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Internal Geometry of Reactivated and Non-reactivated Sandblow Craters Related to 2001 Bhuj Earthquake, India: A Modern Analogue for Interpreting Paleosandblow Craters

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Abstract: The liquefaction attributes and crater geometry related to 2001 Bhuj earthquake has been reconstructed by trenching along large known craters formed near Umedpar in Kachchh. The study characterises the liquefied sediments in a large reactivated crater and distinguishes it from a non-reactivated crater located nearby. These characteristics can help in the interpretation of large paleocraters formed as a result of earthquake induced liquefaction.

Keywords: Liquefaction, Crater Geometry, Intra-Plate Seismicity, Kachchh.

INTRODUCTION

The 2001 Bhuj earthquake (Mw 7.7) is considered as one of the largest earthquakes in an intraplate setting. It generated earthquake induced liquefaction over a large area and produced sand blows in the Great and Little Ranns of Kachchh (Thakkar and Goyal, 2004; Jain and Lettis, 2001; Singh et al. 2001; Tuttle et al. 2001, 2002) (Fig.1). Liquefaction features documented during post-earthquake surveys provide an opportunity to study sedimentary characteristics of such features as the epicentral distance and magnitude of the earthquake is known. Liquefaction features associated with earlier events are reported by Rajendran et al. (2001, 2002). Paleoseismic studies in areas like Rann of Kachchh are difficult because of the multiple seismic events. Four liquefaction craters formed near Umedpar (Fig.2a) during the 2001 Bhuj earthquake. Two craters reactivated and ejected sands but one did not reactivate during subsequent after shocks, while one of the craters released immensely pressurized gas (Rajendran et al. 2001). We have therefore made an attempt to characterise the internal geometry of these craters (Figs.1 and 2) by opening trenches of 2.5 to 3.0 m depth. The trench studies have been found useful in understanding the two dimensional geometry of these craters and characterise the reactivated and non-reactivated craters, which can be considered as a modern analogue for paleoseismic studies.

SEISMIC ACTIVITY IN KACHCHH

The Kachchh peninsula of western India has experienced several large and moderate earthquakes in historic times. The 1819 Allahband earthquake (M_w7.5) is the largest event to have occurred in the Rann of Kachchh in pre-instrumental period. It was located on the northern boundary of the Kachchh rift about 140 km NW of the 2001 event (Fig. 1). A 6 m of uplift along a north-dipping thrust fault during this event was noticed to be a major geomorphological change in the Allahbund area (Oldham, 1897; Bilham, 1998; Rajendran and Rajendran, 1999; Rajendran et al. 2001). The 1956 Anjar earthquake (M_w 6.0) was located nearly 40 km west of the epicentral area of 2001 Bhuj earthquake (Fig.1). It originated at a focal depth of 22 km and occurred along a hidden fault parallel to the Kachchh Mainland Fault (KMF) (Rajendran et al. 2001). Historical records and paleoseismological studies reveal that the moderate earthquakes which occurred in 1668 and 893-894 A.D. modified the shape of the Indus delta north of Kachchh basin (Rajendran and Rajendran, 1999; Rajendran et al. 2001).

The 2001 Bhuj Earthquake and Associated Liquefaction

The epicenter of the 2001 Bhuj earthquake is located at 23.40°N, 70.23° E about 4 km NW of the town of Bhachau (Fig.1). The focal mechanism of the 2001 Bhuj earthquake suggests a south-dipping (50-60°) reverse faulting, while aftershock data suggests 40 km x 60 km x 35 km E-W

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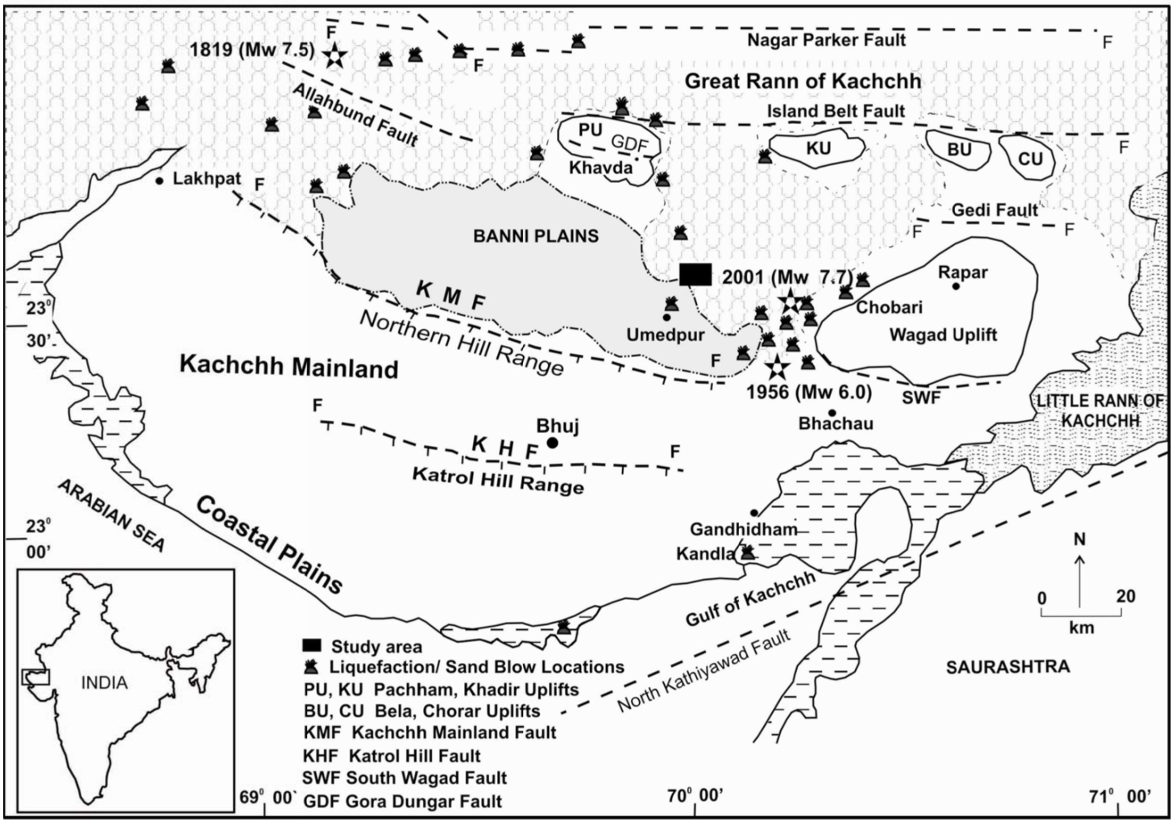

Fig.1. Morphotectonic map of Kachchh showing the major physiographic units, faults and epicentral locations of distinctive historical earthquakes in Kachchh (*after* Tuttle et al. 2001, 2002). Study area is shown by the dark rectangle.

trending rupture zone (NEIC, USGS; Mandal and Horton, 2007). Further, a tear fault close to Manfara village indicates right lateral strike slip movement (McCalpin and Thakkar, 2003). The earthquake induced liquefaction in the epicentral zone was evidenced by venting of water as well as entrained sediment and formation of sand blows as well as sandblow craters (Rajendran et al. 2001, 2002; Thakkar and Goyal, 2004; Tuttle et al. 2001, 2002). Liquefaction was induced in areas far from the epicenter such as the Allahband along the Indo-Pak border and in Saurashtra region (Rajendran et al. 2002, 2008). Vents of the sand blows formed in 1819 and prior to the 1819 event were reactivated during the 2001 earthquake (Rajendran et al. 2001).

Morphology of Large Liquefaction Craters at Umedpar

We investigated in detail four craters near Umedpar village at the transition of Great Rann and Banni plain that were first documented one month following the 2001 Bhuj earthquake (Tuttle et al. 2001, 2002; Rajendran et al. 2001). Several trenches were dug at this site, exposing sand blow stratigraphy and small feeder dikes (Fig.2a). Two of the craters are unusually large and connected, which we named as crater 1 and 2, while the third one is comparatively smaller, and the fourth one is a dry crater, which mainly released gas (Figs. 2a, b). The connected large craters were reactivated several times during strong aftershocks in February and March, 2001, while crater-3 did not reactivate. The digital elevation models of these craters explicitly provide the details regarding their size and relative distances (Fig. 2a). The subsequent monsoons have however modified the surface geometry of the couplet craters.

Craters 1, 2 and 3 showed a visible vent, which ejected volumes of massive sand and clay on the surface. Clays generally do not liquefy but, we found that they occur at the mouth of the crater 3 and crater 2, and do not match with the host stratigraphy. The seismic dykes and vents formed due to hydraulic fracturing and are generally independent of proximity to a topographic low or slope (Obermeier, 1996). However, the topography around Umedpar craters is flat and featureless; therefore, the surface geology, permeability, thickness and spatial relations of sedimentary deposits appear to have influenced the location and mode of ground failure (McCalpin, 1996). The shallow water table and proximity to major basinal fault (KMF) could also be a controlling factor at the present

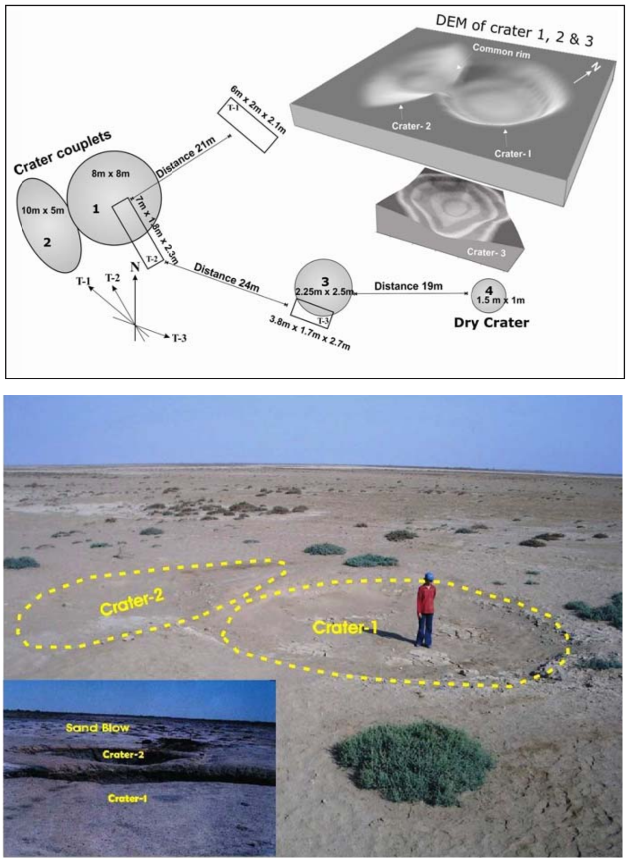

Fig.2. (a) Sketch map of the site of investigation showing locations of four craters and trenches across them. The DEMs and dimensions of all craters and trenches of three craters are mentioned. Note the distance between reactivated craters 1 and 2 and non-reactivated crater-3. **(b)** Photo of crater-1 and 2 taken four years after the earthquake, while the inset picture shows the condition in May 2001. Note the extension of sand away from the craters distinguished by light colour.

site. GPR profiles across the craters confirm the downward extension of liquefaction vents to more than 6.5 m in crater-1(Maurya et al. 2006). The two trenches, across the crater-2 and crater-3 and the third one about 21 m NE of the crater 2 revealed the nature of the host and emplaced sediments (Figs.2a, 3).

Trench 1

To understand the stratigraphy of the host sediments a trench measuring 6 m x 2 m x 2.1 m was opened 21 m northeast of the crater-1 (Fig. 2a). The measured log of the western wall of the trench is used for reconstructing the stratigraphy of the host sediments (Fig. 3). The trench revealed three major units of clay with variable proportions of sand. The lower most unit (130 cm) is composed of alternate bands of clay and sand, finely laminated clay is found in the middle unit (90 cm) and the upper most unit (40 cm) is comprised mainly of silty clay. The surface is covered by a thin veneer of coarse sand ejected from the nearby sandblows.

Trench 2

A 7m x 1.8m x 2.3 m trench was opened from the centre of the crater -1 to beyond its eastern margin (Fig. 2a). The western wall of the trench indicates that the sediments inside the crater are entirely different than the trench-1. They are extensively deformed and related to injection of sand dikes during the 2001 Bhuj earthquake and subsequent strong aftershocks (Fig. 4). The ejected and intruded sediments are characterised by the big clasts of sands and clays of host as well as of surfacial sand (Fig. 5). The clay and sand intrusions remixed with chunks of sandy and clayey sediments make the complex geometry of the crater due to repeated venting. The dyke is composed of fine to coarse

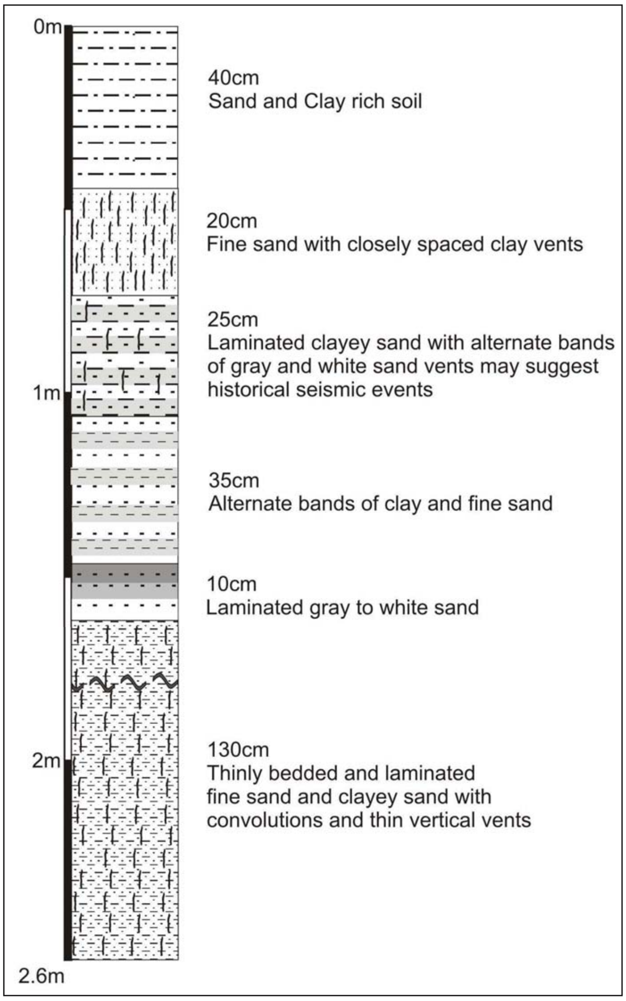

Fig.3. A litholog of trench-1 exhibiting typical host sediments at the Banni-Rann interface.

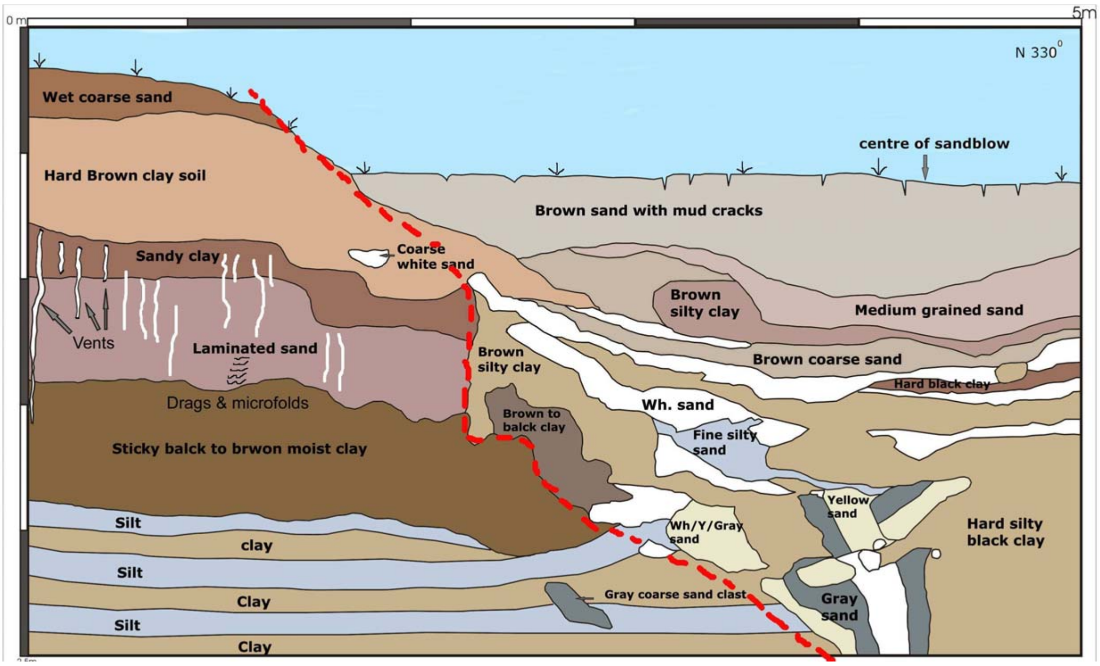

Fig.4. A log of the western wall of trench-2 across the main crater. It specifies the middle portion of the crater where the sediments within the bowl shaped crater are deformed, remixed and showing collapsed blocks of the cap material. Note the hard silty clay confined to the core surrounded by varieties of ejected sands. Coarse whitish sand and gray sands form big clasts within the host sediments which are mainly silt and clay showing drags, micro folds and micro vents in laminated sediments.

sand with minor proportion of silt and clay. Numerous large clasts of clay and sand are encased in well stratified, medium to coarse grained sands in basal part of the crater (Fig. 5). Clasts of the cap material occur in the central part of the crater. Cross cutting relationship between the clasts of sands and clays within the dyke represent more than one episode of venting. Wherever a large amount of sand is vented to the surface, down warping of cap material towards the dyke is observed (McCalpin, 1996). The middle unit of the host sediments of the crater-2 shows tiny sand dikes, miniature folding and convolutions in finely laminated silt, clay and fine sand layers (Figs. 4, 6).

Fig.5. Photograph of the northern wall of trench-2 showing collapsed blocks of hard cap sediments. The blocks also contain coarse to fine sands that ejected during the earlier episodes of liquefaction. Note the complex mixture of liquefaction sands and clays with minor convoluted (mentioned by an arrow) beds indicates reactivation of the vent many times during several aftershocks.

Trench 3

Crater-3 is comparatively small (Fig. 2a), which blows

Fig.6. A close view of seismites like small vertical vents and drag folds not reaching to the top across thinly laminated layers of silt and clay mixed with fine sand of trench-2.

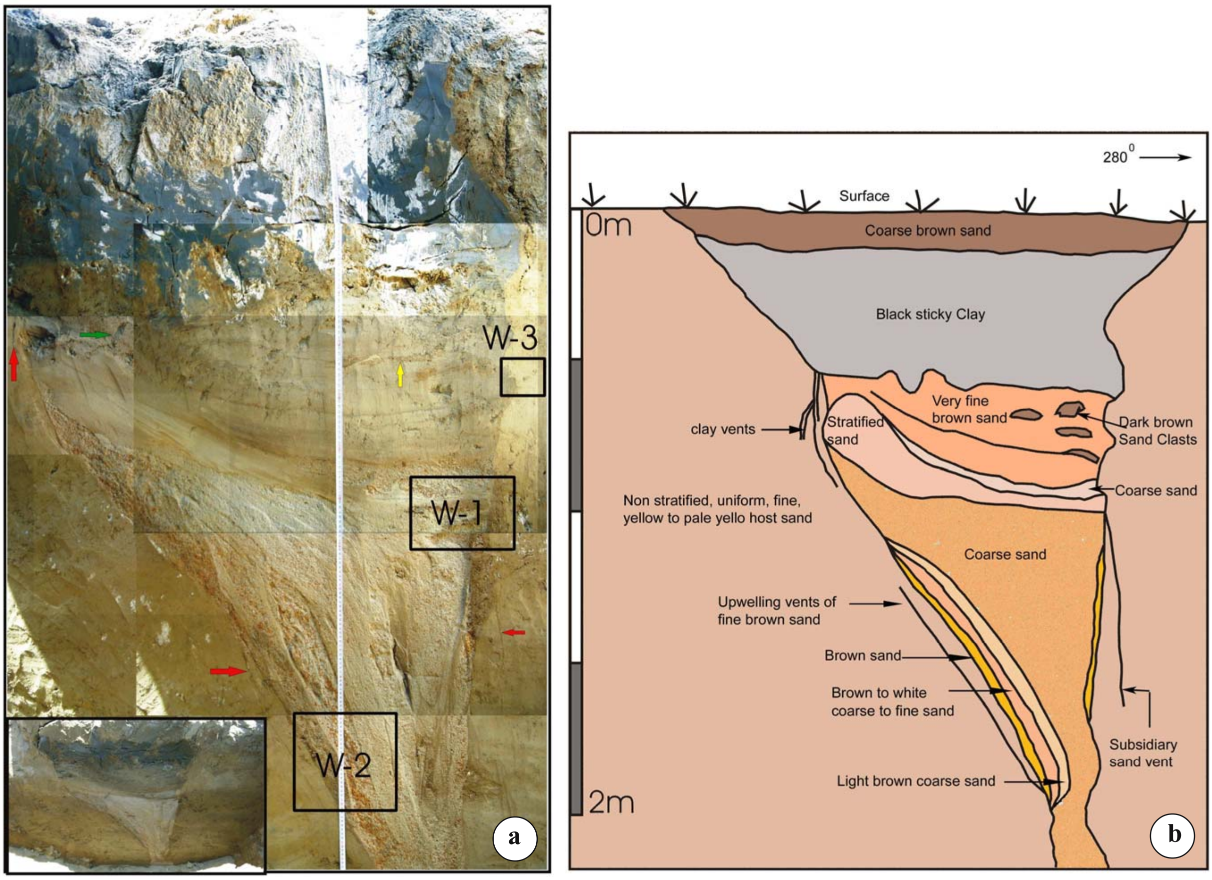

Fig.7. (a) A mosaic picture of the southern wall of trench-3 across the non reactivated crater-3. The inset picture portrays entire vent in cone shape, while the enlarged part illustrates details of the ejected sand and clay. Note a window (W-1) in this figure is enlarged in Fig.8 for specific observation of fining upward sequence in the liquefaction deposits. Clay and sand clasts within the vent are indicated by green and yellow arrows respectively. The vents of millimeter size are shown by red arrows on both sides of the funnel shaped vent. **(b)** Log of the mosaic picture shown in **(a)** with distinct layers inside the funnel shaped vent. Note the uniform, fine and non stratified host sand and also absence of collapsed blocks of the cap within the vent unlike the crater-1 geometry.

out very thick and immobile sticky clay. It oozed only water for some days after the main shock. We opened a 3.8 m x 1.7 m x 2.7 m E-W trending trench in this crater. The host sediments of southern wall of trench-3 are mainly non-stratified fine sand (Figs. 7a, b). Although the source zone of ejected sands and clay capping was not encountered the trench revealed a funnel shaped crater. The upper part of the trench exhibits 1 m thick hard clay which was ejected first and later formed a cap during the low energy phase. The vent shows a fining upward sequence (Figs.7a, 8). Most of the liquefied sediments on the surface are fine to coarse yellow sands similar to that of the vent. The vent exposed on the southern wall is 1.5 m wide gradually decreasing to 20 cm at the bottom, forming a funnel shape. The vent has a sharp contact with the host strata that is very fine and uniformly composed of non stratified silty sand. The lower part of the vent below the sticky clay is

Fig.8. Photograph of a part of southern wall of crater-3. It is a close-up view of the portion indicated by a rectangular window (W-1) in Fig.7a. Fining upward sequence is distinctly seen in the upper part.

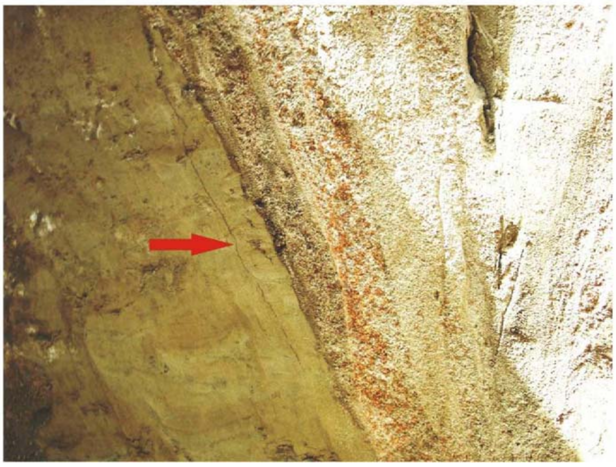

Fig.9. A close up view of the window (W-2) shown in Fig.7a. This indicates vertical stratification of the sands in four different layers on one side of the vent, while on the other side only one layer has developed. The core is composed of various types of sands.

dominated by vertical stratification with bands of varied sands (Figs.7a, b). Four distinct vertical layers of sands are noticeable on the southern wall of the trench (Figs.7a, b, 9). Succeeding over it, occurs a 10 cm thick very fine brown sand layer in half lobe shape, pinching towards the centre of the vent. Two subsidiary vents of 1 to 1.5 mm thickness originate from this layer (Figs. 7a, b). Overlying it is a 30 cm brown, silty clay layer studded with clasts of dark brown sand. The sand clasts are about 10 cm in diameter, which are derived from host sediments (Fig. 10).

The cone shaped dyke extends to the north as a long irregular fissure with two lenses exposed in the northern wall (Fig. 11). The lenses are 10 and 25 cm thick and are located at a height of 70 and 130 cm from the bottom of the trench. The upper lens contains very coarse and gritty, whitish to brown sand in its lower part while a uniform deposit of clay and fine sand with irregular grey colored upper boundary is observed in the middle part (Fig. 12a). The lower lens is divisible in four sand layers, which vary in colour and grain size (Fig.12b). The long patches of clay-remnants within it indicate initial liquefaction of clay.

Fig. 10. An enlarged view of the window (W-3) shown in Fig.7a. Note clay clasts found in host sediments near the vent in Trench-3.

DISCUSSION

The liquefaction associated with the 26th January, 2001 Bhuj intra-plate earthquake generated varied patterns. The immediate documentation of these along with GPR and trench studies near Umedpar have helped in understanding the nature and geometry of large liquefaction craters. The varying characters and contrasting geometries help in distinguishing the reactivated and non-reactivated craters. The liquefied sediments suggest heterogeneous sources with discrepancy in depth. The couplet crater oozed water and sediments even during the strong aftershocks in February and March 2001, conversely the other two craters did not. Trenches opened across craters 2 and 3 show variation in sediments from highly impermeable sticky mud to very coarse sand. The detailed trench studies indicate that the trench-2 (crater-1) showed the complex geometry of the reactivated crater, while the trench-3 (crater-3) revealed the nature and geometry of a non-reactivated crater. The collapsed blocks of the cap as well as surface liquefaction layers found within the core of the crater-1 suggests effects of subsequent strong aftershocks and monsoons. The couplet crater which mostly ejected coarse to fine, yellow to white sand had a source deeper than 6.5 m (Maurya et al. 2006). The presence of clay and silty sand at about 1-1.5m depth suggests that initially clay and silty sand were liquefied. The liquefied clay in the core of the crater-1 and sand blow deposits on the surface suggests liquefaction during the initial moments due to intense pore water pressure. The wider dyke in the crater-1 is interpreted to have formed by highly mobile sediments which flowed into fissures between the blocks of the silty clay caps. Subsequently the fissures opened up as the blocks shifted laterally in response to back and forth shaking. Further, the sharp upturn of the host clay and silt layers in trench -2 suggests repeated liquefaction in the crater. In host sediments of trench-2, the lamination and convolutions, flexures, micro folds and small vertical vents not reaching to surface indicate that they were not formed in a single episode. The clay layers in the host stratigraphy

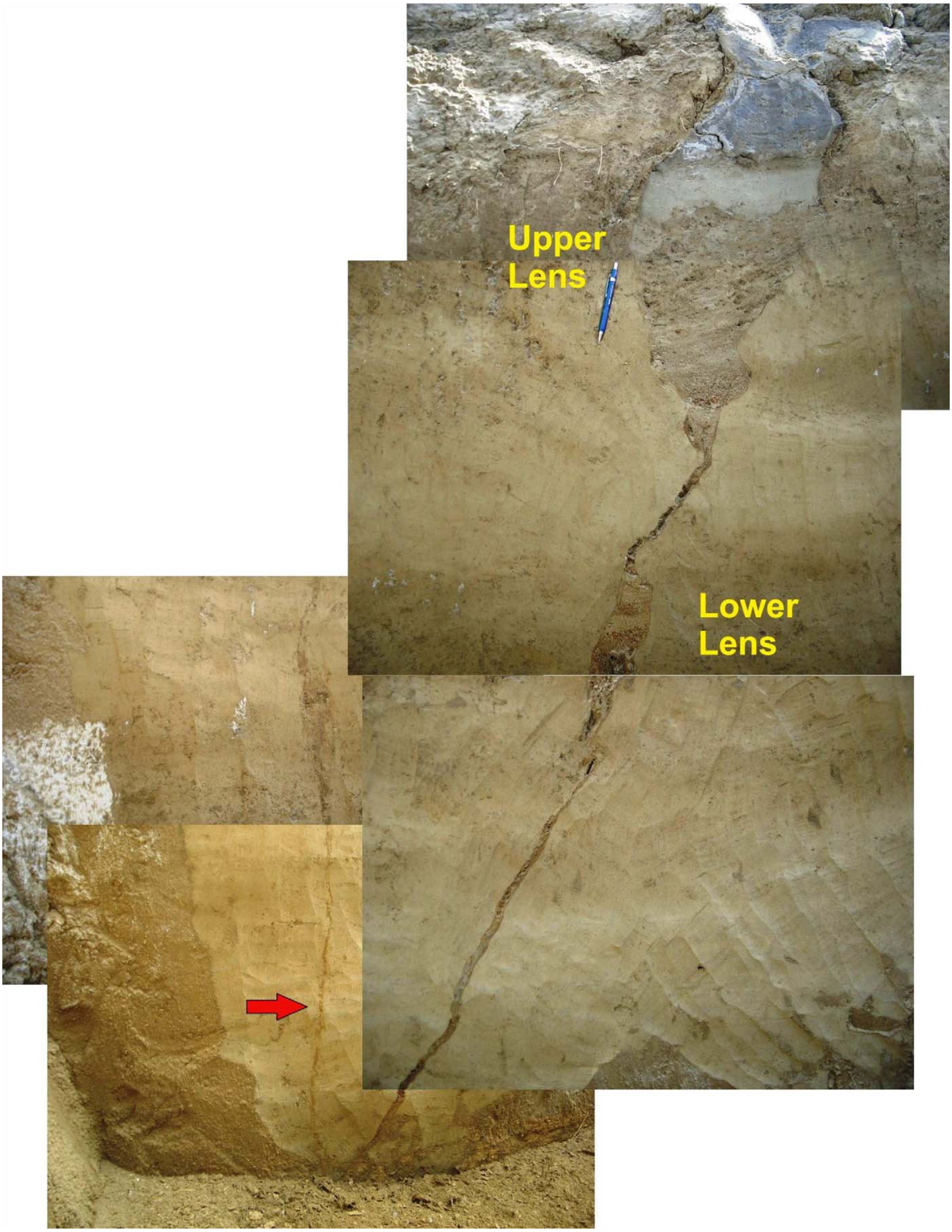

Fig. 11. A mosaic picture of the northern wall of crater-3 showing very thin vent and two sand lenses with fining upward sequence in each of them. The cap of the vent is made up of black, high density clay. Note a thin vein runs upward but vanishes at about half way of the trench. Also note that the host sediments in this trench are uniform, non-stratified and fine unlike the typical host stratigraphy.

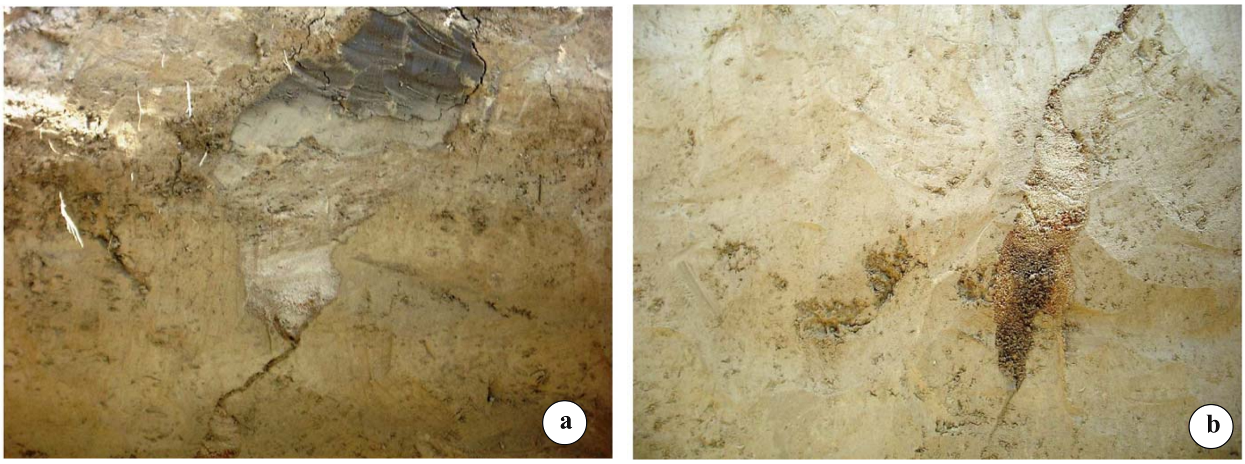

Fig.12. (a) A close view of the sand lens found near the top of a thin vent on the northern wall of the trench-3. Note the ideal fining upward sequence in the lens having finer sands and clay on the top and coarser at the bottom. **(b)** A close up of a lower lens along the thin vent of trench-3. Separation of sand particles is quite distinctive. The fining upward sequence is also visible within the lens.

in trench-2 became instrumental in acquiring pore pressure in lesser time, created an environment for repeated liquefaction.

While the absence of collapsed blocks as well as presence of distinct homogenous zones and intact conical crater geometry in trench-3 is an example of non reactivated crater geometry. Presence of clay clasts, graded sand deposits, vertical laminations near the walls of the vents suggest continuous outpouring of liquefied sediments from the same vent. Periods of quiescence provided time for sorting of the liquefied sands forming gradation and fining upward sequences. The well sorted and fining upward sequence and the uniform host sediment suggests the non reactivation of the crater.

These craters are located about 41 km away from the epicenter of 2001 Bhuj earthquake and about 8 km to the north of Kachchh Mainland Fault (KMF). The proximity to the Kachchh Mainland Fault and availability of shallow groundwater and liquefiable sand source might have played a major role in the size and dimensions of the liquefactions (Thakkar and Goyal, 2004). The strong reaction of seismic shocks, lithological variations in host sediments and widespread liquefaction with varied pattern in the reactivated and non reactivated crater geometries can be used as a modern analogue for understanding paleoseismicity of the tectonically active areas.

CONCLUSIONS

1. The characteristics of the reactivated and non-reactivated craters in the active intra-plate seismic zones depend on the presence or absence of collapsed clasts of host sediments, cap material and liquefied sediments in the vent.
2. The upturns in the cap material at different junctures within the vent indicate more than one episode of seismic blows.
3. The seismic deformation features like lamination and convolutions, flexures, micro folds and small vertical vents not reaching to surface are the characteristics of a reactivated crater.
4. Non reactivated craters reflect the tranquil nature of deposition like, fining sequence and laminations within the vent as well as uninterrupted host and crater sediments.
5. Geometry of a crater depends on diverse patterns of liquefaction, proximity to active faults, magnitude of the shocks and lithology of host sediments may be helpful in understanding paleoseismicity.

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