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LATE QUATERNARY PALAEOENVIRONMENT AND EVOLUTION OF THE NAL REGION, GUJARAT, INDIA

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1. INTRODUCTION

The Nal depression is a low lying tract linking the Gulf of Kachchh through the Little Rann to the Gulf of Khambhat. Lying in the middle of this depression (22°48'N, 72°E) is a large (~120km^2) shallow lake (maximum depth 2m, +14m msl) lake, Nal Sarovar. On the basis of its location and elevation, it has been surmised by many earlier workers that Nal Sarovar represents a remnant of a sea link that existed between the two gulfs until Holocene. However, the region also lies in close proximity to the tectonically active region of Cambay Graben in the east. Thus it is likely that both tectonism and eustasy have played a role in the geomorphic evolution of this region. The region is also located within the palaeo-desert margin, bordering the Thar desert. It is, therefore, a potential site for reconstructing the palaeoclimatic, eustatic and tectonic history of the region. This study represents the first major attempt in this direction and is based on application of a variety of techniques that included: (i) remote sensing analysis, (ii) subsurface lithological correlation, (iii) sedimentological and mineralogical characterisation of sediments, (iv) isotopic studies, (v) radiocarbon, and (vi) luminescence dating. Detailed work was carried out on a 54m long core raised from the bed of Nal Sarovar. This, together with geomorphic evidence, formed the basis of the model proposed here for the evolution of the region.

Presently, there is no major river flowing into the Nal and most of the input is in the form of surface runoff during the monsoon season from the adjoining areas of Surendranagar and Ahmedabad districts. The study area is bounded in the west by basaltic trap rocks of the Saurashtra and in the north-west by the Juro-Cretaceous sandstone. To the extreme north-east of Nal are present the igneous and metamorphic rocks of the Aravallis. In the immediate vicinity to the east are the Quaternary alluvial plains occupying the Cambay

Graben. These show evidence of tectonism in the form of entrenched streams, cliffy sections and fault controlled river courses.

The thesis comprises of two sub themes:

A. Evolution of the Nal region, and

B. Holocene palaeoclimatic investigations.

2. METHODOLOGY:

2.A. Evolution of Nal Region:

The study is based on the interpretation of remote sensing data and subsurface lithological correlation from bore hole lithologs from regions around the Nal Sarovar.

1. Drainage pattern and palaeochannels were identified and mapped using toposheets and IRS FCC 1A imagery (1:250,000 and 1:50,000 scale) for studying past drainage patterns. The channels were identified on the imageries on the basis of colour, tone and linearity. Both pre-monsoon and post-monsoon imageries were studied and compared with the toposheets to identify the defunct channels. These were subsequently confirmed in a few cases in the field.

2. Geomorphological features such as palaeo-deltas, stabilised dunes and mud flats were also delineated and mapped using IRS FCC 1A imagery.

3. Bore hole data were collected for thirty stations spread over the mainland Gujarat and Nal region and three transects in NE-SW and NS direction were drawn.

2.B. Palaeoenvironmental studies:

The basic framework was provided by sedimentological, X-ray diffraction (XRD), heavy mineral, stable isotopic, carbon/nitrogen (C/N) variations,

radiocarbon and luminescence dating studies on the 54m long core raised from the bed of Nal Sarovar.

The results of these studies were synthesised with the available data on the eustatic sea level changes and a scenario for the evolution for the entire Nal region was developed. Within the framework of this scenario paleoclimatic reconstruction during the Holocene was also done.

3. RESULTS AND DISCUSSION:

3.A. Evolution of Nal region:

3.A.1. Transgressive events of the sea:

On the Saurashtra side deltas have been identified, presently 30km inland and >+15m msl. In this region several small streams are seen which terminate abruptly at the palaeo-strandline. The rivers to the west of the palaeo-strandline have large valleys which are incompatible with their present seasonal flow. It is likely that these represent a substantially wetter period in the past when these rivers had higher erosional potential and a larger load carrying capacity. At that time the sea-level was also higher, resulting in the formation of these inland deltas. The entire Nal region would then have been under a shallow sea. At a lower elevation to the east of inland deltas and south of Nal, inland mud-flats have been identified at +14m msl. These show deranged drainage pattern indicating recent development of drainage in this region. No significant entrenchment of rivers is observed in the mud flats indicating that since their formation there has not been any major uplift in this region. Thus, the evidence of topography and drainage points to the mud flats being formed during the most recent, possibly, Holocene sea transgression. This would imply that the inland deltas were formed during the earlier transgression of the sea. Available record of sea level changes indicates a high sea level of +7m during the last major interglacial (~125ka) and a maximum of +5m during the Holocene. Since the inland deltas are presently at elevations higher than +15m msl, assigning an age of ~125ka would require a small tectonic uplift

subsequent to their formation. An entrenchment of ~4m has been observed in rivers draining Saurashtra in the palaeo-delta region.

The geomorphic features thus indicate two episodes of transgression in this area. The low lying Nal region should show the signature of sea level variations in form of changes in the nature of sedimentation.

3.A.2. Subsurface lithological correlation:

Three transects in NE-SW and NS direction were constructed using the bore hole data (depth of sections 60-200m). The NE-SW transect indicated that in the mainland Gujarat the lithology is dominated by sand with intercalations of clay/silty clay. In the vicinity of Nal, however, a change in lithofacies to a layer of sand underlain by a thick (40-55m) sequence of clay/silty clay is seen. The lithological sequence in the NS transect extending from Little Rann near Gulf of Kachchh, to Dholera near Gulf of Khambhat is comparable to the 54m long core raised from Nal Sarovar (described below in section 3.B.1). This indicates a similarity in depositional environment in the entire low lying region extending from Gulf of Khambhat to Gulf of Kachchh, suggesting the possibility of a sea corridor linking the two gulfs.

3.B. Palaeoenvironmental Studies:

3.B.1. Sedimentological and mineralogical studies:

Textural characteristics of sediment like grain size, and mineralogy are good indicators of palaeoenvironment. Three lithounits (see Table-1) were recognised in the core on the basis of texture and mineralogy.

The contact between Horizon-2 and -3 is abrupt whereas the Horizon-2 grades into Horizon-1. The base of Horizon-3 was not reached in the core.

Mineralogically, the clay rich Horizon-3 is dominated (>70%) by smectite indicative of its origin from the basaltic terrain. It has possibly been derived from the basaltic rocks on the Saurashtra side or brought in from the Gulf of Khambhat due to action of tidal currents. The latter possibility cannot be ruled

TABLE-1. Nal Sarovar Core: Description, Chronology and Inferred Environment of Deposition

Lithounit	**Description**	**Age**[1]	**Depositional Environment**[2]
Horizon-1: (0-3m)	Clayey silt with organic matter (0.6-0.9%) with gastropod shells.	0-7ka	Lacustrine
Horizon-2: (3-18m)	Dominantly sandy layer with a red bed (10-14m) and Gypsum layers (at 4m and 7m), no fossils in >63μ size, occasional basalt fragments.	7--73ka	Fluvial
Horizon-3: (18-54m)	Clay and silty clay layer with occasional sand lenses, no fossils in >63μ size occasional basalt fragments. Base not seen.	~73--127ka	Marine

1 See section 3.B.2
2 See section 3.B.1 below.

out considering the RL (elevation wrt msl) of this horizon (-4 to -40m, in the core). Mineralogically and sedimentologically, the sediments in the inner shelf near the Gulf of Khambhat are similar to the Horizon-3 of the core.

Considering (i) the thickness of the silty-clay horizon in the borehole sections (varying between 40-55 m) in the NS transect; (ii) the RL of the bottom and top of this layer (-75 to +3m respectively in the Nal region); (iii) mineralogy (smectite dominated); (iv) geomorphological evidence of transgressive events; (v) the global eustatic sea level curve; and (vi) the possibility of small post depositional tectonic uplift of the region, an age of 73-127ka, corresponding to the entire isotope stage 5, is assignable for the deposition of the silty-clay

Horizon-3. For most part during this interval, the entire region would have been covered by the sea.

In contrast, the Horizon-2 (3-18m) is dominated by sand size grains of quartz, both angular and subrounded. Sorting is poor and the mean grain size is in the range 0.8-1.5Φ. Heavy mineral assemblage consists of opaques, epidote, staurolite and garnet, indicating that this material could have been derived from the metamorphic and/or igneous rocks in the east and north-east. This is in contrast to Horizon-3 which indicates a dominant input from west and/or south. The presence of red beds (10-14m) is indicative of subaerial exposure. Occurrence of evaporite minerals like gypsum at 4m and 7m depth, is also indicative of an arid period. To the east of Nal, there are several abandoned river channels which have been identified on the IRS FCC imagery. These may have been transporting sediments to this region in the past. They became inactive either due to a changeover to a drier climate and/or due to tectonism which disrupted the drainage pattern. The abandoned river courses lie in the Cambay Graben which is known to have been tectonically active.

The presence of a thick (5-35 m) sandy horizon in the bore well sections in the entire Little Rann to Gulf of Khambhat corridor suggests that during its deposition the sea link no longer existed in this region and high energy fluvial sediments were being deposited in this entire belt.

The Horizon-1, overlying the sandy layer indicates a low energy depositional regime. The dominant clay mineral in the Horizon-1 of the core is illite (~70%) indicating the source of sediments to be from east and north-east. The $\delta^{13}C$ and C/N ratios of organic fraction of this horizon, reported subsequently, indicate that lacustrine conditions slowly began to set in and the area became a closed basin.

3.B.2. Chronology:

For the time scale of interest in this study the following methods of dating were used:

Radiometric Dating

^{222}Rn escapes from the soil into the atmosphere and through a series of short lived daughter products decays into ^{210}Pb (half life ~22 yrs). This isotope is subsequently removed through precipitation and gets incorporated into the sediments. The decay of ^{210}Pb is monitored to estimate the age and sedimentation rate of young sediments (<100 yrs). In Nal Sarovar the topmost portion of the core gave a sedimentation rate of ~2 mm/yr.

Another convenient method used for dating of young sediments is based on identifying the layer that was deposited in 1960's when the bomb produced ^{137}Cs (half life: ~30 yrs) activity was the highest. However, in case of Nal Sarovar the concentration is uniform over a depth of 6cm indicating that layers upto 6cm depth are more or less uniformly mixed.

In the radiocarbon method, radioactivity of ^{14}C in the organic matter is used to date sediments younger than 40ka. The top 3m portion of the core contained organic matter which was dated by the radiocarbon method. A total of eight dates on organic fraction were obtained; the top of the core indicated the presence of bomb produced carbon-14, in agreement with ^{137}Cs and ^{210}Pb estimates. The base of Horizon-1 was dated at 6.7ka giving a long term average sedimentation rate of 0.43 mm/yr, significantly lower than that estimated by ^{210}Pb in the upper part. The ages for intermediate samples, in the top 3m, have been estimated by interpolation, using a second order fit to the depth vs radiocarbon age data.

In the 3-54m depth the amount of organic matter is <0.01%. Carbonate nodules found occasionally were dated and gave an age of >38 ka at 16m depth and below.

Luminescence dating:

This method relies on the bleaching of sediments by sunlight prior to deposition. Sun exposure results in the detrapping of charges at various defect centres in the crystal lattice. On subsequent burial, re-acquisition of luminescence, due to irradiation from ambient radioactivity begins. The extent of photo detrapping in fluvially deposited sediments becomes somewhat enigmatic due to net attenuation of solar flux, seen by a mineral grain, by turbulence and sediment load. Initially, partial bleach TL dating of some samples was attempted but it was noticed that plateau region in the equivalent dose (ED) vs temperature plot was small and the computed dates indicated that the samples may have been only partially bleached prior to deposition. Hence optically stimulated luminescence (OSL) method, which samples only the easily emptied light sensitive traps was used for dating of these and subsequent samples.

A plot of OSL dates vs depth showed a general increase with depth. However, samples in Horizon-2 showed a large scatter with some dates (at 4m, 5m and 18m) higher than the stratigraphically older Horizon-3. Partial bleach TL dates could be calculated for two samples of Horizon-2. The sample at 18.3m depth gave an date of ~160 ka which is comparable with the OSL date of 145±9ka. The sample at 9m depth gave a partial bleach TL date of ~80ka which is considerably higher than the OSL date of 37±10ka. The possible causes of anomalous results were examined in some detail. Measurements were carried out to detect anomalous fading and the effect on dose rate due to variation in water content. Neither of these could successfully explain the observed scatter as anomalous fading was absent and correction for dose rate attenuation due to the saturation water content did not increase the ages beyond 20%. Radioactive disequilibrium, which can alter the dose rate, was also checked using HPGe high energy gamma counting. Except for two samples (from 18.3m and 54m depths), others did not show any evidence of radioactive disequlibrium. Even in these two cases the correction due to radioactive disequlibrium was unable to explain the observed anomalies in dates.

The dates around 4m, 5m and 18m are also inconsistent with the radiocarbon age of ~7ka at 3m depth. Since the sand horizon has been deposited by a high energy transporting regime, it is likely that intermittent flood events may have transported older sediments to Nal region without adequately zeroing the geological OSL signal, resulting in anomalously high dates for such samples. An indication of this may be seen in higher mean grain size (0.9Φ) for sediments showing stratigraphically anomalous dates as against a lower mean grain size (>1.2Φ) for sediments giving stratigraphically consistent dates. In view of this and the absence of anomalous fading, the lower OSL dates which are additionally consistent with stratigraphy, have been assumed to represent the true sample ages and the ages of intermediate samples were obtained by interpolation. With this assumption, the measured OSL age of red bed at 12m depth is 47±8ka which is in agreement with, the TL/OSL age of 58±5ka of similar red bed found in Vijapur near Ahmedabad. It may be noted that this particular red bed has a regional occurrence and is used as a marker horizon. The age determined for the sample at 54m depth is 92±9ka but is likely to be underestimated to some extent as some kind of saturation effect is clearly visible in the OSL age vs. depth plot for this horizon. The interpolated age at 18m depth is ~65 ka indicating an age >65 ka for Horizon-3. This suggests that Horizon-3 may have been deposited during the isotope stage 5 and not during the Holocene high stand of sea level - a possibility also ruled out by radiocarbon age data of Horizon-1. The assignment of isotope stage 5 to the deposition of silty-clay Horizon-3 given earlier (Section 3.B.1) is also in agreement with the OSL ages (though poorly constrained).

3..B.3. Palaeoclimatic studies:

Since organic matter was found only in Horizon-1, the stable isotope studies and C/N measurements had to be confined to top 3m (corresponding to past 6.7 ka) of the core. The organic matter is contributed to the sediments in the lake by both terrestrial and aquatic plants. The plants can be classified as C3 (average $\delta^{13}C$ value: -27‰) or C4 (average $\delta^{13}C$ value: -14‰) and show

different ecological preferences. The C4 plants favour conditions of aridity and low soil moisture while the C3 plants thrive in areas of higher precipitation and higher soil moisture. The aquatic plants, however, complicate the picture because they take up their carbon from the dissolved pool and show an enrichment depending on the isotopic composition of dissolved carbon in water. In deciphering the stable isotope $\delta^{13}C$ results, it becomes necessary to know the relative contributions of both the aquatic and the terrestrial components. This is done on the basis of C/N ratios of the organic matter. Autochthonous organic matter has C/N<10 whereas allochthonous organic matter has C/N>20. The surface sediments in Nal Sarovar show a $\delta^{13}C$ value of ~-21‰ and a C/N ratio of ~6.

Palaeoclimate reconstruction for the last ~7ka was attempted using $\delta^{13}C$ and C/N ratios of organic matter from sediments. This is the first high resolution palaeoclimatic study from the palaeo-Thar margin. The observed variations in $\delta^{13}C$ and C/N indicate that the period from ~6.6-6ka was generally drier than present with the exception of a short wet phase around 6.2ka. From 6-4.8ka the rainfall was lower than present but possibly more evenly distributed as a result of a slight increase in winter rainfall. From 4.8-3ka the climate was wetter than present. The trend towards aridity began around 3ka and present day conditions set in ~2ka BP. This picture is somewhat different to the one deciphered by earlier workers from Rajasthan lakes for the period 6.5-4.8ka when, in opposition to the wetter climate in Rajasthan, the climate here was drier. From 4.8ka to present however the climatic changes in this region are similar to those in Rajasthan. Also, a general agreement between periods of glacier expansion in Eurasia and drier periods in Nal Sarovar is observed. This suggests that the palaeoclimatic record from Nal is a regional feature.

4. SYNTHESIS:

Based on the results of various investigations carried out , as above, it is possible to develop a model for the geomorphic evolution of the region covering

the entire low lying tract between the Gulf of Khambhat and the Gulf of Kachchh including the Nal Sarovar.

STAGE 1:

During the last major interglacial when the sea level was higher, a shallow sea linked the Gulf of Khambhat with the Gulf of Kachchh. The palaeo-deltas and the palaeo-strandline observed to the west of Nal Sarovar (upto 30km inland at ~+15m msl) were formed during this period (stage 5e of marine oxygen isotope record corresponding to ~125ka). At that time the entire low lying tract was covered with a shallow sea having a dominant input of sediments from the Saurashtra peninsula and/ or Gulf of Khambhat. The presence of smectite as a dominant (~ 70%) mineral phase in the sediments of Horizon-3 implies that the sediment input at the present location of the Nal Sarovar from the eastern side was small. This probably was due to the depositional front of the rivers draining the mainland Gujarat being farther east in the Cambay Graben. There may have been breaks in the sediment deposition during the sub-stages of isotope stage 5 linked to the fall of the sea level. The OSL age data (though poorly constrained) suggests that the deposition of the silty clay (Horizon -3) in this region ceased when the sea level finally dropped at the beginning of isotope stage 4.

STAGE 2:

With the lowering of base level, the depositional front of fluvial input from the east could now advance westwards. This is suggested by the presence of a thick layer (5-35m) of sand (Horizon-2), with its source in the east as confirmed by the characteristic heavy mineral assemblage. The deposition of sand was not continuous as is indicated by the presence of red beds and evaporite minerals. This sedimentary material was most likely brought in by flash floods and had little sun exposure so that TL/OSL signal from the previous depositional history was not erased. Alternatively, it is possible that the region to the east of Nal Sarovar was tectonically uplifted some time subsequent to the

deposition of Horizon-3 and pre-existing sediments from farther east were rapidly eroded and redeposited in the low level narrow land corridor that still remained, linking the Little Rann of Kachchh and the Gulf of Khambhat. It may be noted that the Cambay Graben lying to the east of Nal Sarovar was topographically the lowest elevation and had acted as a sediment sink at least until Miocene. Presently, this area has a surface elevation of +80 m to +100 m and the low elevation area has shifted to Nal Sarovar which is +13 m to +16 m msl. Evidences of Quaternary tectonism in the Cambay Graben have been reported in the form of entrenched rivers, cliffy sections, fault controlled river courses.

STAGE 3:

As a result of the combined influence of (i) westward advance of the sedimentation front; (ii) tectonism and; (iii) the post glacial sea level rise, the elevation of the Nal Sarovar came to within few metres of its present elevation at about 7ka when it became a closed basin. The present Nal Sarovar, therefore, originated as a result of westward advance of the sedimentation front until it could no longer advance due to the presence of high land of Saurashtra. At that time either due to sedimentation process alone or aided by tectonism the west flowing rivers shifted their courses and presently only the abandoned channels remain. The present day rivers are entrenched in their courses indicating the role of tectonism. Other studies also indicate that the present river courses may have been acquired during late Quaternary. The mud flats, present to the south of Nal, represent recent sea transgressions in the area.

Within the framework of this evolutionary model, palaeoclimatic reconstruction, based on $\delta^{13}C$ and C/N ratios of organic matter in sediments, for the past ~7ka was done. This study indicated following sequence of climatic changes with reference to present climatic conditions:

Period 5	6.6 - 6.0ka	Dry changing to wet
Period 4	6.0 - 4.8ka	Dry with short wet spells
Period 3	4.8 - 3.0ka	Wet
Period 2	3.0 - 2.0ka	Trending to dry
Period 1	2.0ka to present	Similar to present.

In addition to the above mentioned new observations, this study has provided a framework for future work in this region.