

spite of reports that developmental effects caused by azadirachtin are attributed to disruption of endocrine events⁷.

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The odds of a seismic source near Dwarka, NW Gujarat: An evaluation based on proxies

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The Kachchh–Saurashtra region is part of an old rift basin, featuring a number of linear structures, some of them holding potential for occasional $M > 7$ earthquakes. A challenging question is to identify probable sources of large earthquakes in this region. Recognizing earthquake-generated structures preserved within the geological formations is an effective method to constrain the seismic sources in space and time. During the recent excavations at Bet Dwarka, in the Gulf of Kachchh, we identified a seismically generated sand blow that has disrupted an ancient cultural horizon. The age data suggest that the causative earthquake may have occurred about 2000 years ago. While the source of this earthquake remains to be constrained, its timing seems to be singular; our studies elsewhere in Kachchh have not disclosed any feature of comparable age, as yet. This find opens the possibility for another surprise source, adding a new dimension to the seismic hazard of this region.

Two large earthquakes have occurred within an interval of 200 years at two different parts of the Kachchh basin, a Mesozoic rift in northwestern India (Figure 1). Of

these, the 1819 earthquake ($M 7.5$) occurred in the northern flank of the basin and the event of 2001 ($M 7.6$) was sourced at its southern margin^{1–3}. Such a short span of time between the earthquakes as observed here is quite exceptional for a region that is considered to be ‘slow-deforming’, and this naturally calls for an assessment of its potential sources^{4,5}. The traditional approach has been to use historical information for generating database on past seismicity. In the recent years, archaeo- and paleoseismological techniques have developed as useful tools for reconstructing earthquake history^{6,7}. Identifying seismically induced liquefaction features, deducing their stratigraphic context, and dating various sedimentary layers to constrain the age of the earthquakes are common approaches adopted in the palaeoseismological researches⁸. Archaeoseismology concerns with the disruptions to cultural settlements, which are particularly useful because they often contain datable material like pottery, bones and organic matter, and the combined use of both these techniques provides better age constraints^{9,10}.

In this paper, we focus on Bet Dwarka (Figure 1; inset), a locale of ancient habitation that flourished since Harappan times (~3000 yr BP). A major fault is located close to this area (Figure 1), but no significant seismic activity has been reported from here¹¹. One tremor is reported to have occurred on 12 May 1962 near Dwarka and according to local sources, it lasted for a few seconds (Pushkar Gokani, private commun.). Although some archaeological investigations have been conducted in Dwarka earlier, these sites have not been examined from the point of understanding the past earthquakes. Thus, when the National Institute of Oceanography (NIO) excavated some trenches in Bet Dwarka, as part of their archaeological investigations, we chose to examine them for proxy indicators of earthquakes (see Figure 1 for loca-

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tion). This paper reports our findings and discusses their implications.

Bet Dwarka, a narrow strip of island in the Gulf of Kachchh, is located 5 km north of Okha in the mainland of Saurashtra (Figure 1). The island as well as the temple city of Dwarka and the surrounding coastal waters have been the loci of archaeological excavations conducted by several groups¹²⁻¹⁵. Some recent interpretations of the findings indicate that Bet Dwarka had been a port in proto-historic times (~ 3800 yr BP) and continued to host human inhabitations during historical periods¹². The terrain presently supports only scanty vegetation (Figure 2), which reflects dry conditions and a low groundwater table. The island lithology consists of grey and yellow coloured clays with intercalations of brownish sandy clays¹⁶.

The trenches exposed yellowish loamy soil with artifacts of pottery shards, shells, bones and specks of carbon. Of the three trenches we examined, two were shallow (~ 2 m), and did not reveal any features that could be related to sediment deformation, but the deeper trench revealed some out-of-sequence sedimentary layers. We focused our investigations on this trench (BDK-2), located on a terrace on the eastern side of Bet Dwarka (Figure 2). The terrace is at a height of 2.5 m from the present-day high waterline and 4.35 m from the mean sea level (based on hydrographic map no. 2031). On the basis of archaeological evidence, the section in this trench has

been divided sequentially into eleven levels from top to bottom¹². The trench bottomed on a yellowish clay layer (level 11) at 3.35 m, which appeared to be the base of the oldest habitation. The anomalous layer discussed here occurred at level 10 at a depth of 2.75 to 3 m from the surface (Figure 3). This wedge-shaped layer of laminated silty sand with pottery and shells with a smattering of bones and charcoal had a maximum thickness of about 20 cm at the northwestern corner of the trench, and its lateral extension, which showed progressive decrease in thickness, was traceable for more than 2 m eastward, before it got tapered off. Presence of this layer at the top of level 11 suggests that deposition of this layer post-dates the lowermost occupation horizon.

The general profile of the sediment layer followed the southeastward slope of the land. In the middle part of the section, however, the layer seemed to have flexed downward, possibly due to the weight of the overlying material consisting of an assorted assemblage of stones, bricks and other artifacts (Figure 3 *a* and *b*). Increased thickness to the west implies continuity in this direction and what was exposed could only be a partial view of a larger feature. The exposure on the northern wall, in fact, constituted only the tail-end (distal part) of the sand body (Figure 3 *a*). Graded layering and internal lamination suggest that this layer emanated from a mixture of sand and water that flowed for a limited distance. These chara-

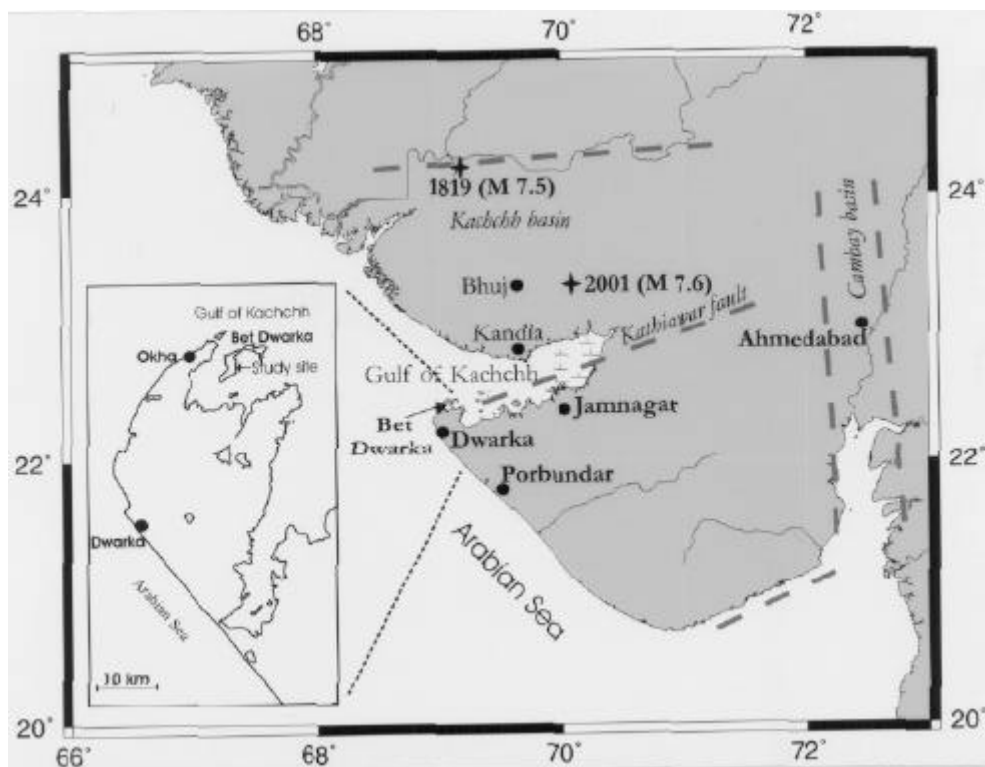


Figure 1. Map of northwest Gujarat showing locations and relevant structural features of the region; dashed lines indicate approximate location of boundary faults. Location of boundary faults adapted from Biswas (ref. 27). (Inset) Index map showing location of archaeological site at Bet Dwarka.

cteristics are typical of water-escape structures¹⁷. Clasts of clay from the host strata were also seen embedded within this layer (Figure 3 *a*; inset).

On the southern wall of the trench, we observed another feature that shares similarities with the one discussed above (Figure 4). This was a bowl-shaped structure with a maximum width of 1 m, which occurred at the same level as the companion feature on the opposite wall. Internally, it showed characteristic graded bedding and overall fining upward sequence. Texturally, the fine sand that constituted this layer was different from the surrounding lithology of reddish clayey silt. Like the previous feature, this structure was also embedded with clasts of clay, rotated bricks and potshards within its matrix (Figure 4). Although located on opposite walls, the comparable characteristics of the twin features and their presence at the same level are suggestive of a common origin. The structural integrity of these features could either be disturbed, during the excavation and/or they may remain concealed within the unexcavated part of the sedimentary section. However, due to the reconnaissance nature of our work, we did not attempt to excavate further into the feature. Besides, such a penetrative style of trenching would have affected the ongoing archaeological work.

To arrive at a reasonable conclusion on the cause of the ancient liquefaction at Bet Dwarka, we need to assess all possible scenarios leading to the origin of such features. Because the site is located close to the sea, we may consider high tides and wave pounding as possible causative factors. However, if this layer was deposited or reworked by high tide or wave action, such effects should be noticeable in other trenches as well. Two trenches within a distance of 500 m are devoid of any such features, ruling out the influence of such regional time-transgressive processes. Furthermore, the site is located landward where impact of high waves and storms is minimum. Besides, the feature itself is stratigraphically restricted, showing no apparent transport direction originating from the sea.



Figure 2. Study site at Bet Dwarka on the coast of Gulf of Kachchh. The trench (BDK-2) shown here is laid in east-west direction.

Fluidization due to high pore-pressure associated with deep-seated, confined aquifers could be another cause, but the features in question occur at relatively shallow depths and the terrain conditions do not appear favourable for the development of confined aquifers. Fluidization can also result from landslides, but we do not have any evidence of favourable conditions at or near the study site, and judging from the low gradient topography it is difficult to imagine such conditions could have existed in the past. Thus, we rule out the above situations, which do not conform to the field conditions. Further, they do not explain the evidence for forceful spouting, a process that requires internal pressure gradient, not explained by any of the above processes. Another possible question is that

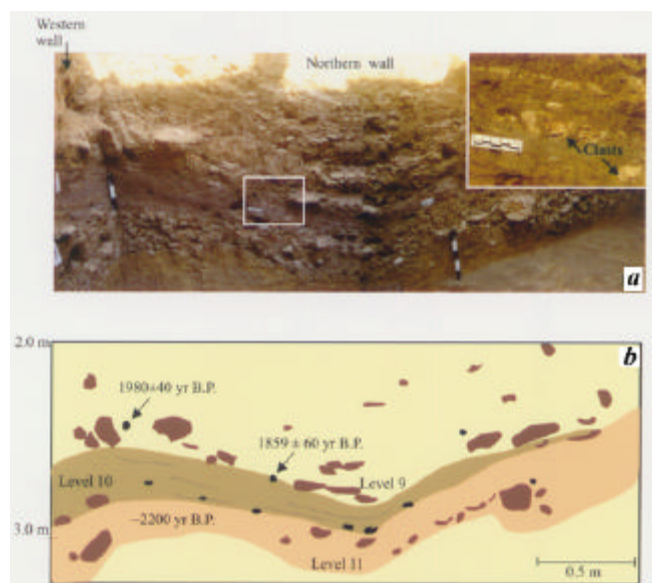


Figure 3. *a*, Composite photograph showing the ancient sand blow on the northern wall, formed over the oldest occupation level (numbered 11 in Figure 3 *b*) at site BDK-2. The section shown here is at a depth of 2 m from the surface. (Inset) Part of the sand blow magnified to show rip-up clasts; bar scale is 5 cm. *b*, Sketch of the northern trench wall showing level 11 and the overlying sand blow deposit.

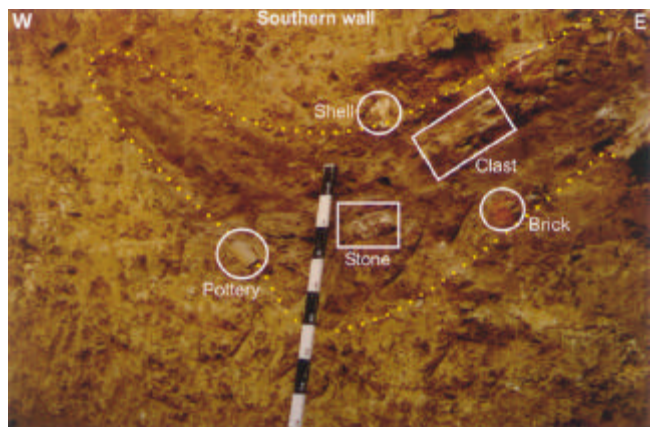


Figure 4. Sand vent (dashed line) exposed on the southern wall at site BDK-2. Bar scale equals 50 cm.

it could be interpreted as a channel-fill. The shape of this layer with its restricted lateral continuity and the presence of clasts scoured out from the host sediment suggest that the feature could be the result of a short-lived surge of fluidized material from below.

Such processes can be easily linked to the intense ground shaking induced by earthquakes that may result in liquefaction of sediments. Liquefaction is initiated when the loosely packed grain framework collapses (due to earthquake-induced shear waves) and the grains become temporarily suspended in the pore-fluid, displacing them upward. The displaced sediment–water mixture forms sand dikes, sand sills and sand blows, depending upon the local pressure gradient and lithological conditions. Liquefaction features induced by ground acceleration have been studied in many sites and the process is well understood¹⁸. Recognition and characterization of seismically induced liquefaction features, however, are not always easy, and they must follow some established criteria⁸. One, they must show evidence for an upward-directed strong hydraulic force that was suddenly applied for a short duration. Two, they must resemble liquefaction features generated by earthquakes in similar settings. Three, they should not be located in areas where other phenomena, notably artesian discharge might produce similar features. Four, where evidence of age is present, it should support the interpretation that features are formed in one or more discrete, short episodes that individually affected a large area. Five, these episodes should be separated by long time periods. Details of features generated by known earthquakes in the same region often provide reliable recognition criteria to identify those caused by palaeo-events. In the case of the feature discussed here, documented characteristics of sand blows and sand dikes formed during two large earthquakes (1819 and 2001) within the Kachchh basin are particularly useful¹⁹.

Let us now examine the features at Dwarka in the light of these recognition criteria as well as the characteristics of better-known liquefaction features in the Kachchh region. The deformation structure exposed on the northern and western walls of BDK-2 fully meets the first three criteria. Presence of texturally distinct suite of fine sand incorporating the clasts of the host sediments, and assorted mix of bricks, pottery and bones that have been rotated within the sand matrix suggests emplacement from a deeper source that broke through the superjacent

layers. The vented sand is deposited on the palaeo-surface, the flow bands representing spurts of fluidized mixture and gradual settlement. The lateral pinch out of the sand layer is suggestive of the abruptness of the sediment transport process, indicative of the cessation of venting.

The above factors compel us to regard the liquefaction feature observed in Bet Dwarka as a sand blow generated by an earthquake. Characteristics of the sand blow discussed here are comparable to those formed during the Bhuj earthquake⁵. Similar features have also been noted in the meizoseismal regions of major earthquakes in comparable geologic environments^{3,7,9,10,20,21}. The extent of ‘fossilization’ of such features could vary from place to place and their chances of preservation in ancient sediments are subject to cultural and climatic factors; what is exposed at Bet Dwarka appears to be only a partially preserved/exposed feature. Although its three-dimensionality is missing, the exposed parts of this feature exhibit clear evidence of internal stratification with an assortment of rip-up clasts, typical of forcefully ejected liquefied sand–water mixture. The outline of the companion feature exposed on the opposite wall at the same level can be considered as an additional evidence for venting of sand.

We collected charcoal samples from within and immediately outside the emplaced sand layer, and analysed them by accelerator mass spectroscopy (AMS; Table 1). Charcoal from the sediment immediately overlying the sand blow provided a radiocarbon age of 1980 ± 40 yr BP (cal. BC 50–AD 100; Figure 5), whereas the sample obtained from the sand body yielded a slightly younger age of 1859 ± 60 yr BP (cal. AD 25–AD 328). The reversal of age – a situation where overlying stratum yields an older age in comparison to the subjacent older sediment horizon – is somewhat anomalous, but not wholly inexplicable. Such reversals in age may occur as a result of mixing and/or remobilization of sediments²². For example, older charcoal pieces from lower levels can be transported to the younger, overlying strata during the ejection and upward movement of sediments. Alternatively, the older piece of charcoal may have been transported laterally down the slope along with the debris, immediately after the liquefaction episode. There is always an element of uncertainty with regard to the dates derived from such samples because of the time-gap between its origin and subsequent deposition. In this case, both the ages are

Table 1. AMS age data for organic samples from a trench at Bet Dwarka

Sample ID	Trench no.	Material dated	¹³ C/ ¹² C ratio	¹⁴ C age yrs BP	Calendar age (2 sigma range)	Calendar years (2 sigma range)
BDK-2-L	BDK-2	Charcoal	– 24.6 ‰	1859 ± 60	1925–1620	AD 25–AD 328
BDK-2-T	BDK-2	Charcoal	– 25.8 ‰	1980 ± 40	2060–1900	BC 50–AD 100

Calendar ages estimated following Stuiver *et al.*²⁶.

somewhat identical, and it is reasonable to believe that the liquefaction event may have occurred close to these dates, approximately at the beginning of the first millennium.

We have used the combined average of multiple mean and standard-deviation estimates to represent the age of this feature²³. This combined mean age, which works out to be 1944 yr BP, is closer to the date of the sample BDK-2-T (1980 ± 40 yr BP) and it has a much smaller error margin compared to that of BDK-2-L. Furthermore, the artifacts and pottery suggest an age of BC 200–AD 200 (~ 2200 yr BP) for the habitation level 11, which underlies the anomalous layer. This age may be considered as the maximum age of the liquefaction episode. However, the continuity of similar type of pottery in the overlying occupation level suggests that there is no time gap between the two levels, and the age of the entire habitation in the trench (BDK-2) may be bracketed between 2nd century BC and 5th century AD. It is likely that the same generation of settlers reoccupied this site, may be within a few years since the liquefaction event. A schematic model shown in Figure 6 may explain the formation of sand blow at Bet Dwarka and its temporal association with the top and bottom cultural strata. The ~ 2000-year-old sand blow at BDK-2 does not show evidence of any subsequent liquefaction, in which case, we would expect to find more than one distinct cross-cutting layer or dikes, typical of reactivated sand dikes^{20,21}. The first inference that one draws from the absence of later-generation sand blows is that no liquefaction events of comparable dimension could have affected this area during the subsequent years.

Having suggested that the anomalous feature reported from Bet Dwarka is induced by a palaeo-earthquake, we now develop two possible scenarios to isolate its source: (1) that it is an outlying feature generated from distant seismic sources and (2) that it is caused by a nearby source. Next, we evaluate each one of these scenarios. First, let us consider that the ~ 2000-yr-old sand blow at Bet Dwarka is the effect of a large, distant earthquake, possibly from the already known sources (1819 and 2001). Till date, no evidence for an ~ 2000-yr-old earthquake has been obtained from the 1819 and 2001 source zones, both of which have been quite well-investigated. Had there been an older event close to these sources, one would expect to find larger features in their proximities. Furthermore, the deformation layer at Bet Dwarka has not been crosscut or disturbed by later events, an indication that this site is outside the probable limits of large-scale liquefaction due to earthquakes originating in the 1819 and 2001 sources. Another possibility that we must consider are the changes in hydro-geological conditions over the last 2000 years that could have affected the liquefaction susceptibility. It appears that the sea level was higher than at present during the last several thousands of years, and therefore the groundwater level at this location must have also been higher²⁴. We are unable to speculate on the role of high water table on the liquefaction potential of this area, due to large distant earthquakes, but an analogy with the Bhuj earthquake is instructive. The Bhuj earthquake whose epicentre is about 200 km away from Bet Dwarka did not generate any noticeable liquefaction even in the low-lying areas of Dwarka, where groundwater conditions are

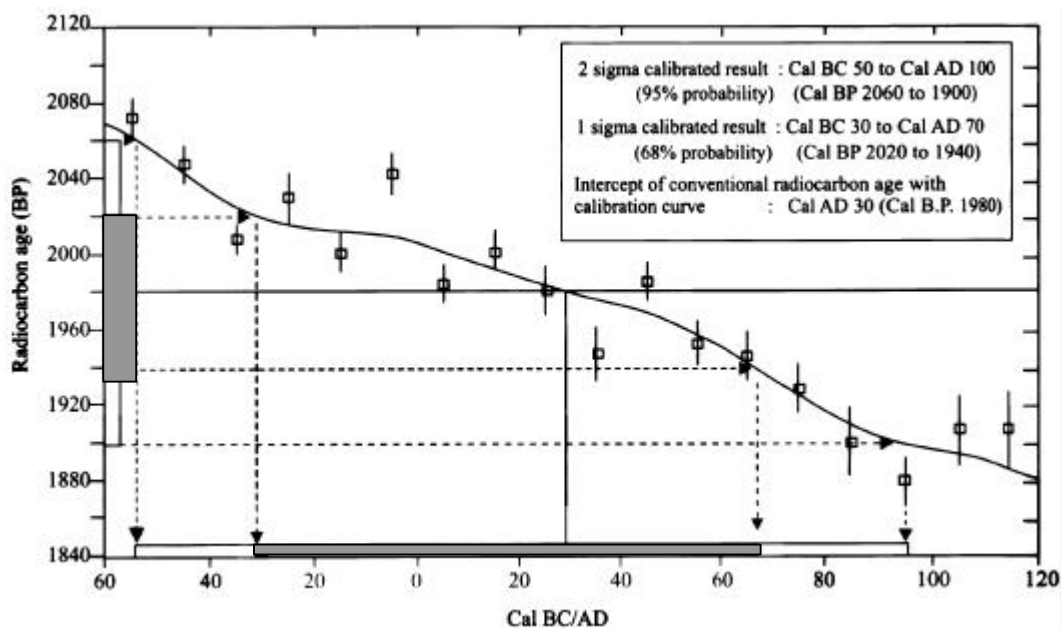


Figure 5. Calibration curve for sample BDK-2-T showing age-probability distribution with 1 and 2 sigma thresholds.

still favourable to liquefaction. A preliminary inference is that the ground shaking from a similar-size earthquake is unlikely to have produced the palaeoliquefaction feature of the kind observed near Bet Dwarka. There are no reports of liquefaction in these areas due to the 1819 earthquake, either. The historical accounts of the 1819 earthquake, however, indicate bubbling of water and small-scale liquefaction near the sea shore at Porbandar, a port city located about 100 km south of Bet Dwarka¹. Even if we accept for the sake of argument, that some undocumented liquefaction effects could have occurred in the low-lying intertidal areas of Dwarka during the 1819 earthquake, their effects would be minimal. The sand blow being reported from Bet Dwarka is more than 20 cm in thickness and at least one of its vents measures up to 1 m. These dimensions are too large to be explained by distant earthquakes from the above sources. We have strong evidence for another earthquake that occurred during AD 893 in the Rann²⁵, but the age of the feature at Bet Dwarka does not agree with this event. Going with the AMS dates, the causative event must have occurred between cal. BC 50 and AD 328 (see Table 1), suggesting that none of the currently known historic earthquakes could have generated the feature at Bet Dwarka.

Earlier excavations by Sankalia in 1963 near Dwarkadish temple (Dwarka temple in the mainland)

revealed thick intervening deposits of clean sand and rolled potshards between successive occupation horizons (see Ansari and Mate¹³ for details). These studies indicated that the earliest occupation level at Dwarka (~ 2000 yr BP) lies buried under 6 m thick sand layer, possibly deposited during sea transgression. However, it is stated in the above report that this sand deposition is a localized phenomenon, not extending beyond 1 km. It is interesting to note that the timing (beginning of the Christian era) of sand deposition somewhat coincides with the age of the liquefaction event reported here from Bet Dwarka. The details that we have on the nature of deposits and their characteristics obtained from the excavations near Dwarka temple are too sketchy to speculate further on this matter; but there is a strong case for future studies.

What makes the Bet Dwarka feature more intriguing is its proximity to an east-west trending rift boundary fault under the Gulf of Kachchh (Figure 1). We do not know if any of the thrust faults under the Gulf of Kachchh or its onshore regions have been active in the recent past. The occurrence of this moderately large, 2000-yr-old sand blow near Dwarka, which we believe is seismically induced, raises an important question whether any part of this boundary fault could have generated large earthquakes in the past. The present analysis, although constrained by limited observations, points to the possibility for an un-

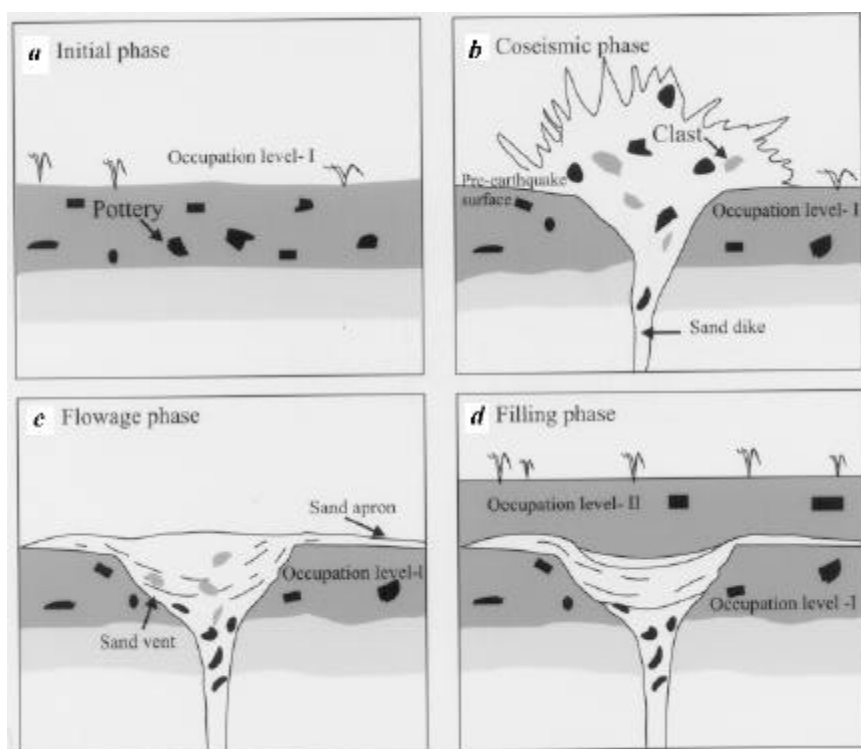


Figure 6. Schematic model showing stages of earthquake-induced sand blow at Bet Dwarka. *a*, Initial phase: Pre-earthquake undisturbed surface that hosts the settlement; *b*, Coseismic phase: Upward directed flow of sediment–water mix disturbs the human settlement; *c*, Flowage phase: Sediment–water mix flows out affecting the occupation level; *d*, Filling phase: Discharged material flows back or collapses into the crater, re-sedimentation process starts and new occupation level is established over the earlier one.

known source in northwest Gujarat. The evidence of an isolated palaeoliquefaction feature itself does not constitute the proof for an independent source near Bet Dwarka. A systematic survey of the area has not been made yet, to search for similar structures from the nearby areas. Therefore, validity of our postulation of an independent large seismic source either in the Gulf of Kachchh or the onshore region is contingent upon the discovery of several coeval liquefaction features of comparable dimensions at least within the 30–50 km radius of Dwarka that will satisfy Obermeier's (ref. 8) fourth caveat, as discussed earlier. On the other hand, if the frequency and size of contemporary features tend to increase away from this location, it would argue for a distant source. We, therefore, emphasize the need to conduct more studies to define this seismic source and constrain the earthquake chronology. Occurrence of an earthquake about 2000 years ago from an unknown source poses new questions on future hazard in the region.

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Human settlement of the last glaciation on the Tibetan plateau

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An archaeological site with 19 handprints and footprints of *Homo sapiens* and the remnant of a fireplace have been found on hot spring travertine at an elevation of 4200 m on the Tibetan plateau. The prints were pressed on soft travertine by humans. The age of the prints and fireplace is estimated to be around 20,000 years using the optically stimulated luminescence method. The result suggests that humans came to the plateau much earlier than was previously thought. This evidence of human settlement implies that the Tibetans occupy high plateau much earlier than the Andeans and the ice sheet did not cover the entire Tibetan plateau during the Last Glacial Maximum.

The literature-recorded history of Tibet is 1400 years old. Archaeological findings of prehistoric remnants are rare on this plateau¹ because of lack of archaeological field expedition. In some geoscience expeditions, different stone tools have been found in central, north and western Tibet without dating information^{2,3}. Only an archaeological site on the northern plateau was dated as 4000 years with Palaeolithic tools. Some authors considered that the civilization progression on the plateau was behind the

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