Chapter 7
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SUMMARY AND CONCLUSIONS

Fifteen sediment gravity cores collected along from the western margin of India at depths between 31m and 1940 m were investigated to better understand the palaeoclimatic and palaeoceanographic conditions during the late Quaternary. Of these, eleven cores are from the northwestern (NW) margin of India between the Gulf of Kachchh and Ratnagiri and four cores are from the southwestern (SW) margin between Mangalore and Cape Comorin.

The terrigenous sediments along the western margin of India are from diverse sources. The composition of the terrigenous sediments and their rate of deposition vary from north to south. The major sediment contributors are 1) The Indus, one of the largest rivers of the world, supplying sediments largely from the Himalayas, 2) Narmada and Tapti, discharged though the Gulf of Khambat, 3) moderate and seasonal rivers of the central and southwestern India and 4) aeolian dust from the alluvial soils of Pakistan and arid land masses of Iran-Makran-Thar regions. Although broad understanding has been achieved on the provenance of the sediments based on mineralogy of surficial sediments and Sr-Nd isotopes, palaeoclimatic studies using exclusively terrigenous sediments have not been attempted. In chapter 3 of the thesis, the rock-magnetic properties (magnetic concentration, magnetic grain size and magnetic mineralogy) of the sediments were investigated in detail and analysed these parameters in relation to other sedimentological properties in order to better understand the past climatic and provenance variations. The major conclusions are as follows:

- The magnetic susceptibility of the sediments is largely controlled by the detrital magnetite content. Regional variations in magnetic susceptibility are in accord with the mineralogical provinces.
The highest MS values correspond to the sediments derived from the Deccan Traps, followed by the sediments from the Indus and least in the sediments off southern India.

Intense chemical weathering in the Precambrian rocks of southern India results in leaching of iron from the source rocks and thereby reducing the MS value of the associated sediments.

Authigenic green grains (Fe-rich clays) and biogenic magnetite at certain intervals in the cores enhance the total MS signal.

Reductive diagenesis in organic-rich near surface sediments reduces the MS signal due to the dissolution of fine-grained magnetite.

The MS contribution from the paramagnetic minerals (ilmenite, garnet, chlorite, smectite, glauconite, olivine, amphiboles, pyroxene) is much greater than that of dia-magnetic minerals (quartz, feldspar, calcite). The MS variations caused by varying carbonate content are minor.

The glacial sediments in a core off the Indus exhibit low S-ratio% corresponding to high acid-insoluble residue. This implies the presence of high coercivity minerals like hematite and goethite and probable aeolian contribution from Pakistan and Indus drainage basin.

The glacial sediments of the SW margin of India are characterised by low MS / high S-ratio% associated with low AIR and high OC and carbonate content, implying low terrigenous supply from the hinterland.
o The early Holocene sediments of both the NW and SW margin of India contain high MS / S-ratio% associated with high AIR and decreased δ¹⁸O values. This implies enhanced supply of terrigenous material through fresh water, perhaps due to the intensified monsoonal activity at about this time.

o During the late Holocene, fine-grained magnetite on the continental slope is minor, may be due to stabilized sea levels and deposition of more terrigenous sediment on the shallow shelf.

o The late Holocene organic-rich sediments of the SW margin of India were subjected to reductive diagenesis and rock-magnetic properties were modified. Therefore, a caution needs to be exercised in interpreting the regional climatic signal through sediment magnetic properties.

Lime muds are abundant in the geological past but their Modern occurrences are confined to the Bahamas and Persian Gulf. Although extensive studies have been carried out on lime muds, their origin is still a subject of debate. The two popular theories exist for the origin of lime muds: a) inorganic precipitation of aragonite needles in hyper-saline, carbonate saturated shallow marine conditions and b) organic origin, whereby the aragonite needles are formed from the disintegration of codiacean algae. Lime muds in late Quaternary sediments of the northwestern margin of India have not been studied in detail and provide an opportunity to investigate and better understand their genesis. In chapter 4 of the thesis systematic studies carried out on lime muds in five gravity cores collected at depths between 56 m and 121 m of the northwestern margin of India were presented. The studies include sedimentology (grain size, acid-insoluble residue, carbonate mineralogy, carbonate content, morphology), geochemistry (Sr content) and isotope (oxygen and carbon) chemistry and radiocarbon dates of the lime muds. The properties of the lime muds were
compared with that of the modern ones and following conclusions have been arrived.

- Gravity cores studied here contain abundant lime muds in the lower section and terrigenous-dominated sediments in the upper section.

- Lime muds are largely aragonitic in composition and are admixed with 30% to 50% terrigenous sediments on the shelf and <5% terrigenous material at the shelf break / slope.

- The grain size of the lime muds varies from 5 to 27 μm. The larger grain size in the shelf break/slope cores was due to aggregation of lime muds into ovoid and/or spheroidal grains.

- The Sr values of the lime muds in the shelf cores (0.18-0.61%) are much less than that of the shelf break/slope cores (0.10-0.83%).

- The Sr values of the slope cores are less than that of the inorganically formed aragonite needles from other regions and oolites.

- Depleted stable isotope ratios of the lime muds of the continental shelf indicate that the muds were formed either in water masses of different characteristic or altered after their formation.

- The lime muds at the shelf may have formed initially from the aragonite-producing plants and subsequently reworked and admixed with terrigenous sediments.
The age of the lime muds on the shelf ranges ~17-12 BP, implying submergence of the Gulf of Kachchh during early deglaciation and neotectonic activity in the Gulf region.

The Sr values, stable isotopes and morphology of the aragonite needles at the shelf break/slope indicate that the lime muds were of organic origin and largely decomposed from codiacean algae.

The organic matter associated with the muds may have facilitated cementation of individual needles into aggregates during early diagenesis and/or transportation at the sea floor.

The age of the lime muds in the shelf break/slope varies from ~16-12 ka BP in shelf break / slope cores.

Younger radiocarbon ages of lime muds between older ones in the slope cores indicate that the lime muds were reworked from the shelf or carbonate platform.

The lime muds ceased to deposit after 14 ka in deeper water cores may be due to the global event (rapid rise in sea level)- associated with Melt Water Pulse (MWP)1A at 14 ka BP.

The lime muds-dominated sediments gradually grade into terrigenous-dominated sediments after 12 ka BP. This change in depositional environment may be due to the combined influence of changes in regional climatic conditions, the Younger Dryas event and MWP1B.

Arabian Sea experiences seasonal reversal of monsoon wind patterns that result in variations in upwelling and related primary productivity. The
increased productivity in the water column resulted in permanent oxygen minimum zone on the continental slope at depths between 150 m and 1200 m and high organic carbon (OC) in the underlying sediments. The factors controlling the enrichment of organic carbon in sediments along the continental margin are a matter of debate for the last two decades. 'Productivity' and 'Preservation' models exist. In chapter 5 of the thesis, six sediment cores recovered from the northwestern margin of India at water depths between 56 m and 1900 m were investigated for organic carbon, calcium carbonate, organic carbon/total nitrogen ratio, acid-insoluble residue, grain size, sand content, planktonic and benthic foraminiferal content. Organic carbon data from the northwestern margin of India was also compared with that of the southwestern margin of India. The factors controlling the spatial and temporal distribution of organic carbon were identified. The summary and conclusions drawn from the study are:

- The organic carbon in the sediments of the shelf cores range from 0.18% to 0.47% and largely supplied from continental sources. In the late Pleistocene sediments of these cores OC was mostly reworked and associated with lime muds.

- The sediment texture, sedimentation rate and oxic water column at shallow shelf have influenced the OC content in the sediments.

- The late Pleistocene sediments of the upper slope also contain abundant lime muds.

- Within the continental slope, the cores from the oxygen minimum contain more OC (1.02%-4.83%) than those above (0.06%-1.14%) and below the oxygen minimum (0.28%-0.88%).
The early deglacial sediments of the NW margin of India, in general, contain low OC content and agree well with that of the Pakistan margin.

A distinct change in sedimentary environment occurs at ~12–11 ka BP in the early Holocene sediments.

OC content increases progressively from 12-11 ka BP to until 7-6 ka BP and remains high in mid and late Holocene sediments. This implies high OC production was after 7-6 ka BP.

The record of high OC content in the Holocene sediments mismatches with the past monsoon intensity record, which suggests that monsoon intensity was maximum at ~ 9-8 ka BP. This implies that factors other than productivity also play a major role in OC enrichment.

Intervals of high OC also coincide with high sedimentation rate and finer grain size.

The abundant aeolian transported material in the glacial sediments of the core off Indus may be responsible for low OC content.

The glacial sediments of the northwestern margin of India contain low OC than that of the southwestern margin of India. This implies OC variations are controlled by localized hydrographic conditions.

Comparison of the OC data between NW and SW margin of India suggests that high OC is not always associated with high productivity areas.
It appears that a combination of several factors influences the special and temporal distribution of organic carbon.

As detailed in chapter 3 the northwestern margin of India receives terrigenous sediments, both from fluvial and aeolian sources. These are largely derived from the Himalayas, arid and alluvial soils of Pakistan and north India and Deccan Traps of the northwestern India. As climatic conditions have changed from arid to humid during the late Quaternary one would expect the sediments contributed by the fluvial and aeolian processes vary at different times in the Quaternary. Similarly, the northwestern margin of India was subjected to late Quaternary neo-tectonic activity. The tidal currents at the Gulf of Kachchh and Gulf of Khambat become operative as the sea level rose to the present position and influence the distribution of fine-grained sediments. In other words, the changing climatic and physiographic conditions on the northwestern margin of India influence the composition and transport of the fine-grained sediments. In chapter 6 of the thesis, clay mineralogy of the <2 μm fraction of the sediments together with illite crystallinity and illite chemistry, clay content and median grain size of the terrigenous mud were investigated in five gravity cores recovered at depths between 56 m and 420 m. The studies were undertaken to better understand the provenance and transport pathways of the fine-grained sediments and hydrodynamic conditions in the depositional environment during the late Quaternary. The conclusions drawn are summarized below

- Reworked sediments are present in the late Pleistocene sediments of the shelf core collected off the Gulf of Kachchh. Abundant illite and chlorite in these sediments represent the Indus-derived material.

- The late Pleistocene sediments on the continental shelf off Saurashtra contain an admixture of clay minerals derived from the Indus and hinterland.
Increased smectite in the early and mid-Holocene sediments of both the shelf cores suggests larger supply of hinterland flux. The influence of tides operating at the Gulf of Kachchh acting as a barrier to the long shore sediment transport can be seen only in the late Holocene sediments.

Increased clay content in the late Pleistocene sediments of the cores on the continental slope indicates direct supply of terrigenous material on to the continental slope during the lowered sea levels.

Abundant illite and chlorite in the late Pleistocene sediments of all the continental slope cores suggest their derivation from the Himalayas by the River Indus and transported to the margin during the lowered sea levels.

Illite, chlorite-rich sediments in the late Pleistocene change over to smectite and kaolinite-rich sediments in the Holocene. This reflects changing sedimentary environment at the core site from Indus-dominated to hinterland-dominated clays.

The progressive increase in smectite content during the Holocene in a core off Saurashtra suggests increased cross shelf transport of clays from the hinterland.

Continuous increase in median grain size despite decrease in clay content in the sediment cores suggests winnowing of fine-grained material is effective in the upper slope sediments, most probably due to gravity currents operating at the shelf edge.

Intensified monsoon conditions during the early and mid-Holocene are evident from the increased concentrations of smectite in the slope cores.
Illite crystallinity and illite chemistry measured from the X-ray diffractograms reveal crystallinity of illite responds much faster for the changing weathering conditions than illite chemistry.

Contribution of aeolian dust to the study area is insignificant, except in a core off Indus. Low S-ratio% and illite dominance at LGM indicate arid conditions. If aeolian is present in other intervals, it must be <5% of the sediment that cannot be identified by X-ray diffraction studies.

Sr-Nd isotopes are very much essential to characterize specific sources of illites off Saurashtra.