Late Quaternary sediments from Nal Sarovar, Gujarat, India: Distribution and provenance

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A 54-m long core was raised from the bed of the Nal Sarovar, a large shallow lake located in the middle of the low-lying region linking the Gulfs of Kachchh and Khambhat, in western India. A three-layer sequence comprising: Zone-1 (top 3 m), predominantly silty-clay/clayey; Zone-2 (3–18 m), sandy; and Zone-3 (18–54 m), dominated by sticky silty-clay/clayey-silt with occasional thin sand layers and basalt fragments was identified. Smectite and illite are the dominant clay minerals with minor amounts of kaolinite and chlorite. Very high content of smectite (53–97%) in the clays of the lowermost zone (18–54 m) and the geomorphic features of the surrounding region suggested that the sediments were derived from the basaltic terrain of Saurashtra and/or via the Gulf of Khambhat. The clay content in the middle zone (3–18 m), dominantly sandy, is very low. Therefore, provenance for this zone was derived using heavy minerals in the sand fraction. The heavy mineral species in this zone suggested the mixed metamorphic and igneous terrain of Aravallis as the major source. The grain-size distribution of this zone closely matched with the sediments underlying the modern Sabarmati riverbed at Ahmedabad, suggesting fluvial depositional environment. Clays also dominate sediments of the topmost (0–3 m) zone with illite as the dominant (74–81%) specie followed by smectite suggesting derivation from the mixed metamorphic and igneous terrain of Aravallis.

1. Introduction

The lake Nal Sarovar (22°48'N; 72°E) is a shallow (~2 m depth) closed basin located almost in the middle of a low-lying belt linking the Gulf of Khambhat with Gulf of Kachchh through Little Rann (figure 1). The lake is also situated near the western margin of Gujarat alluvial plains and within the palaeo-Thar desert margin (Goudie *et al* 1973). Based on its location in a low-lying area, it had been surmised (Merh 1992) that the lake represented a remnant of a sea which linked the Little Rann of Kachchh and the Gulf of Khambhat till as recent as ~2 ka ago.

To understand the geologic and palaeo-environmental evolution of the Nal Sarovar, a 54-m long core was raised from its bed in June 1992. We now report results of clay mineral, grain size distribution and heavy mineral investigations of sediments obtained from Nal Sarovar. Isotopic studies and chronology by radiocarbon, thermoluminescence (TL) and infra-red simulated luminescence (IRSL) methods on this core have been reported elsewhere (Prasad *et al* 1997b; Prasad and Gupta 1999). Four additional cores were also raised from the low-lying belt, linking the Gulf of Khambhat with the Little Rann of Kachchh. Lithology of these cores along with the borehole data of the surrounding region used for sedimentary sequence correlation is also reported in this paper.

2. Geology of the surrounding region

The Nal region is bounded in the west by basaltic rocks of Saurashtra and in the northwest by Jurassic-Cretaceous sandstone (figure 1). To the extreme northeast of Nal Sarovar, igneous and metamorphic suits of Aravallis and in the immediate vicinity to the east of Nal Sarovar, Quaternary alluvial plains occupying the Cambay basin are present. To the south between the Nal and the Gulf of Khambhat are Recent and modern mud flats.

Keywords. Lake sediment; grain-size parameters; palaeo-environment; Nal Sarovar and clay minerals.

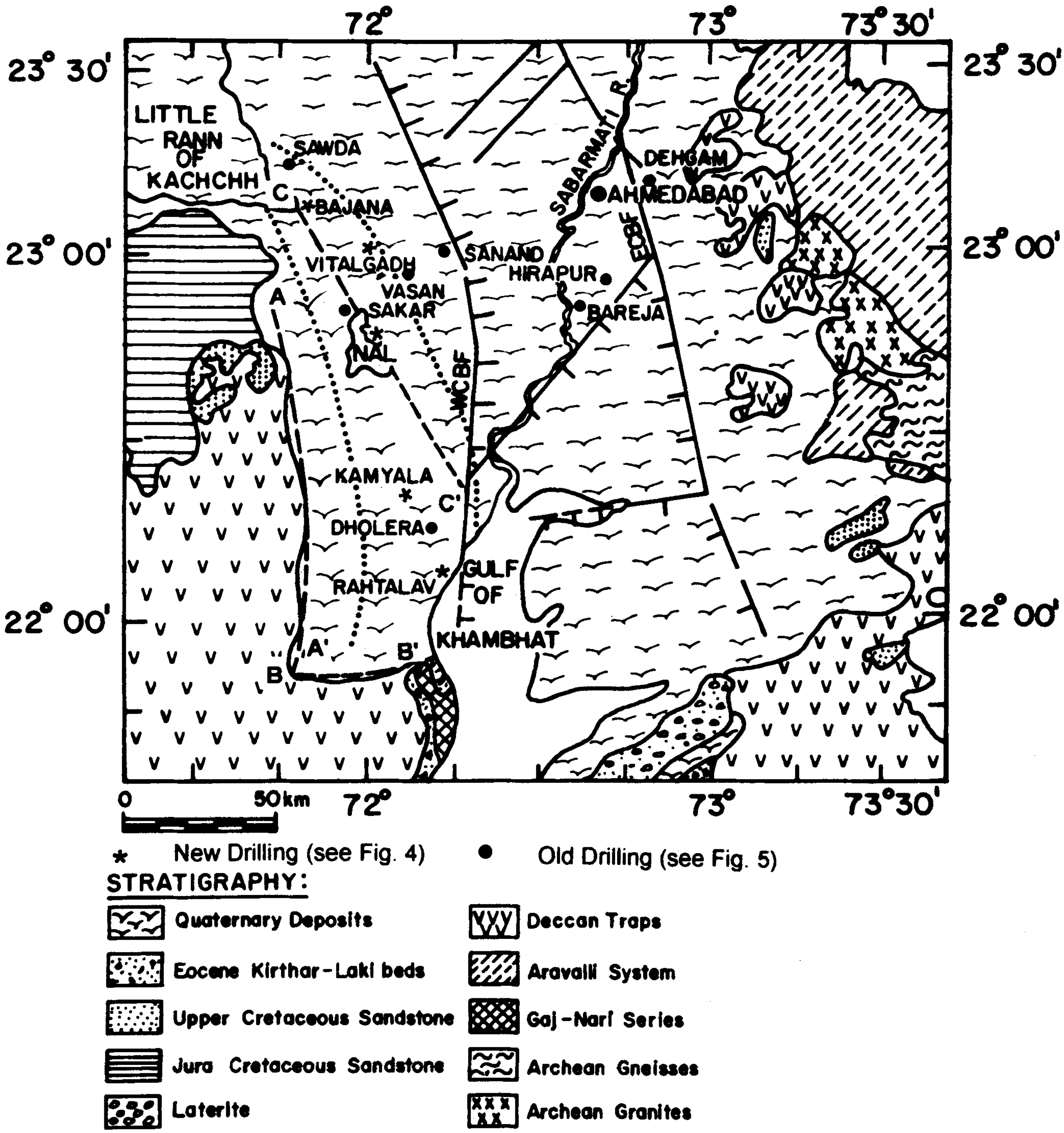

Figure 1. Study area (Nal Sarovar) with geology of the surrounding region. Small filled circles and stars show locations of boreholes used for lithological correlation in figures 4 and 5. Geology is based on information obtained from Ground water Dept., Govt. of Gujarat; Fault traces AA′ and BB′ from Prasad (1996); CC′ from Sridhar (1995) and Cambay basement faults from Chandra and Chaudhary (1969).

3. Material and methods

The core was sub-sampled for sedimentological and mineralogical studies. Sand, silt and clay ratios were determined using standard techniques of wet sieving and pipette analysis (Carver 1971). Nomenclature of sediment types is based on the scheme described by Shepard (1954). The relative sand/silt/clay proportions of samples from different depths are shown in figure 2.

Heavy mineral separation (using bromoform), their identification and grain size distribution studies were carried out in the $> 63\,\mu$m fraction (Carver 1971) of Zone-2 (depth 3–18 m), which is dominantly sandy.

Clays were separated from the bulk sediment by settling velocity employing Stokes's law. Selected

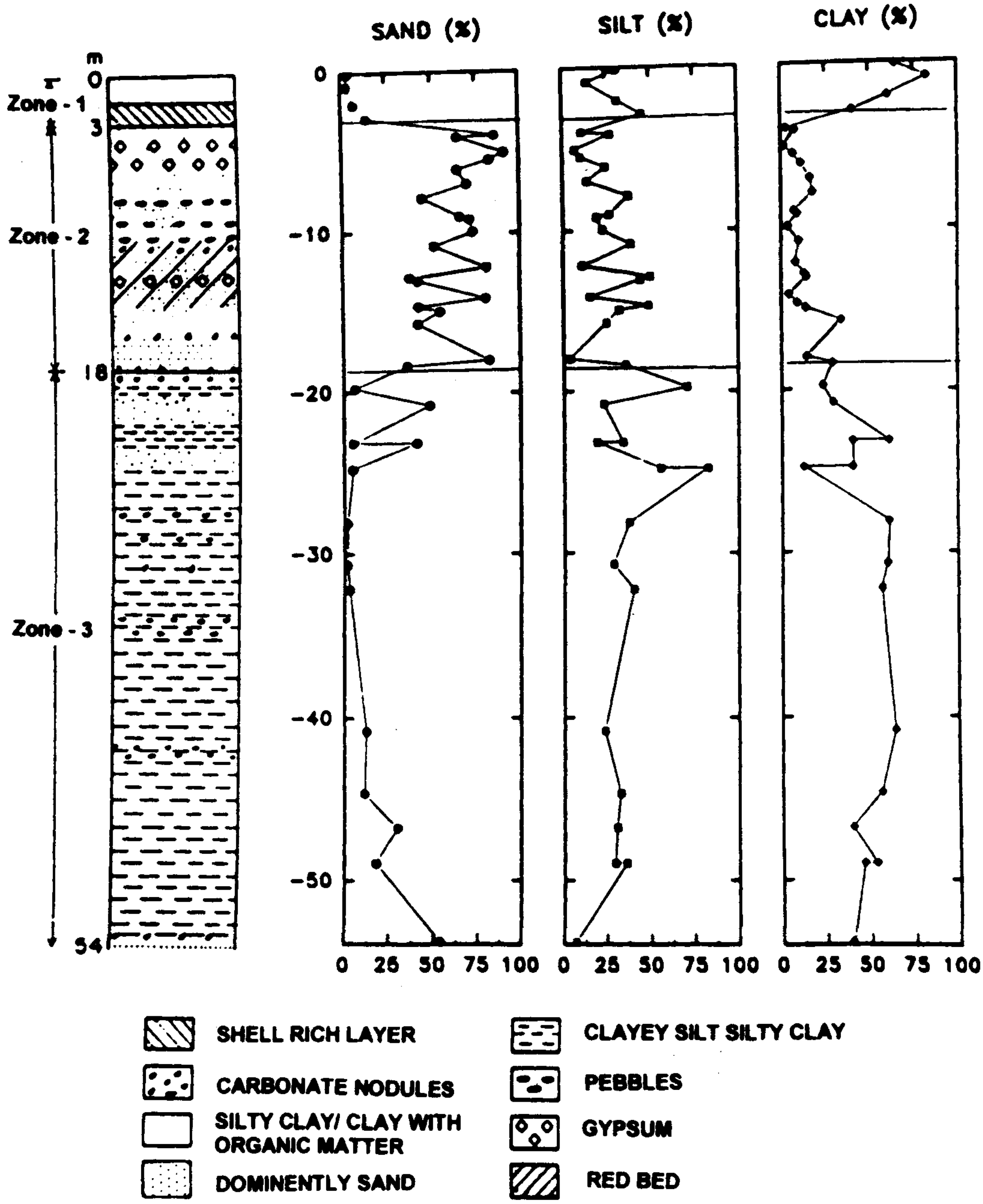

Figure 2. Lithology of the Nal Sarovar core and variations in sand, silt and clay percentages with the depth.

sub-samples were wet-sieved to remove $> 63\,\mu m$ fraction. Organic matter in the samples was removed by oxidising with H_2O_2 and carbonate material removed with 5-10% of acetic acid. Approximately 20 g of $< 63\,\mu m$ sample was used for pipette analysis technique to separate the clay fraction ($< 2\,\mu m$). No dispersant was used in this experiment. Clay fractions of the samples were divided into three sub-samples to give different treatments. The first sub-sample was kept untreated, the second and third sub-samples of clay were saturated with Mg^{+2} and K^+ by keeping them in 1N $MgCl_2$ and KCl solutions for 12 hours respectively. The samples were then washed repeatedly with distilled water. The clay-water suspensions were used to make slides of almost equal size and thickness by pipetting equal volume (~1 ml) of sample on glass slides. All slides were placed in a desicator with silica gel to prevent rehydration before exposing to X-rays. These slides were subjected to X-ray analysis using Philips X-ray Diffractometer (Model No. 1730) with Ni-filtered CuKα radiation. Clay identification and quantification of relative abundance followed the semi-quantification scheme suggested by Biscaye (1965). The untreated clay slides were scanned through 3°–30° (2θ). Slides saturated with Mg^+ were glycolated by vapours of ethylene glycol at 60°C for 6 hours. Slides saturated with K^+ were heated to 550°C for 90 minutes. Glycolated and Mg^+ saturated clay slides were used to confirm the presence of smectite by observing the expansion of peak at 7.3°–5.9° (2θ). K-saturated slides were used to differentiate kaolinite from chlorite by observing the absence or presence of the peak at 12.4° (2θ) after heating. Following the suggestion of Biscaye (1965), kaolinite and chlorite were also differentiated using a slow scan (at 0.5° 2θ/min) of the untreated clay slide from 24°–26° (2θ).

4. Results

On the basis of visual examination of the nature of sediments and laboratory grain-size studies, the core was divided into three distinct zones (figure 2). The Zone-1 (top 3m) is predominantly silty-clay/clayey; Zone-2 (3–18 m) is sandy; and Zone-3 (18–54 m) is dominated by sticky silty-clay/clayey-silt with occasional thin sand layers and basalt fragments. The sediments in Zone-2, are moderate to poorly sorted unimodal with modal class either 0–1ϕ or 1.5-2ϕ. Sand-size gypsum crystals in thin (10–20 cm) layers were also observed at 4 and 7 m depth.

Smectite and illite are the dominant clay minerals and minor amounts of kaolinite and chlorite are also present. It is observed (figure 3) that the illite concentration is very high (74–81%) in Zone-1; 17–38% in Zone-2; and 0–36% in Zone-3. Smectite concentration varies from 7–13% in Zone-1, 43–74% in Zone-2 and 53–97% in Zone-3. It is seen that the concentration of smectite increases with depth, whereas illite concentration decreases. In Zone-3, below 31 m, illite is nearly absent whereas smectite constitutes the entire suite (95–99%) of clay minerals.

Heavy mineral concentration in the samples from 3–18 m (Zone-2) of the core varied from 0.35 to 3.26 wt%. Within this heavy mineral fraction, opaques were dominant followed by garnet, epidote, staurolite, hornblende, monazite, rutile and chlorite. Epidote grains were well rounded whereas only a few garnet grains were rounded.

5. Discussion

Based on the geography of the low-lying region, linking the Gulf of Kachchh through Nal Sarovar to the Gulf of Khambhat (figure 1), four possible sources of sediments could be identified. These are:

(i) from east and northeast through the fluvial system draining the metamorphic and igneous rocks of Aravallis and the sedimentary deposits in the region of the Cambay Graben;
(ii) from west and northwest of Nal Sarovar by small streams draining the basaltic rocks of Saurashtra peninsula;
(iii) the Jurassic-Cretaceous sandstone in the northwest; and
(iv) from south, through the Gulf of Khambhat via sea transgression and/or tidal action. Nature of sediments, heavy and clay minerals abundance and the possible provenance of the individual zones are discussed in the following.

In the Nal Sarovar core, smectite content increases with depth with a concomitant decrease in the concentration of illite (figure 3). In the present study,

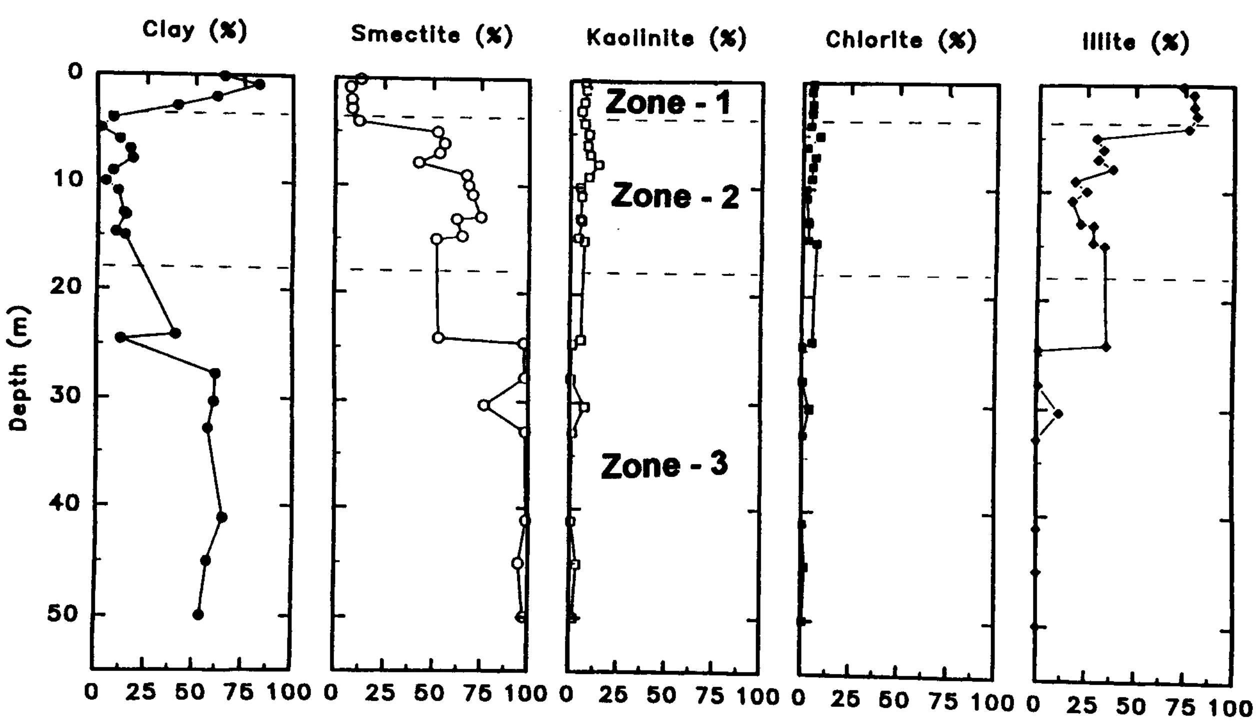

Figure 3. Variations in clay minerals with depth in the Nal Sarovar core.

the possibility of post-depositional alteration of illite to smectite through redistribution of K-ions in the deeper sediments (Hamdi 1977) is ruled out as we found unweathered wood/root fragments at depths of 31.4 m–32.7 m and 47.9 m–50.0 m in the core. The occurrence of fresh and unweathered wood material at these depths suggests that there is no decomposition of organic matter and hence organic acids which are necessary for mobilisation of K-ions from illite (El Sabrouti and Sokkary 1982) were not released. Absence of illite-smectite mixed layered peaks in the present study, which are common in altered clay x-ray diffractograms, also suggest the absence of diagenetic changes in clay minerals. Battacharya (1984), based on studies of clay minerals in surficial and core samples off Saurashtra, reported close similarity in mineral composition in all varieties of samples and concluded that diagenesis has insignificant effect on clay mineral alteration in the region. He is also of the opinion that burial depth seems to have very little effect on diagenesis of such clay minerals which had originated from volcanic rocks viz., basalts and associated ejectamenta. Hence, the clay minerals in Nal Sarovar sediments may be treated as detrital in origin without any post-depositional diagenetic changes. As their abundance reflects the nature of source region, they can be used to trace their provenance.

5.1 *Zone-3 (18–54 m depth)*

Sediments of Zone-3 are very fine-grained in nature. The sand content in this zone is small ($<10\%$) but occasionally few centimetre thick layers of fine sand have been observed in association with basaltic fragments. Smectite is the dominant clay mineral of this zone. On the western side of Nal lies the Saurashtra peninsula comprising of basalts. The weathering of basalt is known to produce smectite (Deer *et al* 1985, p. 268). The occasional occurrence of basaltic fragments in this zone would indicate some sediment input from the Saurashtra side also. But, smectite is also enriched (74% of clay minerals) in the sediments of the Gulf of Khambhat (Rao 1991). South of the study area, the major rivers, Narmada and Tapti, carry smectite-enriched sediments as they drain through the terrain of Deccan Trap basalts. Suspended and bed load collected from estuaries of these rivers revealed abundant smectite (Baskaran *et al* 1984). These rivers dump their load in the Gulf of Khambhat resulting in enrichment of smectite in the sediments (Nair *et al* 1982). It is, therefore, possible that the smectite rich sediments of this zone could have been transported from the Gulf of Khambhat. This was suggested by clay mineral analyses of the sediments from the upper part of Zone-3 in three of the four additional cores (see figure 4) that were specially drilled to confirm the subsurface correlation for the Nal corridor inferred from groundwater drilling data (figure 5). The analyses, in agreement with the suggested correlation, indicated progressively increasing relative proportion of smectite in the upper part of Zone-3 in the direction of the Gulf of Khambhat. This zone was not reached in the fourth core drilled at Rahtalav. Groundwater drilling data also indicated that on the east side of the dotted line (figures 1 and 5) the lithology abruptly changes from the 3-layer sequence seen in the Nal Sarovar core to alternating layers of sand/silt.

With radiocarbon dating of calcium carbonate nodules from this zone yielding ages >38 ka (the limit of ^{14}C dating), use was made of TL and IRSL dating techniques and an age range of 70 to >100 ka was assigned for Zone-3 (Prasad 1996; Prasad and Gupta 1999). During this period, which corresponds to most of the marine isotope stage 5, global eustatic sea levels were in the range $+7$ to -50 m MSL (see Gillespie and Molnar 1995). The present day tidal reach of the sea from the Gulf of Khambhat is $\sim +10$ m MSL. The possibility of a small (≤ 10 m) tectonic uplift of the region subsequent to the deposition of the Zone-3 was also indicated by Prasad (1996). Thus, combining the information on: **(i)** possible sources of sediments, **(ii)** their ages, **(iii)** eustatic sea level, **(iv)** possible magnitude of tectonic uplift and **(v)** high tidal reach; it would appear that the sediments of Zone-3 (RL -3 to <-39 m) could have been deposited in a shallow sea which extended at least up to Nal Sarovar. The occasional thin sand layers with basalt fragments, probably, represent flood-derived material from the Saurashtra side.

5.2 *Zone-2 (3–18 m depth)*

The sediments of Zone-2 are dominantly sandy (37–91%) with little (3–34%) clay. This zone also contained pebbles (~1–3 wt%) at depths of 8, 9, 10 and 16 m. The medium to coarse nature of sands with pebbles, unimodal size distribution and poor sorting indicated that these sands might be of fluvial origin. To confirm the depositional environment of this zone, we first adopted the methods based on grain-size parameters of the sediments. Even though usefulness of grain-size parameters in identification of depositional environments is limited (Solohub and Klovan 1970), we adopted this approach as no other indicator of palaeo-environment for this zone could be identified. We carried out three types of grain-size discriminant analyses.

The first involved, multi-group discriminant analysis (Sahu 1983), where more than two variables can be used at a time. When samples were plotted, they occupied fields of various sedimentary environments such as eolian, beach and turbidites. However, the uniformly similar texture of the sediment in the entire middle zone did not indicate rapidly varying or widely differing depositional environments as suggested by

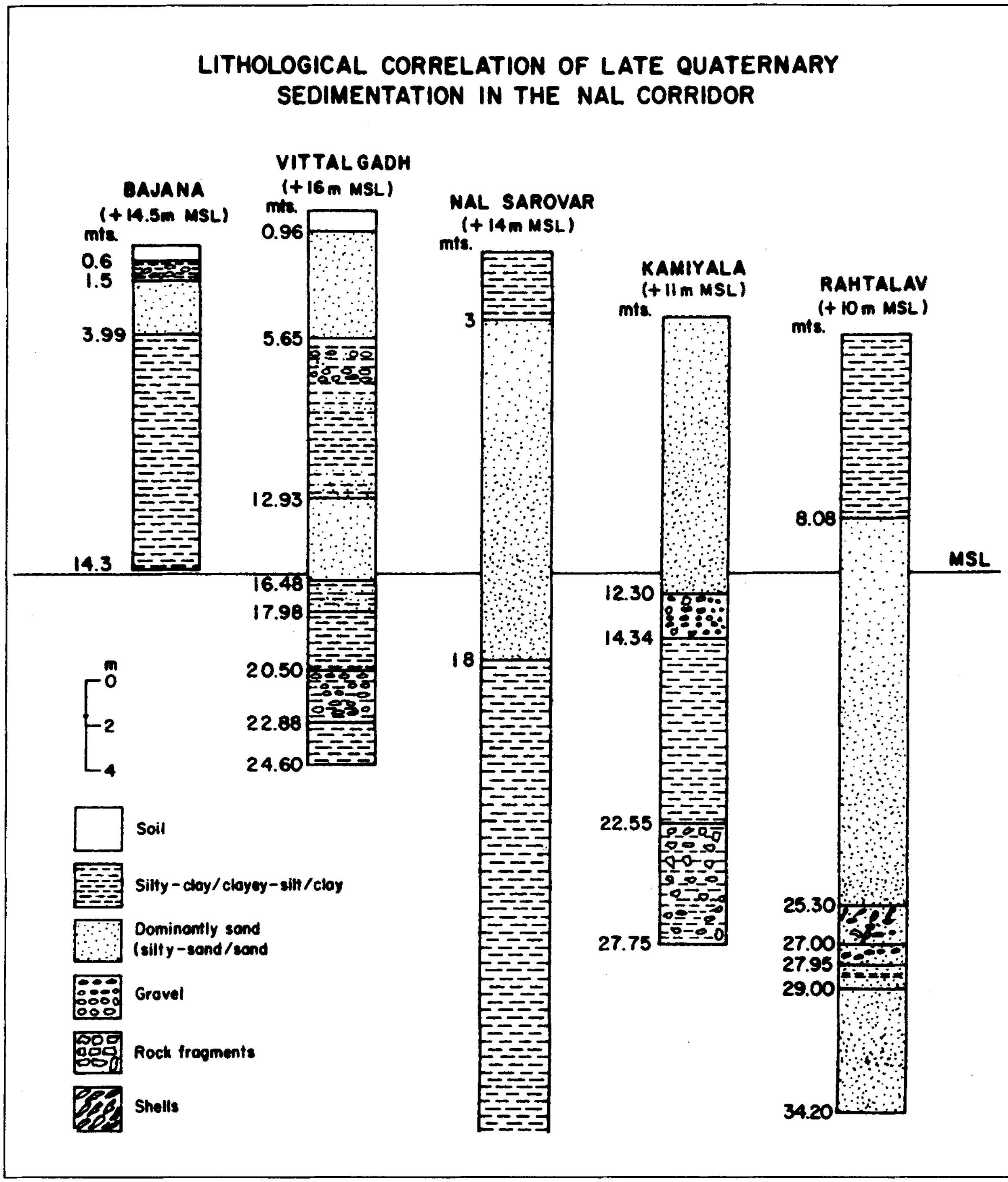

Figure 4. Lithological correlation of Late Quaternary sedimentation in the Nal corridor from specially raised cores. Note that the drill cores confirm the observations made in figure 5 for the lithology on the left side of dotted line as also the existence of Zones 2 and 3 observed in the Nal Sarovar core with a southerly slope.

the multi-group discriminant analysis. Application of multi-group discriminant analysis to the grain-size data of present day Sabarmati riverbed sediments from Ahmedabad, located 70 km from Nal Sarovar, also yielded widely differing depositional environments even though these were clearly fluvial. This indicates the limitations in applying multi-group discriminant analysis in identifying depositional environments.

The second grain-size discriminant analysis involved, Trask's skewness and sorting coefficients (Reineck and Singh 1980). When these coefficients were calculated for Nal Sarovar and Sabarmati river sediments, they did not fall in the suggested coefficient ranges of the sediments for either fluvial, eolian or beach environments.

Other methods such as bivariate plots are also widely used for determining the depositional environments. These involve constructing scatter diagram of

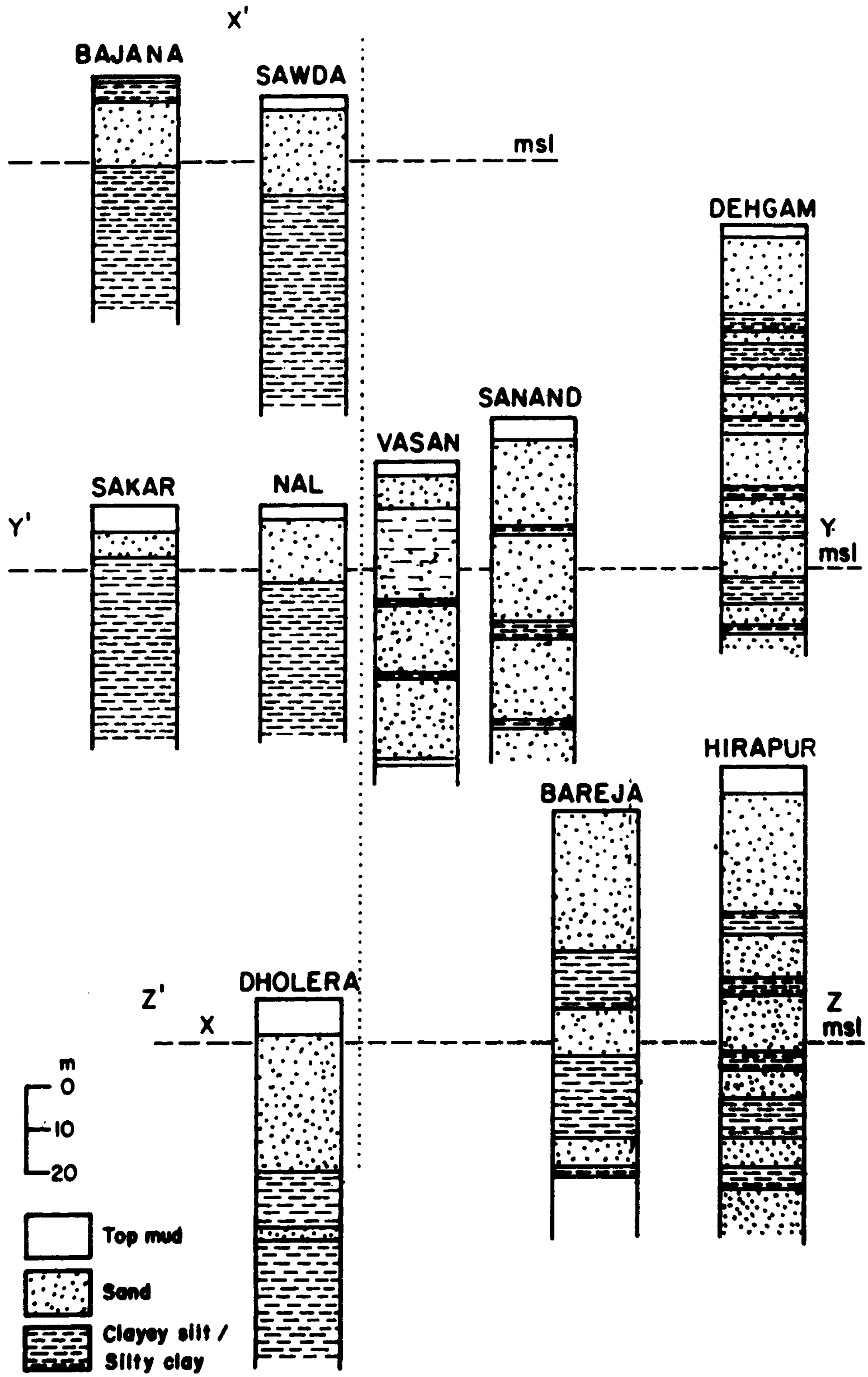

Figure 5. Lithological variation within and across the Nal corridor linking the Little Rann of Kachchh and the Gulf of Khambhat as shown in figure 1, based on drilling data of groundwater tube wells. Note that on the east side of the dotted line the lithology abruptly changes from the 3-layer sequence seen in the Nal corridor to alternating layers of sand/silt.

two variables (Friedman 1961), namely skewness against sorting. In this case also we compared grain-size parameters of Nal Sarovar core sediments with those obtained from present day Sabarmati riverbed. Grain-size parameters of sediments collected at various depths in bore wells drilled within a distance of 10 km on the bed of Sabarmati river passing through Ahmedabad are shown plotted along with the Nal

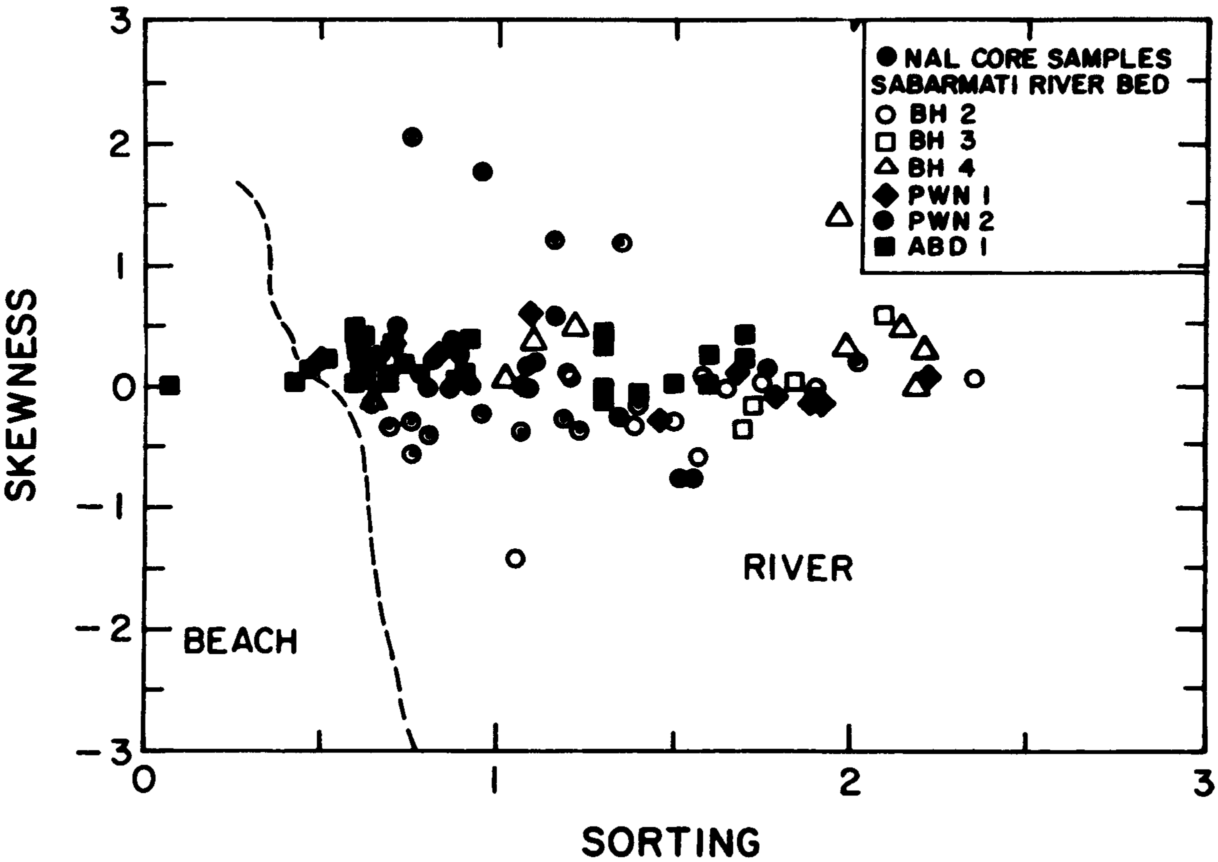

Figure 6. Bivariate plot of Skewness vs. Sorting of sediment of Nal Sarovar and Sabarmati riverbed cores from Ahmedabad. BH-2, -3, -4, PWN-1, -2 and ABD-1 refer to identification numbers of sediment cores raised from different locations from within the Sabarmati riverbed in a distance of ~10 km at Ahmedabad.

Sarovar Zone-2 samples in the bivariate plot (figure 6). In this plot, all samples fall within the field of fluvial sediments.

Sabarmati is presently the largest river originating in the northeast and traversing through the region of Cambay Graben into the Gulf of Khambhat. The sediments of Cambay Graben are overwhelmingly fluvial (Merh and Chamyal 1993) and are believed to have been deposited by a stronger fluvial regime during Quaternary (Sridhar *et al* 1994). It is, therefore, not unlikely that the Nal Sarovar sandy zone was deposited by an older fluvial regime of which Sabarmati was a part. Further, modern sediments of Sabarmati riverbed at Ahmedabad have a similar clay (dominated by smectite followed by illite and minor quantities of kaolinite and chlorite) and heavy mineral assemblage (dominated by opaques followed by garnet, epidote, staurolite, hornblende, monazite, rutile and chlorite) as the sandy zone of Nal Sarovar core. The scatter diagram (figure 6) also shows that the skewness for both, unlike sorting which depends on fluid dynamics of the transporting medium, is almost identical and all the samples fall in the field of fluvial environment. These observations suggested that sands of Zone-2 of the Nal Sarovar core were deposited under fluvial rather than coastal marine environment.

Earlier work (Sridhar *et al* 1994) showed that the river Sabarmati used to flow into the Little Rann of Kachchh along the course of Rupen. Sareen *et al* (1993) suggested that river Sabarmati shifted its course sometime during Late Quaternary as a result of fluvial readjustment in response to neotectonic reactivation in the region. The presence of palaeoriver channels to the east of Nal (Prasad *et al* 1997a) also suggested that these might have been the older courses of the Sabarmati River. The presence of a thick (5–35 m) sandy zone (RL +14 m to −30 m) in the bore well sections along the entire low lying belt, connecting Little Rann to Gulf of Khambhat (figures 4 and 5), supports that these sands may have been transported by an older fluvial regime. Additionally, during luminescence dating (Prasad 1996; Prasad and Gupta 1999), it was found that the sediments from Zone-2 indicated inadequate pre-depositional zeroing of geological luminescence (TL) signal, not an unusual situation in case of fluvial sediments (Berger 1988; Berger and Easterbrook 1993; Forman and Ennis 1991). For this reason, Infrared Stimulated Luminescence (IRSL) method, in which only a few minutes of sun exposure is sufficient to zero the geological signal was used for dating of these sediments. An IRSL estimate of ~7 ka– ~70 Ka (Prasad 1996; Prasad and

Gupta 1999), consistent with ^{14}C age >38 Ka for the calcium carbonate nodules from 7 m depth was obtained for the Zone-2. It may be noted that shallower layers of this zone contained little ^{14}C datable material. The record of global eustatic sea-level changes suggests that sea level in the entire low-lying region during the inferred period of deposition of the sands of Zone-2 was largely lower than the presently existing elevation of either top (+11 to −4 m) or bottom (+3 to −35 m). Due to the lowered sea level, the palaeo-fluvial regime extended its course on the exposed Nal region and fluvial sediments were deposited in the entire low-lying belt. The presence of coarse sand with pebbles and evaporite minerals (depths ~7 m and 12.85–13.24 m; see figure 2) suggests subaerial exposure, TL/IRSL studies indicated inadequate pre-depositional sun bleaching of sediments during episodic fluvial deposition—also suggested by textural data.

In view of the generally corroborating lines of evidences, we conclude that the Zone-2 of Nal Sarovar core was deposited in a palaeo-fluvial regime, during the period of lowered eustatic sea levels. The primary provenance of the sediments was in the far northeast in Aravalli Hills, as is the case with the present day Sabarmati.

Within the clay fraction of this zone (Zone-2), smectite is the dominant (43–73%) clay mineral followed by illite (17–38%) and minor quantities of kaolinite and chlorite. Onshore rocks in the Saurashtra Peninsula (west side of Nal Sarovar) are predominantly the Deccan traps, weathering of which results in release of smectite (Deer *et al* 1985, p. 268). These smectite-rich clays might have been transported to the Nal region by small east flowing rivers. This suggests that though the coarse material, which comprises a major portion of the sediments, was mainly derived from the terrain of Aravallis (east side of Nal), a small proportion might have been transported from the basaltic terrain of Saurashtra (west side of Nal) as indicated by the presence of smectite in clay fraction.

5.3 *Zone-1 (top 3 m)*

The sediments of Zone-1 are very fine-grained (clayey-silt and silty-clay) indicating a low-energy transporting regime. Illite is the dominant clay mineral (74–81%) in this zone followed by smectite, kaolinite and chlorite. Illite can be formed by weathering of silicates, principally feldspars (Deer *et al* 1985, p. 263). The illite-rich sediments of Zone-1, could therefore, be derived from the Precambrian feldspar rich metamorphic and igneous complex of the Aravalli system or derived from adjacent Gujarat alluvial plains, which had their primary source in Aravallis. Based on $\delta^{13}C$ and C/N ratios, Prasad *et al* (1997b) have inferred that the sediments of this zone were deposited in a lacustrine environment during the last 7 ka B.P. The dominance of illite in the clay fraction of this zone also suggests that contribution of sediments to the deposits of this zone from the western side of the Nal (from Saurashtra side) has been negligible.

Jurassic-Cretaceous sandstones which occur to the northwest of Nal Sarovar is dominated by a heavy mineral assemblage of opaques, tourmaline, zircon and rutile and the clay matrix dominated by kaolinite (Ahmad *et al* 1994). Except for tourmaline, all other heavy minerals in the Jurassic Cretaceous sandstone have been found in Zone-2. Though minor amounts of kaolinite has been observed in all the three zones of the Nal Sarovar core, it is not the dominant clay constituent in any of the three zones, as in the case of Jurassic-Cretaceous sandstone formations. Therefore, while it is not possible to completely rule out the contribution from Jurassic-Cretaceous sandstone to the Nal region, it could not have been significant. Otherwise we should have seen a larger proportion of kaolinite in the Nal Sarovar core sediments.

6. Summary and conclusions

On the basis of texture, the sediments of a 54 m-long core from Nal Sarovar and others located in the low-lying belt linking the Little Rann of Kachchh and the Gulf of Khambhat in Gujarat could be divided into three zones. Clay and heavy mineral data revealed different sources for the sediment of these zones: Gulf of Khambhat and/or basaltic terrain of Saurashtra as the source for the sediments of the lowermost (18–54 m depth; Zone-3) of the three zones; mixed metamorphic and igneous terrain of Aravallis and/or Quaternary alluvium (NE of Nal Sarovar) for the sediments of the middle (3–18 m depth) and uppermost (0–3 m) zones in the Nal Sarovar core. The difference between Zone-1 and Zone-2 relate to the environment of deposition-lacustrine for uppermost Zone-1 and fluvial for the middle Zone-2.

Acknowledgements

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