Late Pleistocene relative sea-level changes from Saurashtra, west coast of India

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The fluvial systems of Saurashtra, Gujarat, India have archived signatures of sea-level stands for the Late Quaternary Period. Based on geomorphology, sedimentology and optical dating, the lower reaches of Noli river in southwestern Saurashtra reveal the presence of marine, fluvially reworked and aeolian forms of miliolite. Optical chronology permits us to extend the age range of fluvially reworked miliolites from 75 (as previously believed) to 114 ka. The fluvial sequence of southwestern Saurashtra has responded to sea-level changes through meandering. Presence of aeolian miliolites dated to 23 ka suggests regional aridity during the time of their deposition and preservation. Marine notches in Diu mark Middle Holocene high sea-level stand and their preservation implies active tectonism in the region.

Keywords: Fluvial response, optical dating, miliolites, sea-level change.

COASTAL Saurashtra in western India has preserved the record of environmental changes from Middle to Late Pleistocene in lithified bioclastic limestone, popularly known as miliolite[1]. Owing to their occurrence at distal inland localities, the origin of miliolites triggered a debate regarding their linkages to marine or aeolian processes[2–7]. Based on the occurrence of miliolites at an elevation of >40 m, and even as high as 200 m, it was hypothesized that these were due to marine processes and neotectonism[5]. However, this suggestion was contradicted by the geomorphic set-up of the region[1]. Bhatt[7] laid the origin controversy to rest, by proposing three modes of miliolite deposition: (i) marine (near the shoreline and at an elevation <20 m); (ii) aeolian (obstacle dune deposits at varying elevations, as high as 200 m), and (iii) reworked fluvial (in the form of valley fills: youngest miliolite deposits). Sharma *et al.*[1] demonstrated the application of optical dating for estimating the timing of deposition of Miliolite Formation for all three modes, i.e. >165–44 ka for marine, 80–11 ka for aeolian and 75–17 ka for fluvially reworked formation.

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The Late Quaternary sea-level history for the west coast of India has been discussed and debated[8–10]. Evidence of sea-level comes from two notches at elevation of 5 and >11 m from south Saurashtra coastline. Presence of second level of marine notch at an elevation of >11 m amsl at Diu, is possibly linked with the high sea level stand of MIS 5e, when the sea level was higher by 7 m (refs 11, 12). Similarly, region-wide fluvial incision and subsequent aggradation along with extension of present rivers mouths into deeper sea, have hinted that the sea level was below 100 m than the present during the LGM[10,13,14]. Here, we present data from southern Saurashtra, constrained by optical chronology and scrutinize the available records to understand the sea-level history in the region.

We examined the sediments of southwest-flowing Noli river which originates from the Gir ranges in Saurashtra (Figure 1)[15]. The river traverses through the Deccan Trap basalts in its upper reaches and Quaternary sediments in the lower reaches before debouching into the Arabian Sea. In its lower reaches, the Noli river sediments exhibit typical fluvial to fluvio-marine characters (Figures 2 and 3 *a*). They exhibit features such as channel bars, point bars and large meanders just before the river meets the Arabian Sea. Here we have examined the Noli bridge site where the bottom-most miliolitic horizon is rich in oysters. This 6 m incised valley-fill sequence occurring upstream of the meander (Figures 2 and 3 *a*) comprises 2.0 m thick miliolite limestone with bioturbations and abundant oysters. Upstream this horizon shows convolute bedding (Figure 3 *b*) and is overlain by a 1.0 m thick sandy layer with discrete pebbles of 1–2 cm length (Gmm facies, unit 2) along with abundant oyster shells. This unit is overlain by 0.5 m thick massive miliolitic sand (Sm facies, unit 3), which is in turn overlain by a 1.5 m thick pebbly–cobbly horizon with discrete lithoclasts of older limestone unit. Imbrication is observed in this unit (Gh facies, unit 4). The pebbly–cobbly horizon is overlain by 1.5 m thick sandy horizon of discrete gravels (Ss facies, unit 5). This succession ends with a 1 m thick blanket of miliolitic sand with crude cross-laminations (Ss facies, unit 6).

A section near Kamnath temple (Figures 2 and 3 *c*), upstream of the present site, was earlier studied by Sharma *et al.*[1]. They reported a fluvial aggradation commencing from 32 ka in the form of clast-supported conglomerate with matrix-dominated unit (Figure 2). This was followed by deposition of two distinct layers of miliolitic horizons, the first with scattered boulder clasts and the second with compact micritic composition. Sharma *et al.*[1] suggested that the topmost miliolitic horizon dated to 18 ± 1 ka represented a coastal swamp-like environment. However, this time-frame for the same implied the environment could not be marine, as the sea level was low during the LGM.

The optically simulated luminescence (OSL) samples from units 2 and 6 of Noli bridge site were analysed at

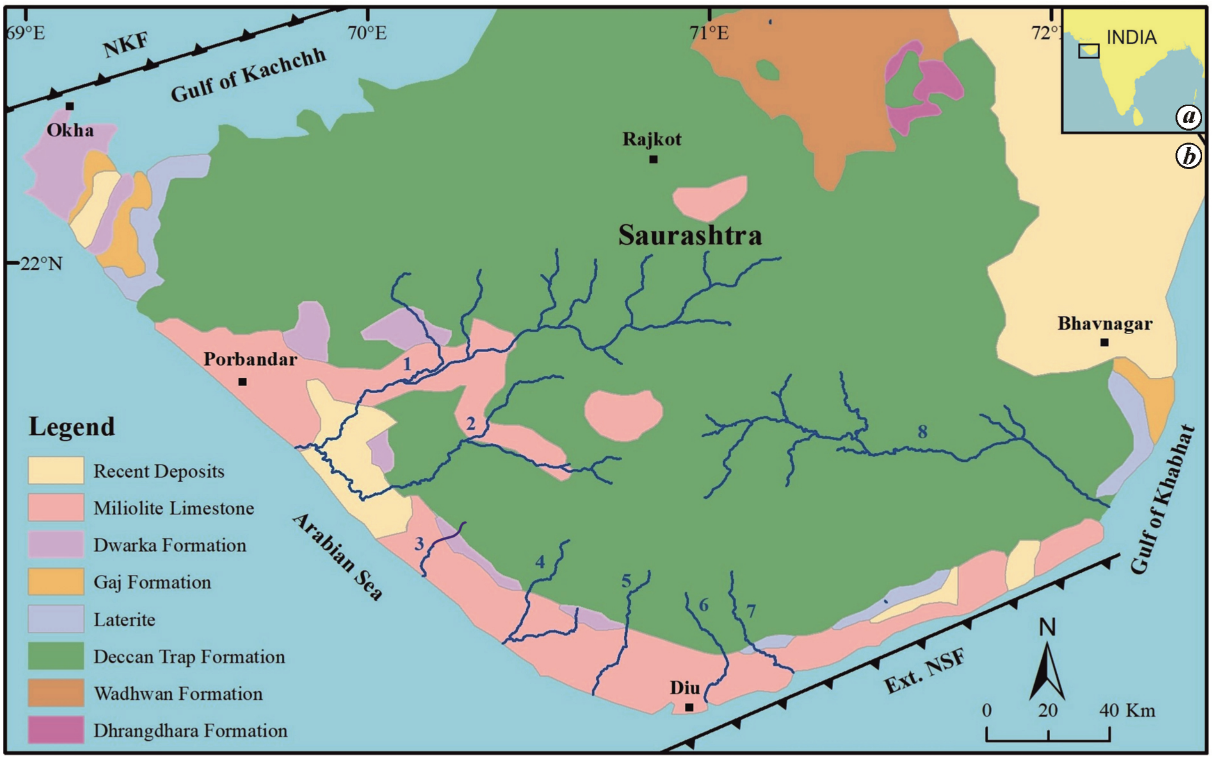

Figure 1. ***a***, Location of Saurashtra in India; ***b***, geological map of Saurashtra along with major rivers and fault systems (modified after Merh[15]). NKF, North Kathiawar Fault; NSF, Narmada Son Fault. Rivers: 1, Bhadar; 2, Ojat; 3, Noli; 4, Hiran; 5, Singwado; 6, Macchuandri; 7, Rawal and 8, Shetrunji.

the Institute of Seismological Research (ISR) following the procedure outlined by Sharma *et al.*[1] for quartz grains. The two ends of the OSL pipes were removed and sample from the middle part of pipe was retrieved in subdued light conditions. The retrieved sample was treated with 1 N HCl and H_2O_2 for removal of carbonates and organic matter. This was followed by separation of 90–150 μm fraction of sample using wet sieving method. The separated fraction was then dried and further subjected to magnetic separation using a Frintz magnetic separator, from which magnetic and non-magnetic fraction minerals were separated. The non-magnetic fraction was then etched with 40% HF for 80 min followed by 12 N HCl for 30 min. This removed the 25 ± 5 μm thick layer over the fresh quartz grains. The pure quartz grains hence extracted were washed with distilled water several times and then dried for further analysis. The feldspar contamination was checked using infrared simulated luminescence (IRSL). The samples with IRSL count <50 were then mounted on 10 mm stainless steel discs with silicon spray as adhesive for equivalent dose (D_e) measurements. The aliquots were made of 1 mm diameter. The luminescence measurements were carried out in RISO, TL/OSL reader under blue LED source (470 ± 30 nm). Beta irradiations were carried out using an on-plate $^{90}Sr/^{90}Y$ beta source. The D_e distribution is shown in Figure 2, which was also used to decide on the various statistical models for age estimation. Unit 2 yielded an OSL age of 114 ± 8 ka using CAM model (OD ~ 16%), whereas unit 6 yielded an OSL age of 23 ± 3 ka using MAM model (OD ~ 52%) (Table 1 and Figure 2).

The present OSL ages along with those published by Sharma *et al.*[1] and sedimentological data suggest that the site archives the deposition of marine, fluvial and aeolian forms of miliolite for the last 150 ka (Table 1 and Figure 2).

The bottom-most miliolite comprises abundant oyster shells, which indicates deposition in a marine environment. The convolute bedding in the upstream sections suggests an intertidal regime[16]. This is overlain by a typical fluvial facies of sandy pebbles which are 1–2 cm long and scattered in horizon. The deposition of this horizon occurred at 114 ± 8 ka. During this period the Indian summer monsoon (ISM) was more intensive and experienced seasonality as seen in the adjoining areas like Gujarat Alluvial Plains (GAP)[10], Bhadar river[17] and the Arabian Sea[18]. Overlying horizon of massive sand facies of miliolitics suggests a depositional environment of channel bar facies. After a brief hiatus (either erosional or depositional), sedimentation occurred from 75 ka and up to 50 ka, under a relatively enhanced monsoonal regime with seasonality. This is also evident by the presence of discreet gravels and clasts in sandy horizon of units 4 and 5.

Similar fluvial response to climate change is also replicated in GAP[10,13]. Western India experienced a sea-level

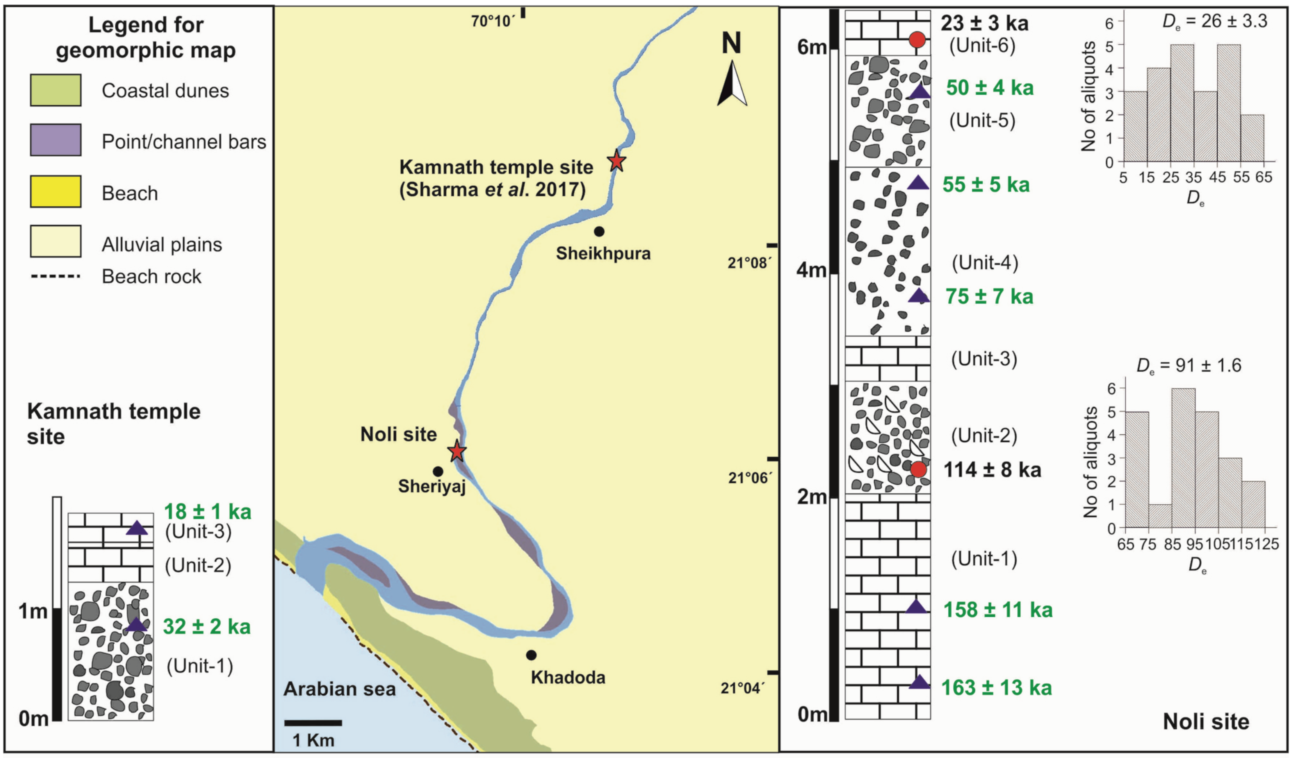

Figure 2. Geomorphic map of Lower Noli river along with lithostratigraphic sections of Noli bridge and Kamnath temple sites. D_e distribution shown in histogram for new OSL ages.

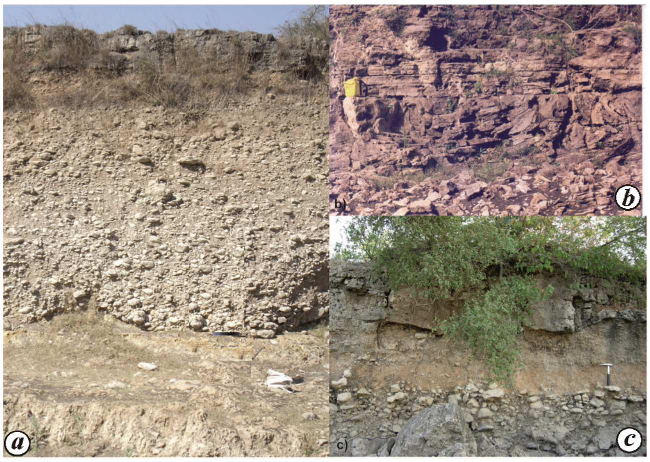

Figure 3. ***a***, Field photograph of Noli bridge site. ***b***, Convolute bedding in lower miliolite unit; ***c***, Field photograph of Kamnath temple site.

fall of about 100 m during the LGM (i.e. around 24 ka)[8,10,14]. The topmost unit of the sequence is made up of fine sand of miliolite, which shows faint cross-beds of aeolian origin. The aeolian sedimentation took place around 23 ± 3 ka, which was aided by the vast exposed continental shelf across the western Indian coastline.

The region lacks archives which exemplify the evidences of high sea-level epochs and subsequent palaeoenvironmental changes. An MIS 5e high sea stand was reported as the topmost marine notch at Diu, at a maximum elevation of 11 m (ref. 12). Bhatt and Bhonde[17] documented the lithofacies of Bhadar and a few coastal rivers (viz. Noli, Hiran and Shingwado) (Figure 1 *b*) and reported evidences of marine flooding up to Kutiyana in Bhadar at elevation of 15 m amsl. However, chronological constrains were absent in the study. The geomorphic set-up of the lower segment of Noli river suggests that meandering of the river occurred on account of rising sea level, in the otherwise straight southwestward-flowing river (Figure 2 *a*). A major meander near the coast is controlled by a lithified (miliolite/shell limestone) ancient beach ridge, which is a palaeo-high sea strand line[19]. Alluvial rivers often meander due to lack of stream power in response to rising sea level[20], which is also observed in most of the southwestward-flowing rivers of Saurashtra. The ages of top aeolian miliolite horizon, after deposition of which the river incised and flows till date, suggest that this occurred < 23 ka. The sea level was rising post the LGM low of 100 m, which would have facilitated meandering of the river and subsequent incision.

The Saurashtra peninsula has experienced pronounced neotectonic activity as suggested by seismicity[21,22], preserved raised marine notches[11,12], development of joints[23] and archeological evidences[24]. Sharma *et al.*[1] reported that fluvially reworked miliolites were deposited during the period 17–75 ka. However, the age of unit 2 in the present case is 114 ka based on the central age model (i.e.

Table 1. OSL dataset along with U, Th and K concentration

Sample ID	U (ppm)	Th (ppm)	K (%)	Cosmic ray (μGy/a)	Dose rate (Gy/a)	CAM De	Age (ka)	MAM De	Age (ka)
ISR-245	0.8 ± 0.04	2.2 ± 0.11	0.4 ± 0.01	155 ± 40	793 ± 52	91 ± 1.64	114 ± 8	84.7 ± 4.8	107 ± 9
ISR-246	1 ± 0.05	4.2 ± 0.21	0.56 ± 0.01	185 ± 10	1123 ± 50	31.5 ± 1.8	28 ± 2	25.5 ± 3.3	23 ± 3

*Water content was considered to be 10 ± 2%.

OD < 40%) (Table 1 and Figure 2). This suggests that fluvially reworked miliolite sediments were deposited much earlier at around 114 ka (ref. 1). This pushes the time range of fluvially reworked miliolites up to 114 ka from previously suggested 75 ka (ref. 1).

Similarly, aeolian deposition in the present site commenced at 23 ka, which is based on the minimum age model as the over dispersion is 52% (Table 1 and Figure 2). Nevertheless, the central age model yields an age of 28 ka, which is also within the LGM period. Our chronological result of unit 6 is not consistent with the chronology given by Sharma *et al.*[1], as they have dated the fine-grained polymineralic fraction, whereas we have dated quartz of coarse-grained (90–150 μm). During the LGM, western India experienced arid climate and sea-level was lower than 100 m relative to the present mean sea-level[8,13]. During this aridity it is plausible to suggest that owing to the vast area of continental shelf exposed, due to lower sea level, the aeolian activity predominated the landscape. Margin of the Thar Desert is believed to have expanded during this period and reached up to areas north of Narmada in GAP[10,13,25].

The marine tidal notches in Diu, another testimony to Late Quaternary sea-level changes, show two pronounced levels of past sea stands. The topmost notch is considered to be the signature of MIS 5e (refs 11, 12), whereas the first level of notch is that of Holocene high sea[26]. Sharma *et al.*[1] dated an aeolian miliolite at Phudam site to be 45 ± 3 ka. The date signifies the dune building period, after which the dune was consolidated and converted to an aeolianite. During the last 45 ka, it was possible to create a notch 2–3 m amsl only during the Middle Holocene when the sea level was considerably high[8,14,26]. Nevertheless, preservation of the notch above the present-day sea-level suggests that either the sea level fell faster than the rate of erosion, or the land was uplifted. Otherwise, the same erosional processes that created the notch would have led to its collapse as well, if the rate of erosion was faster. Kazmer *et al.*[24], based on dysfunctional fish tank reported an uplift of 0.5 m in the last millennium from the coastline of Diu. It is plausible that a similar uplift during the last 3 ka led to the level of notches being raised above the erosional effect of the waves and led to preservation of the notch profile. However, assessing the rate of uplift during the Holocene is not possible due to lack of constrains on the extent of Holocene high sea stand, which is still debated[8,14,26].

The fluvial systems of Saurashtra have indeed archived signatures of sea-level stands since the Late Quaternary period. Based on geomorphology, sedimentology and optical dating, the Noli site provides age constraints for marine, fluvially reworked and aeolian forms of miliolite in Saurashtra. The large meander in Noli river before it debouches in the Arabian Sea and similar geomorphic features of adjacent rivers suggest pronounced geomorphic/landscape response to sea-level rise post the LGM. The optical dating of bottom-most fluvially reworked miliolite suggests the time range of its deposition to be from 17 to 114 ka, older than previously believed[1]. Also, the first-level notch at Diu marks the Middle Holocene high sea stand. The preservation of perfect notch profile also indicates active tectonic activity prevalent in southern Saurashtra during the last 3000 years. We strongly suggest the need to scrutinize these archives in future to decouple the components of sea-level change and tectonic processes with a multifaceted approach.

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Mesoscale model compatible IRS-P6 AWiFS-derived land use/land cover of Indian region

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Mesoscale models, in general, are run using the US Geological Survey (USGS) 25-category land use/land cover (LU/LC) data available at different spatial resolutions. The USGS data over the Indian region suffers from two types of errors, viz. misclassification of LU/LC data and non-availability of up-to-date satellite-based LU/LC data. To improve the accuracy and capture interannual changes better, the LU/LC data generated by the National Remote Sensing Centre (NRSC) using IRS-P6 AWiFS with 56 m basic resolution have been scaled to 5, 2 min and 30 sec resolution which is available at yearly intervals. In the next step, the Indian region of USGS data was replaced with IRS-P6 AWiFS-derived data and made compatible to MM5 and WRF mesoscale models. Thus the resultant product is a global USGS LU/LC data with the Indian region replaced by the information originally derived from AWiFS 56 m resolution imagery, for the years 2004–05 to 2012–13 (nine cycles). This communication describes the required LU/LC data format for MM5 and WRF models and the methodology adopted for compatible product generation. In addition, accuracy of AWiFS-derived LU/LC data converted to 30 sec resolution has also been determined. The present effort will provide the necessary reference for the atmospheric modelling community to address the Indian satellite based model compatible LU/LC data product. These data products are currently available on Bhuvan, the NRSC/ISRO geospatial portal.

Keywords: Land use/land cover data, land-surface processes, mesoscale model, spatial resolution.

LAND use/land cover (LU/LC) changes are considered to be one of the most important factors affecting the regional climate and thus become an area of public concern. LU/LC inputs are a critical part of the meteorological modelling system. The role of the land surface is particularly important in driving boundary layer evolution and ultimately precipitation patterns. Inaccurate LU/LC information often leads to large errors in surface energy

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