CHAPTER 2

GEOLOGY, GEOMORPHOLOGY AND HYDROGRAPHY

2.0 INTRODUCTION

The area of study is encompassed by the Indian subcontinent and the Arabian Sea. Hence, it is felt essential to summarise here the relevant information about these areas which will be of help in interpreting the results.

2.1 CLIMATE

The climate of the area has a regular variation and the weather is more seasonal than in most parts of the world. These seasons are:

The cool season, December to March, when winds are north-westerly and the weather is dry with little cloud except in the south.

The hot season, April and May, when winds are light and variable with sea breezes on the coast. Tropical cyclonic storms (cyclones) may cross the Arabian Sea.

The southwest monsoon or rainy season, June to
September, the wind over the sea is between southwest and west but mainly west to northwest along the coast.

2.2 ONSHORE

2.2.1 COASTAL FEATURES AND GEOLOGY

2.2.1.1 RIVERS - The Indus, the Narmada, the Tapti, the Sabarmati and the Mahi are the major rivers in the adjacent areas of the north-western continental shelf of India (Fig. 4). These rivers drain a variety of geological formations covering vast drainage basins before debouching onto the sea. The Indus River rises over the Himalayas and flows over the Pleistocene and Recent deposits for the major part before entering the sea. The Narmada River flows mostly over the Deccan Trap and the Quaternary deposits of the coastal areas. The river rises in the Amarkantak Plateau and flows over the marble rocks and widens into an estuary entering the Gulf of Khambhat. The Tapti rises in the Satpura Hills and traverses an extensive stretch of alluvium filling a deep basin. The Sabarmati river rises in the Mewar Hills and enters the sea at head of the Gulf of Khambhat. The Mahi River rises in Gwalior region and flows through Dhar, Jhagrua and Gujarat into the Gulf of Khambhat.

Besides these a number of medium and minor rivers are there which become active during the monsoon and flow down the Western Ghats into the sea (Rao, 1979).
Fig. 4 Rivers in the study area
Medium Rivers: Shetrunji, Bhadar, Dhadhar, Purna, Ambica, Vaiturna, Uthas and Savitri.

Minor Rivers: Luni, Banas, Saraswati, Rupen, Machur, Und, Keri, Bhagva, Mandhola, Par, Daman Ganga and Vashishti.

2.2.12 Morphology - The Indian coastline, including major indentations and the shores of Islands, is about 9,000 km long. About 55 per cent has beaches (spits, barriers or sandy stretches on the shore). The total length of prograding shore including deltas, is about one-fourth of the Indian coastline. The rest includes rocky overhanging cliff or combinations of rocky and beach shore (Ahmed, 1972). In particular the coastal features of the two states (Gujarat and Maharashtra) bordering the north-western continental shelf of India are described in the following paragraphs from north to south (West coast of India Pilot, 1961, 1975).

Gujarat - The coastline of the state of Gujarat extends from the eastern boundary of Pakistan and includes Kathiawar Peninsula to the northern boundary of Daman (20° 24' N : 72°49' E).

The most striking physical feature of the State of Gujarat is Ranns or salt marshes in the north-western part of the state. The Rann of Kachchh (Great western Rann) lying north of the district of the same name, is about 250 km long and 128 km broad, with an estimated area of about 17,900 square kilometres. The little Rann, at the head of the Gulf of
Kachchh is about 110 km in length and covers an area of nearly 5,000 square kilometres. With the exception of some of the smaller islands, where grass and a few stunted bushes may be found, there is no sign of floral life. During the southwest monsoon high tides cover the Ranns to a depth of from 0.3 to 0.6 m. The little Rann is undergoing marked changes, there is encroaching further east, making places accessible to boats which were formerly dry. Kal Dongar, the highest point in Kachchh about 465 m high stands out from bed of the Rann of Kachchh.

Kachchh district is practically an island, being almost entirely cut off from the mainland by Kori branch of Indus River, the Rann of Kachchh and the Little Rann. On the whole the country is treeless, barren and rocky with ranges of hills and isolated peaks, but it contains many well filled valleys. To the south, behind a high bank of sand that lines the sea coast, there is a low, fertile land from 30 - 45 km wide, inland of this a broad belt of hilly ground, from 150 m to over 300 m high stretches east and west; Nanu or Nunnomar, Krikubbah and Katrura are the principal submits.

Kathiawar peninsula, except in its northern part, which is almost entirely flat is generally undulating with low ranges of hills running in irregular directions. There are extensive mountain tracts lying within about 60 km of its southwest seaboard; Gir hills, north of Diu Head and Barda Range, northeast of Porbandar, are the principal mountain...
groups. The highest submit, however that of Gorakhnath (Girnar) with an elevation of 1,116 m, lies about midway between them.

Broach district forms an alluvial plain, sloping gently west-ward, varying in breadth from 30 to 65 km; with the exception of few hillocks of sand drift along the coast, there is no rising ground. The soil is highly fertile and well cultivated.

Narmada River, the only other major river of the west coast of India, enters the sea through a wide estuary 40 km north of Tapti River.

Surat district consists of a broad alluvial plain, with small hillocks of drifted sand fringing the greater part of the coast, which in some parts is dry and barren, and in others watered by springs. Through the springs of the river mouths the tide flows up behind the barrier of sand hills, and floods a large area of salt marshes. Beyond spreads a belt of highly cultivated land, restricted by the hills towards the south to a breadth of little more than 25 km, but with a width of about 95 km in the north, where Tapti River forms a deep and fertile delta.

Maharashtra - The coast of the State of Maharashtra extends along the Konkan coast between Daman in the north and Goa in the south. The districts of Greater Bombay, Thana, Kolaba
Ratnagiri and Sindhurg front the Konkan coast from north to south. The Western Ghats, with general elevations from 600 to 900 m but with some peaks over 1,500 m high, run almost parallel with the coast leaving a strip of land upto 95 km wide.

The district of Greater Bombay (18°33', 19°18' N and 72°42', 72°58'E) encompasses Bombay, South Salcette and Trombay Island with an area of 603 sq. km. consists of mostly low lands.

The 955.3 sq. km. coastal region of Thana district, lying between 19°00', 20°22'N and 72°52', 73°45'E, consists of a strip of low land intersected by hill tracks of upto over 750 m high; the flat alluvial belt between Ulhas and Vaitarna rivers is known as North Konkan. To the east and northeast the country becomes elevated and wooded while, near the coast, the land is low and fertile with abundant palm growth.

Kolaba district lying between 17°53', 19°08'N and 72°53', 73°42'E, is very hilly, some of the hill being spurs of considerable regularity and height, running west at right angles to the main range, and the coast. The sea frontage is mostly fringed by a belt of coconut and arecanut palms, behind which lies a stretch of flat rice producing country.

Sindhurg district and Ratnagiri lying between Savitri River and Goa (15°32', 18°05'N and 73°02', 74°13'E) is generally rocky and rugged; near the coast it consists of bare elevated
plateaus, intersected by numerous creeks and navigable rivers, flowing between steep and lofty hills. About 15 km inland the country becomes more open, but a little further it is occupied by spurs of the Western Ghats. The coast is almost uniformly rocky, and consists of small bays coves shut in between jutting headlands, and edged with sand of dazzling whiteness.

2.213 Geology - Along the coast of Kachchh a 5 - 16 km wide strip is largely covered by alluvium consisting of wind blown loam and sand underlain by clay. Between the alluvial belt and the traps, there are two belts of Tertiaries roughly parallel to the shore. The older beds consist of clays and limestones of Eocene age. The younger beds are sandstones and clays ranging in age from lower Miocene to Pliocene (Ahmed, 1972). Occurrence of Miliolite rocks is also reported from Kachchh but no outcrops are seen along the coast (Biswas, 1971).

Deccan Traps occur very close to shore in northern part of Kathiawar coast, while in other areas the traps recede to the interior. Along the southwest coast from Porbandar to Veraval miliolites are extensively exposed along the coast and extend 30 to 40 km inland. The formation over the Pliocene and Miocene rocks directly overlies the Deccan Traps towards the north and east. On the coast, their thickness increase appreciably and these form a thick wedge against the older traps. Along the southern part of the coast, the thickness
of the miliolite formation has been estimated to be 60 m or more (Biswas, 1971). The formation is marked by thin bedding oblique lamination and a gently seaward dip of 5 - 15°. The miliolite is coarser near the shore but becomes progressively finer grained with increasing distance from the shores (Krishnaswamy, 1972).

On the south Gujarat coast, the rivers Mahi, Tapti, and Narmada form broad and fertile alluvial plain at their confluence with the sea. The plain covers a greater part of Surat, Broach and Ahmedabad districts. It extends from the Rann of Kachchh to just south of Daman. In the north it joins the recent deposits of the Indus Valley (Lele, 1973).

Cambay trough runs nearly north-south and it is bounded by faults on its eastern and western sides. The Deccan Traps which are exposed at the surface on both the sides of the trough, in Kathiawar and Baroda areas, have been faulted down to a depth of over 1800 m in the trough. The traps are covered by a full succession of Tertiaries. The Tertiaries between Broach and Surat are capped with laterites. A number of small detached outcrops of Bagh beds (Cretaceous) occur along the east-west trending Narmada Valley from Bagh to beyond Baroda. The formations are cherts, impure shelly limestones, quartzitic sandstones and shales (Wadia, 1970, 1975).
On Konkan Coast from Daman to Vijaydurg, Ratnagiri District, the Deccan Traps is the dominant geological formation and extends upto the coast and possibly continue to the shelf also. The lava flows at some places are separated by thin beds of lacustrine or fluviatile sediments (Wadia, 1970, 1975). The traps usually consist of basalt or dolerite. The most common being a dark green or nearly black normal augite basalt without olivine and often with significant assembly of basic glass. The rocks do not vary in its composition over wide areas. Most of the varieties are homogenous, hard and compact (Pascoe, 1964) but some are vesicular and scoriaceous. The amygdaloidal cavities are filled up by numerous secondary minerals like; calcite, quartz and zeolites. The quartzites are megascopically uniform micaceous (usually biotite) which give rise to a feeble schistosity. The quartzites are dark grey to whitish grey and buffish white fine to coarse grained and massive to well stratified. Massive milky white quartz veins are seen cutting across the quartzites at many places. The quartzites have been intruded by quartz veins and basic dykes.

A laterite of variable thickness caps the geological formations along the coast. The laterite covers almost the entire track except very steep slopes, rivers, valleys and the alluvial area.
2.3 OFFSHORE

2.31 ARABIAN SEA

2.311 Boundary, Structure and Sediments - The Arabian Sea is bordered by arid land masses; the Horn of Africa, the Arabian Peninsula and the Iran-Makran-Thar Desert regions towards the west and north and by the coastal highlands of western India towards the east. According to the International Hydrographic Bureau (Sp. Publ. 23, 1953 IN Robinson, 1966) the geographic boundaries of the Arabian Sea are established in the south-west by a line from Ras Hafun (Somalia) to Addu Atoll, thence up the western edge of the Maldives and Laccadives to Sadashigad Light on the west coast of India (14° 48' N : 74° 07' E). From an oceanographic point of view, Schott (1935 IN Robinson, 1966) bounded the Arabian Sea as follow: the southern boundary runs from the Indian coast near Goa, along the west side of Laccadive Islands to the equator, then it tends slightly to the south to a point on the East Africa coast near Mombasa at approximately 5° S latitude. According to Le Pichon and Heirtzlar(1968) and Mckenzie and Sclater (1971) the Arabian Sea is formed as a result of seafloor spreading.

The important physiographic features of the seafloor beneath the Arabian Sea are: Carlsberg Ridge, Owen Fracture Zone, Murray Ridge, Chagos-Laccadive Ridge and the Indus Cone (Fig. 5).
Fig. 5  Simplified bathymetry of the Arabian Sea with major physiographic provinces and oceanic circulation
The Carlsberg Ridge is part of the mid oceanic ridge system that encircles the global system. The ridge runs from the northern extent of Central Indian Ridge and extends in northwesterly direction towards the mouth of the Gulf of Aden where it is offset in a dextral fashion by about 200 km near the northern end of the Owen Fracture Zone.

The Indus cone was formed by deposition of the enormous sediments brought into the Arabian Sea by the Himalayan River Indus. The Indus flows southwest into the Arabian sea. Seismic refraction studies by Neprochnov (1961) indicated about 5 km thick sediments in the north and the thickness decreases to 1 km in the south. Naini and Talwani (1977) showed that sediments under the proximal parts of the cones are over 9.5 km thick and that the sediment distribution is structurally controlled.

The Chagos - Laccadive Ridge a linear north-south trending ridge that extends over 2200 km between Chagos Archipelago, at about 10° S latitude and Laccadive islands at about 12° N. Numerous hypotheses have been proposed for its origin.

The Owen Fracture Zone extends towards southwest from the coast near Karachi in Pakistan to the middle of Somali basin (5°S latitude). The Murray Ridge and the Owen Ridge in the north and the Chain Ridge in the south parallel to the fracture zone. Heezen and Tharp (1964) showed its
extension further south along the western margin of the Amirante Ridge and the eastern boundary fault of the east coast of Madagascar.

Sediments texture of the Arabian sea are either silty clays, clayey silts or sand-silt-clays (Kolla et al., 1981). In much of the marginal region of the Arabian Sea to the west, north and east (i.e. region near to land), relatively coarse-grained sediments, clayey silt and sometimes sand-silt-clays predominate (Fig. 6). The deep areas of the Arabian Basin (distant areas of the Indus Fan) as well as the somewhat shallow, southwest and southern-most areas of the Arabian Sea are characterised by fine-grained clays. The sediment texture in the marginal areas reflects higher inputs of both the coarse-grained, terrigenous detritus and biogenic components. The terrigenous sediments have been derived through the Indus, Narmada and Tapti Rivers and through the winds from the Horn of Africa - Arabian Peninsula-Iran-Makran Region. The southerly deep areas far from these terrigenous sources, have received only fine grained clays. The combined distribution of the present carbonate free silt and opal generally support these inferences based on bulk sediment texture (Kolla et al., 1981), in addition, the opal distribution shows a significant influence of the biogenic siliceous components in the areas off the Arabian Peninsula-Horn of Africa and off the southern tip of India. The relatively high percentage of carbonate-free silt in southern-most areas
Fig. 6  Distribution of textural types in surface bulk sediments of the Arabian Sea.
with low opaline contents reflects a considerable influx of volcanic rock fragments from the Mid Indian Ridge. Significant amount of silt in the western and southwestern Arabian Sea may also have been derived by aeolian transport from Africa-Arabian Peninsula (Kolla et al., 1981).

2.3.12 Circulation Pattern - The ocean currents in this area are subject to great changes in the course of each year because of seasonal reversals of the monsoon system. The clockwise circulation sets in during summer or southwest monsoon (June-September) which reverses during northeast monsoon (November-February). With the onset of the southwest monsoon a strong surface circulation is developed as a western boundary current flowing north/northeast, off Somali coast. By July, this current reaches its maximum strength. The general flow, north of equator during this period is eastwards. About this time the south equatorial current shifts northward and joins the eastward branch of the Somali current. This Somali current branches into two at about 6° - 10° N. One branch flows in north-northeast-ward direction along Somali and Arabian coasts with average speed of about 4 knots (Bruns, 1958, Stommel and Wooster, 1965; Warren, 1965; Swallow and Bruce, 1966). The other branch joins the eastward flowing current and is known as the monsoon current. Duing (1970) and Sastry and D'Souza (1971) showed that alternate bands of cyclonic and anti-cyclonic cells in the zonal belt of 5° - 15° north off the Somali coast could be the result of formation of small scale eddies. With the cessation of the southwest monsoon, this current system
reverses in the Arabian Sea and an anticlockwise (Fig. 5) circulation is developed and established with its maximum strength by January. The monsoon current flowing eastwards also ceases and the westward flowing north equatorial current develops. The north equatorial current brings water from the Bay of Bengal and flushes into the Arabian Sea and appears to have no influence on the water below the thermocline (Wyrtki, 1973).

2.3.1.3 Temperature - The sea surface temperature of the Arabian Sea has a bimodal distribution and differs from the usual pattern of a single maximum at the end of the winter. Most of the incoming solar radiations in summer is utilised in raising the water temperature and thereby developing a strong summer thermocline near surface. The maximum water temperature are recorded in May. With the advance of summer monsoon, predominant cooling takes place through (i) advection of cold water from the African coast (ii) increased heat flux to the atmosphere (iii) the reduction in the incoming solar radiation and (iv) entrainment of cold sub-surfaces waters into the surface layer (Rao et al., 1976; Murty et al., 1983 and Ramesh Babu and Sastry, 1984). Along Somali and Arabia coasts, summer cooling is supported by horizontal advection of cold waters and coastal upwelling due to strong offshore winds (Wooster et al., 1967; Colborn, 1971, 1975).
of waters and prevention of subsequent formation of the summer thermocline the Arabian Sea exhibits the characteristics of sub-tropical water (Colborn, 1975). The net surface heat loss in the western regions of the Arabian Sea reaches peak towards the end of June, while in the eastern Arabian Sea the peak loss of heat occurs around August because of the four processes mentioned above. The large scale advection of cold water in the vertical and horizontal also contributes considerably. The secondary maximum in the water temperature occurs after the cessation of southern monsoon with the decrease in cloudiness and consequent increase in the incoming solar radiation and reduction in evaporation. During the southwest monsoon the surface temperature in the eastern Arabian Sea drop from 30°C in March to 27°C in August. The extent of cooling will be 2-5°C in the Arabian Sea (Rao et al., 1976). However, temperatures as low as 14°C off Somali coast have been reported in July (Warren et al., 1966; Bruce 1968, 1970). Murty et al. (1983) and Ramesh Babu and Sastry (1984) have investigated the various mechanisms responsible for the lowering of water temperature in the upper layers in the eastern Arabian Sea during the southwest monsoon of 1979. They concluded that this lowering of the temperature is primarily due to downward transfer of heat which accounts to 55 per cent of the total heat loss in the upper layers, while 45 per cent of heat is lost to the atmosphere. The water temperature increases from September onwards once again and reaches to about 29°C over most of the Arabian Sea by November and remains steady over the entire region. The surface layers once again starts cooling.
from December. This cooling first sets in the western and central regions while the eastern parts maintain relatively higher temperature. By January, the surface temperature will be around $25^\circ$ C north of $10^\circ$ N and west of $65^\circ$ E. The central and eastern regions do not cool appreciably and the temperature remains around $27^\circ$ C. This cooling process ceases by February and warming starts. By May the warming is completed and the surface temperature increases to $30^\circ$ C in the open sea while still higher temperatures are reported immediately off west coast of India. In Gulf of Aden, the surface temperature reaches as high as $34^\circ$ C. In this region, the maximum temperature is recorded in August unlike the rest of Arabian Sea (Wyrtki, 1971).

2.314 Salinity - The Arabian Sea is connected to the Persian Gulf through the Gulf of Oman by a 50 m deep sill at the Hormuz Strait. Similarly, a 125 m deep sill at the Strait of Bab-el-Mandab separated the Red Sea from the Arabian Sea through the Gulf of Aden. This is a negative water balance where evaporation exceeds precipitation and runoff. The excess of evaporation over precipitation is maximum (100-150 cm) off the Arabian Coast and decreases steadily towards southeast. A slight excess of precipitation over evaporation (< 20 cm) occurs annually off the southwest coast of India (Venkateshwaran, 1956).
The high rate of evaporation results in formation of several high salinity water masses. The Arabian Sea high salinity water, formed in the north eastern Arabian Sea, flows southward and can be traced as a tongue of high salinity water within the surface layer. The high salinity water in the Persian Gulf, characterised by the $\sigma_\phi$ value of 26.6, flows through the Hormuz Strait and the Gulf of Oman into the Arabian Sea and maintains its density level at about 300 m depth (Wyrtki, 1971). The water mass flows south, mostly east of 63° E longitude (Varma et al., 1980) and loses its characteristics in the southern Arabian Sea (Ramesh Babu et al., 1980). The Red Sea water enters the Arabian Sea through the Strait of Bab-el-Mandab and Gulf of Aden along $\sigma_\phi = 27.2$ surface (Wyrtki, 1971). This water mass is generally confined to south about 17° N latitude (Ramesh Babu et al., 1980). Occasionally, the sub-surface high salinity water mass, the Arabian Sea water and the water masses originating in the Persian Gulf and the Red Sea form a thick layer which is vertically of almost uniform salinity, although the individual layers could still be recognised as weak salinity maxima. The whole layer could be called as the North Indian High Salinity Intermediate Water (Wyrtki, 1973). The occurrence of a salinity minimum at intermediate depths in the Arabian Sea has been a subject of considerable debate. Tchernia et al. (1958) suggested that the Antarctic Intermediate Water may penetrate into the Arabian Sea as a layer of lower
salinity. Warren et al. (1966), however, attributed the salinity minimum to the sub-tropical sub-surface water, a layer of decreasing salinity with an oxygen maxima. The deep and bottom waters are of circumpolar origin, probably transported by a deep western boundary current through a chain of basins (Warren et al., 1966; Warren, 1978, 1981). Following the nomenclature of Ivamenkov and Gubin (1960) they could be called as North Indian Deep Water and North Indian Bottom Water.

2.315 Tropical cyclones - Most of the tropical cyclones in the Arabian Sea are locally generated. Occasionally tropical cyclones from the Bay of Bengal traverse the peninsular part of India and get reintensified over the Arabian Sea. Storm surge causing tropical cyclones occur predominantly either during the pre-monsoon season or during the post-monsoon season, but rarely during the monsoon season (Murty and El-Sabh, 1984). This fact should be emphasised because it is not generally appreciated that there is no relationship, at least directly between the monsoon and the storm surges in the Arabian Sea or in the Bay of Bengal (Murty, 1984).

The predominance occurrence of tropical cyclones during the pre-monsoon and post-monsoon periods is not only true for the severe storms, but holds in general for less severe storms and even for cyclonic disturbances. The fact that a similar result is true for the western part of the Arabian Sea, i.e., those cyclones that hit the southern coast of the Arabian
Peninsula, is also supported by observations. Some cyclones recurve and make a landfall on the west coast of India or on the Pakistan coast whereas others travel towards west northwest and strike the south coast of the Arabian Peninsula. The important point made here is that only rarely, if at all, tropical cyclones from the Arabian Sea travel towards the Gulf of Oman and the Arabian Gulf.

2.32 NORTHWESTERN CONTINENTAL SHELF OF INDIA

2.321 Topography - The topography of the ocean floor to a large extent reflects the structure, tectonics and geological history of the area. The continental margins are the first order features of the earth's crust and the shelves account for almost the world's offshore minerals and oil production. The study of the geomorphology of the continental margin is, therefore, of considerable importance in understanding the structure and origin of this important region. The study of the topographic features of the shelf provides valuable informations on the processes that have shaped the origin in sub-recents times.

Most of the earlier work on the topography of the western continental margin of India was carried out by foreign ships during the International Indian Ocean Expedition. The studies formed part of a regional oceanographic programme and therefore, did not provide the details. Zatonski's (1964)
description of the two profiles off Bombay collected during
the 33rd cruise of R. V. Vitiaz indicated that the shelf has a
slope of 0-0.5°, the shelf break occurs at 140-150 m and the
outer shelf shows rugged topography. Ulrich (1968) studied
the echograms of 1964–65 Indian Ocean Cruise of R. V. Meteor
and observed that the shelf break occurs between 120-130 m
but in profile it is close to 160 m while in others it rises
to 100 m. Hari Narain et al. (1968) and Cloose et al. (1974)
in their papers on continental margins of India and Harbison
and Bassinger (1970, 1973) in their study of the data collected
by the USC & GS Oceanographer presented some bathymetric
profiles but not descriptions. Harbison and Bassinger (1970),
however, indicated that the narrowing of the shelf off southwest
Kathiawar is probably due to a fault.

Heezen and Tharp (1964) prepared the physiographic
diagram of the Indian Ocean which shows the broad geomorphic
features of the western continental margin of India. The
Soviet Oceanographers presented a synthesis of the then
available data in the geomorphological maps published in the
Physico-Geographical Atlas of the world (Gerasimov, 1964) and
later in the Geological-Geophysical Atlas of Indian Ocean
(Udintsev, 1975).

Nair (1972, 1975) noted small scale irregularities on
the outer western shelf and concluded that these are algal and
oolitic ridges formed during Holocene period. Siddiquie and
Rajamanickam (1974) carried out a preliminary study of the echograms collected during the INS Darshak cruises indicated that on the western shelf, the shelf break occurs between 120-150 m (Fig. 7). Furthermore, they divided the continental shelf based on topographic features into even (practically no variation), uneven (about 5 m) and rugged (upto 20 m variations) regions (Fig. 8 A, B and C). The even topography on the Kathiawar shelf and the inner shelf off Bombay probably originated due to the recent deposition of the sediments brought down by the Indus and the Khambhat Rivers (Narmada, Tapti, Mahi and Sabarmati). The uneven and rugged topography on the outer shelf is relict which was formed during the period of lowered sea level. While the area of uneven topography has been covered partly by recent sediments, the area of rugged topography has remained outside the influence of the sediment and uncovered. The abrupt narrowing of the shelf at places off Kathiawar is associated with a fall in the depth of the shelf break. Siddiquie et al. (1977) described the Darshak and other sea mounts in the area and discussed their origin. During the surveys in Gulf of Khambhat and the Bombay Harbour area Vora et al. (1980) reported sand waves in the Gulf and Almeida and Bhattacharya (1980) ripples in the Harbour area.

2.322 Tides and Tidal Streams - The tides at the heads of Gulf of Kachchh and the Gulf of Khambhat maximum spring ranges are about 6.5 and 9 m respectively, as the distance, south
Fig. 7 Bottom profile showing the shelf break off Murud
Fig. 8 Nature of topography (A) Even topography off Murud (B) Uneven topography off Srivardhan and (C) Rugged topography off Alibag.
from the Gulf of Khambhat, increases the semi-diurnal tide decreases until, in about latitude 15° N, the diurnal tide again predominates and the range is about 1 m.

Tidal streams along the Konkan coast sets north wards and strongly so off Port Bankot (17° 59' N : 73° 02' E), its strength increases with the latitude as far as the Gulf of Khambhat.

Along the south and west coasts of Kathiawar peninsula the flood stream sets eastwards between the Gulf of Khambhat and Porbandar and a northern direction to the north of Porbandar. It has been found to set eastward at a rate of from 1 to 1.5 knots off Diu Head, where there are frequent eddies, doubtless caused by the tidal stream during the ebb in the Gulf of Khambhat setting westwards while the flood stream at Porbandar is setting eastwards.

2.323 Temperature - Temperature data collected during the same INS Darshak cruises and subsequently supplement with data collected during R V Gaveshani have shown that at surface, the temperature ranged from 22.5 to 28.5° C with a distinct increase from north to south (Qasim, 1982). Deeper (500 and 1000 m) there was a decrease from north to south. In the inshore areas, the water was isothermal in the upper 30 to 40 m, but in the deeper parts the isothermal layer extends 75 to 125 m, below which
there was a sharp thermocline between 100 and 200 m. At 500 m, the temperature was 12.25 to 13.75°C lower than at the surface. At 1000 m, the temperature varied from 8.5 to 9.25°C. In the southwest the water at this depth was warmer than in the southeast. The temperature at 1000 m was from 14 to 19°C lower than at the surface (Fig. 9).

2.324 Salinity - Qasim (1982) summarising the salinity variations in the northern Arabian Sea based on the data collected during the above mention cruises found that the surface salinity varied from 35.4 to 36.6 which decreased from north to south. At 100 m there was no significant difference in the salinity range (35.3 to 35.5%), with an average of about 35.4% throughout the region. The low surface salinity off the west coast of India south of 20°N is not due to rainfall or land runoff as no major rivers enter this area and rainfall is moderate. The low salinity water largely confined to the top 100 m, may be due to the inflow of water of lower salinity from the south. From the surface to 1000 m the salinity decreases from north to south and from west to east (Fig. 10). The high salinity in the north is due to the inflow of highly saline water from the Persian Gulf.
Fig. 9 Distribution of Temperature (°C) at (A) Surface and (B) 100 m depth of the northern Arabian Sea
Fig. 10 Distribution of Salinity \((X \times 10^3)\) at (A) Surface and (B) 100 m depth of the northern Arabian Sea.