', profile prepared from topographic map. KMF- Kachchh Mainland Fault, KHF- Katrol Hill Fault (after Malik *et al.*, 2001). C: Map showing seismicity of Kachchh in last 300 years from 1668-1997 (after Malik *et al.*, 1999). Data obtained from Indian Meteorological Department, New Delhi, India (1996-97), Quittmeyer and Jacob (1997), Gazetteer of Kachchh District (1971) and USGS National Earthquake Information Center (1998-99).

folded structures show its strong control over the present landscape.

Geomorphologically, the Kachchh can be categorized into four major E-W trending zones: (1) coastal zone demarcating the southern fringe, (2) Kachchh Mainland forming the central portion of rocky uplands, (3) Banni-Plains marked by raised mud flats and (4) Great Rann in the north and Little Rann in the east comprising vast saline-waste land. The boundaries of these geomorphic zones are bounded by major faults (Fig. 2.7).

Morphology and structure of Kachchh Mainland and Great Rann-Banni plains

Kachchh Mainland comprises two major hill ranges viz. The Northern Hill Range and the Katrol Hill Range (Fig. 2.8A, B). Both these ranges are flanked to their north by major E-W striking longitudinal faults, Kachchh Mainland Fault and Katrol Hill Fault, respectively. These hill ranges are characterized by monoclinal flexures, anticlines and cuestas aligned along the southern flanks of the E-W trending faults.

E-W and WNW-ESE striking Kachchh

Mainland Fault mark the northern margin of the Kachchh Mainland, where the Northern Hill Range with average altitude between 130 to 388 m abutting against the low-lying Great Rann-Banni plains. The deformational pattern of this hill range is characterized by steep north facing escarpment and gently south dipping Mesozoic strata. According to Biswas (1980), the Kachchh Mainland fault is a vertical to steeply inclined normal fault at depth, and changes to a high angle reverse fault near the surface. The geomorphic expression suggests a phenomenon of fault-propagation folding as described by Suppe, (1983). It is also suggested that the movement is taking place along a south dipping low angle reverse fault. Several semi-conical alluvial fan lobes developed by numerous north flowing rivers debouching into Great Rann-Banni depression occupy the pediment zone along this range (Fig. 2.8A). The alluvial fan debris are seen resting unconformably on the Mesozoic sandstone+shale succession, with thickness up to 3 to 15 m and are probably of Late Quaternary age.

The Katrol Hill Range with average altitude of 148 to 348 m flanked to its north by Katrol Hill Fault marks the major drainage divide in the Kachchh Mainland (Fig. 2.8A). Uplift and deformation of this range along the Katrol Hill Fault has controlled the development of numerous north and south flowing rivers (Malik *et al.*, 2001). The morphology of deformation in this fault zone is similar to that along the Kachchh Mainland Fault. Intense asymmetric folding of the Mesozoic and Tertiary bed rock has given rise to the range with north facing steep forelimb with gentle back lime due south. Folding in Middle Pleistocene Miliolitic rocks (Sohoni *et al.*, 1999) suggests that similar deformation has continued during Upper-Pleistocene to Holocene. The pattern of micro-seismicity also suggests ongoing tectonic activity along the Katrol Hill Fault.

To the north of this fault lies the Bhuj basin, a longitudinal tectonic depression between the Kachchh Mainland Fault in the north and Katrol Hill Fault in the south. Bhuj basin comprises thin veneer of Quaternary fluvial terrace deposits overlying the Bhuj Formation. Whereas, the pediment zone along the Katrol Hill Range Front exhibits occurrence of several colluvial cones consisting of angular fragments of Mesozoic-Tertiary rocks along with some clasts of Miliolitc rock.

In Great Rann-Banni plains the Island Belt Fault is the another major fault running E-W along the northern fringe of the chain of islands (Fig. 2.7). This fault shows typical en-echelon pattern. Though, the pattern of faulting is different than the two faults of the Mainland, the island show similar morphology to that of hill ranges of Mainland. The nature of deformation along the Kachchh Mainland Fault, Katrol Hill Fault and Island Belt Fault is characterized by the uplift of southern block with gentle backtilting due south. This clearly suggests movement along a low angle south dipping faults, and south to north reverse faulting. In contrast to this, only the Allah Bund Fault exhibits opposite pattern with southern down-thrown side, indicative of movement along north-dipping fault plane. It has been presumed that probably the movement during 1819 event occurred along a north-dipping listric fault (Bilham, 1999) or it indicates typical mechanism of fault propagation folding (Rajendran and Rajendran, 2000).

The Kachchh region has experienced several episodes of earth movements along the various major E-W trending faults all throughout the Cenozoic, and these have not only contributed to the evolution of the present youthful landscape, but have also accentuated the structural pattern (Biswas 1971; Kar, 1988, 1993a, b).

Pattern of micro-seismicity in the area

First attempt was made by Malik *et al.*, (1999a), giving an account of the earthquakes that struck Kachchh since 1668 up to 1997 (over 300 years), and plotted them on the structural map to get a bird eye view of the pattern of micro-seismicity in the region (Fig. 2.8C). It is to be noted that mostly the earthquake those recorded during the historic time shows approximate location. The modern and historic earthquake record (Malik *et al.*, 1999a), and the active tectonic and palaeoseismic evidence (Malik *et al.*, 1999b; Malik *et al.*, 2001; Sohoni and Malik, 1998; Sohoni *et al.*, 1999; Rajendran *et al.*, 1999) suggest that the area has remained under the influence of continued tectonic movements during the recent historic times. The pattern of micro-seismicity reveals that the area have been struck by several earthquakes ranging from $M_L \leq 4$ to 8 and intensities between III and X + (MM) (Quittmeyer and Jacob, 1979; Johnston and Kanter, 1990; Malik *et al.*, 1999a). Apart from the large magnitude earthquakes with M >5 and >6, occurrence of earthquakes with magnitude ranging between M ≤ 3 and < 4 are more common. Amongst all these, the event 1819 Allah Bund earthquake is well documented in the northwestern part of the Great Rann of Kachchh, with M_L 8. It is considered to be the largest in the Indian sheild, and second amongst the earthquakes that have occurred in stable continental region (SCR) of the world, the largest being the 1810-11 New Madrid (USA).

It is noticed that more number of earthquakes with M>5 are confined along the Allah Bund Fault and its vicinity, two events with M>5 of 1821 and 1956 (Anjar event) show occurrence along the Kachchh Mainland Fault. Numerous events with M<4 are seen concentrated along the Kachchh Mainland Fault and Katrol Hill Fault. This suggests that compressional stresses were released in form of large magnitude earthquake M>5 along Allah Bund Fault and Katrol Hill Fault. Whereas, along the Kachchh Mainland Fault the accumulation of energy is going on, and the region along it has been experiencing a period of tectonic quiescence.

Though it was well established that the Kachchh falls under seismic zone V, other than the Himalayas, and has long record of large magnitude earthquakes no attempt was made towards identification of active faults which shows signature of continuous movement along them during the Late Quaternary-Holocene times. Also no detailed paleo-earthquakes studies were carried out to understand their pattern and nature. Only the recent studies carried out with this point of view by Malik *et al.*, (1999a, b); Sohoni and Malik, (1999); Sohoni *et al.*, (1999); Malik *et al.*, (2000); Rajendran *et al.*, (1999) have provided vital information on the aspect of palaeoseismicity and neo-tectonism.

Active Fautls in the Kachchh Mainland

The present study has provided more detailed information by identification of active faults in the Kachchh mainland (Fig. 2.9).

Aerial and field survey was focused along the Kachchh Mainland Fault Zone between Nirona and Bhachau (Fig. 2.10), whereas, only aerial survey carried out along the Katrol Hill Fault Zone from Bharasar to Anjar (Fig. 2.14). Our investigations reveal existence of numerous traces of active faults and tectonic features, which are suggestive of recent tectonic movement in the area. The active faults we found can be categorized as, one those cutting the younger alluvial deposits and second showing prominent alignment along the range front or following the old geological structures. The active fault traces showing dominance of old structure are only the active features we identified in

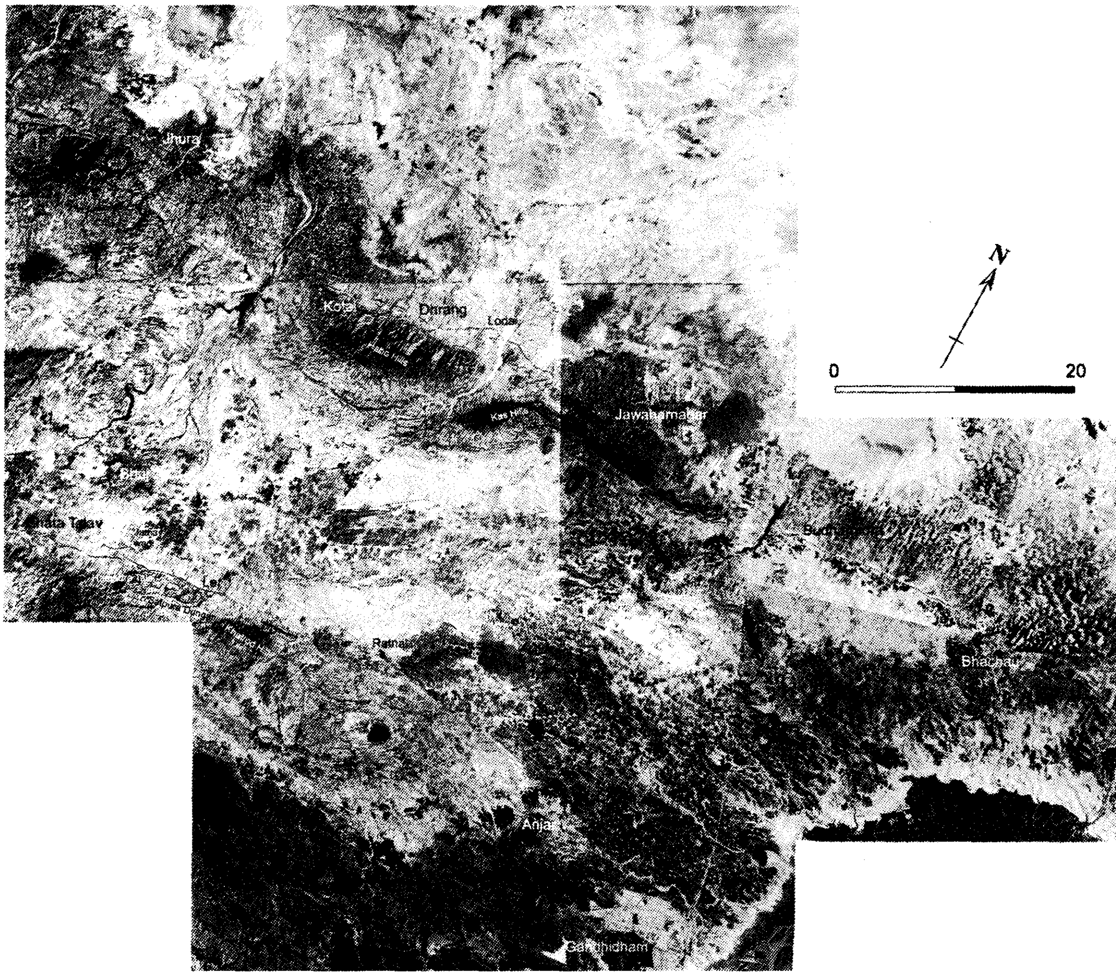

Figure 2.9. Satellite photo mosaic of Kachchh Mainland. Black lines show active fault traces along Kachchh Mainland Fault Zone between Jhura and Bhachau; along Katrol Hill Fault Zone between Bhata Talav and Ratnal. The active faults have displaced along them alluvial fan and colluvial debris of Late Quaternary age resulting in north facing fault scarps.

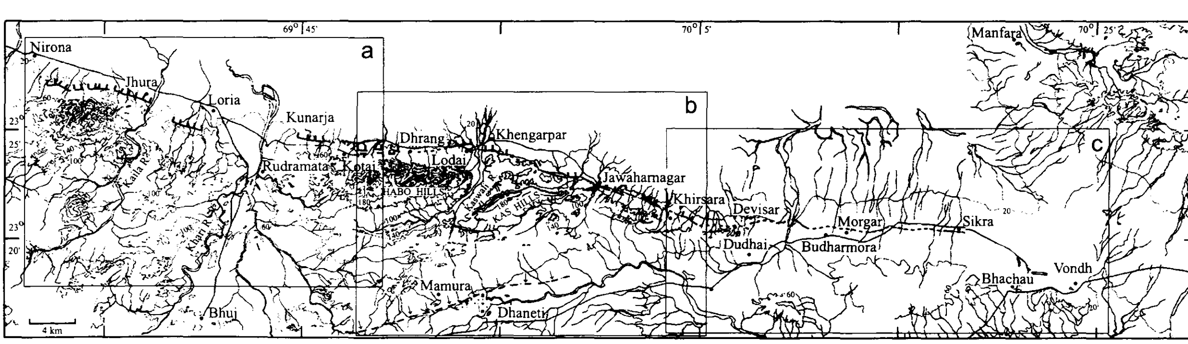

Figure 2.10. Topographic map showing discontinuous traces of active fault in the pediment area along Northern Hill Range in Kachchh Mainland Fault Zone. Box- a, b and c show locations of strip maps. Contour interval 40 m.

the area, however, further detailed studies are essential to strongly pinpoint the recent movement along them. Looking to the present situation after the recent quake, we expect that this information will play a key role in carrying out further in-depth

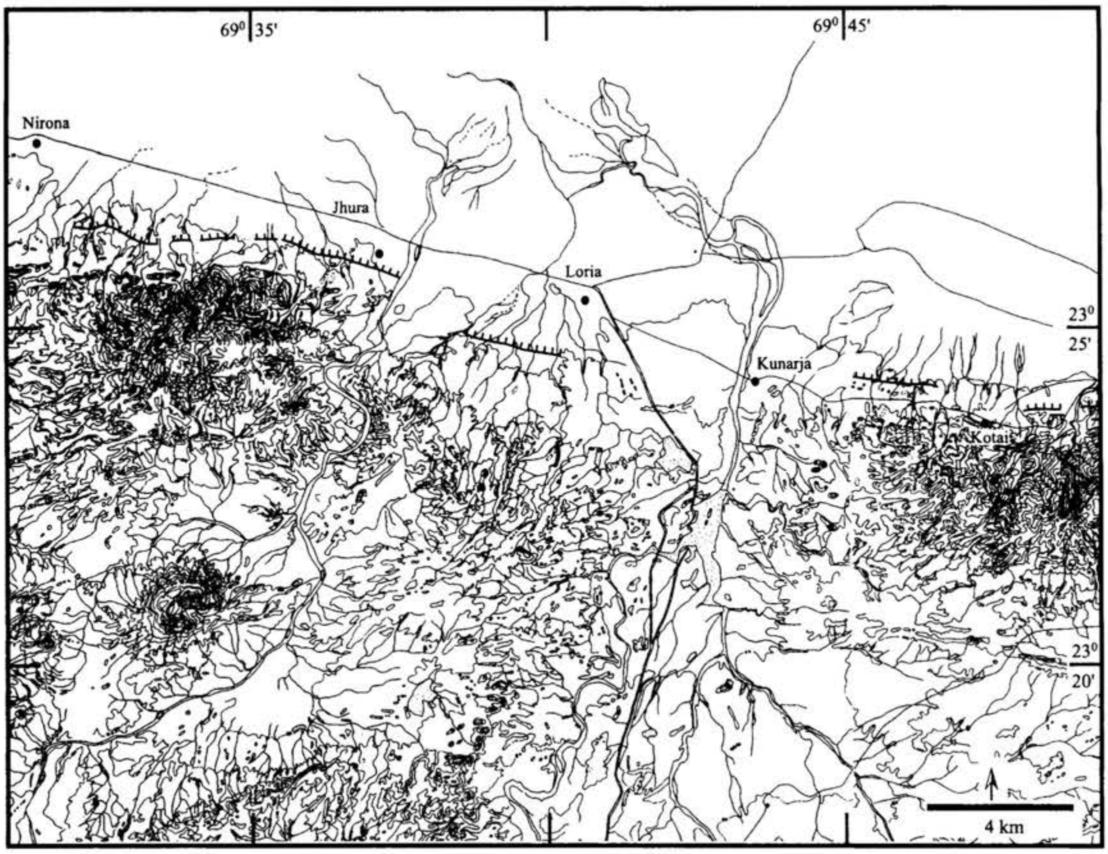

Figure 2.11. Detailed distribution of active faults between Nirona and Kotai. Bold lines indicate active fault traces. Combs are on the down thrown side. Dash lines show active fault traces with uncertain location. Contour interval in the strip map is 20 m.

paleoseismological investigations of this area.

Active fault traces along Kachchh Mainland Fault Zone

Scattered traces of active faults striking WNW-ESE, E-W and NNW-SSE were identified along the pediment zones of Northern Hill Range (Fig. 2.10). The faults laterally show discontinuous pattern and run parallel and sub-parallel to the Kachchh Mainland Fault. In the west of the study area the fault traces striking WNW-ESE lie south of Nirona and Jhura village (Fig. 2.11) The fan surfaces on which these villages are located have been uplifted along active faults, resulting in north facing fault scarps. These vertically displaced fan surfaces show intense gully erosion by the northward flowing distributary channels. This suggests that the surfaces were probably developed during Late Pleistocene to Middle Pleistocene period.

Between Jhura and Kunarja only one distinct active fault trace that runs for about 2 to 3 km was observed (Fig. 2.11). Further east, the area north of Habo Hill from Kunarja to Lodai exhibits many traces of active faults trending in almost E-W direction. The active faults cutting the fan surfaces run 1 km north of Kotai and through the Dhrang village (Fig. 2.12). Little warping within the fan sediments capping the folded Mesozoic rocks was observed near Kotai. Here the faults run sub-parallel to each other with down throws to the north and extend laterally up to 0.25 to 2 km in length. The north facing fault scarps show average height up to 6 to 8 m. Two traces of south facing antithetic fault scarps with E-W trend were found between Kotai and Dhrang. They run parallel to the main faults (with north facing

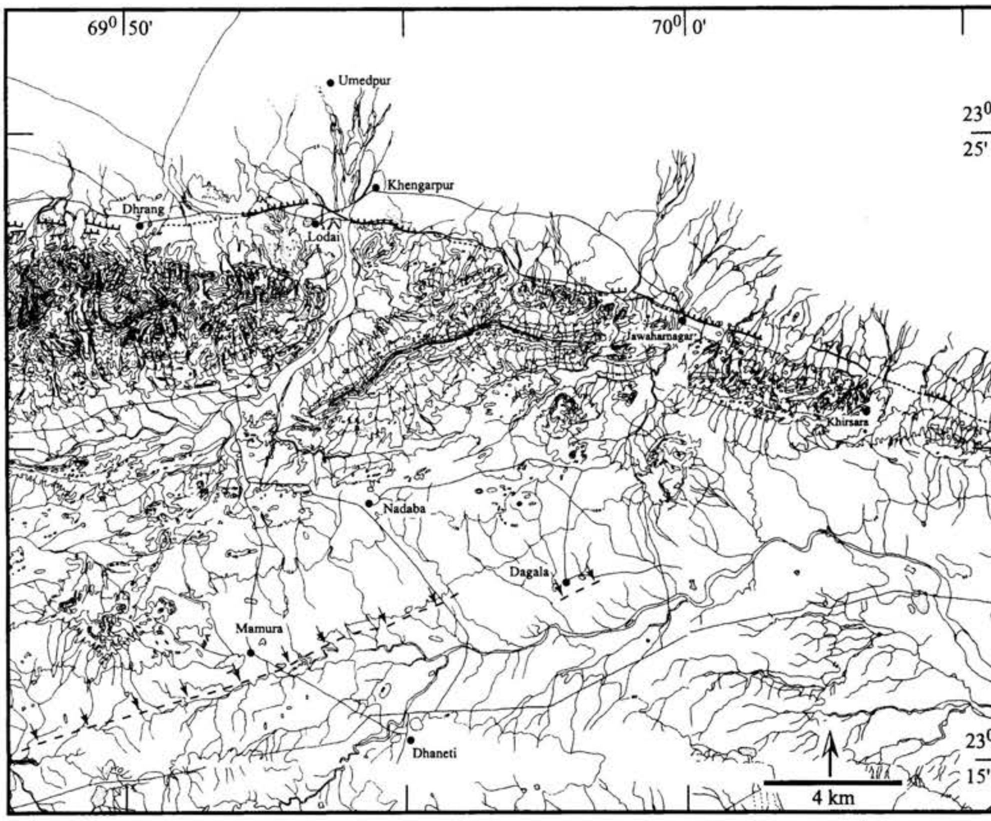

Figure 2.12. Detailed distribution of actives faults between Dhrang and Khirsara in the epicentral area of the Bhuj earthquake. Bold lines indicate active fault traces. Combs are on the down thrown side. Dash lines show active fault traces with uncertain location. Contour interval in the strip map is 20 m.

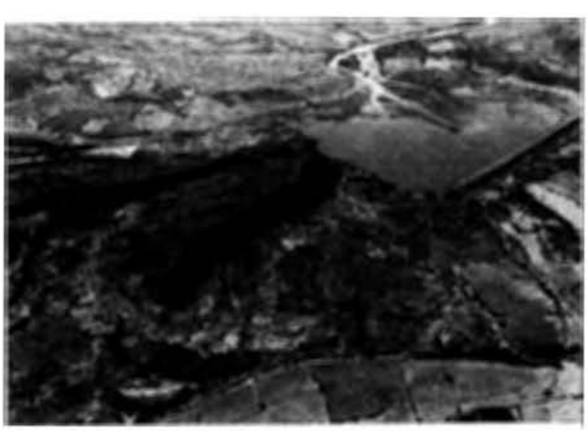

Photo 2.14. Active fault trace on the right bank of Kaswali river, east of Lodai village. Probably this fault is an extension of the fault observed on the left bank. The fault has displaced fan surface resulting into north facing fault scarp. View looking south.

Photo 2.15. Active fault displacing and warping the alluvial fan surface at Jawaharnagar village. The village is located on the down thrown side of the fault. View looking south.

scarplets) and are cutting the same fan surfaces. This suggests that these hill-facing fault scarps probably represent subordinate or subsidiary faults to the main faults, and might have observed the contemporaneous movement during the major phase of deformation.

A prominent trace of north facing active fault scarp trending almost E-W recognized by satellite photo interpretation west Lodai village (on the left bank of Kaswali river) has dislocated three fan surfaces (Fig. 2.12; Photo 2.14). The scarp is about 5 m high across the higher fan surface and about 20 m across the lower surface, suggesting cumulative fault slip. This fault extends for more than 1.5 km and probably further west it connects the active fault near Dhrang. However, it does not show any significant surface trace in field as well as on the satellite photo. The eastern extension of this fault runs north of Lodai village. Here it has clearly displaced the fan surface on which Lodai village is located giving rise to 5 to 7 m

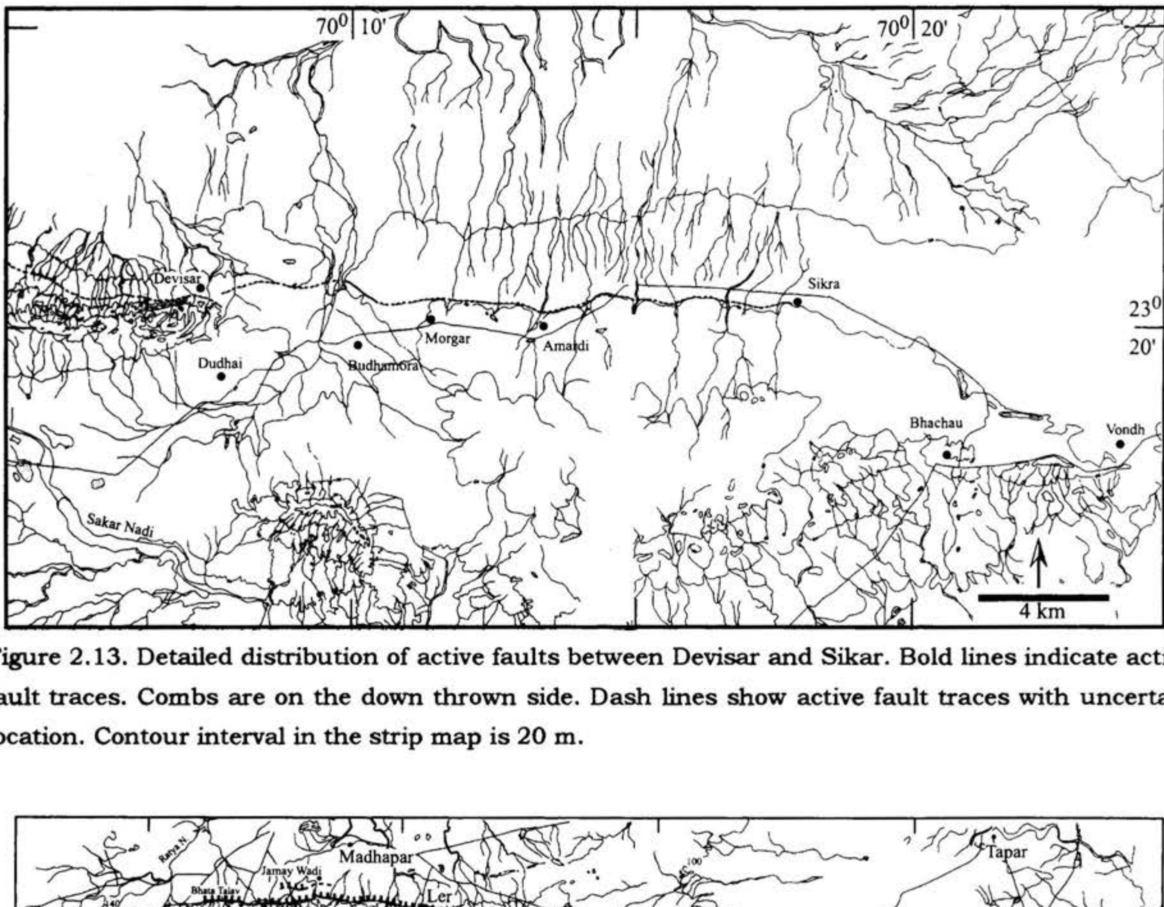

Figure 2.13. Detailed distribution of active faults between Devisar and Sikar. Bold lines indicate active fault traces. Combs are on the down thrown side. Dash lines show active fault traces with uncertain location. Contour interval in the strip map is 20 m.

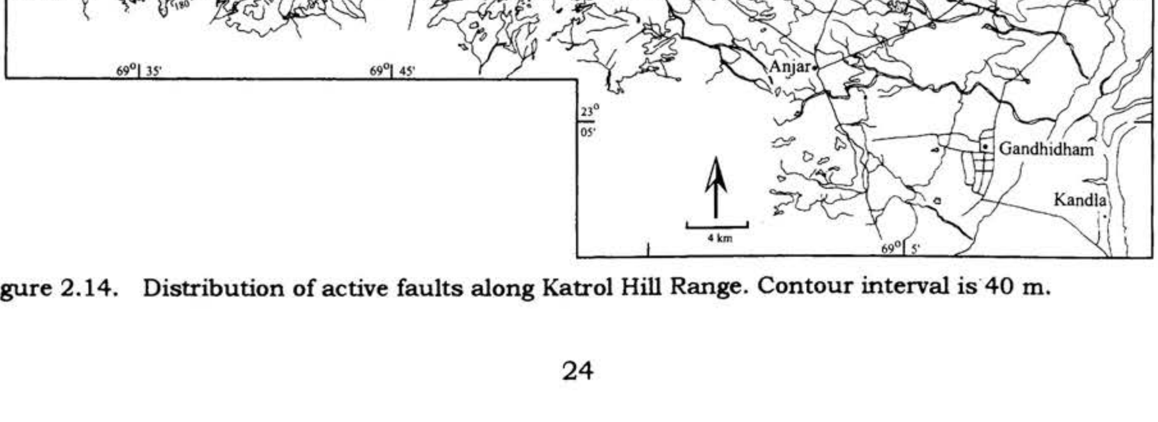

Figure 2.14. Distribution of active faults along Katrol Hill Range. Contour interval is 40 m.

high scarplets on the lower fan surface and about 10 m on the middle fan surface. The fault identified on the right bank of Kaswali river, east of Lodai, shows sinuous pattern striking ENE-WSW and WNW-WSE. This fault is probably the extension of the fault on the left bank. It is presumed that the central portion has been eroded away by Kaswali river flowing across it. These fan surfaces are marked by comparatively less dissection to that observed near the Jhura village, suggesting younger age of the surfaces.

From Lodai further east up to Devisar the active fault traces follow the near range front boundary, where the old structure mingles, making it difficult to decipher the recent movement along it (Fig. 2.12). Possibly reflecting an older movement. However, such sharp features could not be discarded in a terrain where the alluvial cover is very thin and most of the near surface area is marked by outcrops of older rocks. At some instances between Jawaharnagar and Khisara villages a few active fault traces displacing the fan surfaces were observed (Photo 2.15). They lie in discontinuous pattern north of the older fault line with little lateral extent of 1 to 2 km. The Devisra village marks the eastern edge of Northern Hill Range, where the rocky hill dies out into the alluvium. This area is occupied by the medium to fine grained fluvial sediments that very much resemble with the Great Rann-Banni plains succession. Only obscure trace of elevation difference was observed on the satellite photo, which extends linearly in E-W direction with sinuous pattern north of villages like Budharmora, Morgar, Amardi and Sikra (Fig. 2.13). Further east, it strikes in NNW-SSE through Bhachau up to Vondh. It is presumed that this linear feature is probably the expression and further eastward extension of active fault and belongs to the Kachchh Mainland Fault system.

To the south of the Kachchh Mainland Fault Zone near Mamura village in Bhuj

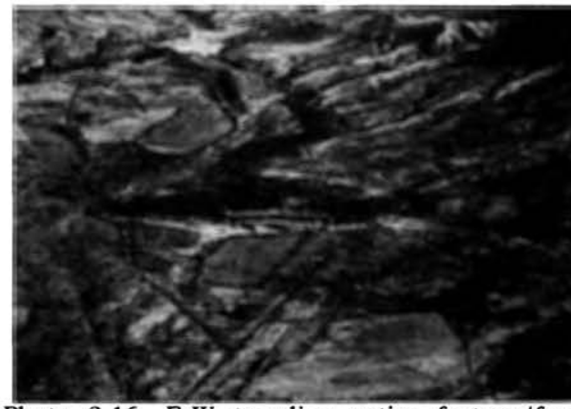

Photo 2.16. E-W trending active feature/fault trace (?) cutting through the colluvial debris in the pediment zone along Katrol Hill Range north of Hamadra Talai. The longitudinal stream flowing parallel to the range front follows the fault trace.

Photo 2.17. Eastern extension of active fault trace aligned along the range front of Satpura Dungar cutting colluvial debris near Ler Village, marked by sharp straight escarpment delineating contact between the alluvium in pediment.

Photo 2.18. Expression flat rocky surface with thin colluvial material cover showing sharp straight contact with the alluvium, view looking to south, probably indicating active feature. Location between Ler and Ratnal.

basin, a linear feature striking ENE-WSW shows warping towards south with gentle dip of surface due north. It extends for more than 15 km parallel to the northern bank of Sang river. The morphology of the deformation suggests that this feature is associated with a north-dipping fault, which is in contrast to the other major faults in the Kachchh Mainland.

Active geomorphic features and active faults (?) along Katrol Hill Fault Zone

Most of the active faults and active tectonic features striking E-W are aligned with the old Mesozoic structure, manifested by straight linear ridges and linear contact between the rocky outcrops and alluvium in the foreground. We describe here a brief account of active fault traces identified on satellite photo and during aerial survey between Bharasar in the west and Anjar in the east (Fig. 2.14). Near Bharasar the fault trace is very obscure, moreover, further east a prominent sharp feature was identified. The active fault north of Bhata Talav showing sinuous pattern has displaced the colluvial debris of Late Quaternary age in pediment zone giving rise to north facing fault scarplet. Similarly, expression of active fault was also observed north of Hamadra Talai (Fig, 2.14; Photo 2.16). One local active tectonic feature extending E-W for about 3 km near Jamay Wadi has uplifted colluvial cone surface with down throw to its north. As this surface does not show high degree of dissection, it suggests being of younger age.

Further east, the active fault follows the range front of Satpura Dungar for about 5 km. At the eastern edge of Satpura Dungar the active fault following range front has also displaced the alluvium in the pediment zone. This fault passes through the Ler village located on the colluvial surface (Photo 2.17). In the foreground a few expressions of flat rocky surfaces covered by thin colluvial material are marked by sharp straight contact with the alluvium (Photo 2.18). This suggests their tectonic origin. However, since the old structure has strong control over the landscape of Kachchh Mainland, these features cannot be ruled out or overlooked. The morphology clearly suggests their tectonic origin and could be the source for large magnitude earthquakes in this area in near future.

Looking at the geomorphic manifestation of active fault traces along the Kachchh Mainland Fault Zone and the Katrol Hill Fault Zone, it is clear that the tectonic activity is propagating northward in the Bhuj lowland and in the Great Rann-Banni plains respectively.

Nature and Pattern of Damage

The severe damage associated with the Bhuj earthquake is rather unusual compared to its magnitude. The Indian peninsula has been struck by eight large magnitude events in the last 182 years. The Bhuj earthquake is one of the most devastating and life taking events in the history of Indian earthquakes.

Though the earthquake epicenter was located northwest of Bhachau, the shock was felt by whole Indian subcontinent, rocking the far located cities like Karachi in Pakistan, Katmandu in Nepal, Dhaka in Bangladesh and from Kashmir (north) to Kaniyakumar (south) and Kolkata (east) in India. Destruction and building collapse was reported from major cities like Surat, Ahmedabad, Rajkot and Morbi.

Damage in Kachchh

An attempt has been made to present the degree of damage in the epicentral area and its vicinity. The observations made during the fieldwork and by aerial survey reveal that the villages and major towns aligned along the fringe of Northern Hill Range (bounded to its north by Kachchh Mainland Fault) and in the vicinity of the epicentral area mark the total destruction.

The villages/towns showing nearly complete damage from east to west are

Samkhiali, Vondh, Bhachau, Kumbharia, Amardi, Budharmora, Morgar, Haboi, Dhaneti, Dudhai, Khirsara, Jawaharnagar, Lodai, Umedpur, Khengarpar, Dhrang, Kotai, Kunaria, Sumarasar, Jhura etc. and numerous other small villages between them. Other major populated towns like Bhuj, Anjar, Gandhidham, Nakhatrana etc., observed comparatively less damage.

In Bhachau and its neighboring small villages, populated with about 150,000 people, none of the houses were seen intact. According to the local people, the approximate death toll has been more than 6000. Similar pattern of destruction was observed at the villages like Budharmora, Morgar, Jawaharnagar, Umedpur, Dhrang, Kotai etc. During the aerial survey we observed that Anjar with a population of 150,000 suffered complete damage in the center of town, whereas some houses were still seen intact with less damage on the fringe of the town (Photo 2.19). At Bhuj the center of the city i.e. the old city enclosed within the Alampana Fort, was completely damaged (Photos 2.20 and 2.21). The fort wall was subjected to heavy destruction during this quake. Even the newly build houses and building with 3-6 stories with reinforced concrete were completely collapsed and some were tilted by 90° (Photo 2.22).

Our regional observation reveals that the towns and the villages located in the vicinity of the epicentral area were fully damaged. Bhachau (Photo 2.23) and Vondh which are located on the rocky platform of Mesozoic sandstone and villages like Budharmora, Morgar, Amardi, Dhamadka, Jawaharnagar etc. located on the soft unconsolidated sediment succession the destruction was nearly similar, irrespective of the ground condition. We found that comparatively less damage occurred in the towns like Bhuj, Anjar, Ratnal etc., which were located far from the epicentral area, particularly with the hard rocky platform. But, the villages like Lodai, Umedpur, Khengarpar, Dhrang, Kotai etc. though located far from the epicenter complete damage was observed. This unusual damage pattern was due to the poor

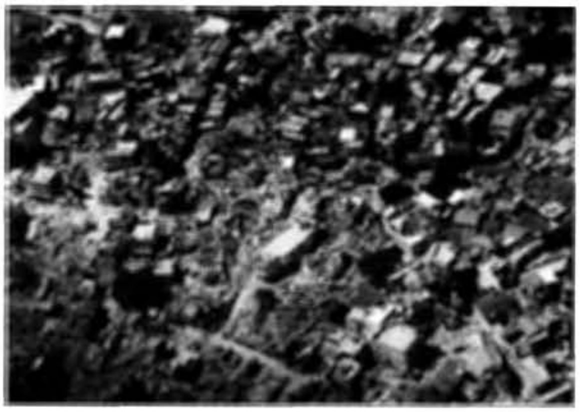

Photo 2.19. Aerial view of damage at Anjar. Note that only the centre of the town was seriously affected by this quake.

Photo 2.20. Old photograph showing intact Alampana Fort that encloses the old city of Bhuj before the earthquake.

Photo 2.21. Alampana Fort after the earthquake.

Photo 2.22. A view of collapsed reniforced concrete building tilted 90° during the present quake at Bhuj.

Photo 2.23. Aerial view of destruction at Bhachau.

ground condition, which is susceptible to liquefaction and lateral spreading. This suggests that the strong shaking during the peak ground acceleration was the main cause for the total destruction in the rocky as well as in the low-lying areas comprising soft sediments. It also clearly points out that mostly the old houses constructed in a traditional pattern using rocky blocks with poor cement or mud were completely damaged. Whereas, in the case of newly build building it indicates the poor quality construction material and design of buildings, without the knowledge that such large magnitude earthquake will ever struck the Gujarat State. Similar was the cause of damage at Ahmedabad, though located about 400 km far from the epicenter.

Deformational Features

Field reconnaissance reveals that no primary surface rupture was caused by the Bhuj earthquake, though the magnitude was Mw 7.6. This clearly suggests that the movement took place subsurface on a blind thrust. The past geological evidence of strong folding in Mesozoic and Tertiary rocks, and in Middle Pleistocene Miliolite rocks suggests ongoing deformation along a low angle south dipping reverse faults. This indicates that the area is under the influence of constant N-S compressional regime, and the present youthful landscape is a manifestation of active warping or an active growing fold.

The deformational features identified during the field and aerial survey are mainly the secondary tectonic features caused by strong ground shaking over a gently sloping surface. These features are prominent development of extensional cracking of near surface ground and liquefaction. This earthquake has provided ideal opportunity to study variety of liquefaction and plastic deformational features in soft unconsolidated sediments and the phenomenon of lateral spreading, specially where there is no surface expression of coseismic rupture.

Evidence of intense lateral spreading was observed in the vicinity of the epicentral area, around Budharmora and Morgar, and these features were documented in detail in the previous section (Nakata *et al*. 2001). Lateral spreading has resulted into pervasive cracking in the agricultural field. The pattern of cracks striking almost E-W are the normal faults associated with the extensional regime, with general trend of down throw due north. At places these cracks/faults, with down throw both towards north as well as south has resulted in the formation of local graben structure. A few evidence of associated liquefaction has resulted in to development of small depressions or craters ranging in diameter from 1 to 1.5 m (Photo 2.24). The scattered wet patches of logged water indicate that the ground water was pored out with pressure during the strong shaking. These were the common features found associated with the cracking.

The lateral spreading of the capped soil occasionally shows evidences of apparent right and left lateral movement. Width between the cracks varies from 20 to 30 cm, along with some as wide as 60 to 70 cm apart. The cracks are generally seen making descending step-pattern down north and occasionally south (Photo 2.25). In the area around Budhamora and Morgar, from north to south, the intensity of the extensional cracks increases and finally dies out with two to three E-W striking longitudinal warps.

About 5 km north of Kachchh Mainland in Banni Plains near village Umedpur,

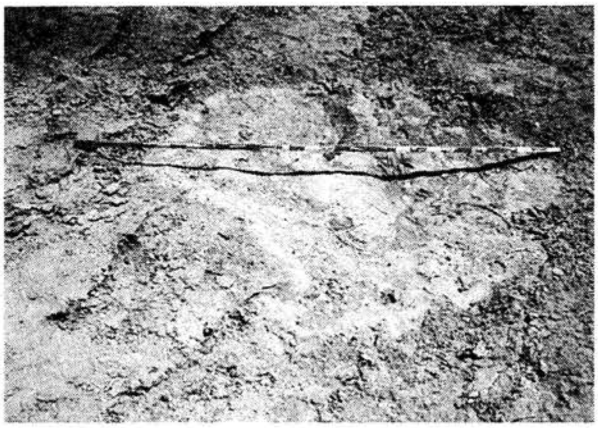

Photo 2.24. Liquefaction associated with lateral spreading resulting into the formation of depression or craters of 1 to 1.5 m in diameter. Location is Budharmora.

Photo 2.25. Lateral spreading resulted in the development of sub-parallel extension cracks or normal faults with down throw due north. Extensional faulting has give rise to development of stair-case pattern at Budharmora. View looking east.

Photo 2.26. N-S striking extensional surface cracks at Umedpur in Banni Plains. Cracks show sinuous pattern. Apparent left-lateral movement results into formation of small pull-apart. Displacement is about 10-20 cm.

Photo 2.27. Slumping down of riverbed along the Khari River at Rudhramata. The riverbed has collapsed down by about 50 to 60 cm down resulting in extension on either side of the bank.

located north of Lodai, the intensity of cracks is seen to be reduced. The cracks are seen occurring in isolation and not in bunch as observed near Budhamora and Morgar. These cracks are characterized by general down throw due north and show sinuous pattern along with 10 to 20 cm left-lateral movement giving rise to development of small pull-aparts along it (Photo 2.26).

In some portions of the field, the deformation has waved-up the surface resulting into alternate pattern of bumps and depressions. This shows how the ground must have moved when the shear-wave (S-wave) passed through the area. The remnant of similar feature was also recorded on the Surajbari bridge where the whole bridge is waved-up. The cracking in the mantled roads and state highways are also the result of extensive lateral spreading of the near surface capped soil.

Riverbank collapse or slumping down of riverbed was noticed along the Khari River at Rudhramata about 10 km north of Bhuj. The riverbed has collapsed down by about 50 to 60 cm down resulting in extension on either side of banks (Photo 2.27).

The above mentioned deformational features were observed confined to the low-lying area where the capping of alluvium is comparatively more. This suggests that the lateral spreading of the near surface water saturated soil horizon is definitely the result of increased pore-water pressure during strong ground shaking, which is a common feature found in an area comprising soft unconsolidated sediment succession. In such case an increase in pore-water pressure decreases the granular shear strength of the sediments at depth, causing it to fail in shear over a very gently inclined ground surface, as gently as 0.1 to 5 % (Obermeier, 1996).

Discussion and Conclusion

Recent studies carried in this region between 1996-2000 suggest the ongoing tectonic activity in this area. However, no attempt was made towards identification of active faults and to work out the repeat time interval of the large earthquakes. The sources of earthquakes are mainly the active faults and their identification bears significant importance towards knowing the seismic potential of the region.

Our data on newly identified active fault traces along the Kachchh Mainland Fault Zone and Katrol Hill Fault Zone provide vital information in this regard and will play a key role in carrying out further in-depth paleoseismological investigations and work out the seismic hazard assessment of this area. The fact that none of the active fault moved during the Bhuj earthquake suggests that probably the movement took place on a blind thrust, and the rupture did not reached to the surface. As none of the active faults moved this time, there is high possibility that large magnitude earthquake could occur along these faults in the future. The sub-surface movement caused gentle warping or folding in the epicentral area, bringing about extensive lateral spreading and associated liquefaction. Strong shaking in the epicentral area and places located far suffered total to nearly total damage, mainly because of the old houses constructed in old traditional fashion.

Since the active faults we found are only the active tectonic features in the Kachchh, a Stable Continental Region (SCR) in Indian plate where the occurrence of large magnitude earthquakes have a long repeat time, it is very much essential to carry out detailed studies likewise dating of alluvial fan surfaces and colluvial debris, detailed mapping of these fault scarplets and trenching along the appropriate active faults. This will help us in deciphering the recent movement along these faults and in building up a long-term record of earthquakes which struck Kachchh peninsula in the recent historic past for evaluating seismic hazard assessment of the area.

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