whereas at P3, marine forms were observed at about 136 cm below surface. The zone being closer to the coast than P6, was inundated much earlier than P6. Few low-salinity mangrove pollen (*Sonneratia*) in the next overlying sequence (at 78–81 cm below surface) of P6 indicate low-energy, brackish water condition that favoured growth of mangroves.

The present intertidal zone was a part of the mixed forest with clayey-silt bottom sediment. Mangroves as well as other freshwater aquatics, cosmopolitan ferns, herbs and tropical epiphytic fungi existed in a low-energy, swampy condition. These areas were very close to the then agricultural fields. Gradually HWL shifted landward inundating the lower areas first and a high-energy condition prevailed resulting in erosion and disappearance of the mangroves. After that, the obliteration of vegetation and accumulation of sand took place simultaneously.

The erstwhile intertidal zone and part of the backshore has been eroded sector-wise in different phases. Modern sands are being deposited on the present intertidal zone over ancient clayey-silt bed. The faunal assemblage, clay balls, heavy minerals and strays of foraminiferal shells indicate that the sands have been transported from near-coastal seabed. Thickness of deposited sand column varied depending on the time span of inundation and the then relief of the area. Sedimentation of modern sands on the present intertidal zone by marine processes has resulted in the development of a sandy beach, thereby changing the configuration and character of the Henry's Island coast.

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ACKNOWLEDGEMENTS. This work was done under a project sponsored by the Ministry of Earth Sciences (MoES), New Delhi. We thank Dr (Mrs) Anjum Farooqui (Birbal Sahni Institute of Palaeobotany, Lucknow) for help in palynological analyses.

Received 31 December 2013; revised accepted 29 May 2014

Kachchh Mesozoic domes, western India: study of morphotectono character and evolution

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Kachchh domes are recognized by the oval to elliptical-shaped outcrop patterns marked by outlines of bedding surfaces which invariably dip in the outward directions. The occurrence of domes in rows without having corresponding basin-like features implies that these are not superposed folds resulting due to constriction-type tectonic forces. Further, in spite of the close time–space relationship, the occurrence of domes is exclusively in the Mesozoic rocks on the uplifted block of the fault. The absence of any such rock formation on the other side of the fault rules out the possibility that these are 'drape folds' developed during the adjustment of the sedimentary blanket over the faulted-up edges of the basement blocks. Hinging on the evidence of intrusive plutonic (mafic) masses in the core of some of the domes, we suggest that the structures evolved through diapiric rise of magma bodies causing dome-shaped up-warping (bending) of the pre-existing (Mesozoic) flat-lying sedimentary formations. Linear disposition of domes is explained as due to channellization of magma along the fractures that developed around large-scale crustal doming during the early phase of the Reunion Plume impingement under the Indian Lithosphere.

Keywords: Diapiric folds, domes, evolutionary history, magma bodies.

AMONGST several features that make Kachchh a geomorpho-tectonically unique terrain in western India, the series of blister-like domes amidst virtually undeformed, flat-lying bedded sequences is considered significant. Reference to the dome-like structures exposing Mesozoic sedimentary sequences endowed with records of rich marine and fluvio-marine fossils are found in early literature on Kachchh geology[1–4]. Geological maps showing closed outcrop patterns with outward dipping (quaquaversal) beds have been prepared by some authors[5,6], which help identify these as 'structural domes' and not as mere topographical features. Occurrence of structural domes in Mesozoic sediments and that too in a 'Stable Continental Region' calls for explanation. The present communication is aimed at finding the evolutionary history of the Kachchh domes.

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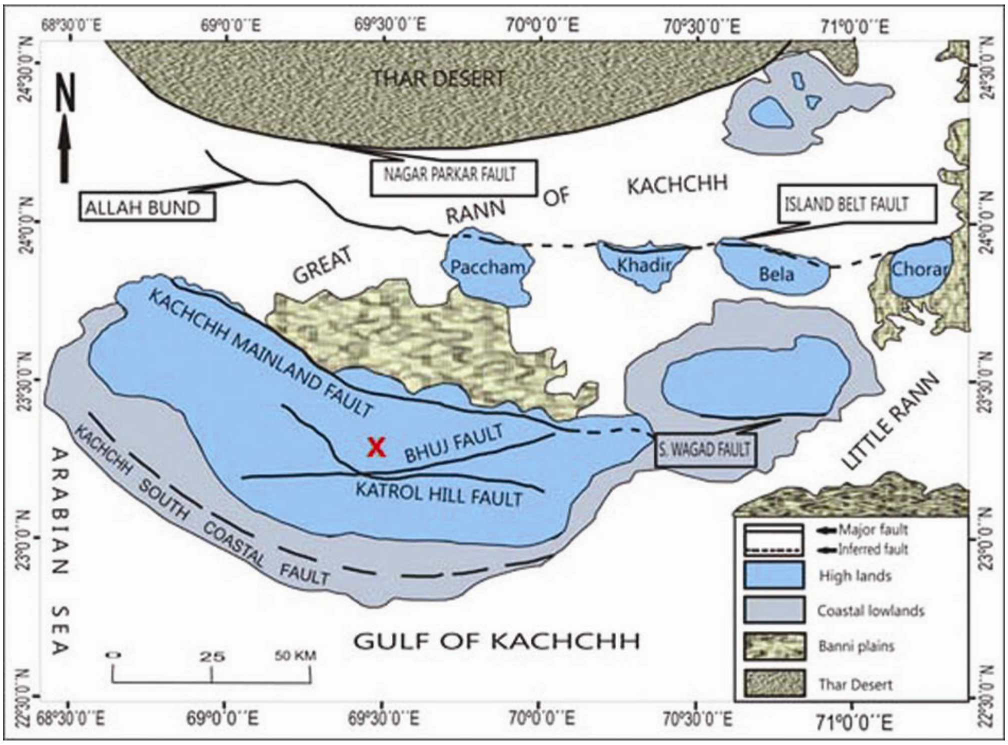

Figure 1. Geomorphotectonic map of Kachchh[7] showing disposition of major faults/lineaments. Red star indicates the location of Bhuj.

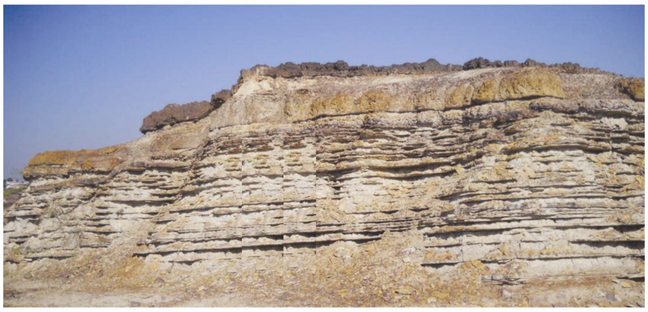

Figure 2. Subhorizontal bedding characterizes almost the entire Kachchh region, barring narrow strips of dome-shaped folds[8].

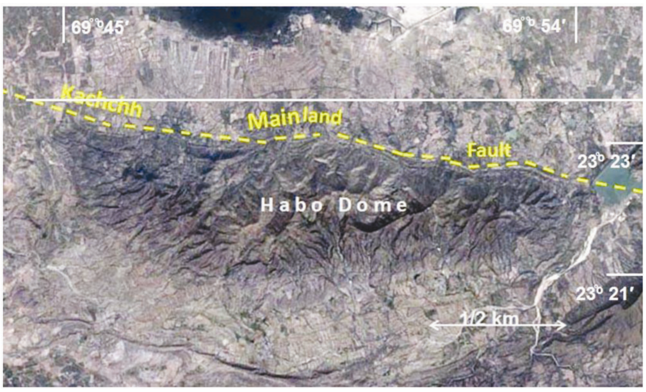

Figure 3. Satellite image of the topographically elevated area of the Habo dome. Kachchh Mainland Fault braces the northern margin of the dome-shaped structure.

Kachchh domes have some special characteristic features. First, these dome-shaped features occur exclusive in the Mesozoic rocks. The oldest components, the Jurassic formations, are exposed almost exclusively in the unroofed core regions of the individual domes. Second is their occurrence in rows sub-parallel to the traces of major faults (also described as lineaments), which from north to south are the Island Belt Fault (IBF), the Kachchh Mainland Fault (KMF) and the Katrol Hill Fault (KHF) (Figure 1). The present study is confined to the strip around KMF, which constitutes the tectonic boundary between the Kachchh Mainland in the south and the Great Rann of Kachchh in the north[7,8].

Tectonically, the entire Kachchh terrain is characterized by the sub-horizontal (dip varying between 0° and <10°) orientation of the bedding surfaces (Figure 2) in spite of the difference in topographic heights at different places. Such a structural feature is broken only along the narrow strips where the rows of domes occur. Appearing as blister-like features, the domes constitute the topographically elevated zones (Figure 3) amidst flat, low-lying areas. The belts of elevated zone described as 'highlands' have been explained as east-west trending oblong uplifts surrounded by residual depression[9,10].

Study of satellite imagery coupled with field investigations along the KMF helped find the precise relationship between the rows of domes and trace of the KMF. The domes are identified in satellite imagery by the occurrence of oval or elliptical-shaped closed outlines marked

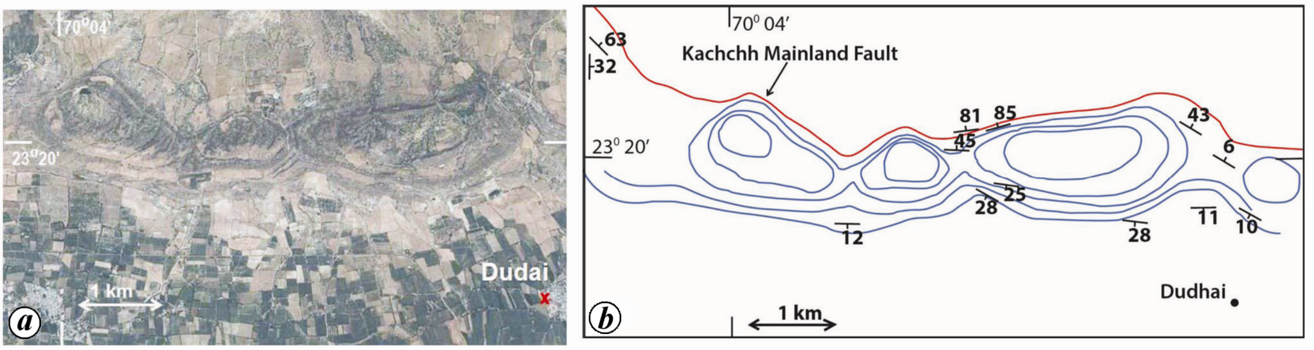

Figure 4. ***a***, Satellite image indicating closed pattern of bedding surfaces of the Dudai domes east of Bhuj. ***b***, Structural map of the Dudai domes. Blue lines indicate traces of bedding, while red line indicates trace of KMF.

Figure 5. Antiformal character of the fold appears in the cross-sectional view of a dome near the flattening of the hinge line.

Figure 6. Zone of steep dip of bedding surfaces occurring close to KMF north of the domal outcrops.

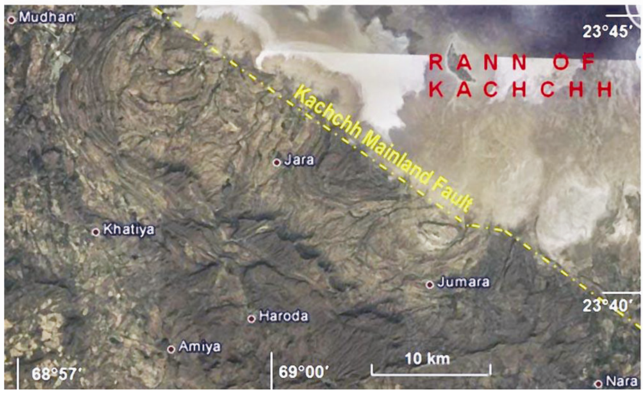

Figure 7. Illustration of composite (truncated) domes occurring within a larger elliptical enclosure.

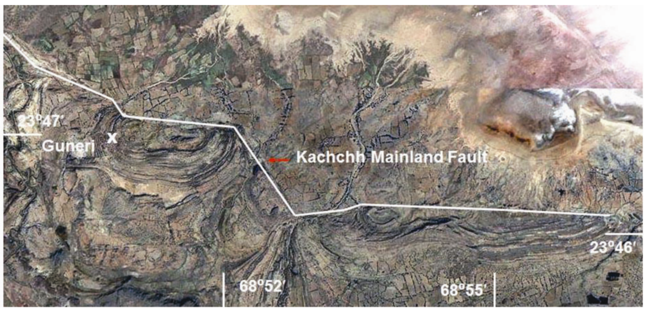

Figure 8. All dome-shaped outcrops in the western part showing truncation along the trace of KMF.

by traces of bedding surfaces (Figure 4 *a*). The long axis of the elliptical outcrops is oriented parallel to KMF, which braces the northern margin of the domes. Confirmation of the dome-shaped structural features comes from the dip orientation of the beds (Figure 4 *b*). The feature helps identify these as 'structural domes' formed due to bending or curving of initially planar surfaces or layers.

The individual domes show the geometry of plane, non-cylindrical, antiformal fold system with the hinge line displaying culmination and depression in the longitudinal direction. Apart from the diverging dip

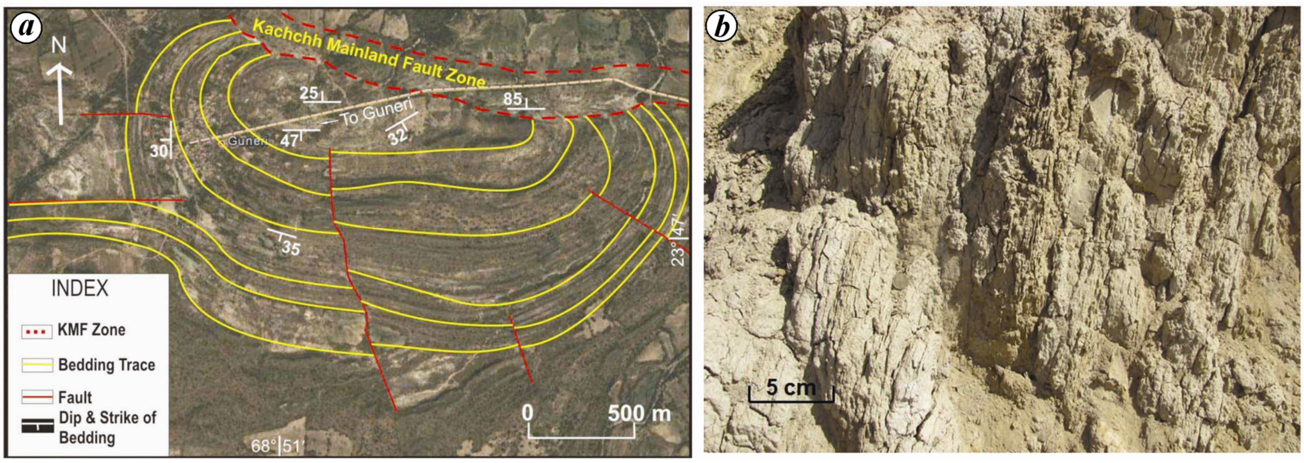

Figure 9. ***a***, Structural map of the Guneri dome showing different geomorphotectonic character drawn on satellite imagery. ***b***, A zone of steeply dipping spaced fractures simulating fracture-type cleavage marking the KMF running subparallel to the steepened bedding planes in the northern part of dome-shaped outcrops.

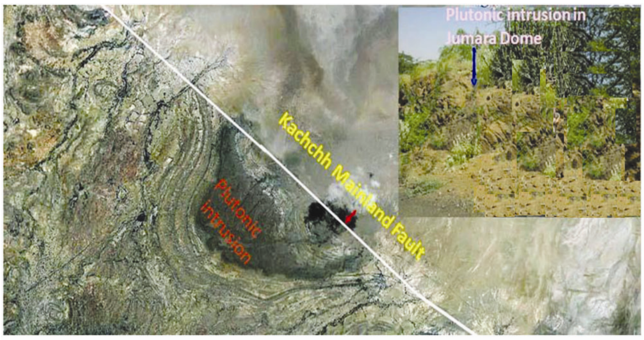

Figure 10. Plutonic intrusion of alkali basalt composition in the core of a truncated 'dome'. (Inset) Outcrops of mafic rocks in the core region of the dome.

orientation of bedding surfaces, the antiformal character of the fold system is indicated in the cross-sectional view at the exposed termination of some of the western domes (Figure 5). The antiformal domes show broad symmetrical orientation of the limbs only near the core region. With the steepening of the northerly dipping beds (at places to almost vertical) (Figures 4 *b* and 6) close to the KMF, the domes change to asymmetric type.

A distinctly different relationship is observed between the domes and the fault from west to east. In the central and eastern zones, the KMF braces the northern margins of the domes causing steepening of beds, but without affecting the outcrop patterns (Figure 4). Truncation of the domes appears in the satellite image in the western part of the region (Figures 7 and 8). The dome-shaped structures do not always occur as isolated features. Instead, some series of domes occur in groups showing smaller, circular to oval outcrop patterns enclosed within large elongate, closed structures (Figure 7).

Apart from truncation in the northern part, detailed mapping of the westernmost Guneri dome indicated development of radial faults which are found in diapirically uplifted pipe-like magmatic plugs (Figure 9 *a*). The fault representing the KMF in this part is marked by a zone characterized by steeply dipping, closely spaced fractures which simulate features of the fracture cleavage surfaces independent of the orientation of mineral grains (Figure 9 *b*).

A feature of great significance is the close association of the domes with mafic intrusive bodies of different types. The intrusive bodies show different types of relationship with the domes. For example, coarse plutonic intrusion (alkali basalt in composition) showing broadly conformable contact with the overlying sedimentary rocks occurs in the core of a few domes (Figure 10).

The classic example of plug-like mafic intrusion of alkali basalt composition is witnessed in the central part of the Habo dome, especially where the deeper level rocks are exposed along some stream-cuts. In spite of the apparent conformable relationship, the presence of narrow tongues and apophyses (made of fine-grained basalt) darting out from the plutonic mass into the sedimentary 'cap rock' provides proof of the intrusive character of the plutonic bodies (Figure 11).

Apart from the intrusive bodies occurring exclusively within the domes, some intrusions occur amidst the flat-lying Mesozoic sediments. There are also some isolated bodies intruding the sedimentary rocks on the southern flank of the domes. One of these occurring at Dinodar (23°27′00″; 69°20′30″) looks like a volcanic vent showing a central collapse zone (Figure 12). These isolated bodies have been identified as the exhumed subvolcanic intrusions[11] within the pre-existing rocks.

The evolution of the Habo dome, the largest of such structures in the Kachchh region, has been explained as due to intrusion of an upcoming mass of igneous body[6] (implying diapiric emplacement). Contradicting the concept, a suggestion has been made that these are drape folds[9] formed during the adjustment of the sedimentary blanket while riding over the faulted-up edges of the basement blocks.

The evidence of truncation of domes (especially on the western side of the KMF) suggests that the movements along the fault post-dated the formation of the domes. Hence, in spite of the close relationship in space, no direct cause-and-effect relationship can be ascribed between the fault movement and formation of the dome-shaped folds. Further, no part of the Mesozoic formations constituting the domes is observed either in the fault zone or on the other side of the active faulted block, not even in the cases where the domes show truncation. On the other hand, as mentioned earlier, there are several well-defined dome-shaped outcrops on the southern side of the fault (KMF in particular), which discounts any possibility of 'drape folding'.

There is also a suggestion[12,13] that local doming-up of beds could result during scraping of veneers of salt along some 'decollément' surfaces, as has been observed in a few oil-bearing formations in some parts of the world. We may, therefore, rule out such a possibility in Kachchh because of the strong evidence of vertical movements that shaped landform patterns in the region[9,10,14]. Finally, we can also exclude the possibility of any orogeny-related tectonism in evolving features like domes for the simple reason that the region is far away from the active zone of mountain-building, forming a part of the 'Stable Continental Region' of the Indian shield. Additionally, the Kachchh domes do not have any basin-like counterparts so characteristic of tectonically evolved superposed folding formed due the constriction-type tectonism.

While addressing the question of formation of domes, the features that stand out, thus helping interpretation are: (i) Domes are blister-like local features restricted to narrow zones sub-parallel to the major faults. (ii) They occur amidst tectonically undeformed, flat-lying sedimentary sequences. (iii) Evidence of plug-like intrusions in the core of the domes. Looking into all possibilities, the weight of evidence favours the formation of domes through diapiric rise of magma bodies in a way similar to that suggested for the Hobo dome[6]. Linear disposition of domes is because of the channellization of magma along the fractures that developed around large-scale crustal doming during the early phase of Reunion Plume outburst in the region[7]. Confirmation for relating the plutonic intrusive masses in the Kachchh region with the Reunion Plume-induced magmatism comes from the similarities in geochemical signatures of the two magma types[15,16]. Further confirmation comes from the isotope dates between ca. 68 and 64 Ma (refs 17–19), as well as from the palaeomagnetic study of mafic magmatism in Kachchh[20]. Presuming that the magma bodies were channellized along the fractures that evolved during the initial phase of magma uplift (at ca. 68 Ma), the present disposition of the faults, especially of the KMF partially truncating the domes, would suggest reactivation of the pristine crustal fractures (along which the magma bodies were channellized) at a later date (possibly during the late Cenozoic and Quaternary) post-dating the formation of domes.

The Kachchh domes, as these are conventionally described, have attracted the attention of early geologists

Figure 11. A body of massive gabbro in the core region of Habo dome showing conformable contact with the overlying Mesozoic limestone. Some apophyses of dyke and sill (A and B) are seen to dart out from the gabbro body.

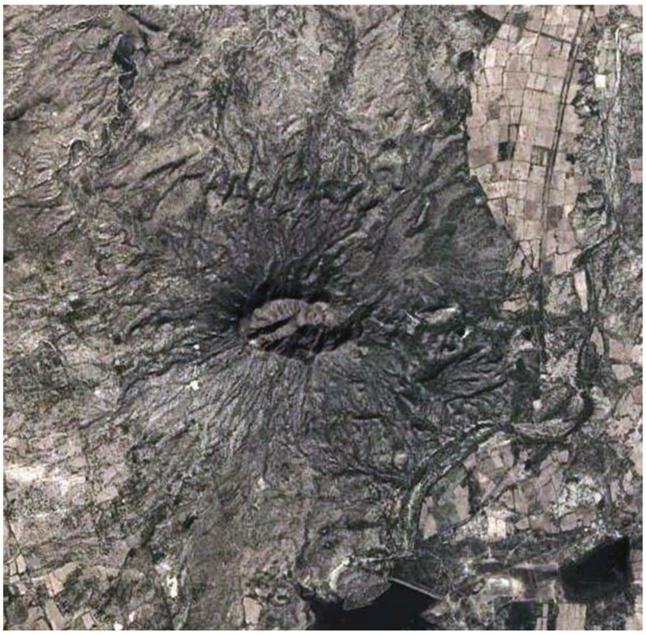

Figure 12. Satellite imagery of a plug-like body at Dinodar, which appears like a volcanic vent.

for a variety of reasons, but particularly for the occurrence of rich marine fossils in the Jurassic formations exposed in the core regions. Apart from that, the development of rows of domes in a terrain of flat-lying beds is considered an intriguing structural feature which needs explanation. In satellite imagery, the domes are recognized by the oval to elliptical-shaped outcrops marked by outlines of bedding surfaces. Confirmation of the dome-shaped structures comes from the orientation of the outwardly dipping bedding surfaces as observed in the field. The occurrence of domes in rows without having corresponding basin-like features implies that these are not superposed folds formed due to any constriction-type of tectonism. On the other hand, the localized occurrence of domes amidst flat-lying Mesozoic rocks and the evidence of diaper-type intrusion of younger (Deccan-related) mafic rocks in the core provide direct evidence of upward-directed magma diapirs causing passive bending of the overlying flat-lying rock formations. Linear disposition of domes is because of the channellization of magma along the fractures that developed around large-scale crustal doming. Confirmation of such a tectonic model comes from direct evidence of diapiric intrusion of younger magma bodies of Reunion Plume affinity into older Mesozoic rocks from below. Presuming that the magma bodies were channellized along the fractures that evolved during the initial phase of magma uplift, the present disposition of the faults, especially the KMF truncating the westerly lying domes, is thought to have resulted during the reactivation of the pristine crustal fractures at a later date (possibly during the late Cenozoic and Quaternary deformation), post-dating the formation of the domes.

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ACKNOWLEDGEMENTS. We thank the Ministry of Earth Science, New Delhi for financial assistance to carry out the research project. We also thank S. Kanjilal, Banaras Hindu University for discussions on Kachchh geology and the authorities of the Presidency University for providing laboratory facilities for the work.

Received 13 October 2013; revised accepted 24 June 2014