

Holocene climatic inferences from the sediments of the Western Indian continental shelf

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Abstract. Data on the distribution and abundance of two of the most prominent sedimentary facies, the relict carbonate sediments and rocks (oolitic limestones, algal limestones and calcareous sandstones) and the modern terrigenous clastics present on the western Indian shelf, form the basis of the inferences on the climate that prevailed during the Holocene (about 10,000 years ago). The extensive carbonate sediments, carbonate cemented rocks, dead algal and coral reefs point to a set of circumstances the dominating factor of which were warmer climates and low terrestrial run-off. Further the quartz grains in the inner shelf are an order of magnitude smaller in size (0.01 mm) than those on the outer shelf (0.8 mm) implying intensified fluvial processes at the time of deposition of the relict sands. Assuming no tectonic change, intensification of fluvial processes can result from shortlived bursts of heavy rainfall quite unlike the pattern of rainfall prevailing in India today. Converging lines of evidence therefore indicate an arid climate during the Holocene, and the contrast between the carbonate and clastics on the shelf suggests rapid change from arid to moist climate. The possibility of arriving at a greater refinement in the understanding of the past climatic conditions over India, especially the monsoons, through the examination of the growth bands of living and dead corals on the western continental shelf is suggested.

Keywords. Paleoclimate; Holocene; sediments; continental shelf.

1. Introduction

It is by now a well-established fact that the climate on the earth has undergone long term (geological) and short term (historical) variations. Much of the recent refinements in the reconstruction of former climate has resulted from the study of sea floor sediments, especially on long cores from the deep sea (CLIMAP 1976). These sedimentary climatic records are based on lithology, fossils (plankton, pollen, molluscs, corals) and the oxygen isotopic study of microfossils. The general features of quaternary climatic changes, evidences of past weather and climate and the causes of climatic change are comprehensively covered by Budyko (1977), Lamb (1977), Gribbin (1978) and will not be repeated here. What is particularly interesting from the record of the reconstruction of past climates is the fact that in all tropical continents definite signs of a marked dessication with northern

glaciation have been found (Fairbridge 1972). Further, tropical geomorphic processes (fluvial, eolian, littoral, biogenic, weathering) reflect the dynamics of climatic changes. On the basis of the variation of these processes, Fairbridge (1976) believes that tropical Africa, Brazil and Venezuela were reduced to savanna or desert about 10,000 years ago. Changes of climate over India during the proto-historical and historical periods have been discussed by Seth (1963), Singh *et al* (1974) and Allchin *et al* (1978). These studies are based on archaeological and pollen data and indicate an alternation of arid and moist climate between 8,000 B.C. and 323 B.C. The acquisition of sedimentologic data from a substantial area of the western continental shelf of India offers an opportunity to draw inferences on the climatic change over India. This report therefore documents the gross features of the climate during the Holocene as recorded in the shelf sediments.

2. Results and discussion

Sedimentologic data pertaining to the surface sediments of about 75% of the area of the western continental shelf have been reported in many publications. The area that has been investigated extends from the river Indus (23° N Lat.) to Cochin (10° N Lat.). Within this domain of 13° lat. are present a variety of climatic conditions but the dominant feature is the tropical monsoon. The northern part borders, the Tropic of Cancer and is a region of high temperatures, low rainfall (300 mm per annum) and encloses the Thar desert. The physiography of the southern part is dominated by the Western Ghats which are characterised by lower temperature ranges and considerably higher rainfall (3,000 mm per annum). These differences result in different geomorphic processes and in turn influence the sediment contribution to the shelf.

Surface sediment facies on the western continental shelf has been reported by Nair and Pylee 1968, Nair 1971, Nair *et al* 1978, and Hashimi *et al* 1978a. The distribution of grain size, light mineralogy, heavy mineralogy and the nature of carbonate components in the shelf sediments have been studied by Hashimi and Nair (1976); Hashimi *et al* (1978b); Kidwai *et al* (1981). The nature of bottom topography and its origin have been discussed by Nair (1975) and the petrology and radiocarbon age of the rocks and sediments have been reported by Nair *et al* (1979). Total calcium carbonate has been determined by Rao (1978). These and a few other sources of data, which will be cited at appropriate places, form the principal material for deriving inferences of climatic changes.

The two primary controls of sedimentation are tectonics and climate. In addition, the sea level exerts a strong influence on the nature and amount of sediment deposited on the sea floor. In the following section, therefore, we shall first discuss the processes and products of sedimentation on the western shelf under the present tectonic, climatic, and sea level conditions.

2.1. Modern sediments

Modern sands of the shore zone occur within a few kilometres of the coast and extend to about 10 m water depth. These sands are composed of quartz with varying proportion of heavy minerals. They are derived as a result of wave erosion of cliffs and promontories of the west coast. Beyond 10 to 20 m are found the

modern muds (figure 1 a, b). These are terrigenous clastics, texturally silts and clays having low carbonate content (<10%) and high organic matter (3%). They extend offshore up to a distance of 160 km off Bombay to a depth of about 60 m (figure 1a). Towards the south, off Cochin, these muds extend up to 25 km offshore to a water depth of 40 m (figure 1b). The source of these muds are the rivers which drain the Western Ghats and the coastal plain at their foot.

To the northwest, off the Saurashtra coast, the shelf is bordered by a semiarid land which is a poor source of sediment but fine grained sediments do occur within a limited distance of the coast. The sharp differences across the shelf in the texture of the sediments, their content of coarse fraction and terrigenous components, and the clay/clay + silt ratio (an index of the accumulation process of fine grained sediments) is shown in a profile off Calicut (figure 2). This profile can be

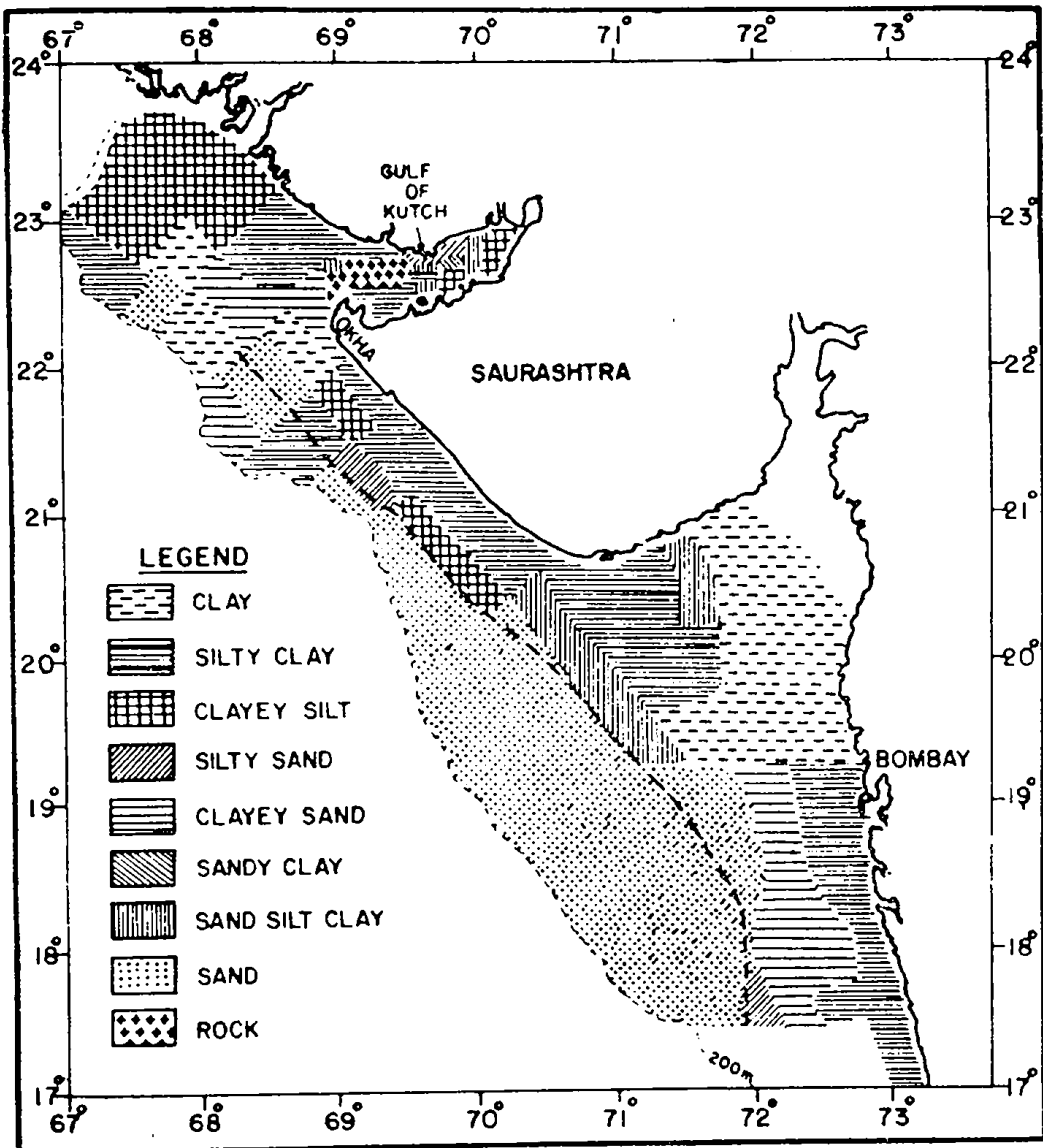


Figure 1 (a). (see captions in p. 302)

taken as being representative of and demonstrating the contrast between the sediments of the inner and outer continental shelf of western India. An obvious conclusion that has to be drawn from these differences is that they reflect the result of different geomorphic processes, the inner shelf muds being identified with the contemporary weathering and fluvial processes.

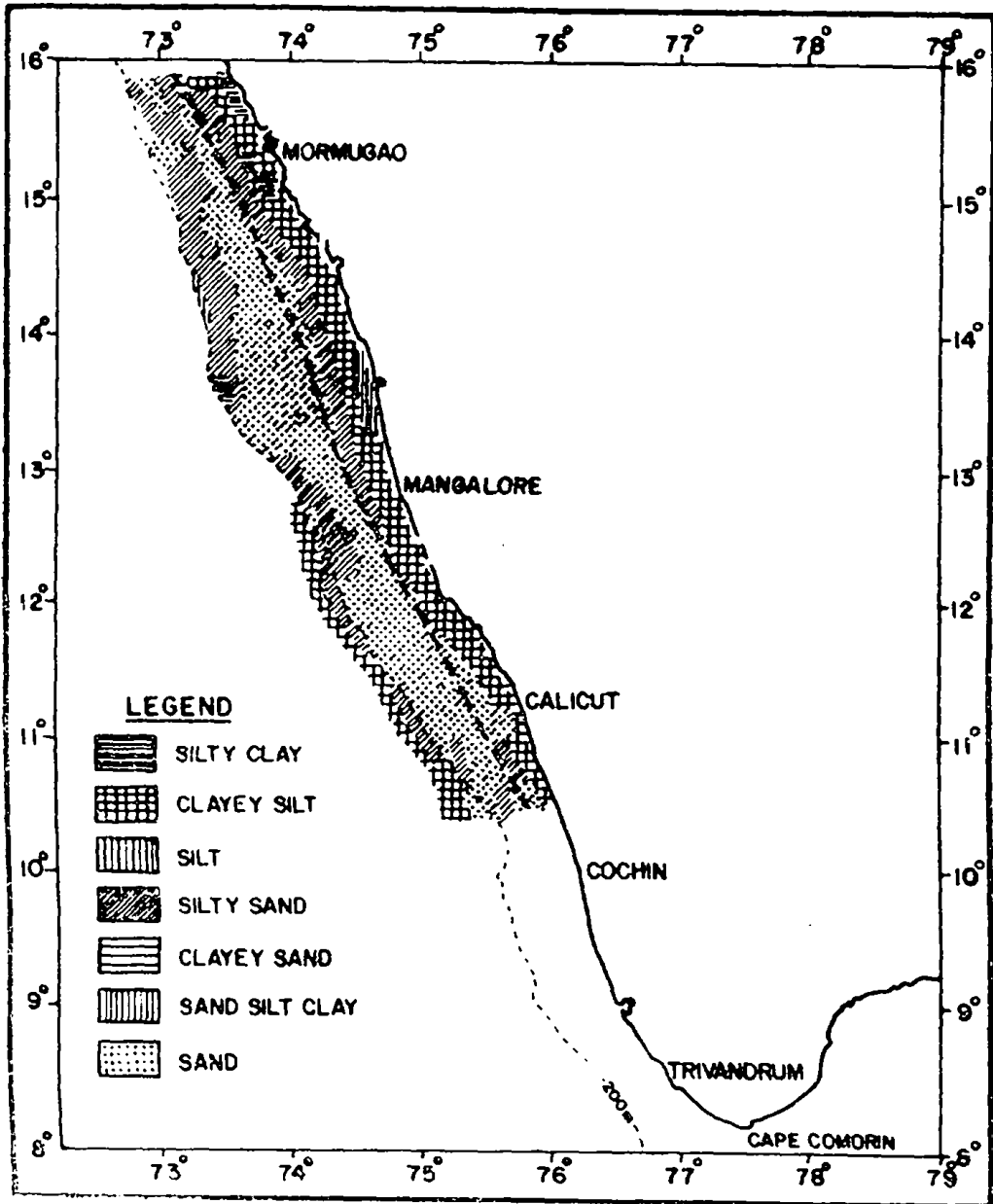


Figure 1 (b)

Figure 1. a, b. Surface sediment on the Western Continental Margin of India. Outcrops of algal, oolitic limestones and calcareous sandstones occur seaward of heavy dashed line.

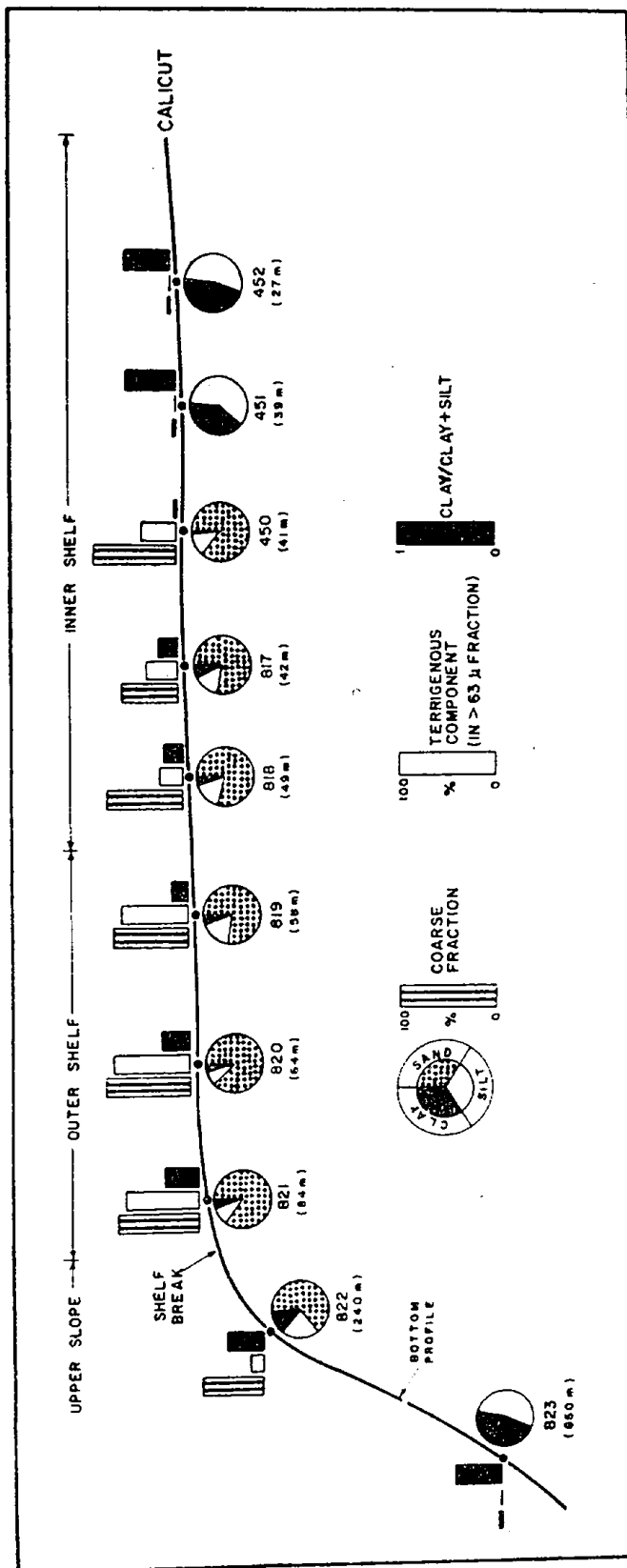


Figure 2. Variation in sediment components on the inner and outer shelf and upper continental slope across a profile off Calicut. Note sharp increase in the abundance of terrigenous component (climatically controlled) on outer shelf (41 m) to (84 m) and relative consistency of the percentage of coarse fraction which is the sum of carbonates (autochthonous) and terrigenous component. Inner shelf has high clay/clay + silt, very low quantities of coarse fraction and terrigenous component reflecting contemporary geomorphic processes.

2.2. Relict carbonate sediments and rocks

More than half the total area of about 300,000 square kilometres of the western continental shelf is covered with sediments which have more than 30% carbonate (Nair and Pylee 1968; Rao 1978). The carbonate content increases throughout towards the shelf margin. The highest values of carbonate are found on the northwestern part of the shelf and the maximum (> 75%) in this region occurs on the outer shelf off Bombay (Rao 1978). The sediments are coarse-grained (1ϕ to 3ϕ) and the carbonate content is mostly in the coarse fraction (> $63\mu\text{m}$) of the sediment. The carbonate assemblage consists of skeletal and non-skeletal components. The skeletal components are represented by bivalves, gastropods, pteropods, foraminifera and calcareous algae, together totalling more than 80%. Of the non-skeletal components ooids and pelletoids constitute the majority (figure 3). They are present to the extent of 50 to 90% on the northwestern part of the shelf and decrease to 30% to the south. South of Mangalore these non-skeletal grains are absent.

Carbonate material is also present on the outer shelf in the form of precipitated carbonate cement which has lithified loose grains of various types into hard rock. Rock samples obtained by dredging on the shelf between Okha and Mangalore indicate the presence of a variety of limestones such as oolitic and shelly limestones on the northwestern part and calcareous sandstones on the southern part of the study area. In addition to these, algal limestones occur throughout the outer shelf and shelf edge. They form discontinuous algal ridges which rise to a height of 1 to 5 m above the sea floor (Nair *et al* 1978). The Gulf of Kutch is also floored over large areas by limestones and dead coral reefs. On sedimentological and faunal evidences the limestones of the Gulf of Kutch and those of the continental shelf are believed to have formed under shallow water conditions (Hashimi *et al* 1977; Nair *et al* 1979). The distribution of these rock types over a large area of the western shelf shows that carbonate precipitation was quantitatively large in the past compared to the present.

2.3. Age of the shelf carbonates

Radiocarbon age determinations (analysed at the Tata Institute of Fundamental Research and Physical Research Laboratory), indicate that the ooid grains range in age from $11,330 \pm 350$ to $9,960 \pm 160$ years (figure 4). Similarly the oolitic limestones are $9,200 \pm 135$ to $8,960 \pm 200$ and the algal limestones are $11,150 \pm 130$ to $10,415 \pm 250$ years old (Nair *et al* 1979). The oolitic limestones are younger than the ooid grains by about 1,500 years because of the incorporation of younger carbonates in the form of cement. These sediments and rocks are thus of late Pleistocene or Holocene age. Sub-bottom shallow penetration profiles taken across the shelf indicate that this late Pleistocene carbonate surface continues under the modern muds of the inner shelf (Siddiquie *et al* 1977). Lithology of oil well logs from the well BS-1 (located on the inner continental shelf off Bombay) of the Bassein Field also indicates the presence of about 230 m of carbonate (shell debris with clay) beneath the modern muds (Sahay 1978). The stratigraphic relationship of these two distinctive facies is shown schematically in figure 5.

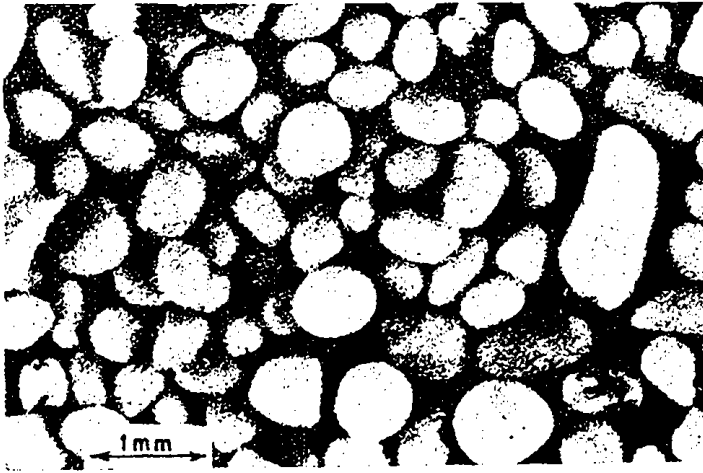


Figure 3. 11,330 years old ooid grains, sample No. N/10 (location in figure 4).

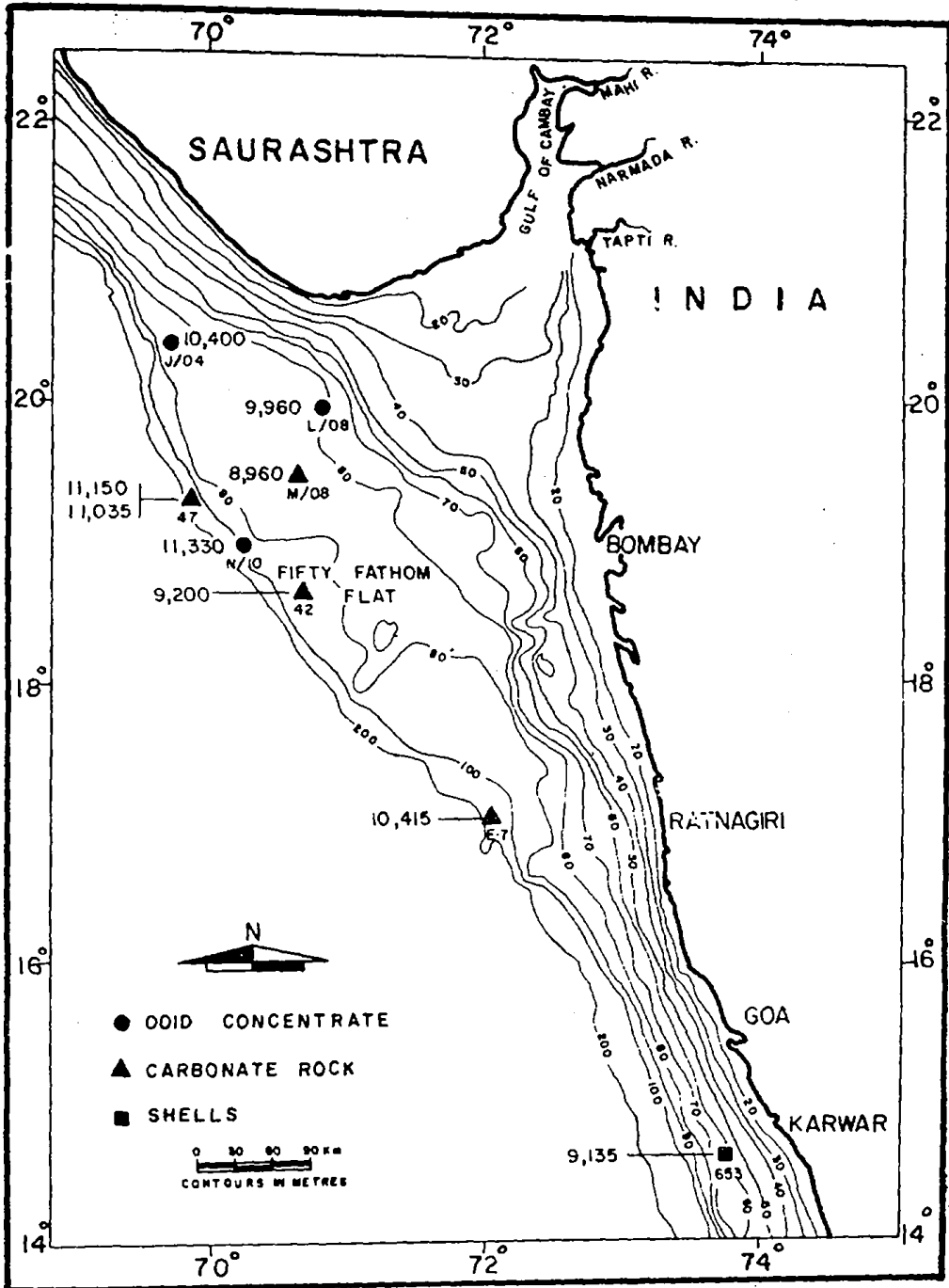


Figure 4. Radiocarbon dates and bathymetry.

2.4. Conditions for deposition of carbonates

Modern carbonate deposition demonstrates a positive correlation between such deposits and temperature (Emery 1968). In addition to warm waters it is also essential that the water be clear and shallow. Clear waters on the continental shelves are found where only minor influx of terrigenous clastics take place

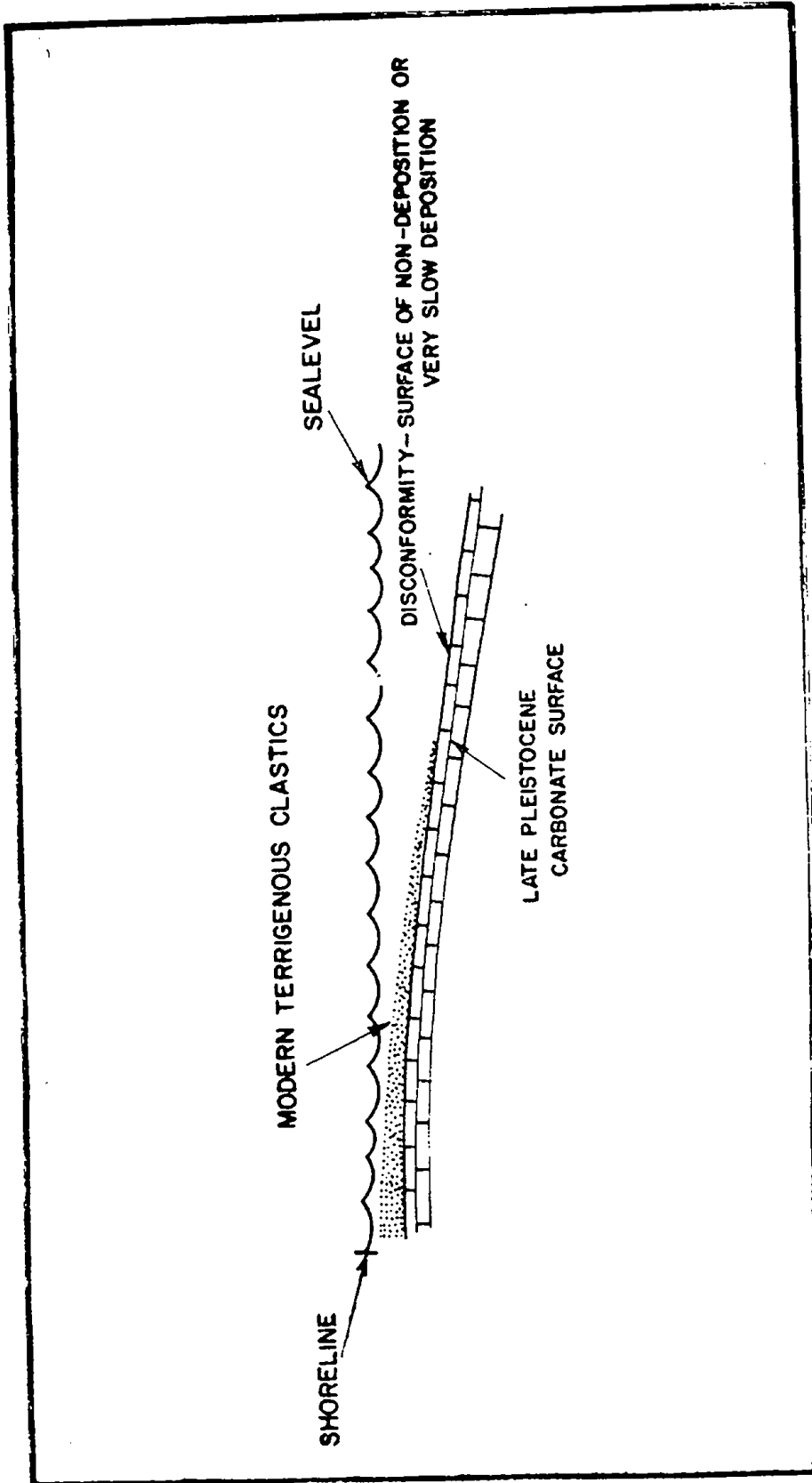


Figure 5. Schematic stratigraphic relationship between late Pleistocene carbonate and modern terrigenous clastics.

whereas on most tropical shelves the carbonate sediments are smothered by fine terrigenous sediments brought by large tropical rivers. The absence of major rivers on the west coast of India has, for example, resulted in the outer shelf carbonate sediments remaining free of mud cover.

At present tropical seas are essentially saturated with regard to carbonate. At least eight mechanisms are known that can cause precipitation of carbonates (Bathurst 1971; Milliman 1974; Wilson 1975). They are : (i) increase of temperature; (ii) intense evaporation; (iii) influx of supersaturated water into an area where carbonate nuclei or catalysers are present; (iv) marine upwelling; (v) mixing of water high in carbonate ion and low in calcium ion with sea water; (vi) organic processes in body fluids; (vii) bacterial decay to produce ammonia; and (viii) raising the pH and increasing the carbonate concentration and removal of carbon dioxide by photosynthesis. Of these mechanisms, 1 to 4 are of regional importance while the others (5 to 8) are of local importance. An important aspect of carbonate deposition that has been documented by Wilson (1975) is that carbonate deposition is rapid but is easily inhibited and therefore was sporadic during geologic time. From a comparative study of modern and ancient carbonates he arrives at average values of production of 1 m/1000 years and 0.04 m/1000 years respectively. These rapid rates of carbonate production is a sensitive mechanism and the rates are easily altered by accumulating to sea level or by turbidity induced by change of climate or source area.

2.5. *Climatic inferences from carbonate sediments*

The above descriptions of the carbonate distribution on the western shelf and the conditions which govern their deposition indicate that the climatic conditions during the time of their deposition, about 10,000 years ago, were different from the present. The extensive deposition of carbonate sediments, the precipitation of carbonates leading to the formation of oolitic limestones, calcareous sandstones and the proliferation of calcareous algae point to a set of circumstances the dominating factor of which was aridity. Under arid conditions precipitation will be limited with the consequence that run-off is reduced. Reduced run-off leads to poor supply of clastics to the shelf which in turn provides clear waters in which carbonate secreting organisms can flourish.

The sharp contrast between the carbonate sediments and the overlying terrigenous fine grained sediments signifies that the carbonate deposition mechanism was 'switched off' within a short period of time. This must have happened when the climate changed "suddenly" from largely arid to more moist regime.

The total quantity of carbonate material precipitated on the western shelf 10,000 years ago was considerably greater than that being produced at present. This can be interpreted to mean that the temperature of the waters of the Arabian Sea (the shelf waters) was higher or that the intensity of the evaporation greater 10,000 years ago. In addition, it is possible that upwelling at that time was more intense. This possibility becomes significant when two aspects are considered. The geographic setting of the ooid distribution on the western shelf shows similarities to the Bahamian ooids in the sense that both are closely associated with the oceanic environment. In contrast to these regions are the ooids of the Persian Gulf (Loreau and Purser 1973) which is a region with restricted connection to the open

sea. In the case of the Bahamian area the modern carbonates have been explained in terms of increasing water temperature and decrease of carbon dioxide as the ocean waters rise upwards (upwelling). Upwelling of a weak nature takes place in the western shelf waters as a result of the baroclinic adjustment of the water structure in the Arabian Sea to the anticyclonic monsoon circulation (Wyrski 1973). Modern ooids are absent in the shelf sediments. Therefore, the presence of 11,330 years old ooids (figure 3) on the shelf may be, but not necessarily, indicative of more intense upwelling at that time. The fact that ooids, pelletoids and aggregates (grapestones) are restricted to certain environments (warm, shallow water, supersaturated) suggests an inorganic control on precipitation and upwelling may be one of the contributing factors.

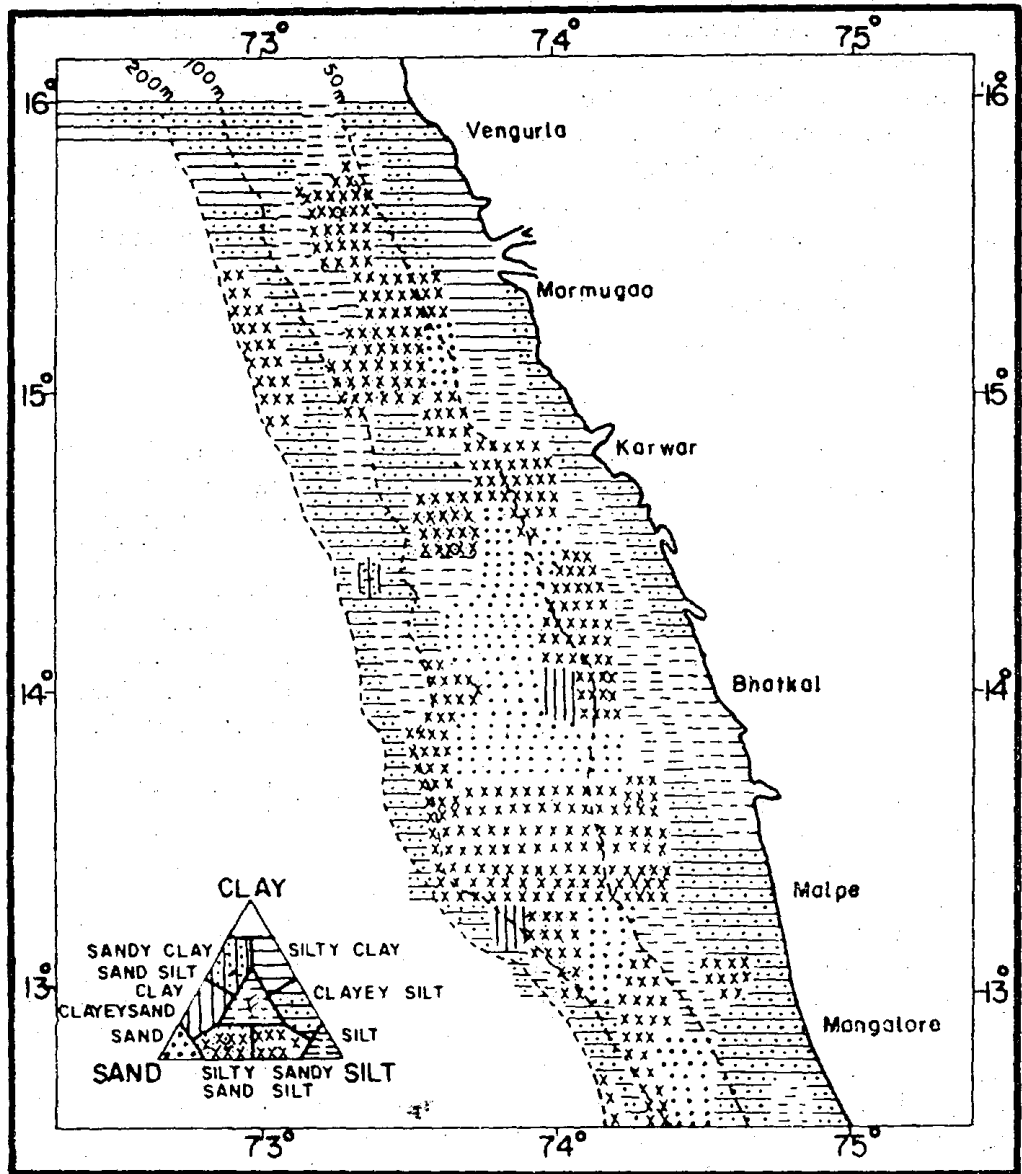


Figure 6. Carbonate free sediment facies on continental shelf between Vengurla and Mangalore (after Nair *et al* 1978).

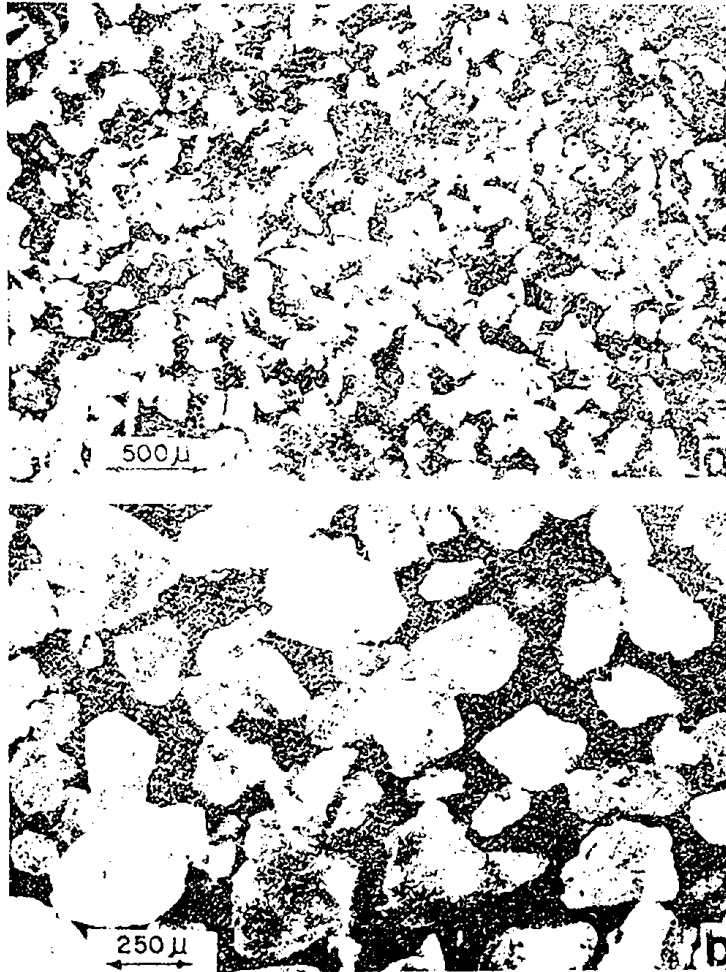


Figure 7. Quartz grains (a) inner shelf, depth 20 m, (b) outer shelf, depth 81 m.

An increase in biological productivity during the late Pleistocene is also indicated by the extensive growth of calcareous algae on the outer shelf and shelf edge. These have not been identified but may consist of the coralline algae genera *Porolithon*, *Neogoniolithon* and *Lithoporella* which according to Adey and Macintyre (1973) are the dominant tropical genera. These algal reefs and the coral reefs of the Gulf of Kutch are now dead or inactive. It is conceivable that the increase in the biological productivity of the shelf waters that was responsible for the growth of these reefs during the late Pleistocene was due in part to an increase in the intensity of upwelling. Apparently, the lone representative of the once extensive reefs of the outer shelf which has survived the Pleistocene drowning is the hermatypic coral reef known as the Gaveshani Bank (Nair and Qasim 1978), located at the shelf edge off Mangalore.

2.6. Climatic inferences from the grain size of the sediments

The marked differences between the inner and outer shelf sediments in texture, grain size and coarse fraction content has been noted earlier. The differences arise principally due to the content of carbonate material. They are fundamentally autochthonous, i.e., produced within a given basin and not introduced from without by rivers or streams. However, by removing the carbonates from the sediments it is possible to enhance the textural variation that is exclusively due to the terrigenous clastics. Figure 6 shows the texture of the sediments on the shelf between Vengurla and Mangalore, for example, on a carbonate free basis. It is evident from the figure that the sediments beyond about 40 m depth, and more prominently beyond 50 m depth, are coarser than those on the inner shelf. These outer shelf sediments are predominantly composed of quartz grains. Figure 7 shows a marked contrast between the quartz grains of the inner and outer shelves. These grains are from the water depths of 20 m (inner shelf) and 81 m (outer shelf). Both the samples are from the same transect. The inner shelf quartz grains (figure 7a) are very angular to angular, are less than 0.01 mm in size, have vitreous lustre and are free of iron oxide stain. In contrast, the outer shelf quartz grains (figure 7b) are sub-angular to sub-rounded, larger in size, and iron oxide stained. The important point to note here is the order of magnitude difference in their sizes. To produce such coarse sands requires climatic conditions that are different from the present, assuming no major tectonic change. In tropical regimes the effect of climatic changes is less marked by temperature effects than by precipitation but at higher latitude the opposite is true. Therefore a change in the pattern of precipitation is the most likely cause. Specifically the distribution of rainfall must have been heavy but sporadic and short lived to cause flash floods. Flash floods are capable of transporting even gravel sized materials for long distances and occur most frequently in desert regions of the world (Flint 1971; Fairbridge 1976). Clarity of water, one of the important requirements for the growth of carbonate secreting organism, is thus maintained. Short-lived turbidity as a result of flash floods is less likely to have adverse effects on reefal communities than prolonged spells (about three months of the monsoon prevailing at the present) of turbidity, and dilution of seawater. These climatic conditions correspond to those prevailing in the sub-tropical arid zones. A further contributing factor, synchronous with climatic aridity, leading to increased

rates of erosion and thus generating coarse sediments during the late Pleistocene will be due to the readjustment of the base level of erosion of the rivers to the lowered sea level.

3. Conclusions

Summarising, we find that the converging lines of evidences from the shelf sediments suggest the following inferences on the nature of the climate during the Holocene. (i) It was warmer and drier than the present, (ii) the rainfall was heavy, shortlived and sporadic, (iii) the change from dry to moist conditions was sudden and (iv) upwelling in the northern Arabian Sea was probably more intense. A wider implication of these results is that the monsoon as we know it today behaved differently in the past. The inference that we have been able to draw from the shelf sediments about the past climate, especially on the nature of the behaviour of the monsoon, are admittedly rather sketchy and only a broad brush reconstruction has been possible. One possible approach to obtaining a greater refinement in understanding the behaviour of the monsoon in the past is to examine the seasonal growth bands of living corals (Buddemeier 1974), for example, the corals of Gaveshani Bank, which is the only known occurrence of live corals on the western shelf of India. Seasonal growth bands on these corals should be less well developed for the monsoon season because of the adverse environmental conditions like increased cloudiness, decrease in the amount of available sunlight, higher turbidity of the shelf waters, and dilution of sea water. The presence or absence of the monsoon "signature" in the dead corals, for example, of the Gulf of Kutch, should then provide a clue to the nature of the monsoon in the past. The validity of this hypothesis is being tested by us.

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