Quaternary alluvial stratigraphy and palaeoclimatic reconstruction at the Thar margin

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Quaternary alluvial record at the Thar desert margin has been examined using the exposed succession along Mahudi, Sabarmati river, Western India. Different alluvial facies, their associations and granulometry have been studied for palaeoenvironmental reconstruction. Clay mineral indices smectite/chlorite and smectite/illite of the alluvial palaeosols have been used as proxy indicators of climate change. These indicate wet phases during the OIS 5 and OIS 1. The overall stratigraphic development is discussed in the framework of fluvial response to climate change during the Late Pleistocene.

OVER the last four decades, fluvial sedimentology has progressed towards understanding how fluvial systems develop and change over time as a response to tectonism, climate and sea level change[1]. A river can exist close to a threshold condition where a small shift in flow or sediment character, possibly induced by climate, can produce a dramatic change in river style[2]. Over the last one decade, the western Indian Thar desert and its margins have attracted attention to understand the alluvial stratigraphy[3–7]. The alluvial plains of central and north Gujarat are made up of thick Quaternary continental deposits of fluvio-marine, fluvial and aeolian origin, and occupy structural depressions related to continental margin rifting and graben formation (Narmada and Cambay)[8]. Some evidences of small-scale deformation, and climate and sea level changes during the Late Pleistocene and Holocene have been documented[7,9,10]; however, the relative importance of these factors in controlling the development of alluvial stratigraphy in the region remains unclear.

In the present study, a 32 m thick succession of Quaternary alluvial and aeolian deposits has been studied along the Sabarmati river to the east of the Mahudi village (Figure 1). The studied section lies within the palaeomargin of the Thar desert (Figure 1), and it is surmised that this area was sensitive to desert expansion and contraction phases. We report here the sedimentological and palaeoclimatic interpretations based on the Mahudi section. The objectives of this study are to investigate:

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1. If clay minerals can be used as a proxy indicator of climate changes in the semi-arid alluvial deposits, and
2. The linkages between the fluvial response and the palaeoclimatic changes.

The present study forms part of our larger comparative study of the desert and the desert-margin alluvial stratigraphic record.

Study area

The Sabarmati river originates in the southwestern spurs of Aravalli hills and traverses a distance of 416 km before meeting the Gulf of Khambat. It shows an incised, meandering course and a perennial flow. Details of the geology of the area and drainage networks are summarized by Merh and Chamyal[8]. The study area falls within the arid and semi-arid zones. Average annual rainfall around the studied regions is up to 700–1000 mm.

Regional chronostratigraphy

In the Sabarmati river basin, four major formations have been identified[4]: Waghpur, Mehasana, Akhaj and Sabarmati. The Waghpur Formation is the oldest, generally occurring at the base of the stratigraphic sections, and has been found to be older than the upper range of luminescence dating in these deposits (> 300 ka)[4]. These older deposits have been used for long distance inter-valley lithostratigraphic correlations[8]; however, more recent studies suggest that such correlations are fraught with uncertainties, for e.g. the basal clays and gravels in the Mahudi and Raika sections are not only of divergent ages but also of clearly different origins[11].

The chronology of the upper parts of the exposed stratigraphic sections (Mehasana Formation) is constrained more robustly by luminescence dating. In the Mahudi section, Sabarmati river, an OSL age bracket of 30–54 ka has been given for this aggradational phase[12]. In the Raika section, Mahi river, a punctuated aggradation between 30–37 and 44–52 ka has been identified[7]. Inter-valley correlations have been attempted using the red horizon in the Mahi, Sabarmati and Luni river valleys[13], and it is also observed in the sediment core in the Nal

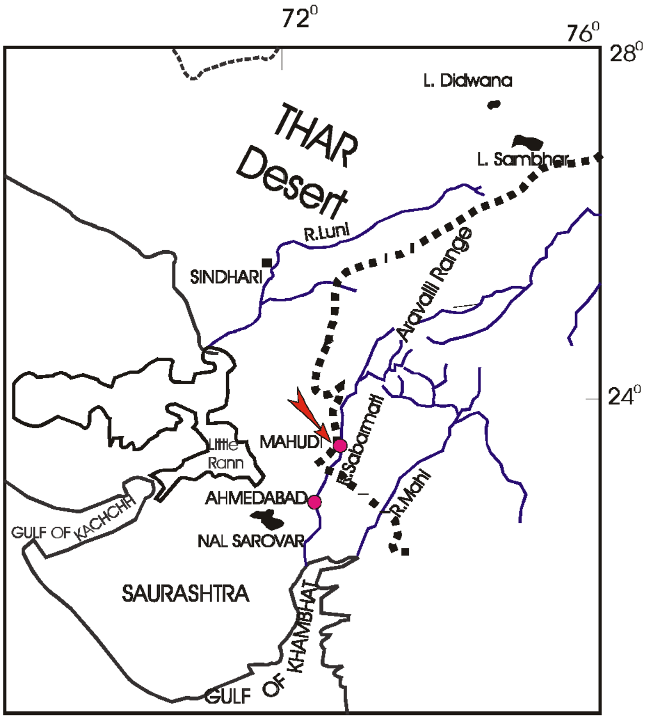

Figure 1. Map of Western India showing the studied locations near Mahudi (Sabarmati basin). The dashed line indicates the extent of fossil aeolian features[34]. The Mahudi section lies at this margin.

region[14]. The reddening has been bracketed between 39 and 58 ka (ref. 4), around 50 ka (refs 10, 14), and between 40 and 25 ka (ref. 7) on the basis of luminescence dates. These diverse ages of the red unit indicate that the landscape reddening was not a single event and occurred differentially on the floodplains of the meandering river deposits over the entire OIS 3. Pandarinath *et al.*[13] suggest reddening under intense rainfall punctuated by a dry season on the basis of illite crystallinity and the presence of gypsum and calcareous nodules. Aeolian dunes, of 12 ka age[12], generally cap the alluvial deposits. The incision by the modern Sabarmati river is bracketed between 4.5 and 12 ka (ref. 12).

Lithofacies associations

The entire section is divided into six units on the basis of lithofacies assemblages and contact relationships. Units 2 to 6 unconformably overlie the unit 1. Different grain size parameters for units 3 to 6 are summarized in Table 1. The lithofacies descriptions are briefly summarized below.

Unit 1: Basal gravel–palaeosol association

Unit 1 consists of a multistoried gravel sheet and interfingering grey–green mottled muds. It is strongly calcrete affected, and has a sharp erosive and strongly undulatory surface that is capped by a calcrete horizon (~ 20 cm thick). It ranges in thickness from about 4 to 13 m, and is relatively thicker in the upstream parts of the section. The individual facies are described as follows:

Grey green mottled mud. The mud shows an interfingering relationship with the lower gravel sheet and ranges in thickness from 50 cm to up to 6 m. In places, it occurs as small lenses within the gravel unit and lacks pedogenic horizonation. Abundant blue to grey-green mottles, vertical to subvertical rhizoliths (up to 15 cm dia), calcrete nodules, and Fe/Mn nodules are present. Pedogenic slickensides (with Fe/Mn stains) occur in clay rich-regions. A microscopic examination of these muds revealed an absence of any marine fossils.

Gravel sheet. The gravels are ill sorted and are conspicuous in terms of an abundance of ferruginous nodules and a near absence of reworked calcrete nodules. The matrix is brownish red and apparently rich in iron cements. There is prominent *in situ* weathering and calcrete development. Three subfacies can be identified.

1. *Massive pebble gravel* (*Gcm*) shows a clast-supported fabric with a matrix of sand-mud, and well-rounded pebbles and cobbles. Average clast size is 5 mm but ranges up to 10 cm. It is moderately cemented.
2. *Trough cross-stratified gravel* (*Gt*) with clast-supported framework is the most common facies and has thickness of 10–30 cm. Towards the top, it may grade into pebbly coarse sandstone. Poorly developed trough cross bedding (~ 50 cm) is in places emphasized by bedding concordant calcrete development. Overturned trough cross beds and cross-cutting trough fills (~ 2 m wide) can be observed. Colour mottles and rhizoliths are abundant; in places, rhizoliths are surrounded by zones of iron cementation. There are also numerous cross-cutting, vertical to subvertical carbonate-cemented cracks (~ 2–5 cm wide and several meters long).

   Pebbles consist dominantly of more than 80% ferruginous nodules (1–5 cm dia). Based on compositional variations, two subunits can be identified: (a) gravel rich in well-rounded pale yellow or cherry red ferruginous nodules (20–30 cm thick), and (b) gravels rich in grit-sized angular quartz and felspars (~ 1.5 m thick). These occur as alternate beds, which pinch out laterally.
3. *Pebbly coarse sandstone* comprises 1–1.5 cm-sized clasts of fresh angular felspars, sub-rounded to subangular polycrystalline and vein quartz, quartzite, jasper and ferruginous nodules. Trough-shaped channels are present.

Interpretation. The multistoried gravel–palaeosol association represents deposits of gravel–sand bedload rivers

Table 1. Folk's grain size parameters of different facies in the Mahudi section

Units	Facies	Sample no.	Mean (ϕ units)	Standard deviation (ϕ units)	Skewness	Kurtosis
Unit 6	Fine–very fine sand (Aeolian)	MH/1	3.33	0.57	0	0
Unit 5	Silty medium to fine sand	MH/2	3.98	1.27	0.03	0.06
Unit 5	Silty fine–very fine sand	MH/4	3.30	0.84	–0.01	0.01
Unit 4	Calcretized aeolian sand	MH/6	3.47	1.70	0.16	0.24
Unit 3	Silty sand	MH/10	4.73	1.79	0.07	0.08
		MH/11	4.49	1.67	0.09	0.10
Unit 3	Sandy silt	MH/9	4.67	1.31	0.05	0.04
		MH/12	6.34	1.82	0.00	0.01
		MH/13	5.54	1.27	0.01	0.01
		MH/16	4.56	1.07	0.03	0.02
		MH/17	4.73	0.67	0.00	0.00
		MH/18	4.77	1.16	0.04	0.03

with well-defined floodplains. The massive clast supported gravels (Gcm) at the base of the unit represent longitudinal bars. The thickness of the trough cross-bedded units suggests flows that were only a few meters deep. The absence of reworked calcrete clasts and an abundance of ferruginous nodules suggest a wet climate.

The strongly erosive and highly pedogenically modified (calcrete development) surface of unit 1, with high relief, suggests a significant hiatus with the overlying unit 2. A reducing diagenetic environment is indicated by grey–green colour with localized oxygenated zones represented by red mottles. There are two diachronous phases of cementation (1) the Fe cements, which dominate the entire matrix, and (2) the carbonate cements, which disrupt the gravel and generally occur as thick rhizoliths. The carbonate filled fractures terminate at the surface of unit 1 and are perhaps of tectonic origin.

Unit 2: Brown pedogenically modified muds (Vertisol) – Calcrete gravel association

Unit 2 overlies the strongly undulatory surface of Unit 1 (Figure 2). The muds are up to 5 m thick. Colour mottling and stratification is absent. Pedogenic slickensides and calcrete nodules (6–10 cm dia) are abundant towards the top. Abundant disseminated sand-sized grains of quartz, felspars and dark Fe/Mn rich calcrete are present. Elongate vertical cracks infilled with reddish silty sand material from the overlying Unit 3 are present. A microscopic examination of the muds did not show any marine fossils.

The *calcrete gravel lenses* are present within the muds and pinch out within a distance of few meters to few tens of meters. They consist of small to medium-sized pebbles dominantly of calcrete (> 90%) followed by minor quartz and felspars. Occasionally, ferruginous nodules reworked from the lower unit may be present.

Interpretation. In the absence of any evidence of coexisting fluvial deposits (channel or overbank), it is difficult to attribute these muds to fluvial origin. Similarly, an absence of lacustrine facies and marine fossils suggests that they cannot be attributed to these environments.

These were possibly deposited as ill-sorted, sediment gravity, cohesive flows, which remained exposed with ongoing pedogenesis for most of the time. Local events of higher discharge gave rise to associated calcrete gravel lenses. The environment is likely to be that of a seasonal wetland. The development of calcrete and vertic features suggest a seasonal but semi-aridic regime.

Unit 3: Sand-silt

Unit 3 comprises of reddish sandy silts, silty sands and laminated sand-silt alternations (Figure 2). These are described below:

1. Reddish sandy silts have an abrupt planar contact with unit 2 and represent relatively finer grained deposits within unit 3. Sorting is moderate to poor (Table 1). Overall this unit has a reddish brown chroma (5YR 5/6); however, in the adjacent section near Vijapur the red colour becomes very prominent. An absence of soil horizonation, and weakly developed slickensides are noted. Rare outsized clasts (3–4 cm) may be present towards the top, while the granule-sized material is disseminated in patches. Calcrete nodules are present throughout.

2. Silty very fine sands (5YR 5/4, 4.4 to 4.7 ϕ) are generally massive; however, millimetre scale laminations can be observed in some beds. Laminated beds are relatively rich in micas and have a dominant 125 μ grain size, and moderate to poor sorting (Table 1). A dominant well-sorted component comprising 85–90% in the very fine sand to coarse silt range is observed[15]. Faint mottling, incipient rhizolith development, calcrete nodules and horizontal carbonate bands can be observed.

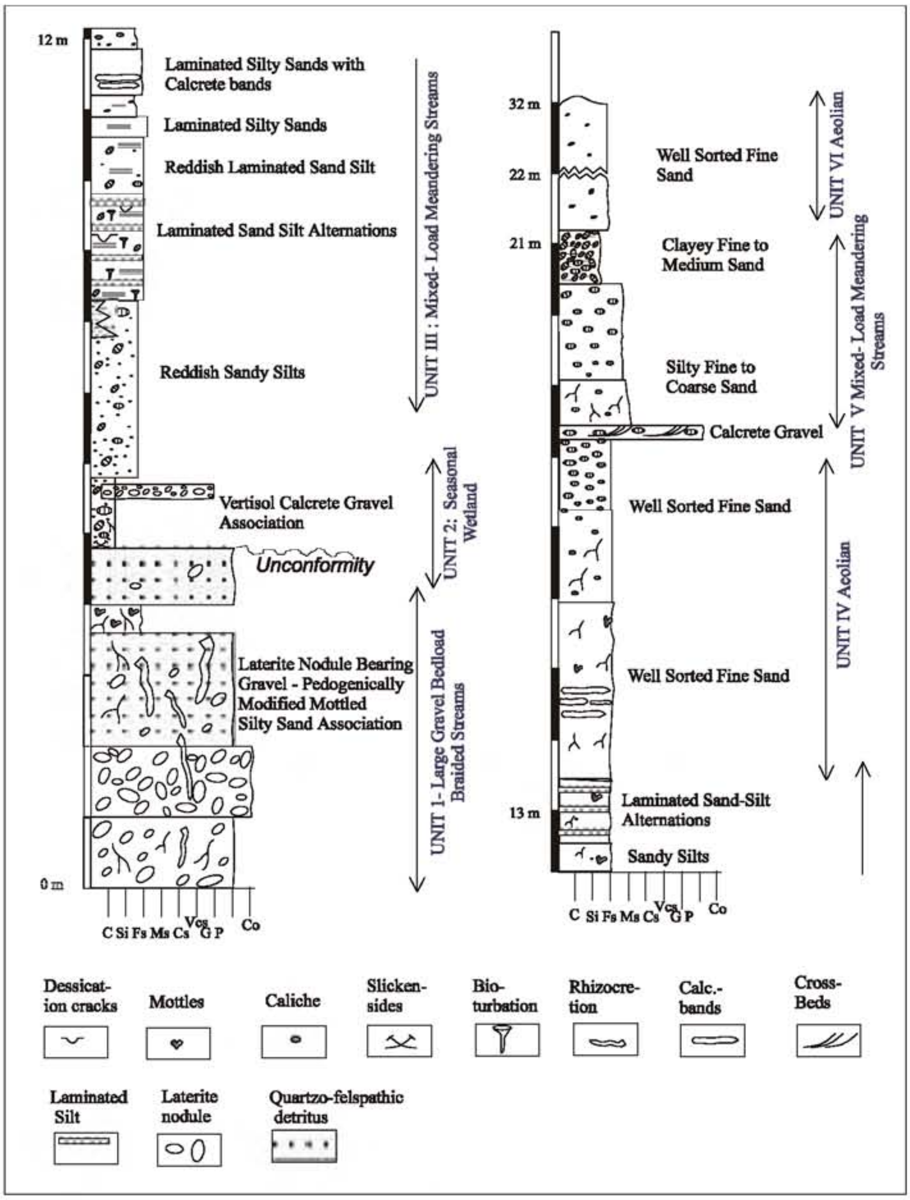

Figure 2. Vertical litholog of the Mahudi section. Six depositional units are observed. Unit 1 is gravel dominated, whereas units 2 to 6 are fine-sand or mud dominated and overlie unit 1 unconformably.

3. *Laminated sand–silt alternations* consist of very fine sands and silts with individual beds about 2–15 cm thick. The colour of sand is 10YR/4 and mud is 10R4/6. Laminations are mm scale, parallel continuous, and are generally defined by micas. Some beds show sub-millimetre scale laminations of sand and mud. In the upper parts, this facies becomes relatively sandier. Numerous mud-filled burrow-like features (~0.7 cm diameter and 0.2 mm –1 cm length) and elongate desiccation fractures are observed. Small vertical to sub-horizontal, horizon-specific rhizoliths are present. In places, bedding concordant cements define carbonate bands. Soft powdery calcrete is present within the muds.

Interpretation. Silty very-fine sands indicate low energy environment and sudden waning of flows leading to simultaneous deposition of silt and clay. The sand layers contain about 70% of very fine sand, whereas, this mode is only about 10% in the sandy silt units. It is likely that the sand fractionation occurred in the proximal floodplain environment. The remaining load is deposited in the more distal situations as sandy silts. For the laminated sand silt alternations, this differentiation occurs only due to settling within the slackwater situations. Sub-aerial exposure is indicated by incipient rhizoliths and carbonate bands (marls). A higher degree of calcrete development and greater reddening of the silts also suggests that they formed in relatively distal overbank environments and were influenced by prolonged sub-aerial exposure. An overall predominance of flood plain development indicates that the rivers are mixed load meandering type.

Unit 4: Fine sands

Unit 4 comprises very well-sorted, pale coloured sands. Two subunits are identified (Figure 2):

1. Calcareous well-sorted fine–very fine sands (10YR 6/6) are buff coloured with faint mottles and discordant elongate rhizoliths. Horizontal calcrete bands are present. The colour mottles are generally associated with carbonate precipitation.

2. Well-sorted fine–very fine sand (~3.4ϕ, 10YR7/4 to 10YR6/6 are two, ~1 m thick, massive and laterally continuous beds. There is a high concentration of centimetre-sized carbonate nodules in the upper bed, while the lower bed is moderately cemented but lacks calcrete development. Sorting is moderate (Table 1), however, ~80% sediment load occurs in well sorted very fine to fine sands.

Interpretation. The well-sorted nature, a dominant mode in the fine to very fine sand, and a lack of fluvially formed sedimentary structures, all indicate that these deposits are of aeolian origin. The grain size distribution is similar to that of the aeolian units in the Thar desert[15]. There was a phase of stability and pedogenesis after the deposition of these aeolian sands as indicated by the calcrete profile development (Figure 2). Minor (10%) medium silt component could possibly be formed during calcareous pedogenesis.

Unit 5: Calcrete gravel – Silty find sands

Unit 5 begins with thin calcrete gravel at the base followed up by silty sands (Figure 2). These are briefly described below:

1. Calcrete gravel beds are 10 to 20 cm thick and pinch out laterally within ~5 m. The thickness increases in local scour pockets. The calcrete clasts range in size from 1 to 4 mm and are supported in buff-coloured (10YR 6/6) fine to medium sands. The gravels are matrix-supported and trough cross-stratified. The foreset layers are about 2 cm thick and show alternation of coarse sand and gravel.

2. Silty medium to very fine sands overlie the calcrete gravel. Mean grain size is about 3.3 ϕ, sorting is moderate and the 1st percentile is 1.5 ϕ (Table 1). About 70% of the population occurs in a very well sorted mode of fine to very fine sand[15]. The remaining 30% occurs in the silt and clay-sized mode. In the lower part, few calcrete nodules and soft powdery rhizoliths are present. The upper part is well cemented, relatively more silty and contains some disseminated coarse sand grains. Indistinct ~1–2 mm thick laminations are present in places.

3. Calcareous brown silty medium to very fine sands (10YR5/4; 3.98ϕ) comprise non-stratified clayey fine sand (125–177 μm) with abundant soft powdery cm sized calcrete nodules. Nodules are subspherical to irregular in shape. Sorting is poor (Table 1). About 95% well-sorted load occurs in the range of medium sand to very coarse silt.

Interpretation. The unit 5 represents resumption of the fluvial processes as inferred from the basal calcrete gravels after the aeolian phase. Calcareous silty medium to fine sands show deposition in a low energy environment as indicated by low mean size and the 1st percentile value. An overall fining upward succession (Figure 2) results from superposition of proximal and distal floodplain facies over the calcrete gravels. The dominant fine-grained detritus, an overall fining upwards trend, and frequent pedogenesis suggests that these were deposited in the floodplain domain of mixed load streams. Pedogenesis and calcrete development affected *silty medium to very fine sand*s and *brown silty medium to very fine sands* differentially, depending on their proximity to the main channel. The dominant well-sorted fine to very fine sand mode could be a derivative from aeolian unit 4.

Unit 6: Fine sands

Unit 6 is the youngest stratigraphic unit with aeolian dune morphology and caps all the alluvial deposits in the section. It is about 10 m thick, massive, regionally extensive and comprises buff-coloured fine sands. The sands have a mean size of 3.33 ϕ and good sorting (0.5 ϕ) (Table 1). Small, dark coloured, spherical (0.5 cm) to elongate, carbonate nodules are present. This unit is cut over by a historical site yielding red burnished pottery, charcoal, bangle pieces and bones[7]. The grain size parameters and the dunal morphology suggest an aeolian origin for these deposits.

Clay minerals (Palaeoclimate reconstruction)

Methodology

For clay mineral analysis, less than < 2 μm size fraction was separated from the deposits in different units. This was achieved by a sequential pre-treatment of the sample with 30% hydrogen peroxide to remove the organic material followed by 1 N HCl to remove the carbonates (if present). Less than 2 μm grain size fractions were separated by pipetting at 30°C after using an appropriate dispersing agent that was washed clean repeatedly after the separation. A few drops of the sample were thinly smeared on a glass slide and dried under room temperature. The XRD was measured on the air-dried and glycolated slides. The diffraction patterns were scanned through 2.5° to 40° 2θ with a step size of 0.02°, and a 0.4 s counting time. Clay minerals were identified by the basal (001) diffraction lines on glycolated samples: smectite – 17 Å; chlorite – 14.2 Å, 7 Å and 3.54 Å; and illite – 10 Å. Clay mineral indices smectite/illite (S/I), and smectite/chlorite (S/C) were obtained from the ratios of 001 illite, chlorite and smectite peak heights of the glycolated samples[16].

Results

Dominant clay minerals in the Mahudi section are smectite, chlorite, illite and randomly stratified smectite–chlorite. Muscovite is present in some units. An overall dominance of smectite in the palaeosols of Mahudi section indicates a broad range of 25–150 cm rainfall with seasonality in the source region[17]. The relative variations in smectite/illite and smectite/chlorite can be used as climate proxies[18–20]. The smectite–illite (S/I) and smectite–chlorite (S/C) ratios for the Late Quaternary depositional units 2–6 are plotted in Figure 3. Unit 1 is not considered for this relative analysis, as there is a large hiatus between the unit 1 and unit 2. There is an overall similarity in the trends of S/I and S/C ratios, except for the calcrete horizon in the unit 4 (Figure 3). In general, an increasing value of these indices indicates relatively greater smectite production at the expense of illite and chlorite. This is a combined effect of weathering in the catchment and post-depositional weathering; both are synchronous within the age resolution, and a function of the ambient climate. Apparent variations in the clay mineral ratios in the stratigraphic section can, therefore, be interpreted as an indication of relative arid-humid changes in the palaeoclimate.

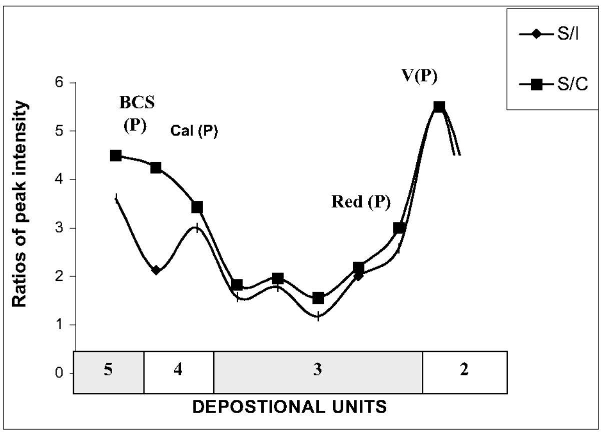

Figure 3. Smectite–chlorite (S/C) and smectite–illite (S/I) ratios of different units in the Mahudi section. P, pedogenic horizon; Cal, calcretized; BCS, brown clayey fine sand; V, vertisol.

The value of S/C and S/I is about 5.5 for the vertisol horizon in unit 2. This indicates a significant alteration of illite and chlorite either in the provenance or the alluvium in a warm-wet climate, and is consistent with the extrapolated age of ~125 ka as this was a relatively warm and wet period within the Indian context[21]. In unit 3 palaeosol horizons, the S/C ranges from 1.5 to 3. The value is highest for the laterally extensive red soil horizon and lowest for the unaltered silty sand horizon (Figure 3). This suggests that there was an *in situ* alteration of illite in the more distal flood reaches. The S/C value increases to about 3.5 in unit 4, suggesting an apparently wetter climate for unit 4 as compared to the unit 3. The increase is partly an added effect of calcrete development, as smectite formation is increased in an alkaline medium; and can be produced at the expense of illite[22]. In the more calcrete-affected horizon of the same unit, there is a significant drop in the S/I ratio and an increase in the S/C supporting that an increase in the smectite content is due to alteration of illite under alkaline conditions. For the overlying palaeosol horizon within the fluvial unit 5, the S/I ratio increases further to about 4, suggesting a similar, relatively wetter, climatic regime as for unit 2.

Discussion

Mahudi section bears testimony to the Late Pleistocene climatic changes in Western India (Table 2). The unit 1 represents gravel-sand bedload streams with thick floodplain development. The fluvial regime was most competent during this time compared to the overlying units. The deposits lie beyond the limit of luminescence dating[4], and the surface of the gravel represents a large hiatus manifested in significant weathering and calcrete development. The gravels in unit 1 are conspicuous in two aspects:

1. Clasts of ferruginous nodules are dominant as compared to the reworked calcrete nodules in the younger gravels.
2. The streams are gravel bedload braided in unit 1; while, the gravels in younger units represent ephemeral flows with dominantly lateral inputs.

Both these characteristics suggest a drastic change in climate after the deposition of unit 1. Two diachronous phases of iron and carbonate cementation are recognized in the gravel. These suggest a marked change in climate

Table 2. Stratigraphic framework of the Mahudi section. Different units, their characteristic facies, and depositional environments are summarized. Ages are extrapolated from earlier work in Sabarmati and Mahi basins[4,7,12]

Unit	Facies	Environment	Age
Unit 6	Well sorted fine to very fine sands	Aeolian	~ 12 ka; OIS-1
Unit 5	Calcrete gravel; Silty fine to very fine sands; fining – up succession	Mixed load streams with floodplain development and intermittent pedogenesis; meandering streams	~ 12–14 ka*; OIS-1
Unit 4	Calcretized fine to very fine sands	Aeolian followed by phase of pedogenesis (calcrete development)	~ 14–30 ka*. Pedogenesis during the wet phase perhaps ~ 14 ka; OIS-2
Unit 3	Sandy silts; silty very fine sands; laminated sand-silts	Mixed load streams with floodplain development and intermittent pedogenesis; meandering streams	60–30 ka; OIS-3
Unit 2	Brown calcic vertisol–gravel association	Mud flat? Seasonal wetland?	~ 125 ka*; OIS-5e
Unit 1	Gravel–vertic soil association. Abundant ferruginous nodules; significant relief and post-depositional weathering	Fluvial (gravel–sand bedload streams)	> 300 ka Pre Quaternary (?)

*Indicates indirect ages based on regional correlations or bracketing from the adjacent deposits (details in the text).

since the laterite formation. On account of dominantly ferruginous nodule clast composition and an earlier iron cementation, it is conceivable that the unit 1 gravels are coeval with the laterite formation, or formed just before its burial in the highlands. This may imply that these gravels are of pre-Quaternary age.

Unit 2 represents a mud-dominated depositional environment with vertisol development in a seasonal climatic regime. A lack of foraminifers[23] and other marine organisms, and the inland nature of this site suggest that these deposits are non-marine. The palaeoenvironment for these thick mud facies is perhaps a seasonal semi-arid wetland. On the basis of clay mineral indices, this represents the most warm-wet climate in the Late Quaternary deposits (units 2 to 6) and is consistent with the interpretation of Clemens *et al.*[21]. The palaeoclimatic evidence from clay minerals and lithostratigraphic correlation with the Raika section suggest that this unit is coeval with the lower vertisols assigned to 125 ka in the Raika section[7].

Unit 3 records fine-grained dominated floodplain deposits of mixed load meandering streams with pedogenically altered overbank deposits (red horizon). A comparison of chronologies from the Mahi and Sabarmati rivers[4,7], suggests that reddening was a gradual process, during the OIS 3, on the distal floodplain reaches. A broad age bracket of 60–30 ka can be given[4,7,12] for the unit 3. The clay mineral evidence suggests that this time was relatively less humid than the OIS 5e (unit 5) (Figure 3). This inference is consistent with the model precipitation curve[24] and the regional palaeoclimatic proxies[21,25,26]. Globally, this was a period of enhanced fluvial activity[27,28].

The aeolian deposits of unit 4 represent an arid phase in the Late Pleistocene followed by a phase of calcrete development. The age bracketing by units 3 and 5 suggests that these formed in a broad bracket of 14–30 ka (Table 2). This is consistent with older dunes in the region dated to ~ 22 ka (ref. 29). It is difficult to infer the time of pedogenesis. The S/C index for these sands is higher than that in the unit 3 (OIS 3). This is, perhaps, because the sands were deposited during the OIS 2 and possibly the pedogenesis occurred during the subsequent OIS 1 wetter phase, as the intervening period was significantly arid[30]. The calcrete formation led to a significant destruction of the illite (Figure 3).

Unit 5 indicates resumption of fluvial regime represented by mixed load meandering streams. The overlying aeolian deposits (unit 6) have been dated to ~ 12 ka in Mahudi[12]. The aeolian activity was regionally extensive around this period[31]. The age of unit 5 can be bracketed between 12 and 14 ka, as the fluvial activity, after the Last Glacial Maxima, is generally seen to begin at ~ 14 ka in western India[32]. This period corresponds to increase in the intensity of the southwest monsoons[15,33]. The mixed load meandering mode perhaps occurred due to re-establishment of vegetation in the catchment, which controlled the discharge, sediment supply and bank stability. The flood plain deposits experienced pedogenic alteration and calcrete formation. The clay mineral indices for unit 5 show high values similar to unit 2, which was deposited during last interglacial. This is in agreement with the fact that last interglacial and Early Holocene–Latest Pleistocene had similar, and relatively wettest climate[24]. The Sabarmati river incised after the deposition of unit 6.

This might have been concomitant with intense vegetation growth in the catchment and reduction in the sediment supply. We speculate this to have occurred at the onset of Holocene.

Conclusions

The Mahudi section of the Sabarmati basin represents one of the most complete records of the Late Pleistocene palaeoenvironmental change in the Thar desert–margin Gujarat alluvial plains. The following palaeoclimatic and palaeoenvironmental inferences can be drawn:

1. Unit 1 represents a different fluvial system and a more humid climate as compared to the Late Pleistocene alluvial succession, and is perhaps of pre-Quaternary age.
2. In the Late Quaternary deposits (unit 2 to unit 5), the fluvial response has fluctuated from meandering rivers during the relatively humid phases to defunct systems during the arid phases. Arid phases are represented by aeolian deposits. Incision occurred in response to increased discharges and reduced sediment supply (vegetation effect) at the onset of the Holocene.
3. Clay mineralogy of the alluvial palaeosols indicates wettest phases during the OIS 5 and OIS 1 and relatively subdued wet phase during the OIS 3; this is in conformity with other regional and global palaeoclimatic studies. These preliminary results have significant implications towards use of clay mineral record as an independent palaeoclimatic proxy in semi-arid fluvial settings.

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