Quaternary fluvial sequences of South Saurashtra, Western India

Nilesh Bhatt* and U. A. Bhonde

Department of Geology, Faculty of Science, M.S. University of Baroda, Vadodara 390 002, India

Studies of the fluvial sequences exposed in river bank cliffs of Bhadar, Nali, Hiran and Singwado river valleys of south Saurashtra have revealed the presence of trough cross-bedded gravels (Gt), massive sand (Sm) and planar cross-bedded sand (Sp) facies. Thin palaeosol (P facies) layers developed on the substrate of basalt and limestone as well as on the fluvial gravels and sand are also observed. The clear influence of marine flooding in the river valleys is recorded in the form of bioclastic carbonate sand-dominated units that contain biogenic structures and associated tidal clays. Punctuation in the fluvial sequences in the form of pedogenesis, erosion and marine flooding provide clues for changes in regional climate and sea level. The maximum elevation of the marine flooding clusters around 10–15 m. Acheulian tools and radiometric dates of the associated miliolite limestone indicate that the marine flooding in these river valleys is possibly linked to the marine oxygen isotope stage five.

CHANGES in the climate and consequent changes in the sea level are reflected in spatial shifts of geomorphic domain, and associated sedimentary packages[1]. In this respect, palaeoclimatic fluctuations and neotectonism in Quaternary are investigated using the bioclastic carbonate deposits (miliolite limestone) occurring in the region[2,3]. Earlier studies turned into a century-long controversy on the marine vs aeolian origin of the miliolite limestone, with little attention being paid on other Quaternary records of Saurashtra (summarized in earlier papers[4,5]). Fluvial landforms and associated sedimentary packages, especially of the coastal areas, provide an important continental record of change in the sea level. Rivers draining the southwestern coastal plains of Saurashtra were examined to collect data on lithofacies characteristics and bounding surfaces, and to evaluate their significance within and across the fluvial systems.

The Bhadar river basin (Figure 1) has been studied in detail to establish the sedimentary sequences as well as to identify marker horizons. The studies from Bhadar river basin were then extended to other rivers further southwards, and includes Nali river near Mangrol, Hiran river near Veraval and Singwado river near Kodinar (Figure 1 *a*).

*For correspondence. (e-mail: nilesh_geol@yahoo.com)

Lithofacies in Bhadar river basin

Bhadar is the longest river of Saurashtra peninsula, and its basin covers an area of about 4143.75 km^2 (Figure 1 *b*). The basin consists of nine sub-basins drained by several streams, viz. Vinu, Moj, Phophal, Champavadi, Gondli, Karmali, Vasvari, Survo and Galoliya. The river originates near Jasdan and flows towards west about 185 km to meet the Arabian Sea near Navibandar. Basalt and other magmatic derivatives belonging to Deccan Trap Formation (Late Cretaceous) dominate the geology of the basin. Fluvial sequences are exposed in riverbank cliffs of moderate height (8–10 m) downstream of the Bhadar dam about 20 km east of Jetpur (Figure 1 *b*). Figure 2 (*a* to *d*) shows six major facies that are characterized by gravel and gravelly sand units. Following the conventional two-letter coding scheme[6], the gravelly units can be categorized in trough cross-bedded gravel (Gt) facies and crudely bedded gravel (Gh) facies. The sandy units chiefly exhibit massive sand (Sm) facies and planar cross-bedded sand (Sp) facies. These facies, in general, are overlain by silty sand facies that is designated as flood plain deposits (Fl facies). The contact between the adjacent lithofacies is sharp, and in places feeble to moderate degree of pedogenesis (P facies) is observed in the lower units.

Palaeosol facies (P)

The prominent breaks in fluvial sequences of Bhadar basin can be seen in the form of palaeosol layers that have been designated as P-facies. Based on its stratigraphic occurrence, palaeosol developed over the pre-Quaternary substrate is referred to as P1 facies, and the other palaeosol layer that caps the lower gravelly unit as P2 facies (Figure 2 *a*). The P1 facies in Bhadar river is developed on Deccan Trap basalt, and is dark greyish brown (5YR 3/2-3/4) in colour. It shows vertisol characters with numerous fractures, and subangular to angular blocky soil peds. The fractures, in places, are filled in by calcareous matter but, the overall nature of soil is weakly calcareous as it gives very little reaction with mild HCl[7]. The contact with substrate is clear and its lateral continuity is wavy. The organic carbon content is about 0.31%. P2 facies is developed on the Gt1 facies and Sp facies

(Figure 3). This is light brown (5 YR 5/5) to yellowish brown (10 YR 5/2) in colour, and also shows a few degrees of fine to medium size mottling with faint contrast[7]. The soil peds are fine granular to blocky. It is calcareous in nature. The organic carbon content is about 0.39 to 0.54%. The contact between P2 and substrate gravels is gradual and its lateral continuity is broken.

Trough cross-bedded gravel facies (Gt)

The trough cross-bedded gravel facies is the most dominant lithofacies in the study area. Stratigraphically, two units Gt1 and Gt2 have been identified. The Gt1 facies, 1–4 m thick, occurs unconformably either over Deccan Trap Formation or over the palaeosol developed on it. The average length of individual trough ranges between 12 and 20 m whereas, its width reaches up to 7 m. Average height (amplitude) of troughs is about 1.5 m. The trough axes are oriented in 30°–210° direction. The average size of clasts, dominantly basalt, constituting this facies is about 2.5 cm. Individual foresets in Gt1 also show normal grading. The thickness of individual strata ranges from 2 cm to about 20 cm and the average dip of all the foresets is between 18° and 28°. The Gt2 facies is distinctly different from the Gt1 facies both, compositionally and geometrically. This younger unit rests over the pedogenetically altered top (P2) of the Gt1 facies and Sp facies that overlies the Gt1. The Gt2 facies has trough widths of about 3 m, lengths of about 6–8 m and heights of about 1m with an orientation of troughs along 110°–290°. The thickness of individual strata ranges between 2 and 7 cm. The average dip amount of the foresets is about 28°. Locally, the Gt2 facies grades into planar cross-stratified sand (Sp) facies (Figure 2 *b*). Both, the Gt1 and Gt2 facies show multistoried stacking of the troughs.

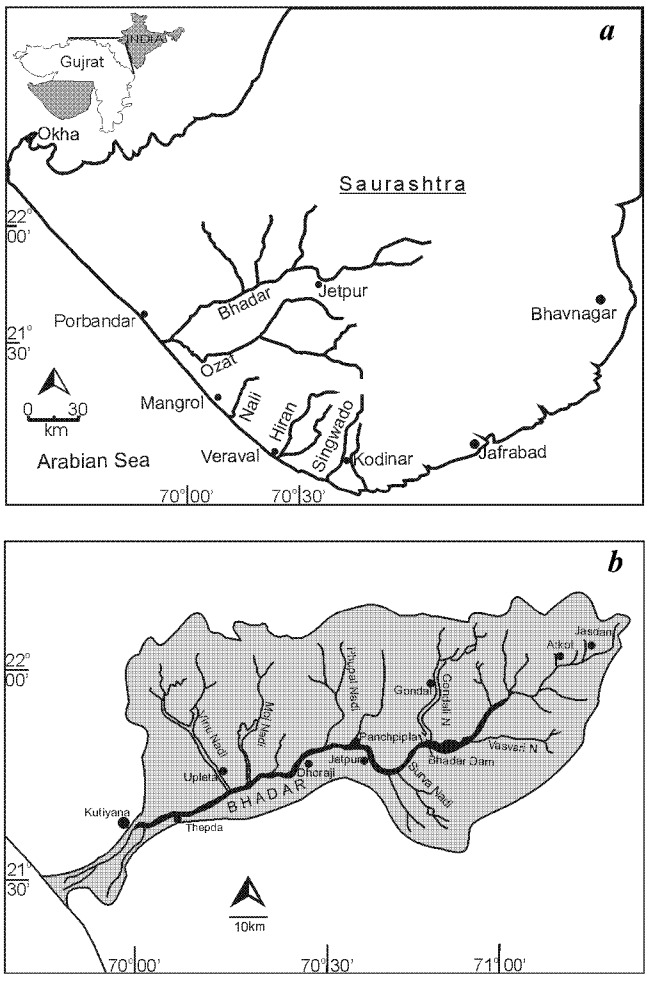

Figure 1. Location map showing (***a***) major rivers investigated in south Saurashtra and (***b***) the Bhadar river basin with localities referred to in the text.

Crudely bedded gravel facies

The gravelly sequence also consists of a clast-supported, crudely bedded and unsorted facies, which is designated as Gh facies. The clast size ranges from 1 cm to 15 cm. A few boulders larger than 60 cm are also observed. The majority of the clasts are angular to subangular and elliptical in shape. Basalt and other magmatic rocks are dominant clast constituents; however, the larger fragments consist of limestone. Locally, the clast imbrication is 220°. The thickness of this unit ranges between 0.5 m and 1.5 m. Stratigraphically, this unit is equivalent to the Gt2 facies as it occurs over the same bounding surface.

Planar cross-stratified sand facies

The sandy unit that unconformably lies over the pedogenetically altered top of Gt1 or Deccan Trap basalt, is characterized by the presence of very gently dipping (10°–15°), Sp facies (Figure 2 *c*). In general, it consists of medium to fine sand. However, locally it grades into gravelly sand that occurs as shallow scour fills (Ss facies). This unit ranges in thickness from 1 to 2 m and its top is pedogenetically altered. The palaeosol layer (P2facies) capping this unit is relatively lighter in colour and contains few rhizocretions.

Massive sand facies

Another significant unit of the fluvial sequences of the Bhadar river is Sm facies that overlies the Sp facies or Gt2 facies with a sharp contact (Figure 2 *d*). This unit, 1.5 to 2 m thick, comprises medium to coarse sand with faint horizontal laminations. This sand facies is characterized by significant amount of biogenic carbonate sand (about 23%) along with the dark coloured basalt sand and other detrital constituents. In places, this unit shows hori-

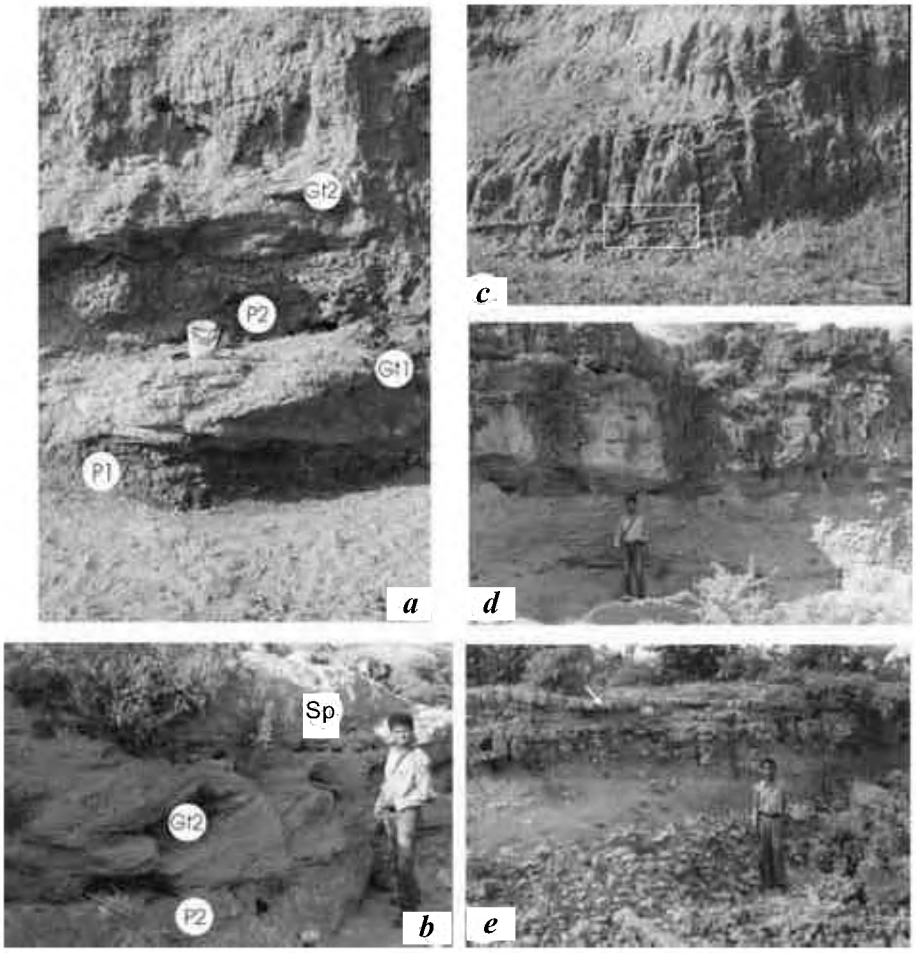

Figure 2. Photographs showing (*a*) various lithofacies in fluvial sequence of the Bhadar river as exposed near its confluence with Survo river. Bag height is 20 cm. (*b*) Gt2 facies that grades in to Sp facies near Jetpur. Height of the person standing is 165 cm. (*c*) Planar cross-stratification in Sp facies made visible due to the presence of thin clay layers, as exposed in Survo river. Length of the hammer is 60 cm. (*d*) Bioclastic carbonate dominated Sm facies underlain by non-calcareous Sp facies, exposed near Panchpipla, Bhadar river. Height of the person standing is 165 cm. (*e*) Compact calcareous tidal clay unit (shown by an arrow) capping the pedogenetically altered top of fluvial gravels as seen near Kamnath temple, Nali river. Height of the person standing is 165 cm.

zontal cylindrical, branching and non-branching burrows with an average diameter of 2.5 cm. Texture and composition-wise, this unit is similar to impure miliolite limestone. The miliolite limestone (*per se*) is very fine to medium grained, well rounded to sub-rounded, well sorted sand (dominantly allochemical, subordinately detrital) deposit that can be designated as massive carbonate Sm facies and Sp facies due to its texture and structure, when it is found forming a part of fluvial sequences.

Lithofacies in other fluvial sequences of Saurashtra

Lithofacies and marker horizons are identified in the fluvial sequence of Bhadar basin. The record from Bhadar is compared with the fluvial records of the other rivers like Nali, Hiran and Sigwado in south Saurashtra (Figure 4).

Fluvial sequence of Nali river consists of mainly Gh facies that lies over the limestone of Gaj Formation (Miocene) with either a sharp erosional contact or a palaeosol layer in between. The palaeosol unit, about 0.5 to 1 m thick, extends upstream-ward where it caps over the basalt of Deccan Trap Formation. It shows dark brown (5 YR 3/5) to light olive brown (5 Y 5/6) colour. The palaeosol developed over the Gaj limestone is strongly calcareous in nature, and exhibits gradual contact with the substrate. This unit is correlated with the P1 of Bhadar river because of its pre-Quaternary substrate. The Gh facies of Nali river attains a maximum thickness of about 2 m, and locally grades in to Gt facies. The clast size ranges between 2 cm and 25 cm. The larger clasts are mostly of locally derived limestone, but those of

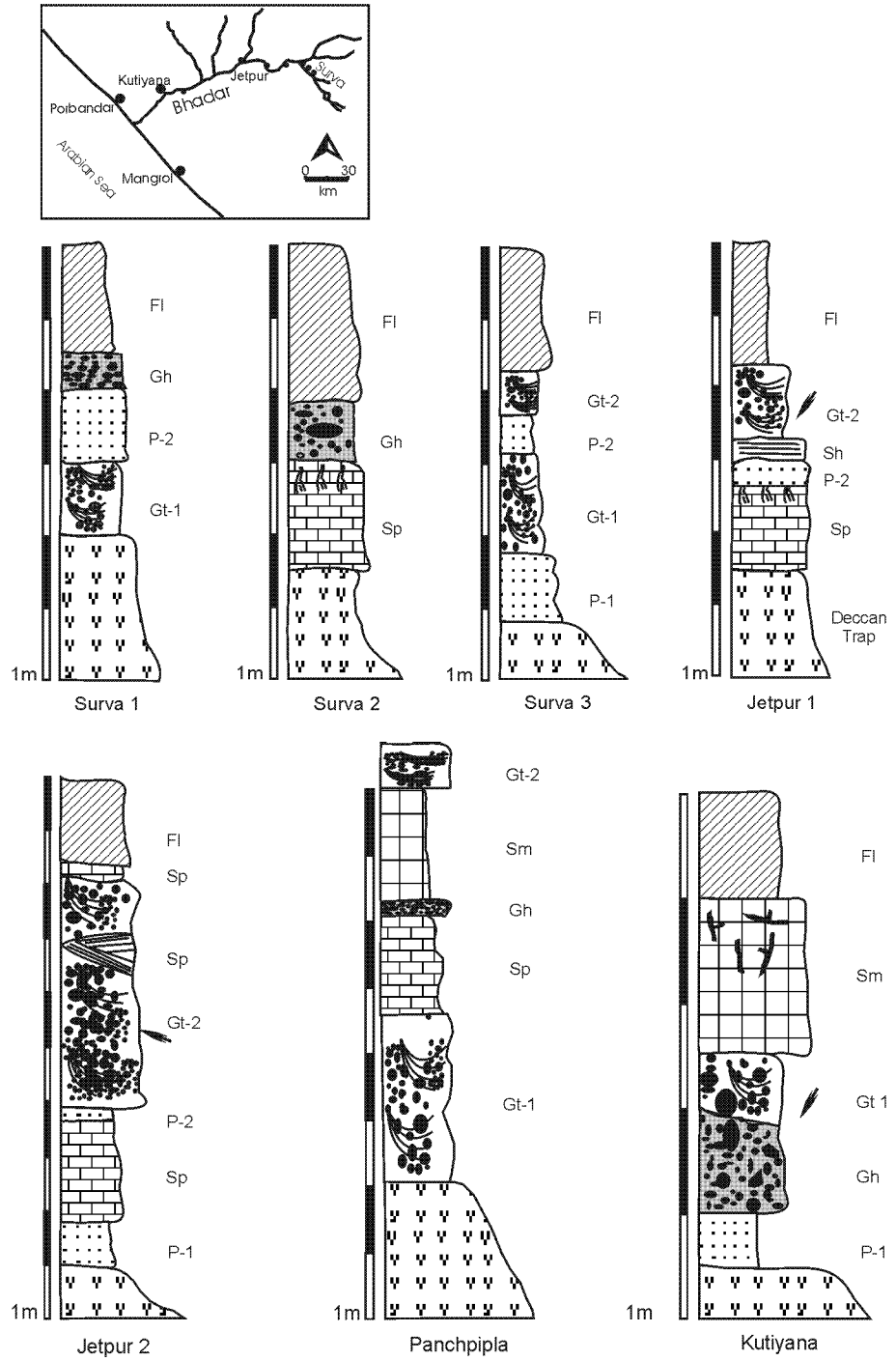

Figure 3. Lithologs showing the stratigraphic relationships among various lithofacies exposed in the Bhadar river basin. Refer to the key map for geographical positions of locations.

basalt are dominating. The top of Gh facies is pedogenetically altered. This has been designated as P2 facies. It is yellowish to brown (10 YR 6/6 to 6/5) in colour and calcareous in nature. This is overlain by Sm facies that is about 2 to 3 m thick. Texture and composition-wise this unit is similar to the Sm facies of Bhadar river. At Kamnath, 10 km east of Mangrol, signatures of marine flooding can be seen in the form of compact calcareous tidal clay unit (Figure 2 *e*) at an elevation of about 18 m. This unit grades upstreamwards into trough cross-bedded sand (St) facies composed of bioclastic carbonate sand. The St facies can be designated as miliolite limestone, as it is referred to in the literature.

The fluvial sequence of Hiran river near Veraval has also been investigated by other workers[8,9] with special reference to the miliolite problem. This sandy facies lies

over the Gh facies that has yielded Early Acheulian tools in the Hiran valley[8,10]. Fluvial sequence of the Singwado river near Ghantwad and Chhachhar, 12 km north of Kodinar, is composed of mainly gravelly and sandy units. The gravels are poorly sorted, subangular to subrounded and crudely bedded Gh facies. The clasts, dominantly basalt, range in size from 1 cm to 15 cm. The sandy unit is locally horizontally bedded (Sh facies) but, major part appears massive (Sm facies). This unit also consists of bioclastic carbonate sand, and sedimentary structures suggestive of marine flooding. The palaeosol (P1 facies) developed over basalt substrate, exposed at the base, shows similar characteristics to the P1 facies of Bhadar and Nali rivers. This palaeosol unit is overlain by either Gh facies or directly by Sh and Sm facies. A palaeosol layer (P2) that is developed over the Sh facies separates two sandy units (Figure 4). This light yellow coloured granular soil is calcareous in nature, and shows rhizocretions in its upper part. The fluvial sequences of these rivers of south Saurashtra are correlated based on marker horizons like the palaeosol developed over pre-Quaternary substrate, extensive gravelly facies and the characteristic carbonate dominated sand facies. The erosional surfaces can be traced out in the region not only in the fluvial record but also in the coastal deposits[3,11].

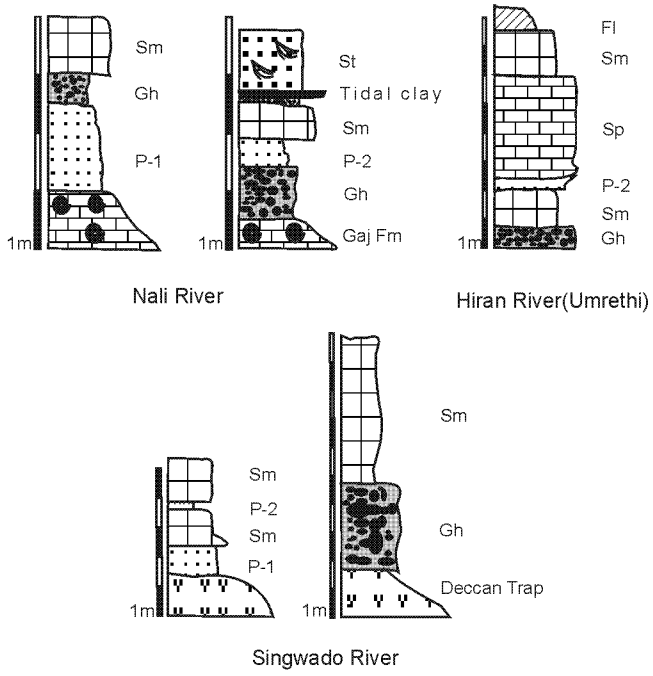

Figure 4. Lithologs showing various lithofacies in the fluvial sequences of other rivers in south Saurashtra.

Links of fluvial records to sea level change

Late Quaternary fluvial sequences of south Saurashtra are composed of gravelly and sandy units which are classified into Gt, Gh, Sp, Sm, St and Sh facies. Table 1 summarizes the facies identified in the fluvial sequences of southwestern Saurashtra and also its probable time range. In general, the fluvial sequences of the study area suggest two distinct aggradational phases separated by a profound break. The Gt facies has manifested this, and so it is subdivided into Gt1 and Gt2 facies on stratigraphic considerations. The Quaternary record begins with the P1 facies exhibiting typical vertisol characters, over the pre-Quaternary (Deccan Trap and Gaj formations) substrate suggesting a stable landscape that allowed a fair degree of pedogenesis. The Gt1 facies, sharply overlying this palaeosol unit, is related to the first phase of fluvial aggradation during Quaternary time. In the absence of any geochronological data from equivalent units in the region, it is difficult to ascertain the age difference between the pedogenesis and deposition of these gravels. This facies is associated with the Sp facies that does not contain bioclastic carbonate sand. Together, Gt1 and Sp facies constitute a sequence typically of ephemeral stream that could deposit the gravels as channel-fills and sand as overbank deposits[6]. The P2 facies suggests termination of this phase; however its limited extent and

Table 1. Summary of the lithofacies of fluvial sequences of south Saurashtra

Lithofacies	Description	Remarks
Fl	Mainly consists of silty sand facies, feebly pedogenetically altered at top. Mostly structureless semi-consolidated in nature	Related to the youngest fluvial aggradation (Holocene to Recent)
Gt2	Relatively thicker unit dominated by basalt clasts, and few chalcedony and limestone clasts. Grades locally into Sp facies	Has yielded middle palaeolithic tools at Jetpur older than 56.8 ka (ref. 9)
Gh	Mainly basaltic and limestone clasts	Locally developed facies
Sm	Medium to coarse sand, dominated by allochems. Biogenic structures are present. It is similar to the miliolite limestone	U-series age range 75–115 ka (ref. 12)
P2	Pedogenetically altered top of the Sp facies shows presence of rhizocretions. Lighter in colour and also occurs above Gt1 facies	Late Acheulian tools are reported from this unit, that is dated late Middle Pleistocene (ref. 10)
Sp/Ss	Medium to fine sand, locally occurs as scour fill gravelly sand	Associated with Gt1 facies
Gt1	Comprising mainly of basaltic clasts	The Early Acheulian tools recovered in Hiran river are dated > 196 ka (ref. 9)
P1	Mainly vertisol developed over the Deccan Trap basalt, and in places, over Gaj limestone	Oldest palaeosol found on pre-Quaternary substrate

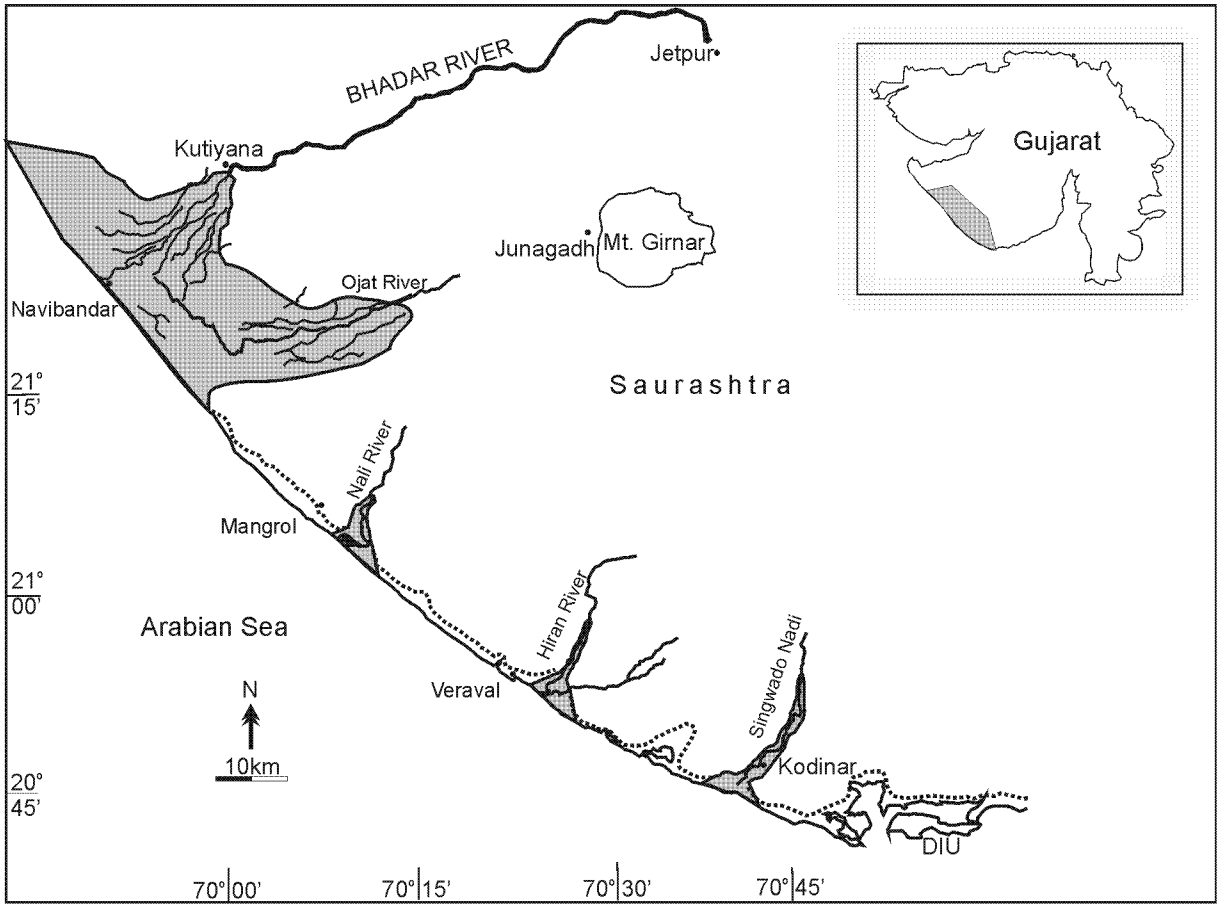

Figure 5. Map showing possible extent of the marine flooding envisaged in various rivers of south Saurashtra. The dotted line joining the shaded areas suggests shoreline of that sea, inferred based on the coastal geomorphic units examined in the study area.

less prominent soil peds along with absence of any pedohorizon are perhaps suggestive of a lesser degree of pedogenesis and/or drier climate. This palaeosol unit is capped by a prominent marine flooding event recorded in the form of bioclastic carbonate dominated sand (Sm facies), biogenic structures, tidal clays, coarse grained bioclastic limestone, etc. The elevations of the occurrence of such lithological units suggestive of marine flooding are clustered around 10 to 15 m amsl. Figure 5 illustrates the extent of this marine flooding in various rivers of south Saurashtra inferred vide present study. A palaeosol unit, equivalent to P2 facies in the rivers studied, has been reported occurring at the base of coastal miliolite sequence of south Saurashtra; the Late Acheulian tools that occur over this soil unit were considered to be of late Middle Pleistocene age[3,10]. The gravelly unit (Gh facies) at the base of Hiran river sequence has yielded Early Acheulian tools that have been dated older than 196 ka (ref. 9). This unit is correlated with the Gt1 of Bhadar river. The U-series ages of the carbonate sands–miliolite limestone (M-II 75 to 115 ka) lying above the Gt1/Sp and P2 facies suggest linkage to higher sea level of perhaps OIS substage 5e (ref. 12). These dates were seriously doubted, questioning the suitability of bulk miliolite for radiometric dating and its simplistic interpretation to invoke tectonic uplift of the whole Saurashtra peninsula for about 200 m (ref. 13). However, in view of the ESR ages of molluscan shells (94.9 to 115 ka) (ref. 14) and recent U-series dates of oyster and clam shells (126.2 ± 5.7 ka and 87.2 ± 9.7 ka) (ref. 15) associated with the raised shore deposits occurring in the coastal areas, the marine flooding in the rivers studied can be linked to the last interglacial (i.e. OIS substage 5e). This has been followed by another phase of fluvial aggradation recorded in the form of Gt2 facies that shows local variation in to Gh and Sp facies of limited extent. The sequence is covered by Fl facies, commonly occurring in the rivers of study area that can be linked with the youngest aggradation phase. The last interglacial (OIS sub-stage 5e) sea level high-stand has also been recorded in the lower Mahi basin as inferred from the occurrence of marine clay and IRSL chronology[16]. A regional marine flooding during this time (IRSL date range 69–100 ka), connecting the gulfs of Kachchh and Khambhat has been envisaged based on the study of a 54 m long core from the Nal Sarovar[17]. The occurrence

of last interglacial marine flooding reaches a maximum of up to 18 m in the study area, with the exceptional heights of about 60 m in Hiran river and 40 m in Singwado river. However, globally it is recognized that the last interglacial sea level was only 6 to 7 m higher than the present[18–20]. This suggests the possibility of neotectonic influences in the sedimentation history of the fluvial sequences in south Saurashtra.

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ACKNOWLEDGEMENTS. We thank DST, Govt. of India for financial support (Project: ESS/23/VES/019/98). Critical comments from Prof. S. N. Rajaguru and Prof. S. K. Tandon have greatly improved the original version of the manuscript. Dr L. S. Chamyal is thankfully acknowledged for discussions during the period of investigation. This paper is a contribution to IGCP 449.