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On the relation between magnitude and liquefaction dimension at the epicentral zone of 2001 Bhuj earthquake

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The 26 January 2001 Bhuj earthquake (*Mw* 8.7) is one of the largest seismic events of its kind in India and also in the intra-plate zones in the world. Complete documentation of the liquefaction-related deformation features are difficult in the hostile salt-playa areas of Kachchh, however we attempted shallow trenching study at previously identified liquefaction sites that partially fills the gap in the liquefaction database of 2001 Bhuj earthquake. Liquefaction dimension was found to be a function of epicentral distance, magnitude of the earthquake, depth of the hypocenter, availability of the source material and also proximity to the major lineaments. We relate the above factors for 2001 Bhuj earthquake using shallow trenches at Umedpur, Chobari, Baniyari and Amarsar villages and reveal comparative picture of the dimension of liquefaction at the epicentral zone. Proximity to the active fault system, availability of shallow groundwater and liquefiable sand source has played major role in the size and dimension of the liquefaction in 2001 Bhuj earthquake. This study discusses the scope and limitations relating the sizes of sand blows and their relation to epicentral distance and the magnitude of the causative earthquake.

THE 2001 Bhuj earthquake (*Mw* 8.7) is one of the largest seismic events amongst the intra-plate earthquakes in the post-instrumental era. The energy was released on a 90 km long E–W trending and 55° dipping fault plane.

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This earthquake generated negligible traces of the primary surface deformation; however, secondary deformations like liquefaction, lateral spreads, sand blows and rock falls are common in meizoseismal areas. One noteworthy aspect was the large liquefaction field covering nearly 10,000 km^2 area in Kachchh. The salt-playa, known as Ranns provided the best ground for liquefaction during the 1819 Kachchh earthquake and also during earlier earthquakes. The present liquefaction features and their characteristics can be useful in assessing the magnitudes and epicentre location of older events. Shallow trenching around Umedpur, Chobari, Baniyari and Amarsar villages reveals a comparative picture of the dimension of liquefaction at the epicentral zone. Thickness of the sand-blow deposits was found to decrease with increase in epicentral distance in some cases, while this relation does not hold in some other sites in the epicentral area. It is not always true on major active fault zones because huge liquefaction is reported on the plain of Banni along the Kachchh Mainland Fault zone and also in the Great Rann of Kachchh along Allah Bund Fault. The present study aims to relate vertical and lateral distribution of liquefaction associated with the 2001 Bhuj earthquake with its magnitude, distance from the epicentre and depth of origin.

Structurally controlled landscape of Kachchh is mainly dominated by first-order morphotectonic features[1]. The E–W trending major basin bounding faults (Figure 1) have direct influence over the landscape and have been reactivated many times in the geological history[2,3]. Transverse faults have also played a major role in shaping the present landscape of Kachchh[4,5]. Apart from the 2001 Bhuj earthquake, Kachchh has also witnessed two major events and several minor events in the past[6,7]. The 1819 Kachchh earthquake produced unusual co-seismic topographic changes like elevation of ~ 90 km long track of Allah Bund[8] (Figure 1). Evidence of liquefaction-related to Debal earthquake of AD 893 is reported at the Indo-Pak border[6–8]. The 2001 Bhuj earthquake is the largest intraplate event in the world in recent history. Since the 1819 event occurred in the pre-instrumental era, we have no instrumental record preserved and have to rely on historical, archaeological and geological records in the soft sediments. The epicentre of the 2001 earthquake is located at 23.36°N, 70.34°E near the town of Bhachau (Figure 1) and sourced at a depth of 22 km, reported by the US Geological Survey. This earthquake provides an opportunity to study the dimensions of liquefaction and the magnitude of the earthquake, and developing empirical relations with older liquefaction layers (provided a uniform condition of liquefaction susceptibility is available). The process of liquefaction depends on the existence of a liquefiable sand layer overlain by a thin non-liquefiable stratum and the shallow groundwater table[9]. The development of liquefaction-induced deformation is also dependent on the shaking intensity, proximity to the epicentre and focal depth, seasons and also the proximity to major active fault lines in the area. In general, liquefaction can be developed at earthquake magnitudes as low as about 5,

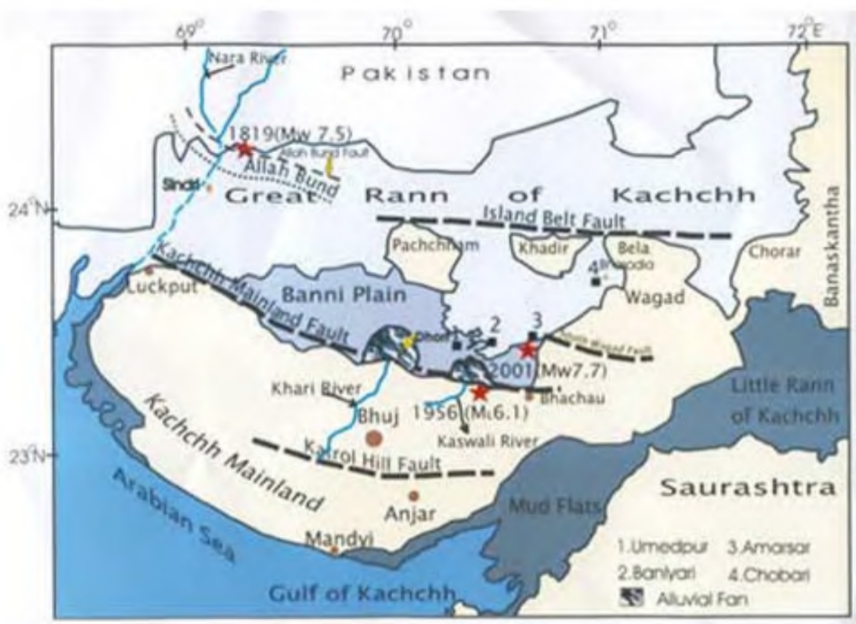

Figure 1. Map showing locations of 2001, 1956 and 1819 earthquake epicentres and shallow trench sites of the present study (nos 1–4). Major faults are indicated by thick and discontinuous lines, while broad geographical regions are distinguished by colour differences. Note two of the trench sites are close to the Alluvial fans, while most of the sites are close to any of the major lineaments.

but a magnitude of about 5.5 to 6 is the lower limit at which liquefaction effects become relatively common[10]. Thus the presence of palaeoliquefaction structures signifies past shaking of $Mw \geq$ VII[11].

Systematic documentation of liquefaction-related features around the epicentre was made just after the 2001 Bhuj earthquake[12–14]. It is also reported that this earthquake has produced massive liquefaction far from the epicentre at Allah Bund area[12], where sand blows have been found to rework the 1819 sand vents and their predecessors[12,13]. An attempt is made here to relate the vertical and lateral dimension of liquefaction with the epicentral distances, magnitude and depth of origin and to discuss the limitations of such work. Characteristic features of compressional tectonic regime, but rarely seen surface deformation features like monoclines were reported around Bharodiya village by Rajendran *et al.*[12]. A 'tear fault' close to Manfara village at 23.46°N, 70.38°E was first reported by Seeber *et al.*[15] and is explained as a transverse right-lateral fault in the study carried out by McCalpin and Thakkar[16]. They observed other surface ruptures like monoclinal welts, tear faults, mole tracks; low height thrust scarps and 'pop-up' structures[16]. Apart from the surface ruptures mentioned above, the bedrock deformations are also reported at the north of Bharodiya village[16]. Massive liquefaction, lateral spreads and sand boils are observed in the Ranns, Banni Plain, river beds and mud flats near Kandla, while remarkable landslide-type of lateral spreads or flow failures are reported from Budharmora, Khari River near Rudramata bridge, Manfara and Chobari villages[12,14,16].

Massive liquefaction is observed at the transitional belt between the Rann and the Banni Plain, 6.5 km NE of Umedpar. The size of liquefaction craters exceeds 3 m in diameter (Figure 2) while the lateral dimension of the sand blows are as large as 70–80 m (Table 1). The total thickness observed at the shallow trench (see inset, Figure 2) is 18–20 cm (Table 1) of varied composition, which reveals different episodes of liquefaction respectively, during the main shock and strong aftershocks. Trenching at another liquefaction crater, 18 m east of the earlier one exhibits 0.75 m thick liquefaction pipe (Figure 3), composed of grey to black coloured sticky mud, highly contrasting compared to the coarse yellow sand of the other craters. Near the biggest crater, gas ejection is also reported where its cap was blown 15–16 m away from the crater[12]. It should be noted that this site is close to the Kachchh Mainland Fault (Figure 1) which is 8–10 km due south. The blowing direction of the cap was opposite that of the epicentre[12].

Baniari is located on the edge of the Rann of Kachchh (Figure 1), where compositionally varied sands were ejected during the 2001 earthquake. Liquefaction study at Baniari is confined to three shallow trenches, NW of the village, into the Rann and Banni Plain nearly 16 km west of the epicentre (Figure 4). In January 2003, we observed 80 m long N 75°E trending enechelon cracks (~150 m long), which ejected 5–8 cm thick yellow sand with water. An elongated crater 2.5 m long, located 50 m SW of the enechelon cracks ejected yellowish, gritty and coarse fluvial sand of 25–27 cm thickness with lateral dimension of 20 m × 6 m. Enormous liquefaction is observed 1 km NW of this crater in the Rann of Kachchh, where a shallow trench shows 35 cm of 2001 liquefaction (Figure 5). This includes 5–6 cm brown-to-black sandy clay on the top, which is underlain by 4–6 cm thick fine whitish and buff sand, while the bottom is composed of fine sand with brown silt. Below 2001 liquefaction layer, up to the bottom of the trench, we observed alternate whitish fine sand and silty clay. The bottom is made up of hard and black clay bed.

Figure 2. Photograph showing liquefaction crater of > 3 m diameter at 6.5 km NE of Umedpur. A distinctive liquefaction field surrounding the craters suggests some proximal sand and water source. (Inset) East-facing wall of a shallow trench made at the site indicated by arrow, showing liquefaction sand cover of various colours and compositions ejected in different episodes during 2001 Bhuj earthquake. The original size of the trench is 11 m × 0.5 m × 0.5 m.

Figure 3. Photograph of west-facing wall of a shallow (1.6 m × 1.4 m × 0.75 m) trench made 25 m east of the crater shown in Figure 2, with an exceptionally thick (0.75 m) vent of 2001 liquefaction (limits are indicated by dotted lines). Note sticky black-coloured mud-like material ejected out through the vent and made a small crater on the surface. Red arrow indicates subordinate feeder dykes. The notable feature in this trench is a small and faint older liquefaction layer (indicated by yellow arrow) with a thin, irregular sand vent at 25–30 cm below the surface.

Table 1. Measurements of liquefaction features produced during 26 January 2001 earthquake in Kachchh

Trench	N lat	E long	Type of deformation structure	Aerial distance from epicentre (in km)	Direction from epicentre	Maximum thickness of ejected sand (cm)	Geomorphic setting	Original sediments
NW of Amarsar (A-1)	23° 25′26.5″	70°15′28.8″	Sand blow	6.25	N 64°W	16–18	Boundary of Rann and Banni Plain	Clay and fluvial sand
NW of Amarsar (A-2)	23° 26′10.1″	70°15′27.1″	Sand blow	7.25	N 58°W	7–8	Rann	Hard, swelling clay and desiccation cracks
NW of Baniari (B-1)	23°24′24.8″	70°09′52.1″	Sand blow and ground cracks	16.1	N 83.5°W	6–7	Banni Plain	Very hard clay (alluvium)
NW of Baniari (B-2)	23°24′21.2″	70°09′51.4″	Liq. crater and sand blow	16.1	N 84°W	28–30	Banni Plain	Very hard clay (alluvium)
NW of Baniari (B-3)	23°24′43.5″	70°09′39.6″	Liquefaction ground	16.25	N 85°W	32–35	Rann	Silty clay of Rann
North of Chobari (C-1)	23°34′07.8″	70°20′44.1″	Liquefaction ground	18.6	N 09°E	6–8	Rann	Silt and clay
North of Chobari (C-2)	23°33′55.8″	70°20′57.9″	Small sand blow	17.75	N 10°E	3–4	Boundary of Rann and Banni Plain	Hard clay and sand
North of Chobari (C-3)	23°35′03.4″	70°20′53.8″	Liquefaction ground	20.4	N 08°E	8–12	Rann	Silty clay
NE of Umedpur (U-1)	23°29′17.5″	69°54′54.6″	Liquefaction ground and big craters		N 64°W	18–20	Rann	Silty clay
Bharodiya	23°57′308″	70°41′320″	Flexture	–	–	–	Banni Plain	–
Vighakot 1	24°27′483″	69°33′316″	Sand blow craters	–	–	–	Great Rann	–
Vighakot 2	24°27′166″	69°34′250″	Sand blow craters	–	–	–	Great Rann	–

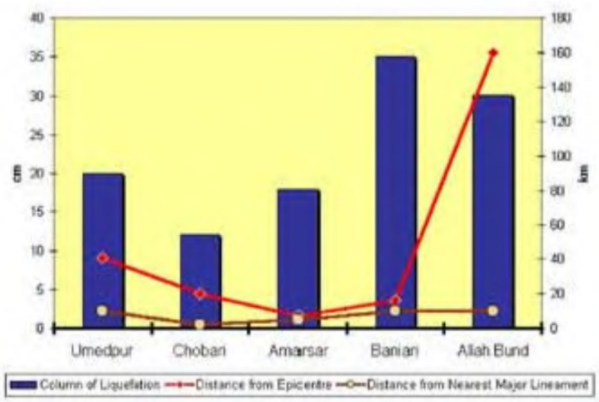

Figure 4. Graphical presentation showing the relation among three parameters, viz. distance from the epicentre, distance from the nearest major lineament and thickness of the maximum liquefaction at the sites of present study. Note thick liquefaction at 160 km from the epicentre at Allah Bund and relatively lesser at the epicentre near Amarsar. Umedpur, being far from the epicentre shows thick vertical dimension; so it is noted that the size of liquefaction has distinct relation with lineaments.

Figure 5. Close view of the eastern wall of a shallow trench at GPS location: 23°24′43.5″N, 70°09′39.6″E, NW of Baniari village. Note the 35-cm thick alternate dark and light sand layers of 2001 liquefaction (the site was once visited in February 2001 when we identified a large liquefaction field, which is re-examined for the detailed trenching study), which suggest prolonged and episodic flows of sand during liquefaction.

In Chobari village about 800 fatalities have been reported and about 50% of the total 400 bore wells had failed due to either ground shaking or liquefaction. A well of nearly 40 ft depth had been filled with liquefaction sand and turned into a flat ground[12]. During our preliminary study using shallow trenches, we observed two distinct sand layers related to the present liquefaction event in the first trench located at 23°34′7.8″N, 70°20′ 44.1″E (Figure 6*a* and *b*). Convolution structures are seen in the lower sand layer, while the upper one contains silty and brown

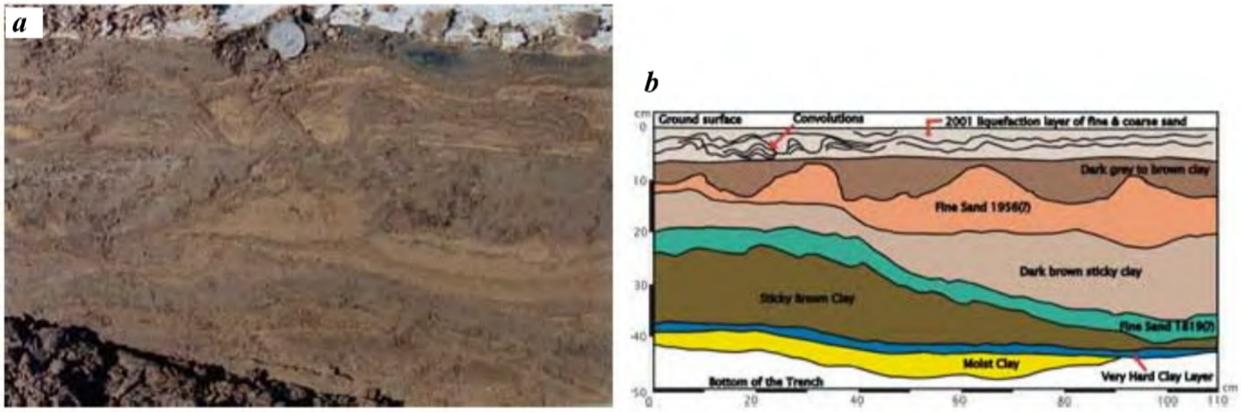

Figure 6. ***a***, Eastern wall of a shallow trench 6 km north of Chobari village (GPS 23°34′07.8″N, 70°20′44.1″E). Convolutions in the latest liquefaction sand layer suggest either drags during the mobilization of sand or a subsequent seismic shaking. Possible older liquefaction sand layers below the present one are distinguishable features. There are two sand layers at the site that might be related to the 1956 and 1819 events respectively, from the top. ***b***, Log of the trench in **5** (***a***) shows different layers with scale and characters.

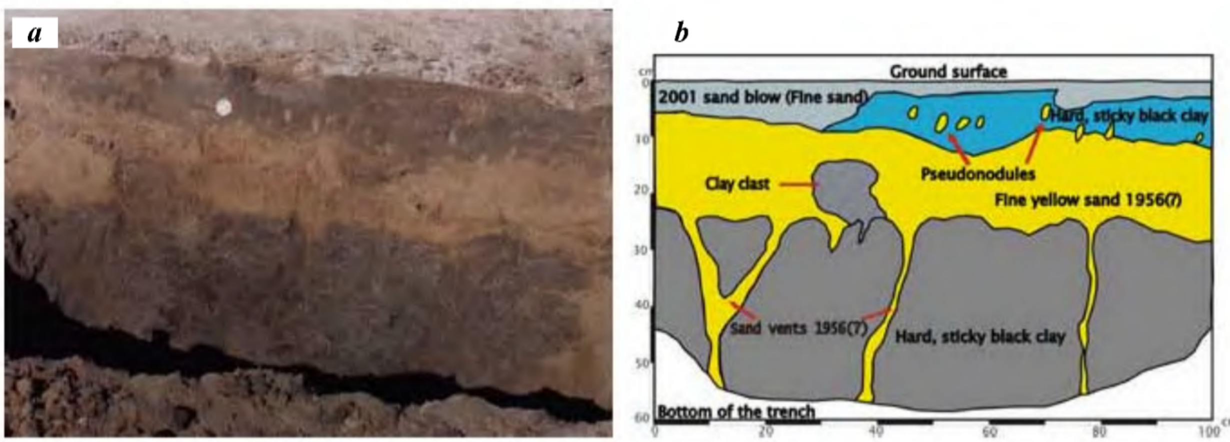

Figure 7. Photograph (***a***) and trench log (***b***) of the eastern wall of a shallow trench dug at a small pre-identified sand boil, north of Chobari village. Note a very thin (2–3 cm) layer of 2001 liquefaction, while possible older sand layer (yellow coloured) is fed by three sand vents. A big clay clast of the underlying black and sticky clay of Banni sediments and pseudonodules found in the overlying sediments are indicative of seismically induced liquefaction layer. Further it is not cutting the upper layer of 2001 liquefaction, which suggests the layer of liquefaction is older (1956?).

sand that does not show convolutions. We selected the trench sites where the 2001 liquefaction has been reported[12,14]. The overall blanket of liquefied sand is 7–8 cm thick and is underlain by dark grey to brown clay layer, which is again underlain by thick sand layer. The fine sand in this layer of probably older event (1956?), thickens and thins out at places, but the maximum thickness is 13–14 cm. This is again underlain by dark brown, sticky clay layer of variable thickness, ranging from 4 to 15–16 cm, followed downward by thin sand layer of 3–5 cm thickness inclined towards N 200°. It is composed of very fine sand that also suggests a layer of palaeoliquefaction (1819?). Another shallow trench (Figure 7 *a* and *b*) located at 23°33′55.8″N, 70°20′57.9″E and 2 km SE of the previous trench site, exhibits 3 cm thick yellowish sand layer of 2001 liquefaction which rests unconformably over the hard brown-to-black sticky clay that contains small pseudo-nodules of fine yellow sand, probably of older liquefaction. A 10–20 cm thick fine yellow sand layer (Figure 7 *a* and *b*) of older liquefaction is fed by 15 mm thick branching dykes that do not reach the surface and do not cut the clay layer over it; therefore it appears to be the older liquefaction (1956?). The third shallow trench at a few kilometres north of the second trench site shows 10–12 cm thick, black silty sand ejected through a 9–10 mm thick sand pipe, cutting various sand and clay layers (Figure 8 *a* and *b*). Massive liquefaction with extensive lateral dimension is reported from this site[12]. Varied colours and compositions of underlying sand blankets are yet to be dated, but many of them seem to be fluvial in origin.

Sand blows are also reported NE of Amarsar village located near the epicentre. Trench-1 (Figure 9) north of Amarsar shows fluvial sand of mixed grain size at the bottom and brown to yellow silty sand of the present *a* *b*

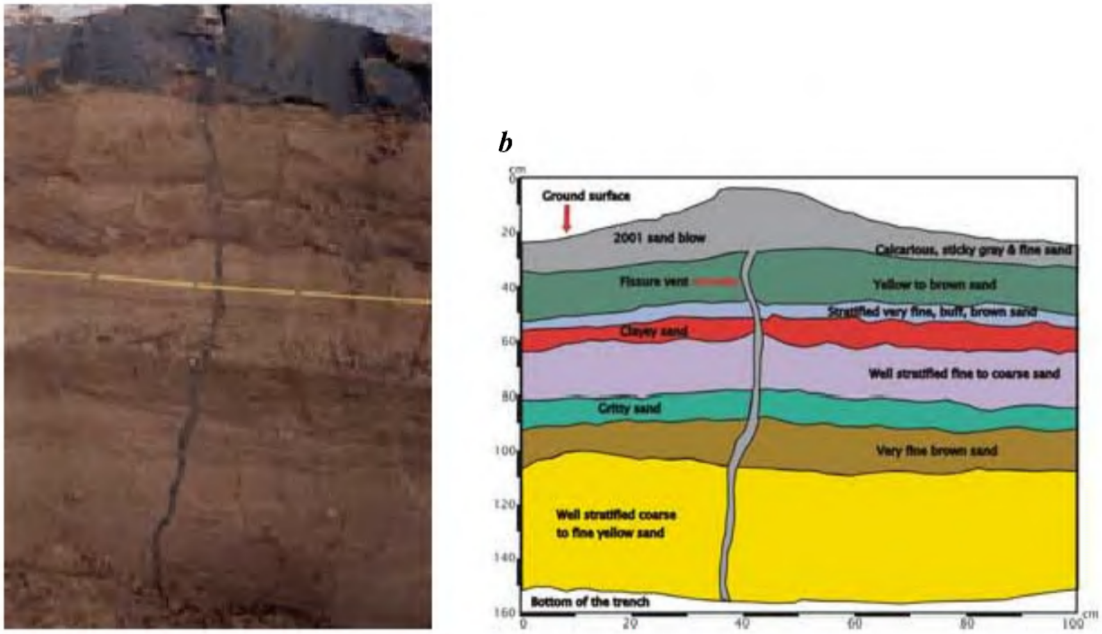

Figure 8. A photograph (***a***) and trench log (***b***) of a west-facing wall of a trench made at 7 km north of Chobari village (GPS 23°35′03.4″N, 70°20′53.8″E). Note a black coloured sand vent of 2001 liquefaction cutting various sand layers and feeding the topmost apron of black, fine and grey sand mixed with silt. The site was visited previously by Rajendren *et al.*[12] for the documentation of the liquefaction features.

Figure 9. Photograph of a north-facing wall of a shallow trench made 4 km north of Amarsar village. Distinctive convolution and flame structures in the top 25-cm sand layers of 2001 are indicative of severe liquefaction and seismic shaking in the area. The base of the present liquefaction seems to be fluvial sand.

event, ejected on the surface from fissures and cracks trending in N–S direction. There are convolutes and flame structures made up of fine sand within silt layers of total thickness 20–25 cm, which is more than the average thickness found at Chobari. The other trench made 2 km north of the first one shows a comparatively small sand blow, where whitish coarse sand has punctured very hard, swelling clay layer on the surface. Vertical and lateral dimension of this sand blow is lesser than that of Chobari sand blows. Two sand pipes of 6–12 cm thickness merge into one at around 40 cm below the surface. The source sand is not visible since the depth of the shallow trench is not more than 0.6 m.

The liquefaction associated with the 2001 earthquake offers an opportunity to develop relations to constrain the magnitudes of the past earthquakes in the same tectonic set-up. The liquefaction generated during this earthquake is the best reference to compare their dimensions with the palaeoliquefaction and thereby to access the recurrence intervals for large events for the same seismic source or an average interval for a region. The 2001 event is also a great challenge for palaeoseismologists to identify the earthquake-prone areas and to contribute to earthquake hazard assessment. Further, this earthquake has also raised many questions for palaeoseismologists in India, because now we could understand that there are multiple seismic sources in the Kachchh region and the picture of recurrence interval multiplies manifold when ground data are lacking. The present shallow-trench study is part of a documentation of liquefaction features. Additionally, we have also derived an empirical relation between the size of liquefaction, magnitude and distance from the epicentre and prominent lineament (Figure 4).

The sand-blow craters NE of Umedpur are exceptionally large and the material ejected is also in great quantity, though it is located 41 km from the epicentre (Figure 4). However, Umedpur craters are 7–8 km far north of Kachchh Mainland Fault (KMF). Further, the ejected sand from the Umedpur crater suggests alluvial fan sediments, which are virtually part of the big Kaswali fan lobe that happened to be the source of sand during the liquefaction process. The sand blows of Baniari village are thicker and more extensive, but large craters are not found except ground cracks and huge liquefaction. Nearly 30–35 cm thick, dense silty sand ejected in the form of tens of metres wide sand blows suggests extensive ground fissures and less fluvial sands. The locations of sand blows at Baniari are 16 km west of the epicentre into the Rann of Kachchh and not more than 10 km north from KMF. Thick liquefaction is reported at 4 km NW of Amarsar, where fluvial sand and hard clay of typical Banni sediments are punctured. Lack of any major fluvial system is inferred from restricted lateral and vertical dimension of the sand blows at Amarsar and Bandhadi. Very thick liquefaction can be expected at this place because it is located on the epicentre.

Three trenches north of Chobari village reveal extensive sand blows in Chobari Rann. These sites are close to the assumed surface projection of the seismogenic fault plane of 2001 Bhuj earthquake. Chobari is located on a major geomorphic lineament that separates the Rann of Kachchh and Wagad Uplift. Extensive study is needed to complete the documentation of huge sand blows and craters of interior Rann, where they are reported in post-earthquake imageries. Trenching study at Chobari reveals thinner but more extensive sand blows in the area during the 2001 earthquake. Possible palaeoliquefaction sand suggests that the site shows great potential for comparative study of various earthquakes in Kachchh. Further field investigations and dating will reveal a clear picture of the past events from the same or nearby seismic sources. Proximity to the fluvial sand source of Khari river fan and also to the KMF is inferred for massive liquefaction near Dhori village (Figure 1), north of Bhuj. Unusual liquefaction craters are reported at the Indo-Pak border, NE of Vigakot, which is 160 km NW of the epicentre (Figures 1 and 4). At the site of the 1819 Kachchh earthquake, fluvial sand and estuarine deposits of the old mouth of Nara and Hakra channels of Indus river became the source of liquefaction. Thus if the source sand is abundant and the area is close to the active fault system, huge liquefaction may occur even if it is far from the epicentre. It is also concluded for the liquefaction features of 2001 Bhuj earthquake that proximity to the active fault system and availability of shallow groundwater and liquefiable sand source has played a major role in the size and dimension of the liquefaction. On the other hand, the relations of total thickness of liquefaction and distance from the epicentre and intensity of the event give a complex picture which needs to be studied. Further, detailed site-specific study covering criteria like liquefaction susceptibility index of the Rann and Banni sediments, shallow subsurface mapping of soft sediments, subsurface geophysical data, and diurnal water table fluctuation can help in relating the size of the liquefaction with the epicentre distance and focal depth.

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