The 2001 Kutch (Bhuj) earthquake: Coseismic surface features and their significance

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The Mw 7.7, 2001 Kutch (Bhuj) earthquake that occurred in the northwestern fringes of the Indian craton is the most damaging earthquake during the recent history. Although the main fault rupture did not reach the surface, the epicentral area is characterized by the development of secondary features, including flexures and folds that are related to compressional deformation, in a wide area of the Banni Plain. Based on the spatial distribution of these structures and their inferred mechanics, we propose that the earthquake originated on an imbricate blind thrust, located north of the Kutch mainland fault. Besides surface deformation, the earthquake also induced widespread liquefaction, leading to ground failure including lateral spreading. Although a large earthquake had occurred in the Rann of Kutch in 1819, preliminary assessment based on ancient monuments and temples in the region indicates that the source of the 2001 earthquake may not have experienced similar size events at least since 9th century A.D. Occurrences of this and the 1819 earthquake underscore the need for recognizing hidden faults in the Kutch–Saurashtra region and assessing their seismogenic potential.

THE 26 January 2001 Bhuj earthquake (Mw 7.7) that occurred in Gujarat is the most disastrous earthquake in India's recent history. While the actual figures of death and injury remain uncertain, at least 20,000 people are feared dead and more than 200,000 injured. Nearly 400,000 houses were destroyed and twice as many damaged. Although damage of such proportion is astonishing, the occurrence of the event itself is not surprising, considering the geologic and seismic history of the region. Two damaging earthquakes are known to have struck the Kutch Peninsula during the last two centuries, namely, the 1819 earthquake that killed more than 2000 people and wiped out several centres of human settlements in the Rann and the more recent event in 1956 that killed 115 people and damaged a large part of the town of Anjar.

The 2001 earthquake has attracted tremendous attention from the national and international research community. Several study teams arrived within a week to study different aspects of this earthquake including the damage pattern, response of structures, field effects and aftershock activity. Uniqueness of its tectonic regime, especially the influence of an active plate boundary on the stress field and analogies with other intraplate earthquakes associated with ancient rift basins are issues that generated interest among the scientific community (see http://clifty.com/hazard/archives.html).

One aspect that adds to the uniqueness of the Bhuj event is its location in a region considered to be part of a stable continental region (SCR) that had generated an Mw 7.5 earthquake in 1819. Occurrence of another earthquake of similar size within a short interval of time gives a rare opportunity to compare its effects with those generated by the previous event. Such data are useful not only for the seismic hazard assessment in western India, but also in other regions of analogous geologic settings. Because of its exceptional geologic significance, a special session on this earthquake was organized at the 2001 Annual Meeting of the Seismological Society of America (San Francisco) and another one is planned for the spring meeting of the American Geophysical Union.

The Kutch region is underlain by a Mesozoic rift system[1]. Faults within such rift systems are known to have the potential to generate large earthquakes[2]. In fact, the 1819 earthquake has been cited as one of the classic examples of SCR earthquakes in an ancient rift[2]. In a recent paper, Rajendran[3] noted that the Kutch rift can be differentiated from other SCR palaeorifts by its relative proximity to an active plate boundary, an important factor that influences its level of seismicity. In a forthcoming paper, Bendick *et al.*[4] have made some preliminary observations about the strain changes following this earthquake. In this paper we do not deal with these issues, but restrict our discussion to the post-seismic field observations and their implications on the mechanism of the earthquake.

Tectonic setting and past seismicity

The Kutch aulocogen owes its origin to Mesozoic tectonic events initiated during the break-up of Gondwanaland and the northward drift of the Indian plate. The rift basin evolved as a consequence of this break-up and was controlled by a series of normal faults, which are still

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exposed in the region. Movement along these faults produced a number of horsts and grabens[1]. A change from extension to north-south compression probably occurred about 40 Ma ago, subsequent to the collision of India with Asia. Low-angle reverse faults exposed in this region provide geologic evidence for such a tectonic reversal[5], which is indicated also by the thrust-type focal mechanism obtained for the 2001 Kutch event (USGS) as well as the 1956 Anjar earthquake[6]. The stress field oriented in the N-S to NNE-SSW direction[7] is considered to be responsible for this reversal of movement and the ongoing deformation. Talwani and Gangopadhyay[8] provide a good summary of the tectonic evolution of the Kutch region, particularly in the context of the recent earthquake.

The Kutch region has experienced large and moderate earthquakes since historic times[5,9,10]. The 1819 earthquake (Mw 7.5) is the largest event to have occurred here during the historic times and the 1956 Anjar earthquake (Mw 6.0) is the largest during the post-instrumentation period. These earthquakes are located about 150 km northwest and 40 km west of the 2001 event (Figure 1). The Anjar earthquake originated at a focal depth of 15 km and is believed to have occurred on one of the southern boundary faults of the Kutch rift[6]. Due to its spatial association with the Kutch mainland fault, the earthquake is generally considered to be associated with this prominent south-dipping structure, exposed at a number of locations. However, in the absence of any observable surface deformation associated with the earthquake, this may remain a conjecture. The 1819 earthquake occurred on the northern boundary of the Kutch rift. Morphological evidence of deformation, including a south-facing surface scarp of maximum elevation of about 6 m showing a northerly slope suggests that it was associated with thrust motion on a north-dipping fault[9,11,12]. Mechanisms of both these earthquakes are suggestive of reactivation of preexisting normal faults in a reversed stress field. Reversal of the stress field from extension to compression and reactivation of normal faults are also observed in other ancient rifts in SCR India[6,13].

The prehistoric record of seismicity in Kutch is incomplete and palaeoseismological studies in the region are at a very early stage[3,5,12,14]. Studies initiated in the epicentral region of the 1819 earthquake suggest one previous event about 800–1000 years ago in the same source zone[5]. Palaeoseismic history of the fault/s that broke during the recent earthquakes (1956 and 2001) remains unexplored to a large extent and not much information is available. Several historic monuments/temples in the meizoseismal area, dating to 9–11th century A.D. were totally or partially destroyed during the 2001 earthquake. The fact that they had remained intact for nearly 10 centuries suggests that the present epicentral region has not been subjected to such severe shaking, at least during the life of these structures. Thus, from the available data since historic times and based on the inferences drawn above, the 2001 earthquake appears to be the largest event originating in this zone, at least during the last 1000 years or so.

Epicentral location and surface effects

The India Meteorological Department (IMD) has located this earthquake at 23.40°N, 70.28°E, using 53 stations forming part of a national grid[15]. The U.S. Geological Survey (USGS) located it at 23.36°N, 70.34°E, based on teleseismic data. Focal depth estimates of this earthquake according to IMD and USGS are 24 km and 22 km, respectively. Both locations are north of Bhachau, a town that was totally destroyed in this earthquake; we have used the USGS location for our interpretations. Preliminary analysis by the seismology team from the Mid-American Earthquake (MAE) Center, Memphis, suggests that the aftershock activity is mostly confined to a region of about 100 km^2 around Bhachau, their focal depths ranging from 8 to 40 km (Arch Johnston, pers. commun.). Locations of the main shock and the general region of aftershock activity are shown in Figure 1. Focal mechanisms for the main event (IMD and USGS) indicate thrust motion on a westerly-striking plane. An intriguing aspect about this earthquake is that there was no surface rupture associated with the event (at least none has been mapped so far). With no displacement on the surface, it becomes very difficult to understand the characteristics of the causative fault/s. Preliminary analysis of part of the aftershock data collected by the MAE centre suggests that the fault plane dips 40–50° south (Arch Johnston, pers. commun.).

Although the main fault rupture did not reach the surface, the epicentral area showed secondary structures characteristic of compressional tectonics. The earthquake also generated a variety of liquefaction-related features, including lateral spreading, sandblows and waterspouts. Most of the surface effects discussed in this paper are from within 50 km around Bhachau, but we also recorded several types of liquefaction features around Khavda, Allah Bund and further north, near the international border. Some of the sites of liquefaction are located in the marshy Rann and/or in the border zone, which are not easily accessible. Documentation of distant liquefaction features is incomplete at this stage. Liquefaction features and waterspouts (along ancient river channels) have also been reported from regions on the other side of the border and from Hyderabad in Pakistan. Thus, our report is by no means a complete documentation of what might have been generated during this earthquake. In the following part of this paper, we discuss some of the features we mapped, with their locations keyed to Figure 1.

Liquefaction and related ground failure

The Bhuj earthquake is characterized by widespread liquefaction in the meizoseismal area, giving rise to sandblows, craters and lateral spreading. During the reconnaissance survey, we relied on the accounts of local residents and post-earthquake SPOT images to select specific sites for detailed observations. Some of the largest sandblows we observed occur near the village of Chobari and also at Lodai and Umedpur (Figure 1 for locations). Several craters at Lodai (site 1) and Umedpur (site 2) were spouting saline water at the time of inspection, three weeks after the earthquake. One of them is a 3-m wide crater at Lodai (Figure 2). The largest crater (10 m × 5 m) that we mapped is at Umedpur, located about 50 km north-west of the epicentre. An apron of vented greyish sand, 33 m × 32 m, is associated with this crater. We excavated a trench through the apron and found that the vented sand has a maximum thickness of 26 cm adjacent to the crater. Two dry craters, the largest of which was about 2 m across, also occur at this site (Figure 3). Large clasts ejected out of one of these craters are strewn over a zone extending about 30 m in a westerly direction. At the base of the eastern wall of this crater we found a deep hole and since it was dry we attribute its origin to release of gas. Cracking and localized subsidence of ground observed near the edges of this crater (Figure 3) are probably related to the release of gas. Although we found several 'dry blows' aligned along many of the fissures and cracks, none of them was as spectacular as the one at Umedpur.

Figure 1. Map of the Kutch area showing the epicentre (USGS) of 2001 Bhuj earthquake. Locations of 1819 and 1956 earthquakes are also shown. Observations at sites 1 to 10 are discussed in the text. Square indicates the approximate extent of the aftershock zone based on the MAE center data.

Much of the ground failure caused by the Bhuj earthquake is related to lateral spreading, an important issue that needs to be understood while interpreting surface deformation. Lateral spreading caused by liquefaction of subsurface sediment generally develops on very gentle slopes (most commonly between 0.3 and 3°) and is gravity driven. Flows may consist of completely liquefied sediment or blocks of intact material, riding on layers of liquefied sediments. Lateral spreading, like other forms of mass movements, often leads to failure of engineered structures[16,17]. The mechanism of lateral spreading is illustrated in Figure 4 *a*.

We recorded a series of ground cracks showing step-like displacements as well as downslope compressional features in the epicentral area and relate them to lateral spreading. At Budharmora (site 3), we surveyed a topographic profile across a disturbed zone about 140 m wide and 400 m long, with a gentle (~ 1°) northerly slope. Ground deformation at this site includes 1-m-wide extensional cracks, back-rotated soil blocks, ejection of sand and shortening at the toe. Step-like extension fractures caused by the lateral spreading are numerous in the epicentral area and an example is shown in Figure 4 *b*. An

Figure 2. Wet crater (3 m wide) near Lodai, which continued to spout water for three weeks after the earthquake.

Figure 3. Dry hole at Umedpur formed by the release of gas. Note ground cracking and the presence of clasts ejected from the crater.

irrigation pipe shows extensional movement of 1.3-m at the head of this deformation. The same pipe is displaced at the toe, causing vertical displacement and horizontal shortening of 0.8 m each (Figure 5).

Venting of water and entrained sand due to liquefaction of subsurface sediment has led to the formation of numerous sandblows composed of considerable volume of sand. At most locations, the water and sand have vented through ground cracks or fissures. For example, many sand vents in the Rann are aligned in an east-westerly direction. Vents aligned in directions opposite and oblique to this trend are also observed. At least in some locations, water had evaporated after the venting of sand, leaving the craters dry and their shapes perfectly circular (Figure 6; site 4). While some of the craters in the Rann had become dry and were covered by silvery crystals of freshly-formed salt, many others were wet and flowing during our visit in late February.

Deformation related to compressional tectonics

An intriguing aspect about the Bhuj earthquake is that it did not produce surface rupture indicative of reverse motion. However, as the strata in the hanging wall deformed, several extensional as well as compressive features were produced. These include flexures, folds, extensional cracks and tear faults, categorized as secondary features commonly associated with thrust-faulting earthquakes[18,19]. These features were well developed in the regions north of Bhachau, presumably part of the hanging wall block. We discuss a few of them in this paper. A schematic sketch showing these features formed on the hanging wall of a south-dipping blind thrust is shown in Figure 7.

Extensional cracks

At a location south of Manfara village (site 5), we observed a series of ground cracks oriented N 60° to 90°E, a few of them crossing the road to Manfara, forming a bulge in the tarmac. Some of the larger cracks extend to a distance of about 1 km and show vertical offsets

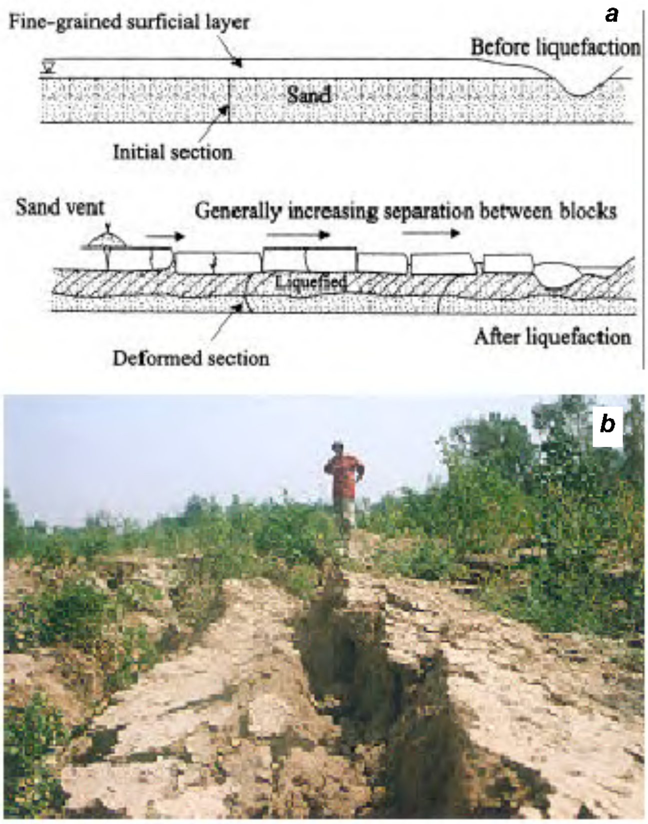

Figure 4. ***a***, Schematic diagram showing vertical sections of the ground before (top) and after ground failure (bottom). Liquefaction occurs in the hatched zone, which causes movement of surface layer down the gentle slope causing ground breakage. Sand is vented through some fissures (after Youd[16]). ***b***, Step-like extension cracks formed due to lateral spread near Budharmora village. An irrigation pipe was laterally displaced by 1.3 m in this field.

Figure 5. Horizontal shortening and vertical displacement (0.8 m each) of the irrigation pipe due to compression and bulging. Photograph taken from the toe bulge formed by the lateral spread shown in Figure 4 *b*.

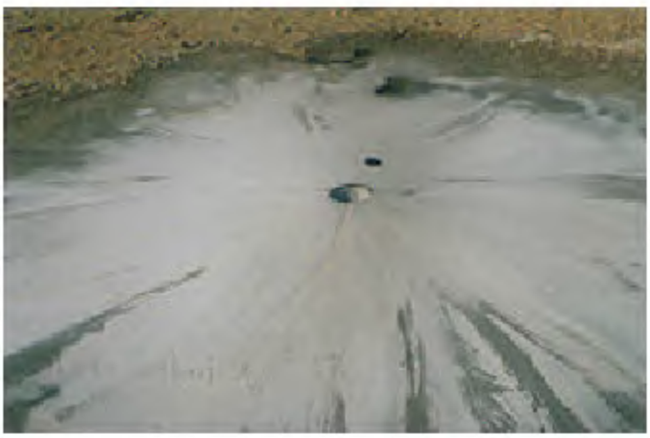

Figure 6. A view of a sandblow near Ranbir village, near Chobari. Sand and water were spouted through the circular vent. Note salt crystallizied on the apron.

of 10–15 cm, the northern and southern sets showing motions in the opposite sense. On the largest and the most prominent ground crack that extends through the road, the south side is up by 10 cm, whereas a parallel crack located 100 m to the north in the same field, shows movement of about 15 cm on the northern block. The block within these two cracks is cut by several parallel fractures with little or no vertical displacement (Figure 8). Formed parallel to the trend of the main thrust, these cracks may be part of a graben-type extensional feature formed on the crest of the folded surface, as exemplified by some large earthquakes resulting from reverse-faulting[19].

A 3-m-long trench excavated across the larger fractures did not expose any obvious displacement of the strata at depth. Fine sand was found filling the cracks, whose width narrows to 2–3 cm at the base of the 3-m deep trench. It is likely that the sand was injected along the fracture planes as the result of liquefaction, but not vented on the surface. Small sandblows do occur in the nearby field to the south. Development of such structures is an illustration of how the liquefaction of subsurface layers and related ground failures can complicate the surface deformation.

Another set of extensional fractures occurs on a gently-folded surface about 5 km north of Chobari (site 6). These parallel fissures, spaced about 10 m apart, are oriented in a N 40°W direction. This set of fractures shows vertical displacement in the opposite sense, east side up (~ 13 cm) on one of the fractures, whereas the west side is up (~ 8 cm) on the other. Sets of conjugate fractures about 2 m × 2 m, oriented in N-S and N 80°W directions occur within the down-dropped block. Water and sand have been ejected through these cracks. Unlike the structure near Manfara, this one is oblique to the main fault. Structures similar to what are described here are reported in association with large reverse-faulting events and they are considered to be the effect of rotation of the faulted block[19].

Monoclinal fold

A zone, about 80 m long and 10 m wide, in an agricultural field near Bharodia is elevated by about 80 cm and shows a gentle north-easterly dip. Crops in the arched portion of the field have dried due to the sudden change in the moisture content. Several ground cracks oriented in a NW direction have developed on the upwarped portion. We suspect this structure to be a monoclinal fold formed as a result of compression and deformation of the surface layers, but this suggestion needs to be substantiated with more field evidence.

Tear faults

Seeber *et al.*[20] have reported a north-west striking fault at a location close to 23.46°N 70.38°E which they refer to as the Manfara fault. According to their preliminary report, this fault displays a right-lateral strike-slip motion with a maximum lateral displacement of 32 cm. They have described this as a 'tear fault' in the hanging wall block above the fault plane. We examined parts of this fault oriented N 10°E to N 20°W near Manfara village (close to site 5). The fault exhibits a horizontal offset of 16 cm, with a small oblique component and is characterized by a series of right-stepping en échelon fractures showing right-lateral movement (Figure 10). We noted several 'dry blows' (a few centimetres in diameter), but there were no signs of ejection of sand or water within the disturbed region. A similar fault, about 1 km long and striking

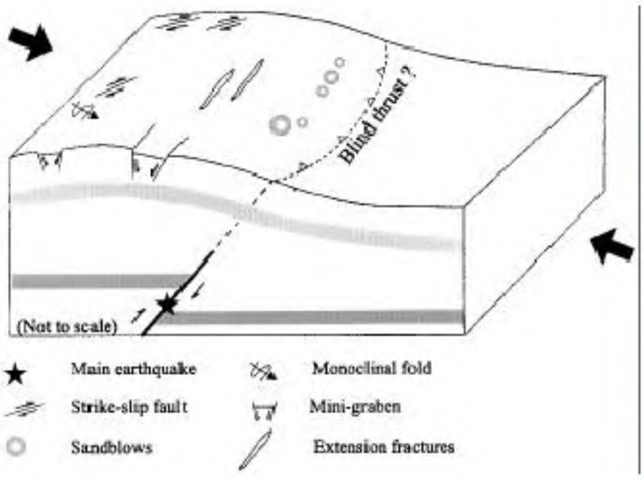

Figure 7. Schematic diagram showing features developed on the hanging wall block due to a south-dipping blind thrust. Displacement of rocks may occur at depth, but the slip reduces as the rupture propagates to the surface and the top layers may deform by folding. The arrows indicate sense of compression.

Figure 8. Parallel ground cracks near Manfara village forming a small graben with a maximum vertical offset of 15 cm (view from south). Note that the cracks within the down-thrown block show little or no vertical displacement.

N 12°W is exposed near the village of Bharodia (0.5 km north-east of site 7). The maximum lateral offset on this fault was 4 cm, with a small oblique component. This set of strike-slip fault also appears to be a tear fault, whose geometry and sense of movement are conformable with the near north-south compression postulated in the tectonic regime of this earthquake[7]. The kinematics of the Manfara and Bharodia structures and their dynamic relation to the nearby NE dipping monoclinal fold needs to be worked out in detail. Although there is no apparent evidence of a main surface fault, based on the spatial concentration of the deformation features discussed above and the geometry of the fault inferred from the earthquake data (as illustrated in Figure 7) we suspect the fault to fall in the close vicinity of Bharodia.

The 2001 earthquake: A window to past seismicity

Damage to monuments

The Bhuj earthquake destroyed several historical monuments in the region, dating back 9th century A.D. Among them are the Aina Mahal Palace (~ 200 years old), *Lakhpatji's Chhatardi* (A.D. 1752–1761) in the city of Bhuj and some of the old temples in its vicinity. The Sun Temple at Kotai (11th century A.D.) and the Punvareshwar Temple at Manjal (9th century A.D.) are among the oldest temples that were destroyed. While the *Chhatardi* collapsed completely, Aina Mahal Palace is still standing, with extensive damage. These structures seem to have survived the 1819 and 1956 earthquakes, but the ground shaking was apparently too severe during the recent earthquake. The damage to the two temples mentioned here is not severe; their main structures are intact. A view of the Punvareshwar Temple at Manjal is shown in Figure 11 (site 8). Although the damage is not severe, it is conceivable that the 2001 earthquake was the largest to have occurred in the close proximity of these structures since 9th century A.D. During our post-earthquake survey, we examined only a few structures, with limited available documentation. Detailed study of such historical monuments will provide much more information on the historic seismicity of the region, useful for assessing ground-motion characteristics.

Palaeoliquefaction features

A record of past earthquakes could be preserved in the geologic record, if sediments are susceptible to liquefaction. The Rann sediments appear to be prone to such processes as documented also in the eyewitness reports on the 1819 earthquake. However, our previous investigations in the meizoseismal area of the 1819 earthquake were not guided by surface evidence of sandblows, because they had either been buried by estuarine deposits and/or destroyed by eolian and fluvial action. However, trenches excavated prior to 2001 near the inferred epicentre of the 1819 earthquake had exposed two generations of liquefaction features and the older event was dated to be 800–1000 yr B.P. (refs 3 and 5). Because earthquake-induced liquefaction can recur at sites underlain by susceptible sediment[21,22], sites of liquefaction induced by the 2001 Bhuj earthquake offer prime targets that could be explored for earlier liquefaction events.

We examined several sandblows in the region north-east of Vigakot, located in the northern extremity of the Rann, which also roughly coincides with the international border (site 9; Figure 1). Although located about 150 km

Figure 9. Arched portion of a field near Bharodia village showing an uplift of 80 cm. Note the drying of crops where people are standing.

Figure 10. Right-lateral strike-slip fault with an oblique component observed near Manfara village. Several right-stepping en échelon cracks are noted to the right of the fault.

north-west of the epicentre of the 2001 earthquake, sandblows here are larger in size and frequency, compared to the intervening area between Vigakot and the southern fringes of the Rann (Figure 1). In our traverses from Bhuj to Khavda and Vigakot, it appeared that sandblows were smaller and less frequent in the Rann between Khavda and Vigakot than north of Vigakot. In addition, sandblow craters appeared to be concentrated to the north-east of Vigakot. The reason for the spatial concentration of these liquefaction features at this location is not clear. Due to the limited logistic support and security problems of working in a politically sensitive region, we could not make a complete inventory of these features. Only a few of the sandblow craters could be examined. Some of the craters measure about 4 m across and are associated with a considerable amount of vented sand. While most craters were half-filled with saline water, some were dry and we could clean and examine their walls.

Figure 12 shows exposure from one of the cleaned crater walls near site 9. Freshly-ejected greyish sand layer (~ 10 cm) exposed on the ground is interpreted as a 2001 sandblow deposit. Below this fresh layer of sediment and separated by a thin layer of clay occurs a layer of yellowish sand that we interpret as an older sandblow. We could trace its feeder dike to the base of the crater (Figure 12). Similar features, possibly related to three episodes of liquefaction occur in a few other trenches in the area. We have not dated any samples or made detailed trench logs, nor have we examined the sedimentary characteristics of various sand layers. More systematic study of these features will be required to further constrain the ages of these events. However, based on the historic documentation of the liquefaction events in the area and the nature of exposures from numerous trenches excavated near Vigakot[5], we attribute the second layer to the liquefaction related to the 1819 earthquake.

An important observation that pertains to the development of these individual sandblows is their relative sizes. Maximum thickness of the recently-ejected sand near site 9 is about 15 cm, whereas the thickness of earlier sand ejection is more than 30 cm. It appears that liquefaction was more severe at this site during the 1819 event, which was located closer to this site than the Bhuj earthquake. Whether the thickness of the sandblows can be correlated with the distance to the source (of similar size earthquakes) is something that needs to be assessed. Extensive search and systematic studies will be required to characterize these features.

In an excavation of the 2001 sand blow at the Umedpur site mentioned above, we found a thin older layer of sand and possible feeder dikes that may be related to an earlier earthquake (Figure 13). Additional study is needed to determine whether or not these features are related to earthquake-induced liquefaction and if so, whether they were formed in response to the 1956 Anjar or 1819 Kutch, or any other historic earthquake in the region.

Discussion

The 2001 Bhuj earthquake, the largest and the most destructive to have occurred in independent India, is both a challenge and an opportunity to the research community. A challenge because it is a test of our ability to mitigate damages on the basis of identification of earthquake-prone areas and an opportunity because it provides several new lessons to learn. Understanding the nature of liquefaction features and their spatial distribution has important implications for earthquake hazard assessment in similar tectonic and geologic environments. The Bhuj earthquake offers an excellent opportunity to study the deformation pattern related to large thrust events in analogous tectonic environments. Similarities have been drawn with the great 1897 Assam earthquake[4] and com-

Figure 11. Damage at the Punvareshwar Temple at Manjal, built in 9th century AD.

Figure 12. Two generations of sandblows exposed on the walls of a crater located northeast of Vigakot. The grayish sand forming the top layer is due to the recent earthquake and the yellowish sand below is due to an earlier earthquake, probably 1819. Note the vent of the yellowish, lower layer.

parisons are underway with the 1811–1812 New Madrid earthquakes[23].

This earthquake provides an opportunity to compare the new liquefaction features with those generated by the 1819 and other past earthquakes in this region. Our preliminary investigations suggest that these recent sites of liquefaction may be the best locations to search for palaeoliquefaction features resulting from past earthquakes. During our investigations, most of the sandblow craters were wet and conditions were not ideal for trenching. Therefore, excavation of 2001 sandblows for the purpose of palaeoseismic study needs to be taken up at a later date.

Mapping of liquefaction features in areas far from Bhuj is not complete yet. Distance to the farthest liquefaction features provides a useful criterion to calculate the magnitude of palaeoearthquakes[24]. For example, the moment magnitude of the 1819 earthquake was calculated[5] based on the distance to the largest liquefaction feature, which was reported from Porbander. Observations from an earthquake of comparable size in the same area, for which instrumental data are available, will be useful to calibrate some of these earlier estimates.

The observation (so far) that the main fault rupture did not propagate to the surface suggests that the earthquake was generated by a blind thrust. Tear faults, grabens and monoclinal fold mapped in the hanging wall are indicative of compressional tectonics. We identified various types of extensional cracks, most of them related to liquefaction and lateral spreading. Due to the predominance of liquefaction-related ground failures, one has to be very careful in interpreting the surface deformation features such as vertical and lateral offsets, both of which are also produced by lateral spread.

Another important issue is to understand the spatial association of the earthquake with the fault/s in the region. Although its epicentre is very close to the Kutch mainland fault, the recent earthquake is unlikely to be related to this structure for various reasons. One, there are no indications of any visible movement on this fault which is well exposed. The best illustration for the lack of movement along this fault comes from an exposure in the Jhura Hills; a domal structure presumably formed due to the magmatic upwelling in the early Cretaceous and is considered as an expression of the mainland fault[25]. We observed a linear fracture running parallel to the southern edge of the Jhura Hills (site 10). Slumping has taken place along the down-slope side of the cliff (Figure 14), where no apparent displacement on the fault has taken place. Two, the earthquake originated at a focal depth of 22 km (USGS) on a fault dipping 40–50°S (Arch Johnston, pers. commun.), with its epicentre located north of the mainland fault. Based on the above observations we infer that the Kutch mainland fault could not be the source of the earthquake. From the severity of damage and pattern of deformation it appears that the blind thrust that generated this earthquake occurs north of Bhachau, probably closer to Bharodia. Imbricate faults within a rift may have the potential to be reactivated and one such hidden fault located north of the Kutch mainland fault appears to have produced the recent earthquake. Seismic threat from blind thrusts has been recognized for a while and mapping hidden faults is part of the agenda for better seismic hazard assessment[26]. Mapping of such faults in the Kutch–Saurashtra region and assessing their seismic potential may remain one of our long-term goals, but efforts towards that direction must start now.

Figure 13. Two generations of sandblows exposed in a shallow trench near Umedpur. The laminated top layer of greyish sand was ejected during the recent earthquake. The features below, including a sand vent represent an earlier event.

Figure 14. Slumping of the hillside along the southern face of the Jhura Hills. Part of the fracture can be seen on the right-hand side. Liquefaction of the riverbed (spouting of saline water) can be seen in the left-hand top corner, indicated by an arrow.

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