

Changing Sedimentary Environments During Pleistocene-Holocene in a Core from the Eastern Continental Margin of India

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Abstract. Sedimentological and geochemical investigations of the sediments in a core from the eastern continental margin of India, at a water depth of 1200 m, revealed two distinct sediment types. The Late Pleistocene sediments are greyish-black in colour and consist of mud turbidites in the lower part and dolostone breccia in the upper part. They also consist of illite and chlorite-rich clay minerals with high organic carbon and sulfur. Organic matter is of dispersed nature. These are similar to black shales and are apparently formed by rapid burial of terrigenous organic matter by turbidites with intermittent reducing conditions during lowered sealevels. Dolostone fragments appear to have been transported by mass movement processes during the terminal Pleistocene. The Holocene sediments are moderate yellowish-brown in colour and with detrital vivianite nodules at the base. These sediments are clayey with montmorillonite-rich, illite-poor clay minerals, lower organic carbon and sulfur contents and ferruginised pyrite grains, deposited under oxidising conditions. The marked changes in the sedimentary environments are attributed to climate and sealevel changes during Pleistocene and Holocene.

Keywords. Environment, Pleistocene, Holocene, Black shales, off Penner River, Continental margin.

INTRODUCTION

During the 42nd cruise of *ORV Sagar Kanya*, a 263 cm long sediment core was collected using a box corer at a depth of 1200 m on the continental slope, off the Penner River, eastern continental margin of India (Fig. 1). The core consists of two distinct lithological units: moderate yellowish-brown oxidised clays underlain by stiff greyish-black clays. Dolostones, vivianite nodules and several types of pyrite grains were identified at different intervals. The purpose of the present

study is (1) to describe the core sediments and to discuss the changes recorded in the sedimentary environment through time and (2) to report the occurrence of Quaternary black shales hitherto unreported in the Indian Ocean.

METHODS

During sub-sampling the sediment core onboard, colour was noted. Textural analysis was carried out. The less than 2 μ m fraction was used for clay mineralogy and the procedures adopted are given in

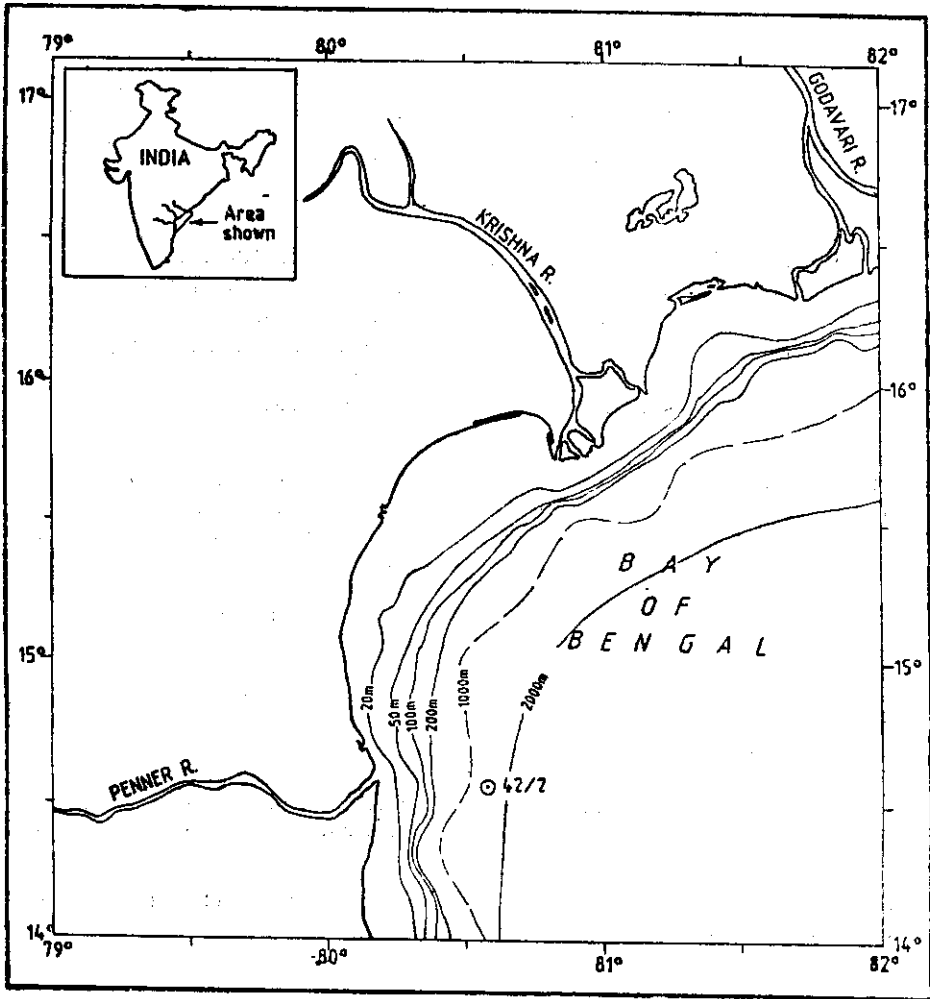


Figure I. Location of core 42/2 - the east coast of India.

Rao V.P. *et al.* (1988). Silt fraction mineralogy was carried out by X-ray diffraction. Coarse fraction components in the fraction greater than $125 \mu\text{m}$ were identified by using a binocular microscope wherein 300 grains were counted. Surface features of vivianite nodules were examined by JOEL scanning electron microscope (SEM)

Organic carbon content was determined by the method of El Wakeel and Riley (1957). Total reduced sulfur was determined by treating the wet sediment

with aqua regia, with subsequent addition of BaCl_2 to the filtrate, and weighing the resulting precipitate as barium sulfate (Sheu and Presley, 1986). Total carbonate was measured by weight loss method. Rock-Eval pyrolysis was used to determine the type of organic matter.

RESULTS

Two distinct sediment types observed in the core are moderate yellowish-brown (10YR5/4) clays in the upper part

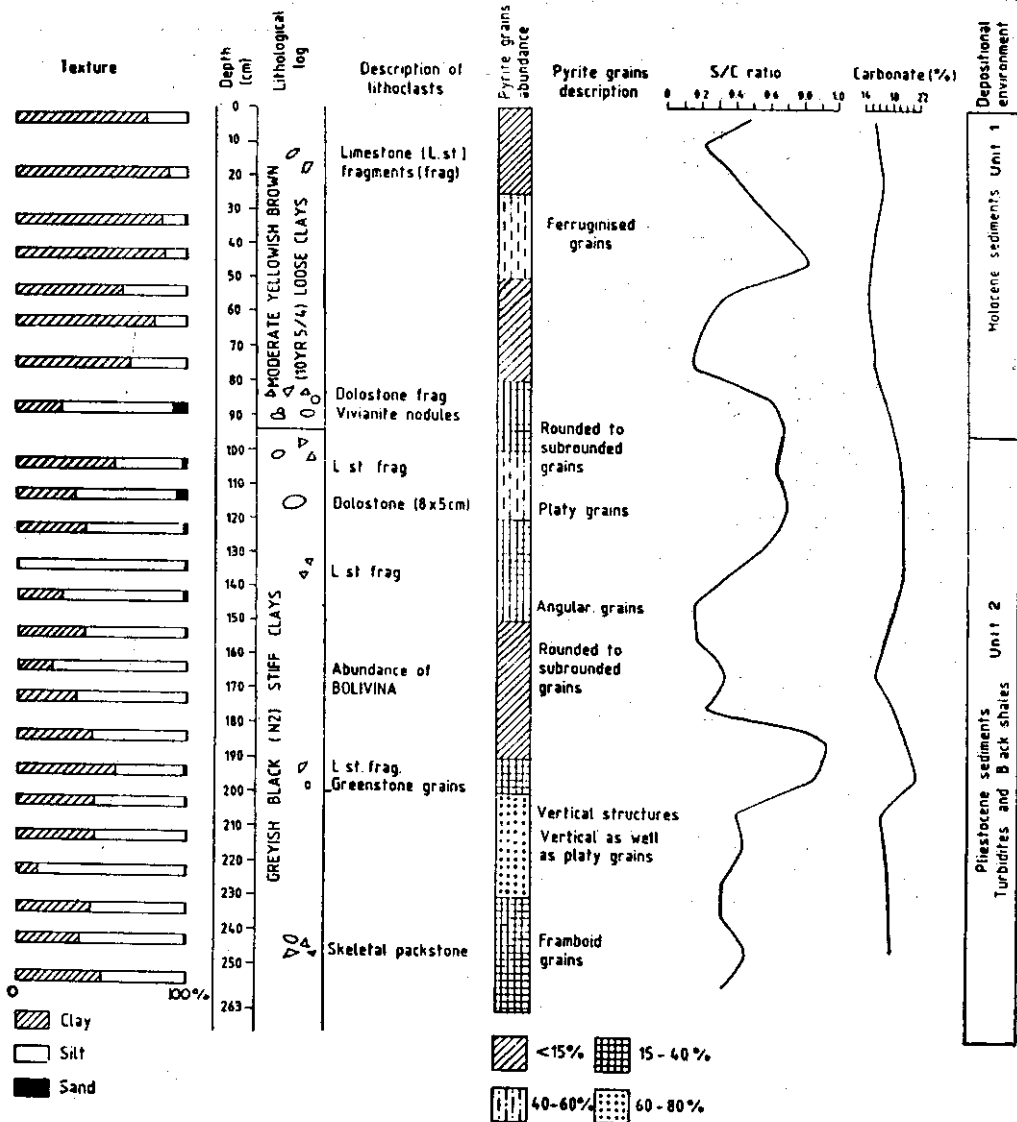


Figure 2. Lithological, textural and geochemical log of the core.

(0-94 cm) and greyish-black (N2) stiff clays below (94-263 cm) which are designated here as units 1 and 2, respectively.

Texture and mineralogy

Unit 1 sediments are clayey with no definite downcore variation in grain-size.

In unit 2, silt is the dominant size fraction. Textural gradation with progressive coarsening up in silt content within 30 cm interval was observed between 130 and 263 cm (Fig. 2). This graded sequence was interrupted by ungraded sediments at the top in some places. These graded and ungraded sequences seem to correspond to

E3 and E2 divisions of Piper (1978) and E division of Bouma (1962). These sediments resemble mud turbidites described by Stow and Piper (1984). Higher clay content has been observed in the sediments between 95 and 130 cm without any gradation.

Montmorillonite, kaolinite, illite and chlorite are present in decreasing order of abundance in the clay fraction of unit 1 (Fig. 3a). Within the silt fraction quartz is the abundant mineral (70%) followed by calcite (15%), feldspar (7%) and illite (8%: average values). Chlorite and illite are relatively rich in unit 2 (Fig. 3b), as compared to unit 1. The approximate order of abundance is montmorillonite, illite, chlorite and kaolinite. Quartz, feldspar, calcite, pyrite and illite in the silt fraction and their average values are 65, 12, 7, 6 and 4 per cent respectively, suggesting that feldspar and pyrite are high when compared to unit 1 sediments.

Coarse fraction

Pyrite grains with characteristic ferruginous coating (Fig. 4a) are present in unit 1. Comparatively, in unit 2 several types which include subrounded to rounded pyrite grains with surface weathering (Fig. 4b), platy pyrite (Fig. 4c), pyritised vertical structures (tubules) of 0.06 to 0.08 mm diameter (Fig. 4d) with tapering edges and rough surface texture, framboidal pyrite, pyrite infillings and pyrite encrusted planktonic forams are present at several locations (Fig. 2).

Vivianite particles occurring as spherical (Fig. 5a) and in spheroidal aggregates

are found exclusively at 80–94 cm interval. These are dark blue in colour and range in size from 475 to 6000 μm . Grain surfaces are composed of linear ridges

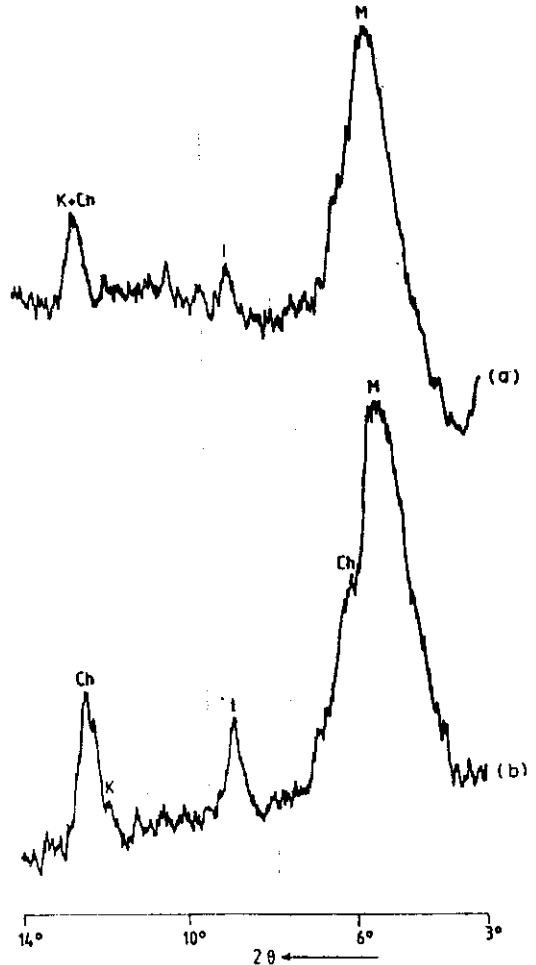


Figure 3. Representative X-ray diffractograms (glycolated) of the clay minerals of $<2\mu\text{m}$ fraction, (a) moderate yellowish clays, (b) Greyish black clays, M—montmorillonite, K—kaolinite, I—illite, Ch—chlorite.

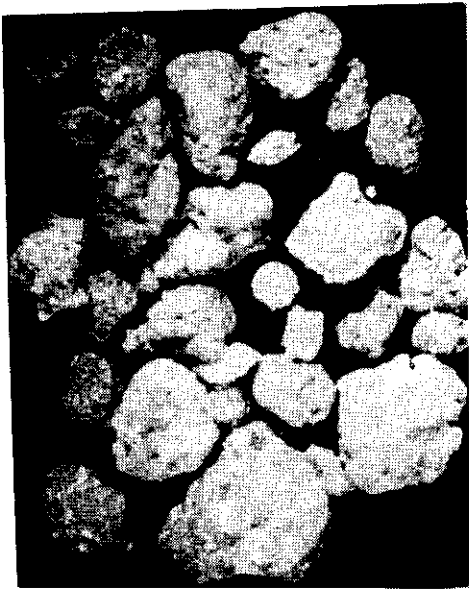
EXPLANATION OF FIGURE 4

Photomicrographs: a. Pyritised grains showing ferruginous coating; b. weathered pyrite grains; c. platy pyritised grains, note partly pyritised grains below; d. pyritised vertical structures (tubules).



a

0.6 mm



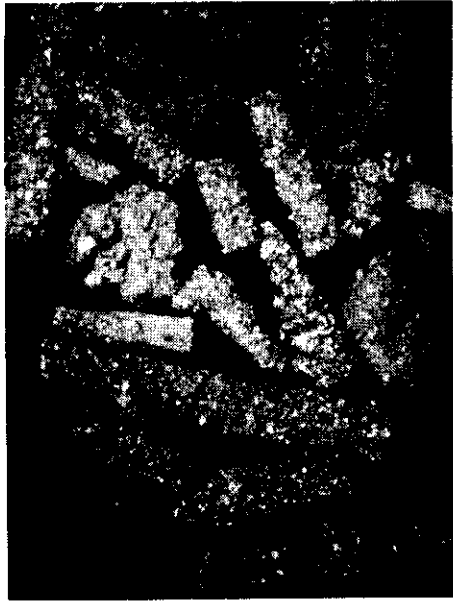
b

0.6 mm



c

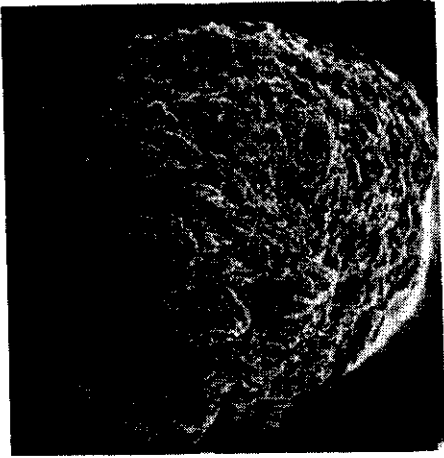
3.3 mm



d

2.0 mm

Figure 4.



a

740 μm



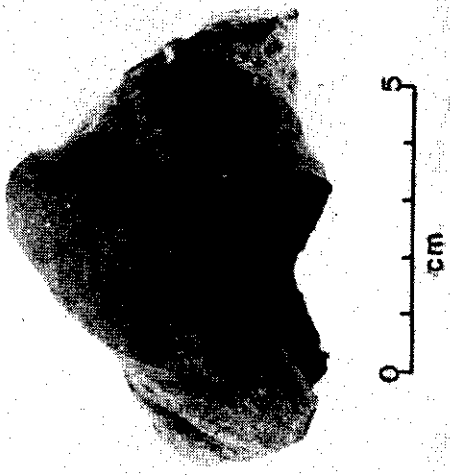
b

37.5 μm



c

100 μm



d

cm

0 5

Figure 5.

with adjacent pits. SEM examination revealed that linear ridges are made up of platy and lath shaped crystals. Abrasional and dissolution features (Figs. 5b and 5c) are found on lath surfaces.

Grey-green coloured fine-grained indurated massive rock identified as dolostone is found at 110–120 cm (Fig. 5d). Dolostone fragments are found between 94 and 120 cm interval and also in association with vivianite. Other lithoclasts rarely present at different intervals are rounded limestone grains and skeletal packstones (Fig. 2).

Skeletal material is dominated by benthic foraminifera with less than 12% planktonics in both the units. The unit 2 interval between 150–200 cm is characterised by an abundance of *Bolivina*. Other benthic genera identified are *Uvigerina* and *Operculina*. *Globigerinoides sacculifer*, *G. ruber*, *Globigerina bulloides* are the most common planktonic species in the unit 1 sediments.

Organic carbon, Sulfur, and Carbonate content

Organic carbon (C) and total sulfur (S) contents range from 0.8 to 1.8% and 0.23 to 1.1% in unit 1 and from 2.1 to 3.4% and 0.5 to 2.6% in unit 2, respectively. Carbonate content varies from 14 to 16% in unit 1 and from 15 to 21% in unit 2. Rock-Eval pyrolysis of the sediments yielded hydrogen index values between 16 and 68 mg HC/g TOC. The temperatures of maximum pyrolysis yield (T_{max}) are below 440° indicating that the organic matter is immature. According to the plot of Hydrogen Index and T_{max}

the sediments contain organic matter of kerogen type III (Fig. 7).

DISCUSSION

Unit 2

A sharp change in colour occurs at 94 cm interval. This colour change is accompanied by textural variation and the relative abundance of clay and silt minerals. The underlying greyish-black clays are more silty and richer in pyrite, feldspar, illite, chlorite, organic carbon and sulfur than the overlying yellowish-brown clays. This reflects the more detrital character of the greyish-black sediments. It is, therefore, assumed that the colour change at 94 cm marks the boundary between Holocene and Pleistocene.

The sealevel was at least 80 m below the present position during Late Pleistocene in this region (Rao, M.P. 1957). The narrowness of the continental shelf (20 km) and the existence of shelf break at 90 m depth off the core site (Venkatratnam, 1968) thus suggest that the present day shelf must have been subaerially exposed beyond the shelf break during the last glacial maxima. Then the river Penner was discharging sediments directly onto the continental slope. Higher slope gradients must have favoured the formation of turbidity currents and mud turbidites. Therefore, it is reasonable to suggest that the mud turbidites of unit 2 are of Late Pleistocene age.

Dolostone occurs as massive rock (Fig. 5d) rather than individual dolomite crystals in the upper layers of unit 2 (Fig. 2). Most probably, it is detrital rather than formed by authigenic dia-

EXPLANATION OF FIGURE 5

a-c. SEM photographs of vivianite nodule. (b) and (c) showing abrasional and dissolution features on crystal surfaces of vivianite; (d) dolostone.

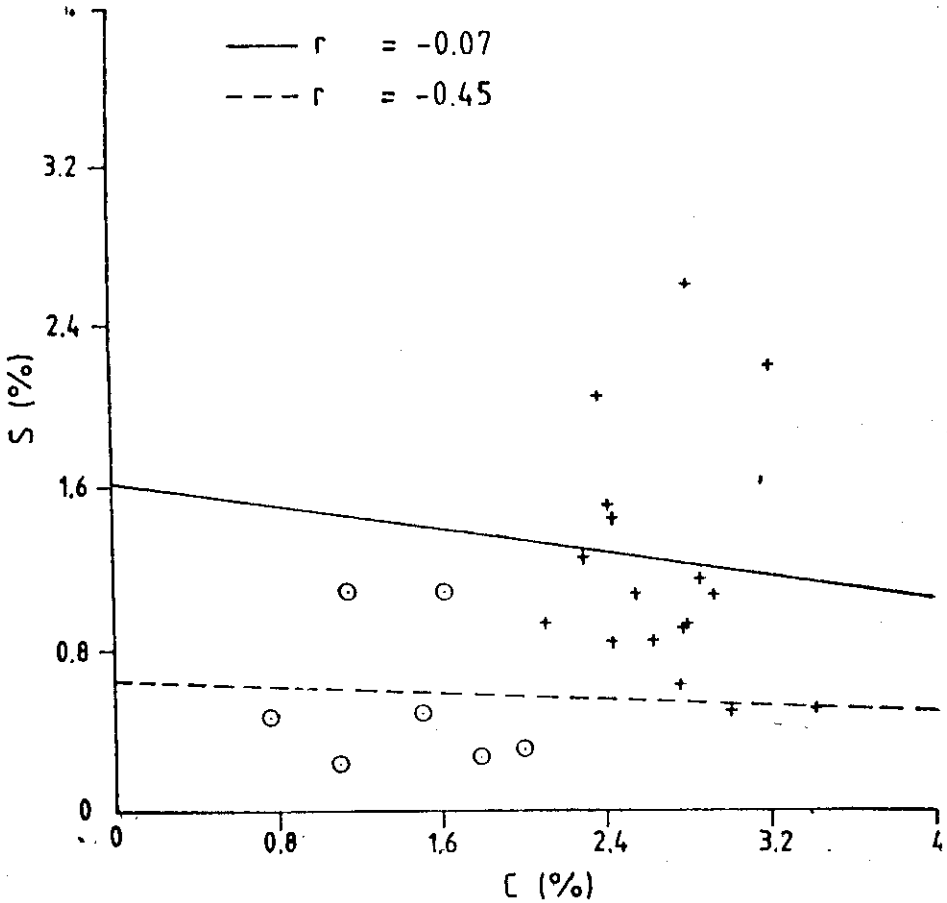


Figure 6.

Organic carbon (C) -Sulfur (S) relationship on a X-Y plot. Dashed line and dots indicate moderate yellowish brown clays. Continuous line and crosses indicate greyish-black clays.

genetic processes in the deep sea environment (Baker and Kastner, 1981). These could have originated from the Vempalli Formation of Cuddapah basin which consists of dolostone associated shales (Rao BKN. *et al*, 1987) of Proterozoic age. The dolostone fragments in the top layers of unit 2 may have resulted from changing climatic conditions which took place at the end of the Pleistocene. Heavy monsoonal rains in the Indian Ocean and an evidence of great increase in precipitation are reported in many parts of

the world at the Holocene/Pleistocene boundary (Kutzbach, 1983); heavy rains could have been effective in eroding the dolostone formations. Subsequent large discharge of water accompanied by sediment gravity flows may have transported these coarse clasts to the continental slope.

Depositional environment

Bolivina is a benthic foraminifer indicative of cold water and reducing environmental conditions (Phleger and Soutar,

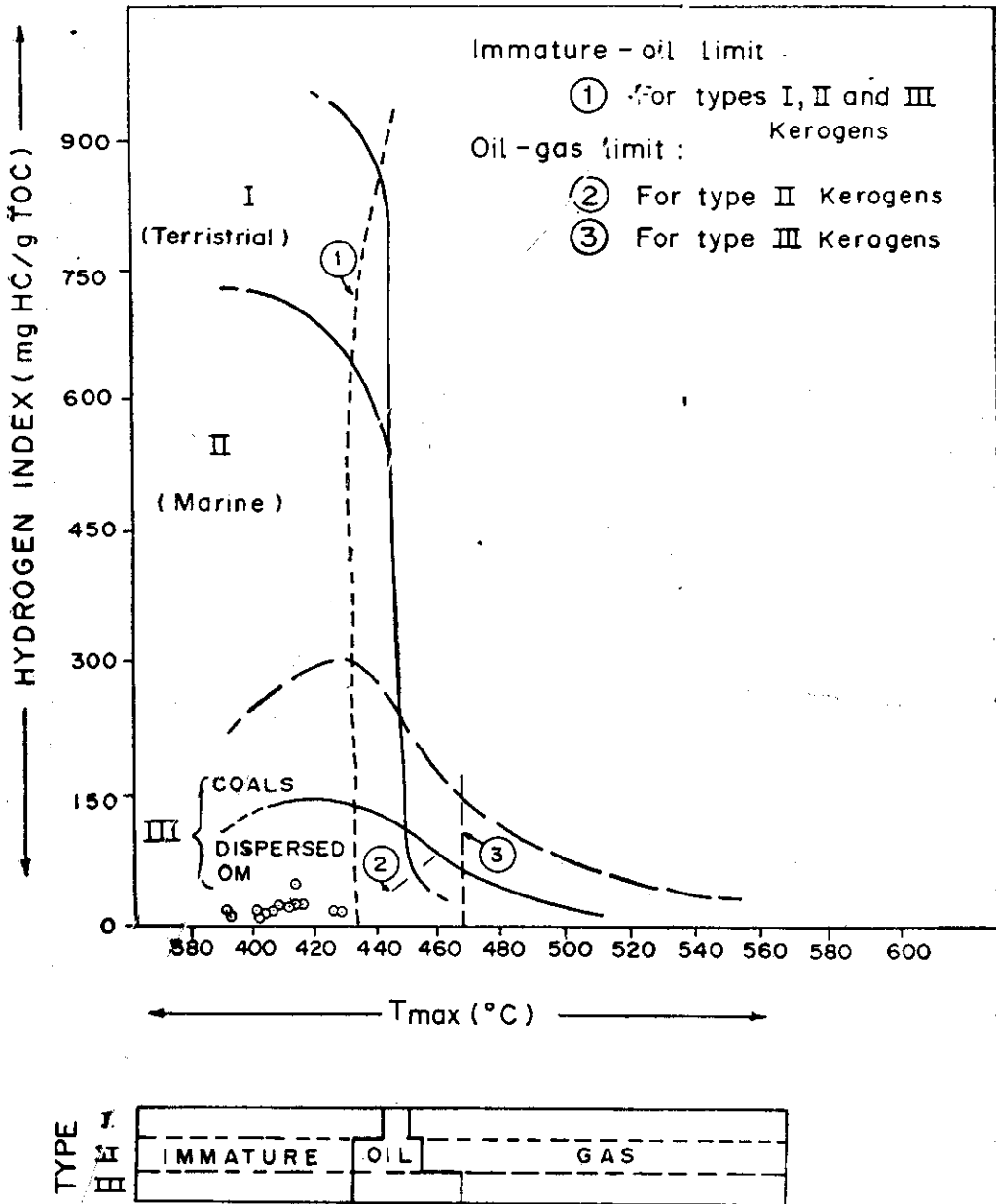


Figure 7.

A plot of Hydrogen Index (HI) versus Temperature maximum (T_{max}) for the greyish-black sediments.

1973; Haynes, 1981), The presence of *Bolivina* zone at 150-200 cm indicates that reducing conditions existed between two turbidite flows. This may be due to coincidence of an oxygen minimum layer at mid water depth. Pyritised vertical structures (Fig. 4d; Fig. 2) at different levels in the core are probably the casts of burrowing organisms and thus indicate bioturbation at these depths.

The S/C ratio is a useful parameter to distinguish the original depositional environment. The S/C ratio of recent marine sediments deposited below oxygenated bottom water is 0.36 and the C-S plot shows a linear relationship with the line of best fit passing through zero (Leventhal, 1983). In case of euxinic sediments, the S/C ratios are high and the C-S plot shows positive correlation with the line of best fit positively intersecting the S-axis (Leventhal, 1983; Berner and Raiswell, 1983). However, S/C ratios in the unit 2 varies from as low as 0.20 to 0.9 with an average value of 0.50. The C-S plot (Fig. 6) shows no correlation suggesting that there may be two depositional processes operating independently. These processes could be (i) authigenic pyrite formation and (ii) transportation and accumulation of additional sulfur/pyrite in the depositional environment from land and/or by slumping from adjacent slope. Peaks of high S/C ratios correspond to the enrichment of sub-rounded to rounded pyrite grains in the coarse fraction (Fig. 2). These grains (Fig. 4b) further show surficial weathering and are common at all depths in the core which may suggest transportation from subaerial exposure. The other particles such as vertical structures, platy, framboid and encrusted pyrites on lithoclasts may indicate a diagenetic pyrite formation *in situ*. This leads to the fact that S/C ratios are influenced by two sources of sulfur in the sedimentary column and the

depositional environment appears to be largely oxidising with intermittent reducing conditions. High contents of feldspars and illites may reflect the reduced chemical weathering that prevailed on land during Pleistocene.

Unit 1

Sediments of this unit do not show textural gradation which indicates that the rise in sealevel and landward shift in shore line minimised the turbidity current activity. Most probably coarser sediments were trapped in nearshore region. Moderate yellowish-brown colour, ferruginised pyrite grains, increase of montmorillonite and kaolinite and less illite in Holocene sediments were due to different climatic conditions on land. Low latitude regions have experienced arid and warm and humid climate in Late Pleistocene and Holocene, respectively. Chemical weathering which predominates in warm and humid climates leads to finer grain-size and removal of potassium from micas and favours the formation of kaolinite (Catt, 1986). Whereas, the soils under arid climates suffer less chemical weathering and thus decrease the clay illuviation. Lower S/C ratios (Av. 0.4, range 0.15-0.7) and no correlation between carbon and sulfur (Fig. 6) suggest two sources of sulfur as in unit 2 and the presence of oxidising depositional environment during their formation.

Vivianite nodules at the base of unit 1 may also mark the climatic change on land during early Holocene. Vivianite is a stable ferric phosphate mineral and is commonly reported in lacustrine (Mackereith, 1966; Rosenqvist, 1970; Dell, 1973; Nriagu and Dell, 1974), riverine (Hearn *et al.* 1983), and in estuarine sediments (Bricker and Troup, 1975). Its presence has not yet been reported in deep marine sediments. They occur in association

with dolostone fragments and shallow water fauna. Abrasional and dissolution features (Fig. 5b and 5c) are evident on crystal surfaces suggesting that they have been mechanically abraded during transportation. It is thus suggested that the vivianite nodules were formed in their classical river/estuarine conditions and have been transported. The vivianite nodules formed in fresh water sediments often show surface oxidation due to the presence of lipscombite, beraunite and rockbridgielite (Dell, 1973). However, X-ray diffraction studies exclusively show the reflections of vivianite. Therefore, their formation in river environment is unlikely. Vivianite was probably formed in estuary and subsequently transported to the continental slope by gravity displaced flows. The vivianite nodules are absent in greyish-black sediments but present immediately above, in association with moderate yellowish-brown clays. This may suggest that (i) climatic change during terminal Pleistocene/Early Holocene favoured the formation of vivianite in the estuary. It is perhaps due to abundant release of iron oxyhydroxides in the estuary which is a prerequisite for the formation of vivianite (Hearn *et al.* 1983) by chemical weathering during Holocene. Limited supply of iron in Pleistocene might have restricted its formation. (ii) Since the vivianites occur at the base of the Holocene sediments, they are similar to vivianites extensively reported in post-glacial clays (Mackereth, 1966; Rosenqvist, 1972; Dell, 1973).

Origin of Black Shales

The black shales are organic carbon-rich (>2%) strata and are important indicators of palaeoceanography (Degens *et al.* 1986). The sediments below 94 cm depth in the core are characteristic of black shales. The genesis of black shales can be explained by (i) high flux rates of

organic matter in areas of high oceanic productivity (ii) high flux rate of terrigenous organic matter and/or increased preservation of organic matter in areas of anoxic deep water environments as well as due to rapid burial of organic matter e.g. turbidites (Degens *et al.* 1986 and the papers therein). The carbonate content is less than 21%. Mineralogy of silt and clay fractions suggest the dominance of terrigenous material. Only 12% of the coarse fraction consist of planktonics and the rest is dominated by lithoclasts and benthic foraminifera suggesting that the organic matter source from the overlying waters is significantly less than the terrigenous source of organic matter. Rock-Eval pyrolysis further indicates that organic matter is of a dispersed nature (Fig. 7). Therefore, the influx of land derived organic matter, most probably, recycled from the weathering and erosion of shaly sequences in the Penner basin, might have reached the slope under the influence of Pleistocene dry climates.

The presence of bottom water reducing conditions as well as well oxygenated bottom waters in the core are indicated by the *Bolivina* zone and bioturbated zone, respectively. Therefore, burial of terrigenous organic matter due to rapid sedimentation by turbidites and the existence of moderately reduced conditions between turbidite flows appear to be the most likely mechanisms for the preservation of organic matter and the formation of black shales. Quick burial due to turbidites favours better preservation even under oxygenated bottom water conditions; reducing conditions can be established with sufficient organic matter supply which can lead to pyrite formation (Habib, 1983; Robertson and Bliefnick, 1983). These black shales are Late Pleistocene in age and their absence in Holocene sediments can be attributed to marked climatic and sealevel changes.

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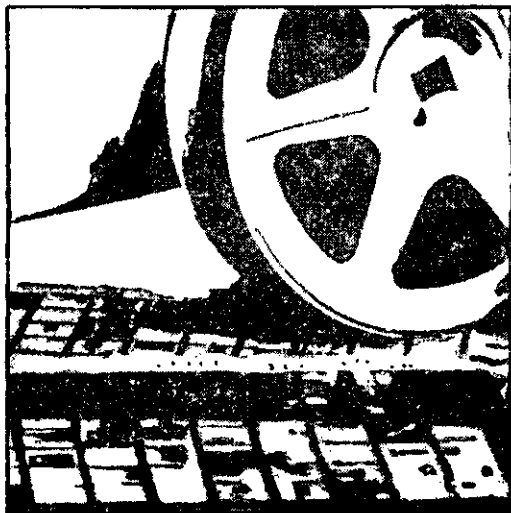
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