PART-III

OFFSHORE STUDIES

CHAPTER

IX

OFFSHORE PROCESSES

CHAPTER IX

O F F S H O R E   P R O C E S S E S

GENERAL

The Gulf of Khambhat marks a site which comes under the influence of strong tidal influence. High tidal range and low wave energy characterize the Gulf waters, and the area typically comprises the macrotidal type of Hayes' (1979). The various depositional features along the different segments of the Gulf coast as well as the offshore sand and mud deposits are typical of a tide dominated coastal waters; its offshore areas present a complex picture of sediment input, transport and deposition, and the gulf coastline alongwith its deposits like mud banks, shoals and underwater ridges reveal a high tide domination, strong tidal currents, low wave energy together with other variables like coastal physiography, tidal prisms, fluvial sediment influx and riverine input.

The offshore depositional features and the presence of extensive mudflats provide a good example of a coastal environment which is essentially controlled by a well defined pattern of tidal currents, topography of the Gulf bottom and width of the shelf-zone. Considerable similarity is observed between the conditions prevailing in the Gulf of Khambhat and those described by Hayes' (1979) and Off (1963) from other parts of the world.

In this chapter the author has attempted to describe the behaviour of the Gulf waters in terms of tidal range, tidal currents and waves; he has also tried to identify and describe the controlling factors responsible and their contribution to the evolution of Gulf coast and bathymetry.

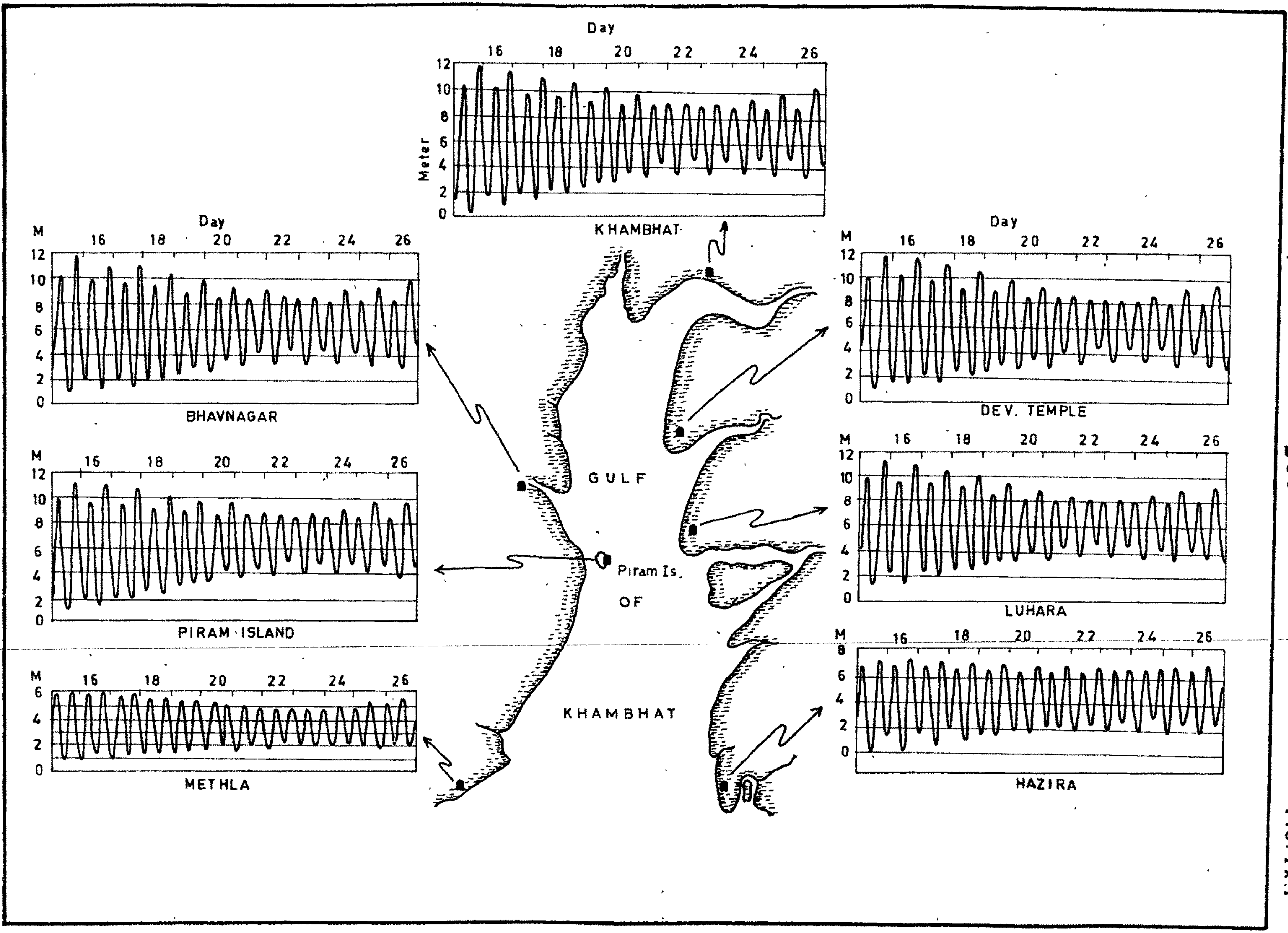
TIDES AND TIDAL CURRENTS

The tide is the periodic rise and fall of the sea which, in on an average, occurs every 12 hours 26 minutes. Tides are essentially, due to the passage around the earth, as it rotates, of two antipodal bulges of water produced by the differential attraction of the moon and sun. Rising up and lowering down the level of the sea water during high and low tides are known as flood and ebb tide respectively.

The tide heights for both flood and ebb tide also vary according to the differential movement of the sun and moon around the earth. When the earth, moon and sun fall along the same straight lines, the tide-raising forces of sun and moon help each other, and the tides of maximum range, known as spring tide result. The moon is then either new or full. But when the sun and moon are at right angles relative to the earth, the moon produces high tides whereas the sun produces low. As a result the tides are then less high and low than usual and are called neap tides.

The Gulf of Khambhat which comes under the influence of high tides perhaps comprises one of the very few coastal areas in the world where tide rises as high as twelve meters (12 m). It is an area under the influence of highest tides along the West Coast of India. Fig.IX.1 illustrates the tidal range in different parts of the Gulf. The author has observed the time difference for the peak high tides at various spots around the Gulf with reference to high tide time at Bhavnagar concrete Jetty, as under:

FIG. IX.1



TIDAL CONDITIONS AT DIFFERENT LOCATION IN THE GULF OF KHAMBHAT

Location	Time Difference with ref. to B.C.Jetty
Methla	−80 min.
Gopinath	−70 min
Piram	−15 min
Ghogha	−10 min
Khambhat	+60 min
Dahej	−70 min
Hazira	−70 min

Apart from the phenomenon of the rise and fall of water level, the tide generates very strong tidal currents. These currents during the flood and ebb tides have been responsible for most of the depositional and erosional features in the Gulf.

The Gulf together with its vast coastal mud deposits, mudbanks, shoals and underwater linear ridges strikingly shows resemblance to the type diagram for macrotidal coast postulated by Hayes' (1979), a shallow water zone dominated by high tides (Fig.IX.2). The geographic location and configuration of the Gulf in relation to the Saurashtra coast and the South Gujarat Mainland coast, the broad extensive shelf zone within which the Gulf is located and the dominant direction of the monsoonal winds, all these factors in combination with the irregular floor of the Gulf bottom have been responsible for the complexity of the

FIG. IX. 2

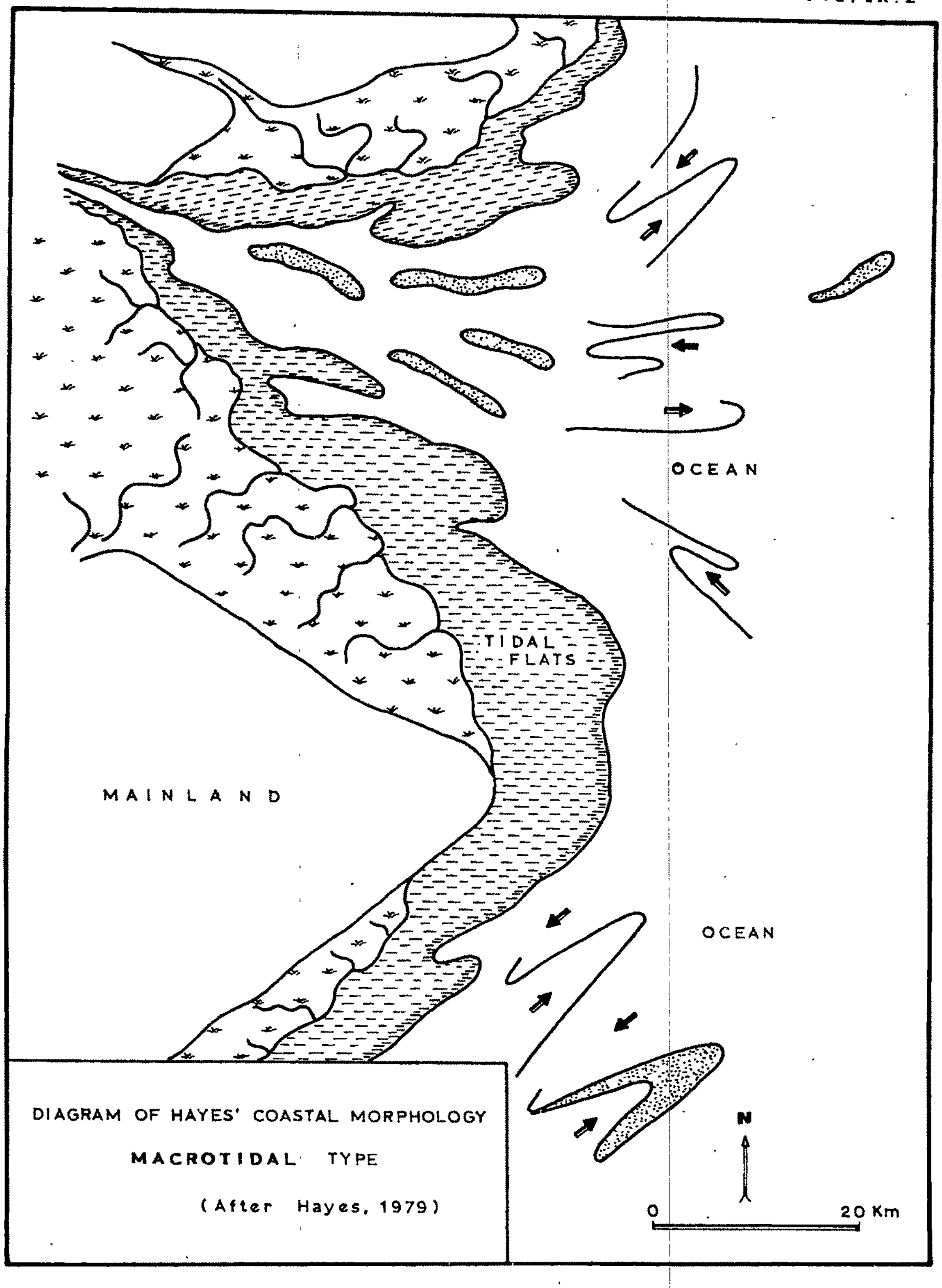


DIAGRAM OF HAYES' COASTAL MORPHOLOGY
MACROTIDAL TYPE
(After Hayes, 1979)

pattern and behaviour of tides and tidal currents.

The author must mention that the phenomena of high tide generation and complexity of tidal current is not yet fully understood. However, with the availability of satellite imagery some useful and authentic data on tidal current path and pattern of suspended sediment transport during rising and receeding tides are now available. The author with the help of a few available representative landsat imagery, has been able to prepare generalized maps of tidal current difections in the Gulf during flood and ebb tides (Fig.IX.3,4,5,6).

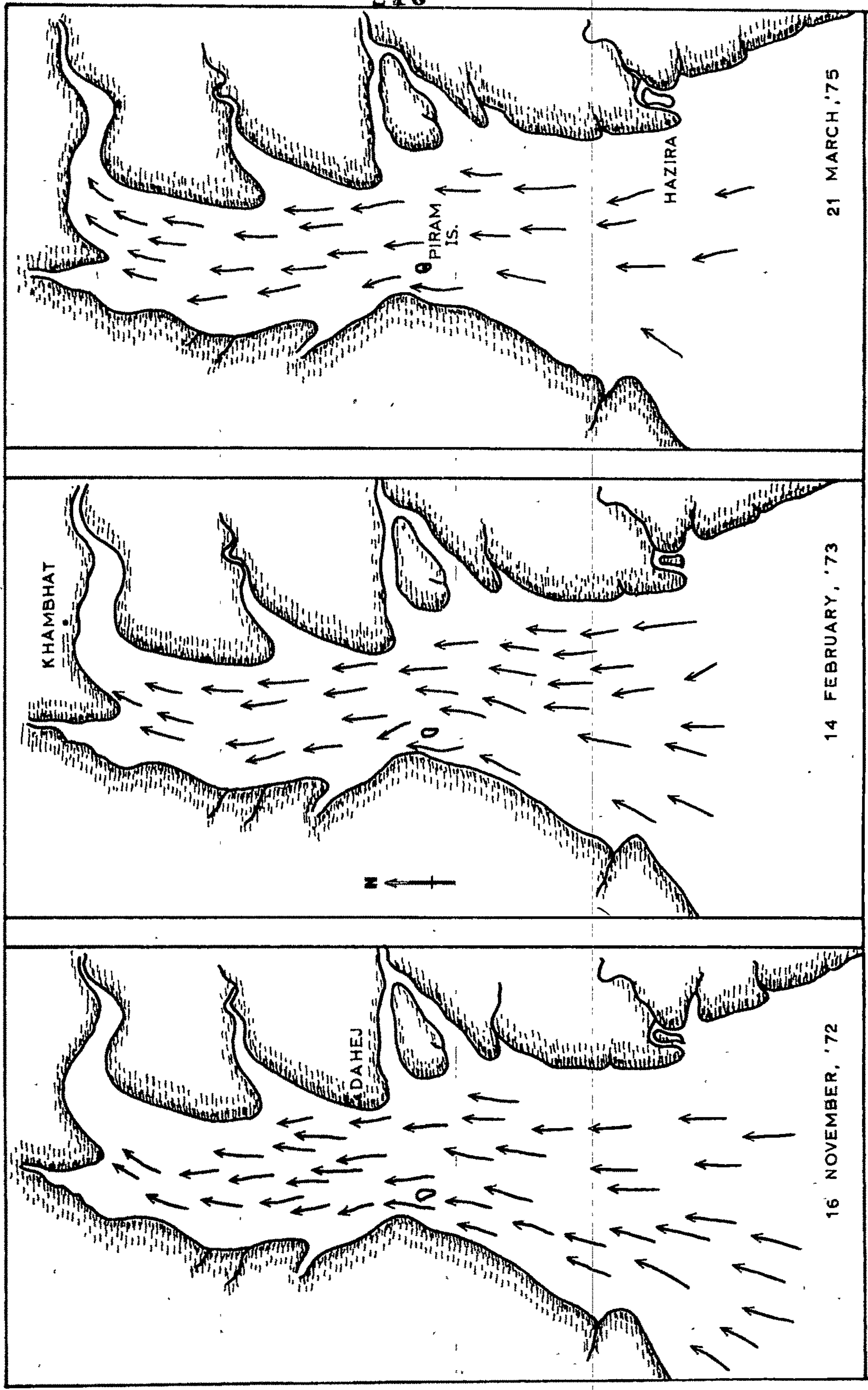
The tidal current directions as observed on satellite imagery establish following facts:

(i) The current directions during flood and ebb tides have almost identical paths.

(ii) The tidal currents bothways follow the bathymetric features of the Gulf.

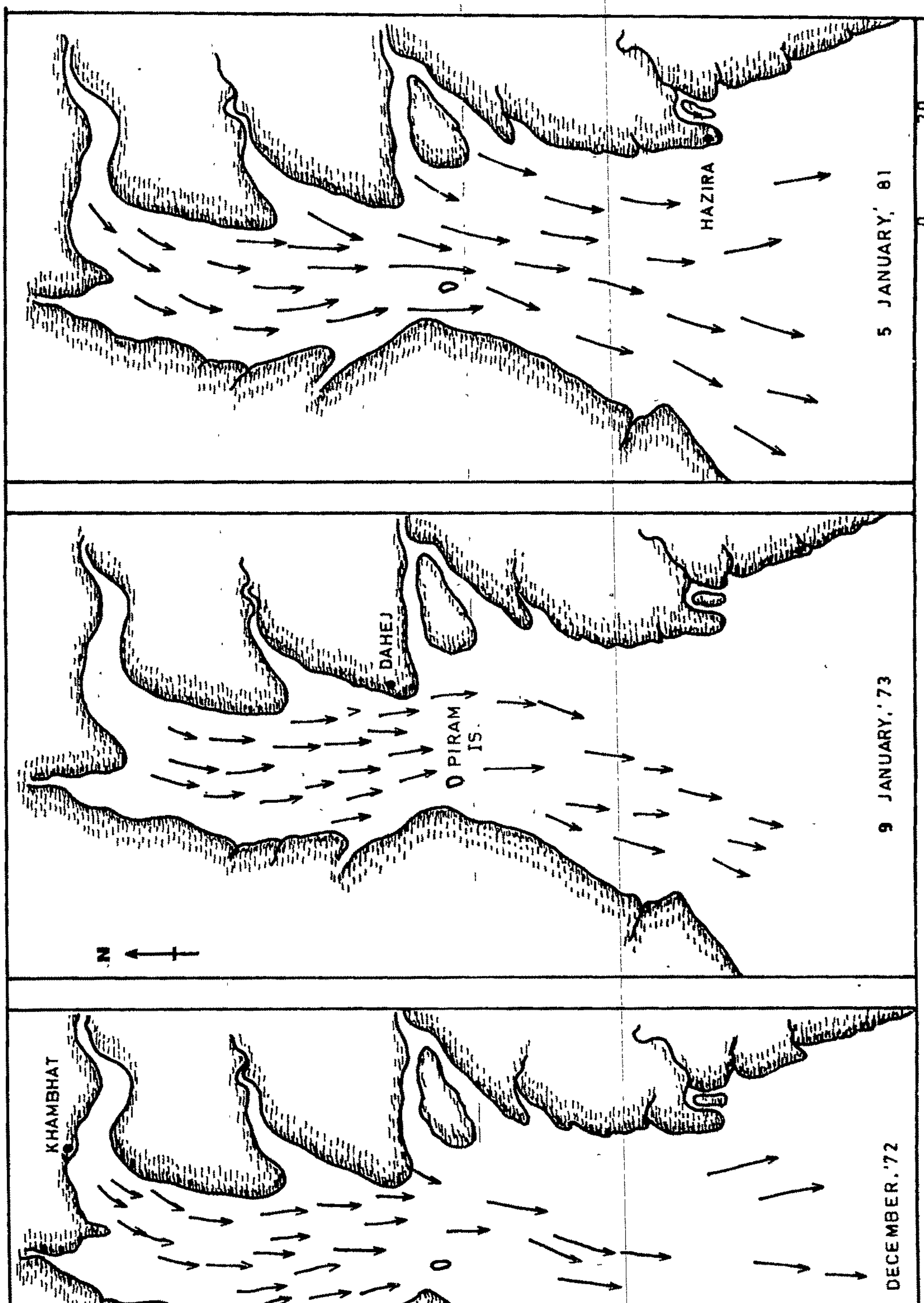
(iii) The fanning pattern outside the mouth of the Gulf is closely related to the presence of numerous underwater rythmic linear ridges (Fig.IX.7) which regulate the entry and exit of the tidal waters.

FIG. IX. 3



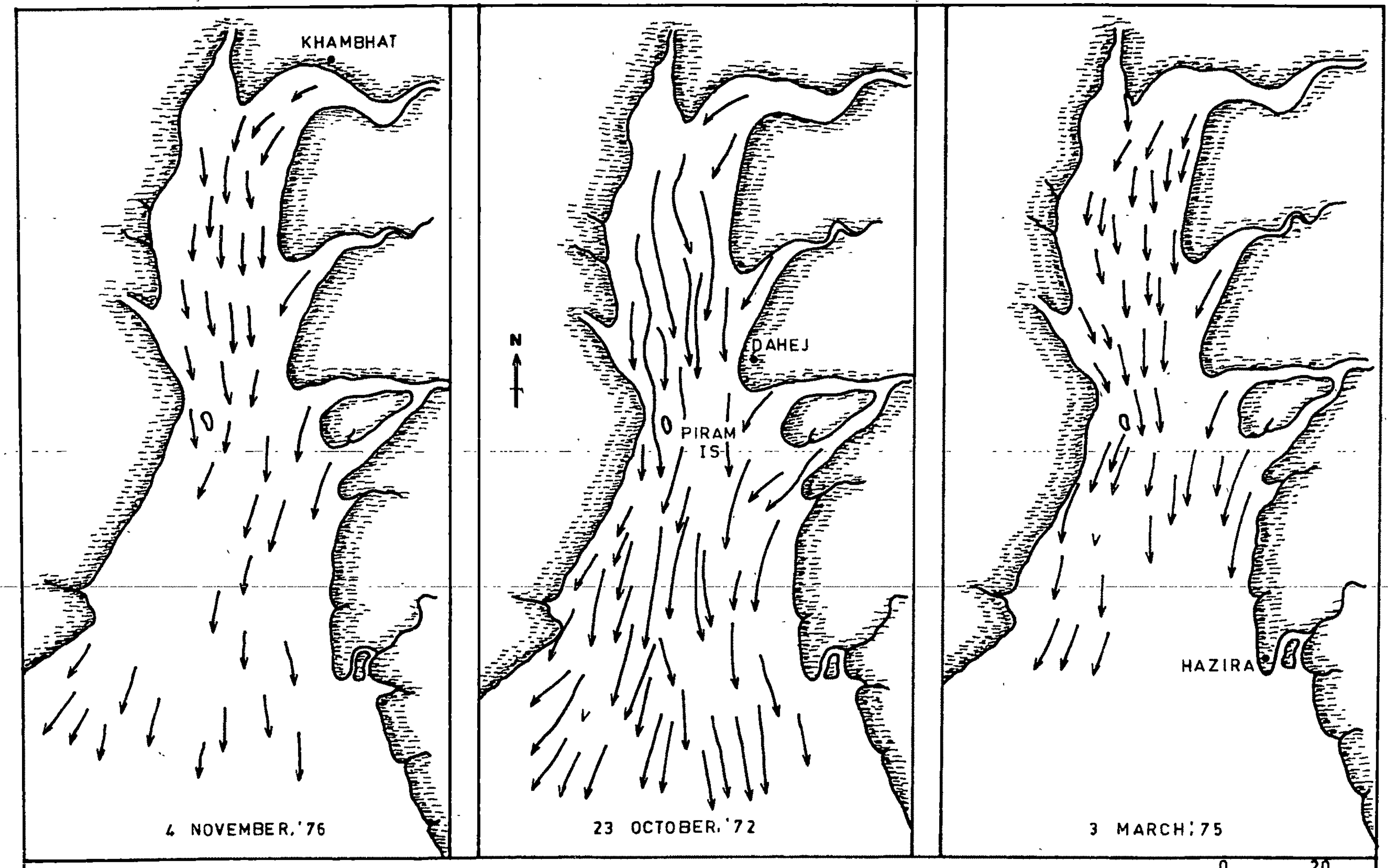
TIDAL CURRENT DIRECTION PATTERN DURING FLOOD TIDE CONDITIONS

FIG. IX.4



TIDE CURRENT DIRECTION PATTERN DURING EBB TIDE CONDITIONS

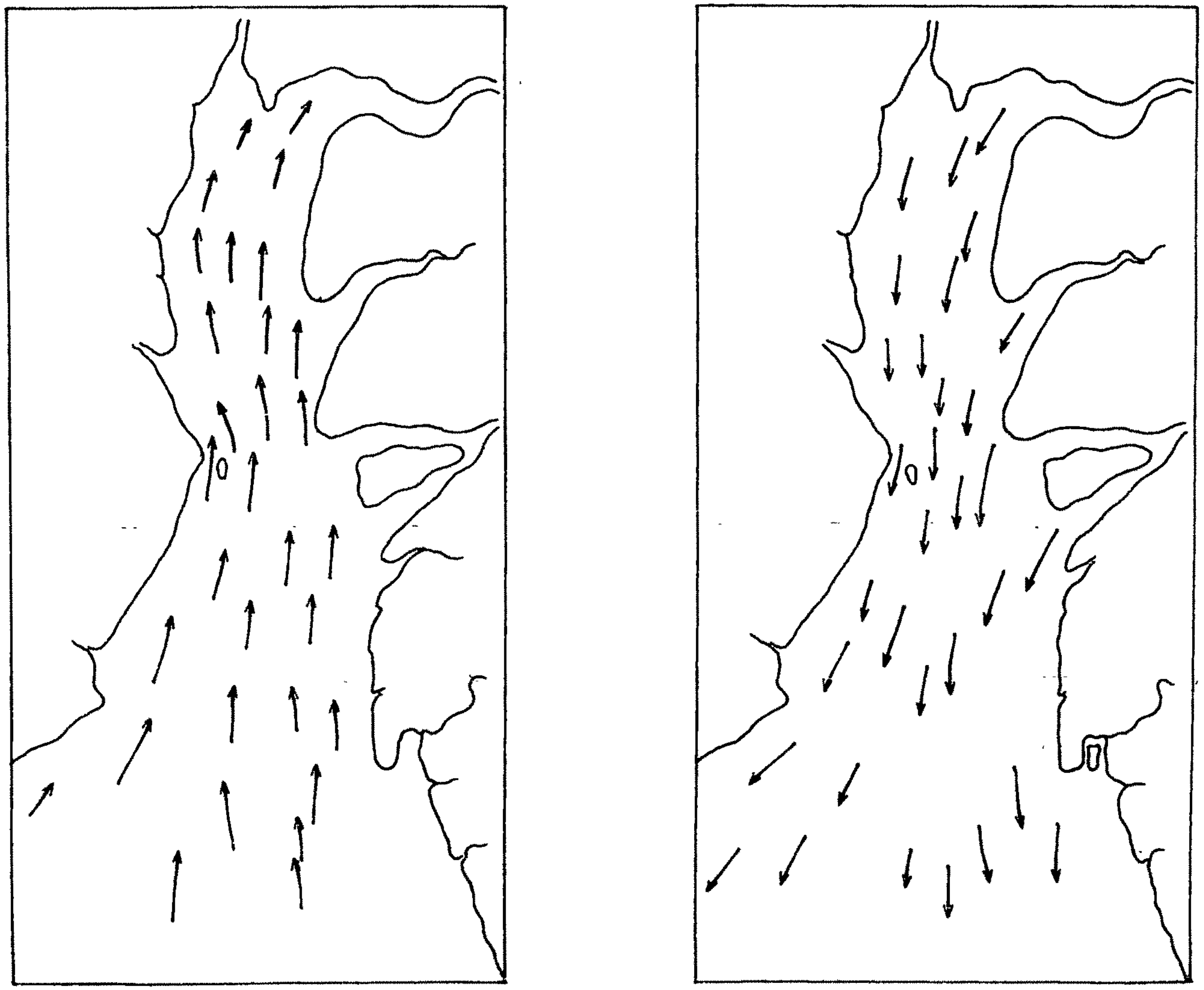
FIG IX.5



TIDAL CURRENT DIRECTION PATTERN DURING EBB TIDE CONDITIONS

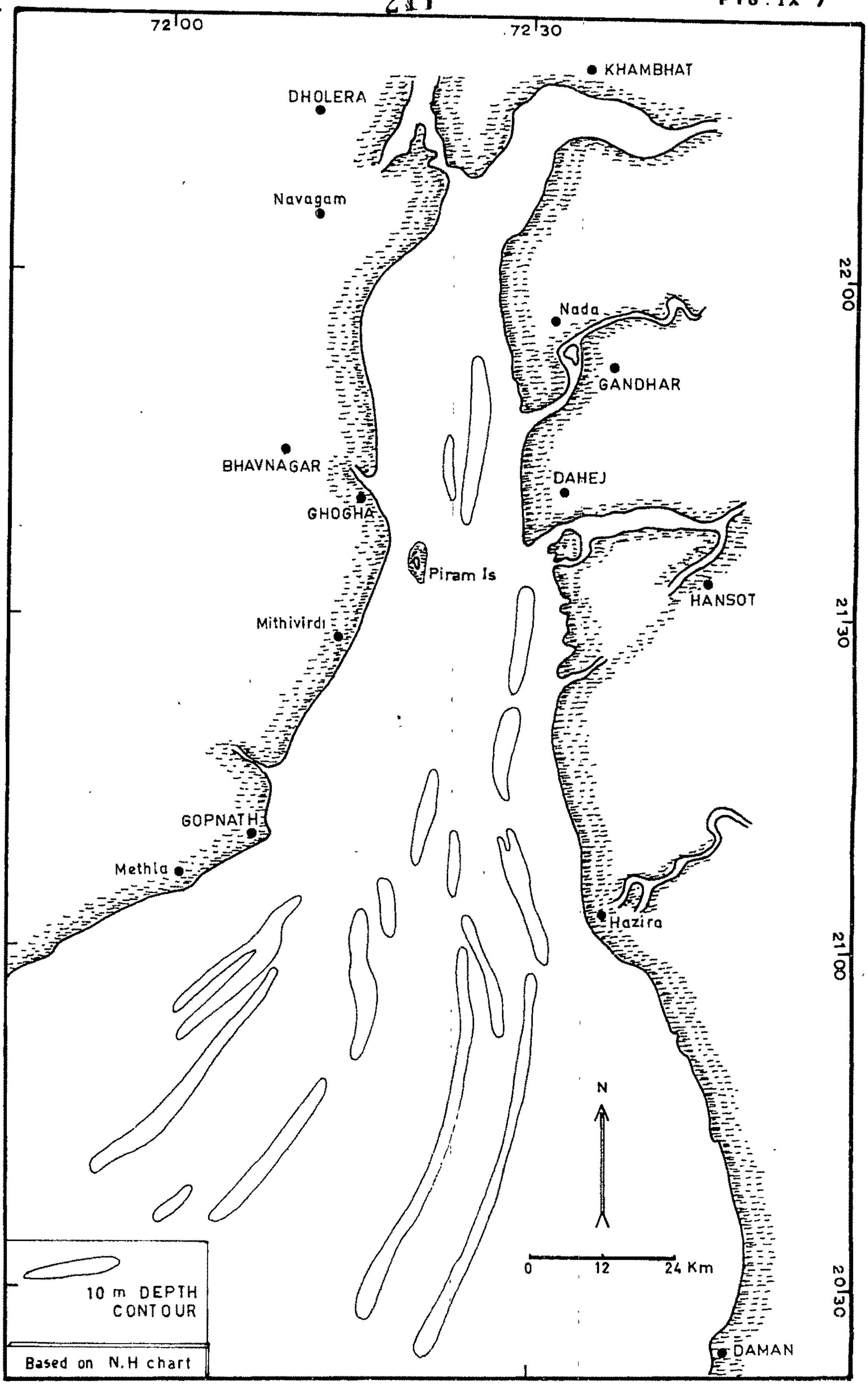
FIG.IX.6

(A) (B)



GENERALISED TIDAL CURRENT DIRECTION PATTERN (A) FLOOD TIDE (B) EBB TIDE

FIG. IX 7



RHYTHMIC LINEAR RIDGES IN THE GULF OF KHAMBHAT

(iv) The uneveness of the inner Gulf bottom characterised by numerous mudbanks and shoals, and the obstruction caused by the Piram Island are also the factors that govern the movement of tidal waters.

A worth noting fact is that the various river mouths, especially of Sabarmati, Mahi and Narmada, react differently to the rising and receeding tides. During the flood tide, the inflow of river waters would experience a resistance, thereby slowing down or even reversing their flow direction. However during the ebb tide, the river water would join the seawater in its outward journey. From these observations, it stands out that the tidal currents are rather weak at the river mouths during flood tide, whereas they are quite strong during the ebb tide.

TIDAL CURRENTS VIS-A-VIS SUSPENDED SEDIMENTS

The tidal currents though broadly following identical paths during flood and ebb tides, appear to carry different sediment loads. A qualitative assessment of sediment distribution in different parts of the Gulf during different seasons was made by ISRO scientists (Nayak & Sahai 1985; Muley et al., 1985).

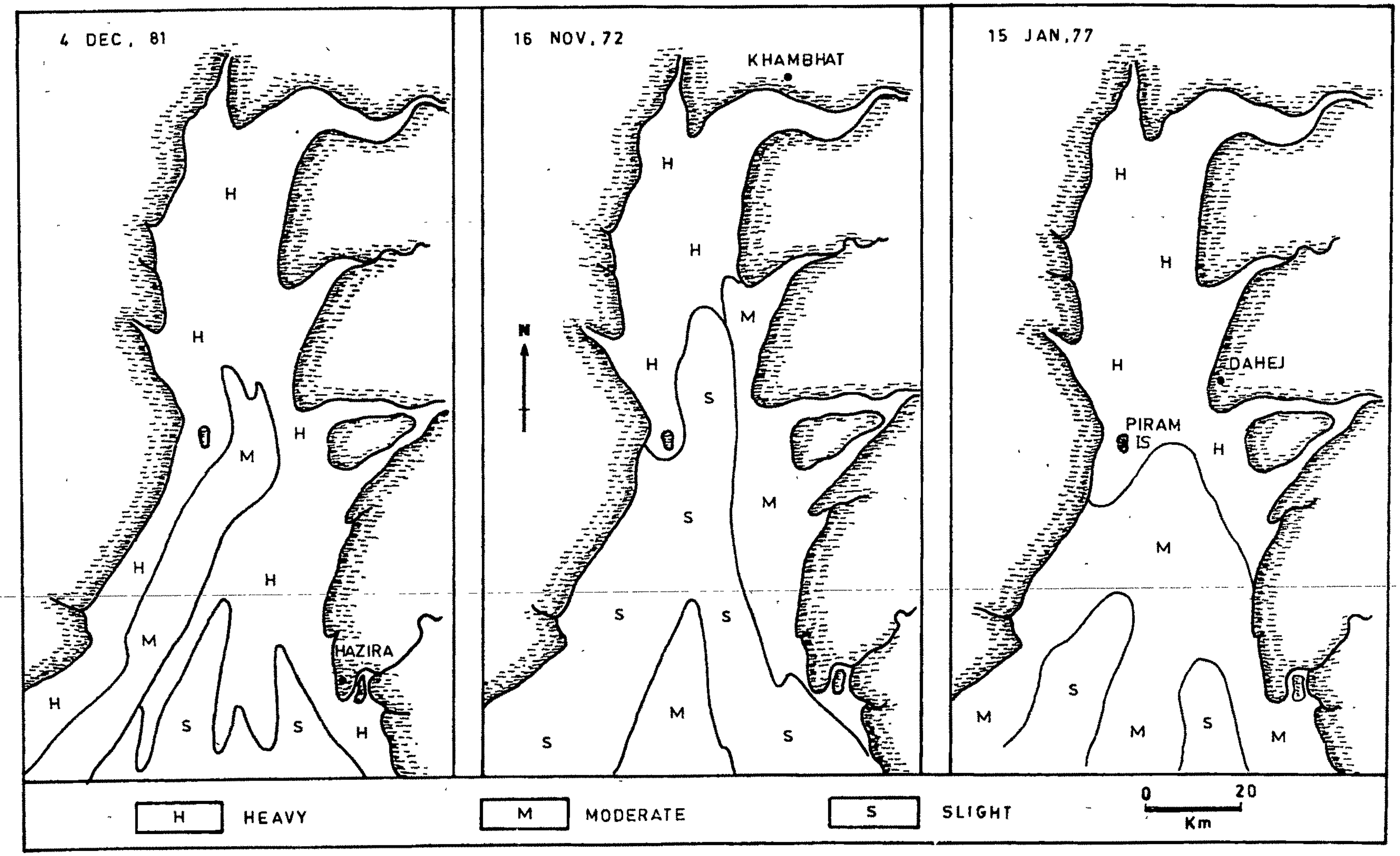
The present author has however, attempted to go into greater details of the nature and pattern of sediment load under flood and ebb tide conditions during different seasons. He has based his observations on (i) available Landsat imagery (ii) published data by Nayak & Sahai (1985) and Muley et al (1985) and (iii) his own observations and data collection. He has prepared a number of generalized sketch maps of the Gulf showing the concentrations of suspended sediments under conditions of flood and ebb tides, spread over different seasons. The illustrations, based mainly on satellite imagery show sediment load upto a depth of 10 m only (Fig. IX.8, 9, 10). On the basis of these sketch maps, following vital information could be obtained:

Flood tide conditions

(a) The inner part of the Gulf becomes heavily charged with suspended sediments during flood tide conditions. This is on account of the churning up of the bottom sediments as well as those of the tidal flats, mudbanks and shoals, the energy being provided by the strong currents when they encounter considerable resistance from the sides as well as the shallow bottom.

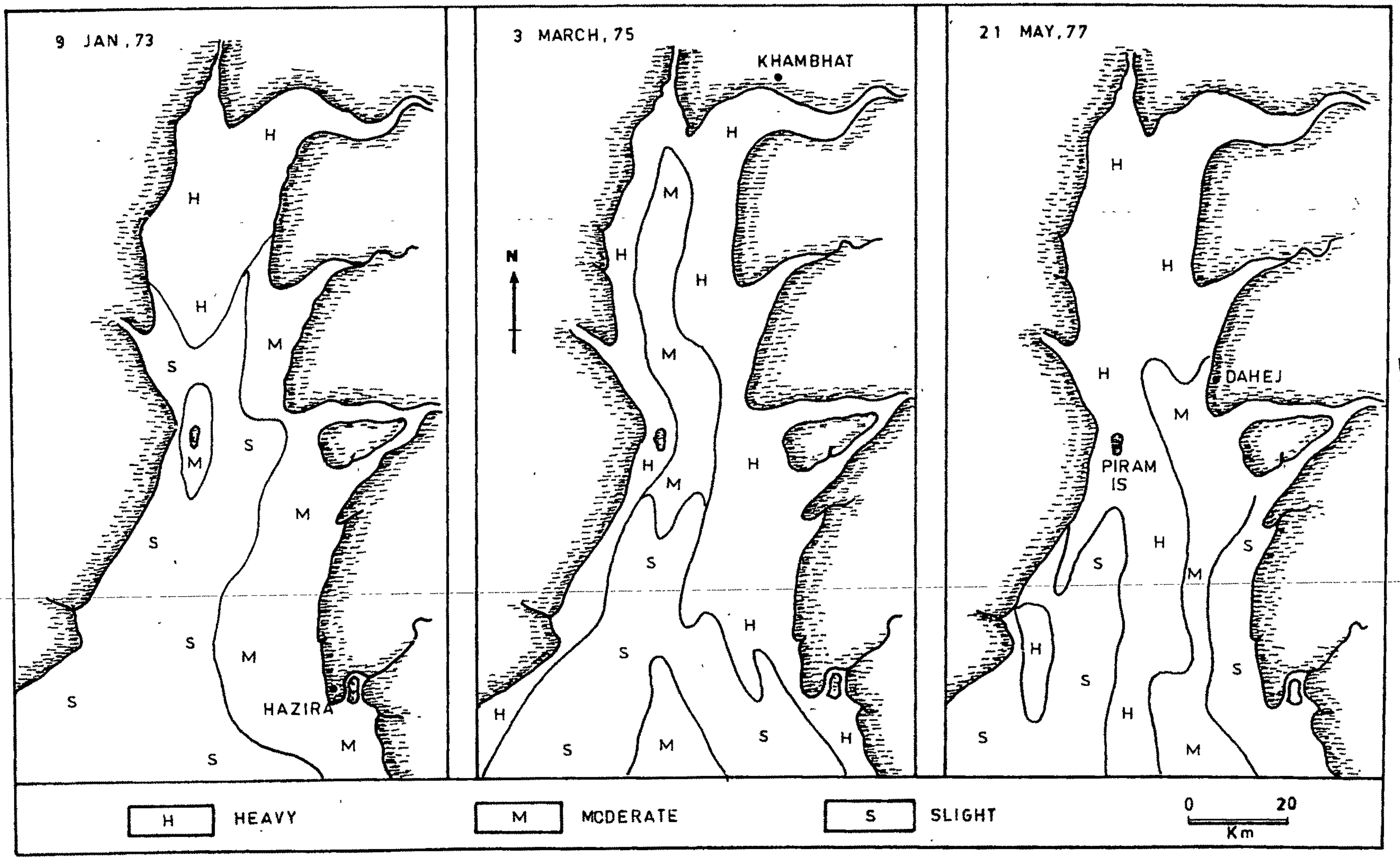
(b) The sediment laden tidal waters on reaching the inner parts of the Gulf tend to spread and inundate all low-lying (inter-tidal) areas and river mouths. On account of the spreading out accompanied by stagnation, the waters leave behind a part of their load while receding.

FIG. IX-8



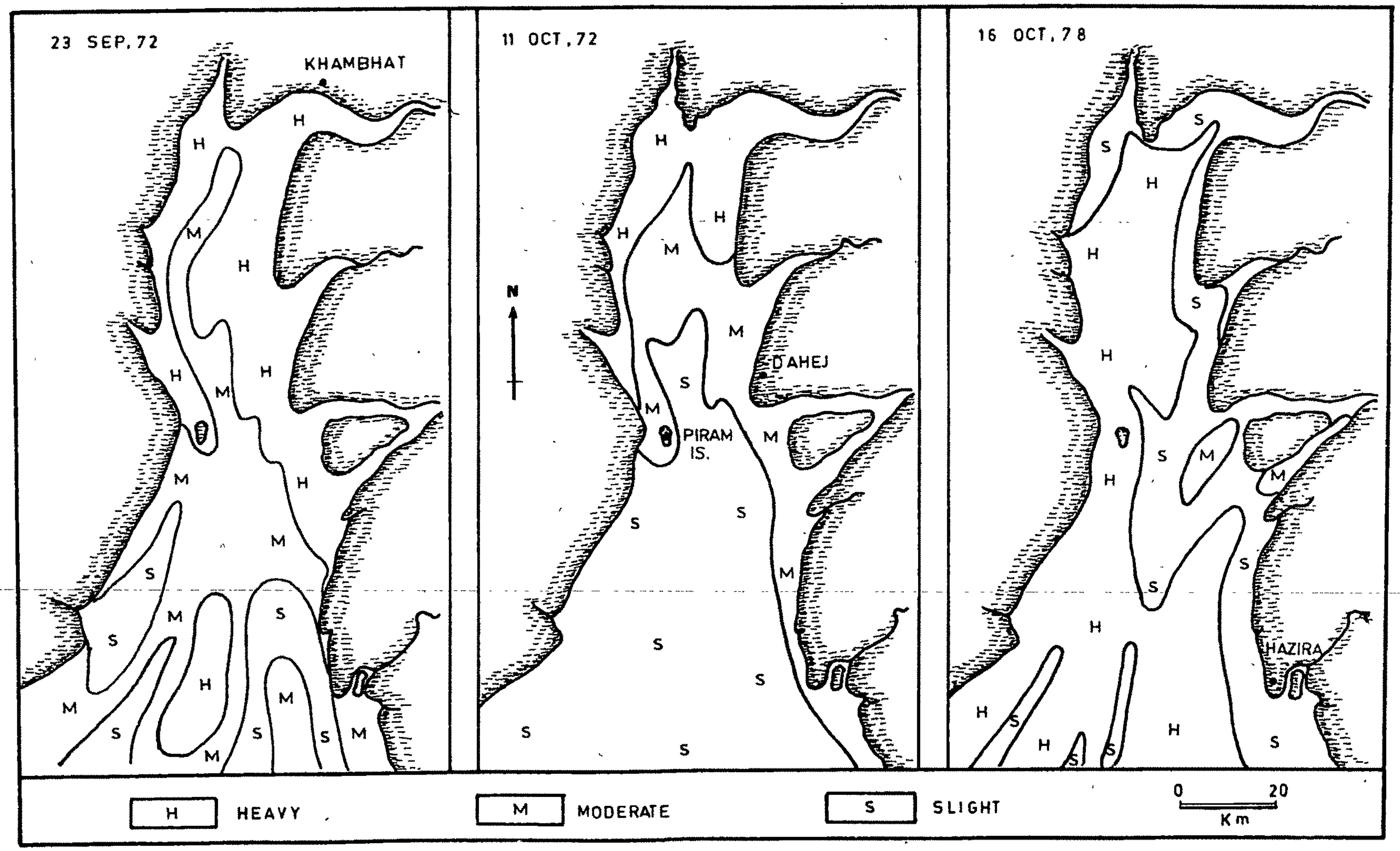
SUSPENDED SEDIMENT CONCENTRATION DURING FLOOD TIDE CONDITIONS IN THE GULF OF KHAMBHAT

FIG. IX-9



SUSPENDED SEDIMENT CONCENTRATION DURING EBB TIDE CONDITIONS IN THE GULF OF KHAMBHAT

FIG. IX-10



SUSPENDED SEDIMENT CONCENTRATION DURING EBB TIDE CONDITIONS IN THE GULF OF KHAMBHAT

(c) The high proportion of suspended load is directly related to the shallowness of the Gulf inlet, mudflats, mudbanks, shoals and other offshore features.

(d) The pattern of concentration is also indicative of the trends of tidal currents and bathymetry.

(e) The proportion of sediment load near or outside the Gulf mouth is much less. This points to the vital fact that incoming tidal waters are relatively less loaded with suspended sediments.

(f) The sediments are carried by tidal currents, such that the influx is both from the south Saurashtra coast as well as from the south Gujarat Mainland coast.

Ebb tide conditions

(a) During receeding tide there is an overall decrease in the sediment content. At the peak high tide the stagnation of water would cause settling of the suspended sediments especially the sand and silt size particles.

(b) Heavier concentration during ebb tide is restricted to the inner tidal muddy areas only. The median portion of the Gulf shows only moderate to slight concentrations, except where the tidal water flow over the submerged ridges.

(c) The distribution pattern of sediment load during different seasons are observed to be quite variable.

No well defined distinction can be made seasonwise. In a general way it is observed that the premonsoon and postmonsoon patterns are different to some extent. But the author is quite convinced that amount of suspended load appears to be controlled mainly by the river discharge from the Mainland coastal areas, which in turn, might depend on the season's rainfall. The monsoonal precipitation in Gujarat being very erratic, quantity of river water received by the Gulf would be very variable. This fact would be reflected in the sediment concentration pattern. In the years of heavy monsoon the coastal waters tend to be clearer.

In order to obtain some idea of the quantities of suspended sediment load falling within the categories of 'heavy', 'moderate' and 'slight', the present author has considered the sediment content of his tidal water samples collected from different stations during the four seasons. The table below gives a reasonably good idea of the range of variation of the sediment load:

Quantity of suspended sediments in gm per 100 liters of tidal water

Sr. No.	Location	April '85	July '85	October '85	January '86
1	Methla	67	126	56	64
2	Gopnath	89	126	23	32
3	Piram West	312	188	159	67
4	Piram East	52	164	199	248
5	Ghogha	209	111	41	24
6	Bhavnagar Jetty	91	167	22	56
7	Dholera	329	408	287	295
8	Khambhat	413	309	331	243
9	Devjagam Temple	123	142	153	106
10	Dahej	82	213	309	86
11	Hazira	61	81	83	88

From the above data, the author has arrived at following approximate figures to indicate the sediment load concentrations:

Slight = upto 100 gm/100 liters
Moderate = 100 - 250 gm/100 litres
Heavy = 250 and above gm/100 litres

CAUSES OF HIGH TIDE IN THE GULF

The author has already discussed routine factors responsible for high and low tides, as well as for the spring and neap tides. Along open coasts, the normal difference between high and low tide is only a metre or so but within restricted areas like a gulf, the tidal range always increases. In the Gulf of Khambhat, the pattern of variation in the height range of high and low tides, is strikingly different near the mouth and the interior part. Whereas the maximum tidal height at Pipavav Bandar (41 km southwest of Methla village), is +4.5 m, the height of the tide of Bhavnagar Concrete Jetty is + 12 m. Equally high tides are indicated in the areas around Dholera and Khambhat. The author has critically studied the main causes of very high tides which could be listed as under:

(1) Convergence of shorelines: Very high tides are caused by strong tidal currents generated due to the concentration of rising water level between converging shorelines. Naturally when the tidal input of water with a greater velocity has to accommodate itself in a smaller area and a close system, it will rise to a higher level.

(2) River water input: During the rising tides, the total volume of the water within the Gulf becomes substantially larger than that brought by incoming tides because of the augmentation of the inflowing

water from the various rivers. This results in the blocking of a huge quantity of water in the Gulf, thereby raising the height of the tides.

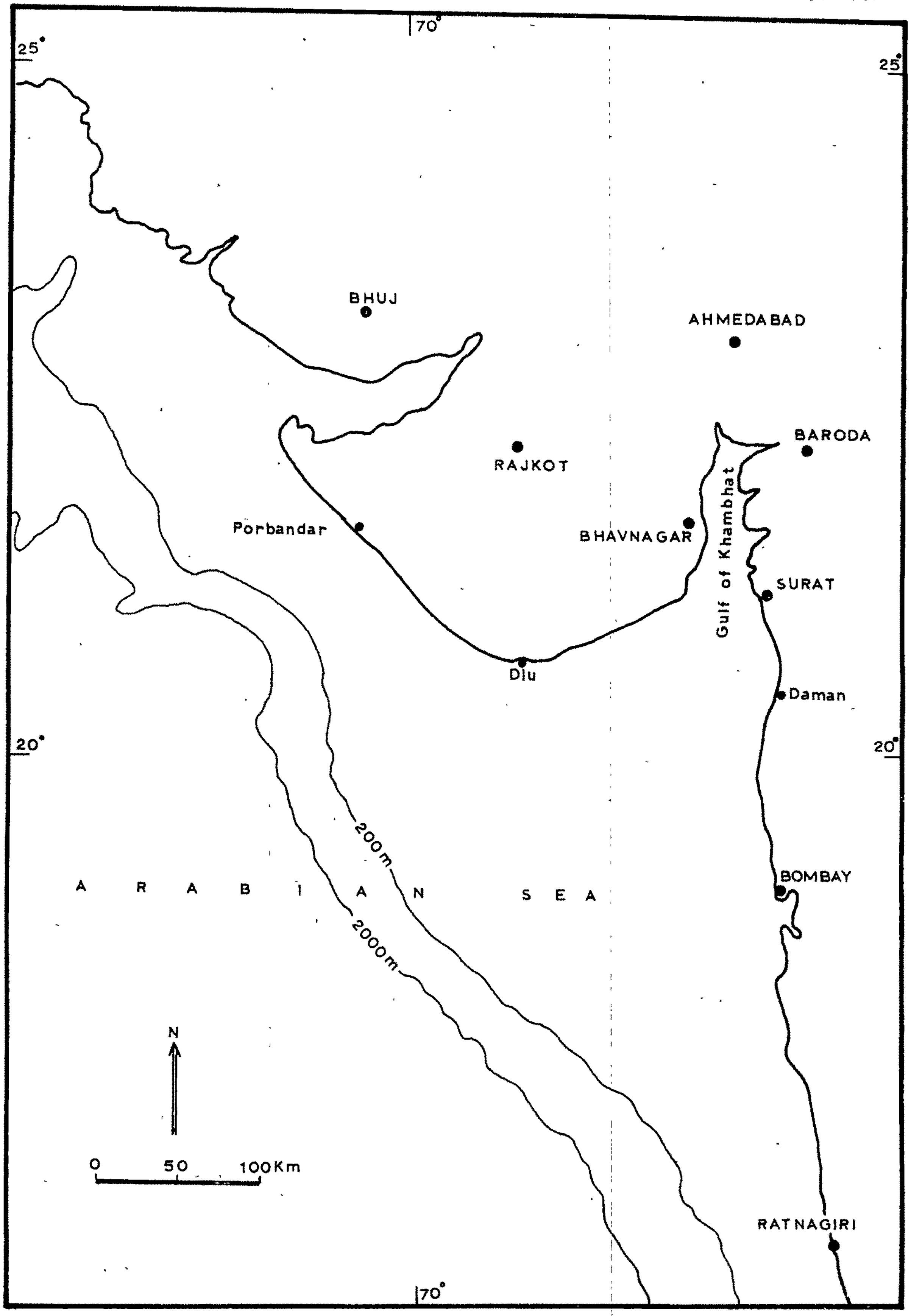
(3) Shallowness of the Gulf: The gulf is located on that part of the West Coast which has got the widest continental shelf, the maximum depth being around 55 m only (Fig IX.11). This wide shallowness plays a dominant role in raising the tidal height.

(4) Action of wind: Strong southwesterly monsoonal winds also, under stormy conditions augment to the height of the tides; thereby causing extensive flooding of the low lying coastal areas of Saurashtra and Bhal.

WAVES

The Gulf by and large comprises an area of low wave energy. Waves are generated generally by winds and the geographic location of the Gulf and its configuration is such that the Gulf waters do not come under the direct influence of wind generated waves. Unlike the other coastal areas of Saurashtra and of south Gujarat which experience strong southwesterly winds, the Gulf is protected by the Saurashtra landmass. A perusal of the climatic data clearly reveals that for most part of the summer and monsoon months, strong

FIG. IX.11



LOCATION OF GULF VIS-A-VIS CONTINENTAL SHELF winds blow from west and southwest, whereas during winter months landward breeze blow from north or north-northeast. It is observed that the southwesterly winds generate relatively high amplitude waves in the open sea (outside the Gulf mouth), but they reach the Gulf coast after considerable refraction and thereby losing most of their energy.

The following table gives an idea of the wave heights observed during different seasons:

Locations	Winter	Monsoon	Summer
Methla	2 - 3 m	4 - 5 m	2.5 - 3.5 m
Gopnath	1.5-2.5 m	3 - 4 m	2 - 2.5 m
Ghogha	1 - 2 m	2 - 3.5 m	1.5 - 2 m
Khambhat	.5 - 1 m	1.5 - 2 m	1 - 1.5 m
Dahej	1.5 - 2.5 m	3 - 4.5 m	2 - 3 m
Hazira	2 - 3 m	3.5 - 5 m	2.5 - 3.5 m

BATHYMETRY

The bathymetry of the Gulf of Khambhat is equally varied. From north to south and from east to west it shows striking depth variation. The topography of the Gulf bottom is seen to comprise a large number of shoals, underwater ridges and deep channels. The floor of the Gulf as well as some of the ridges are seen to rise above the low water line.

The author has prepared Gulf bottom topography maps and cross profiles with the help of Naval Hydrographic Chart (Figs.IX.12 & 13). The illustrations adequately bring out the pattern of unevenness of the gulf-bottom and also reveal the various factors responsible for the same. The author has observed that tectonic and sedimentation factors have played a dominant role in imparting diversity to the gulf bathymetry. The features of the Gulf bottom are essentially the product of (a) Graben faulting related to the tectonics of the Cambay Basin and (b) accumulation and distributed deposition of sediment load by tidal currents.

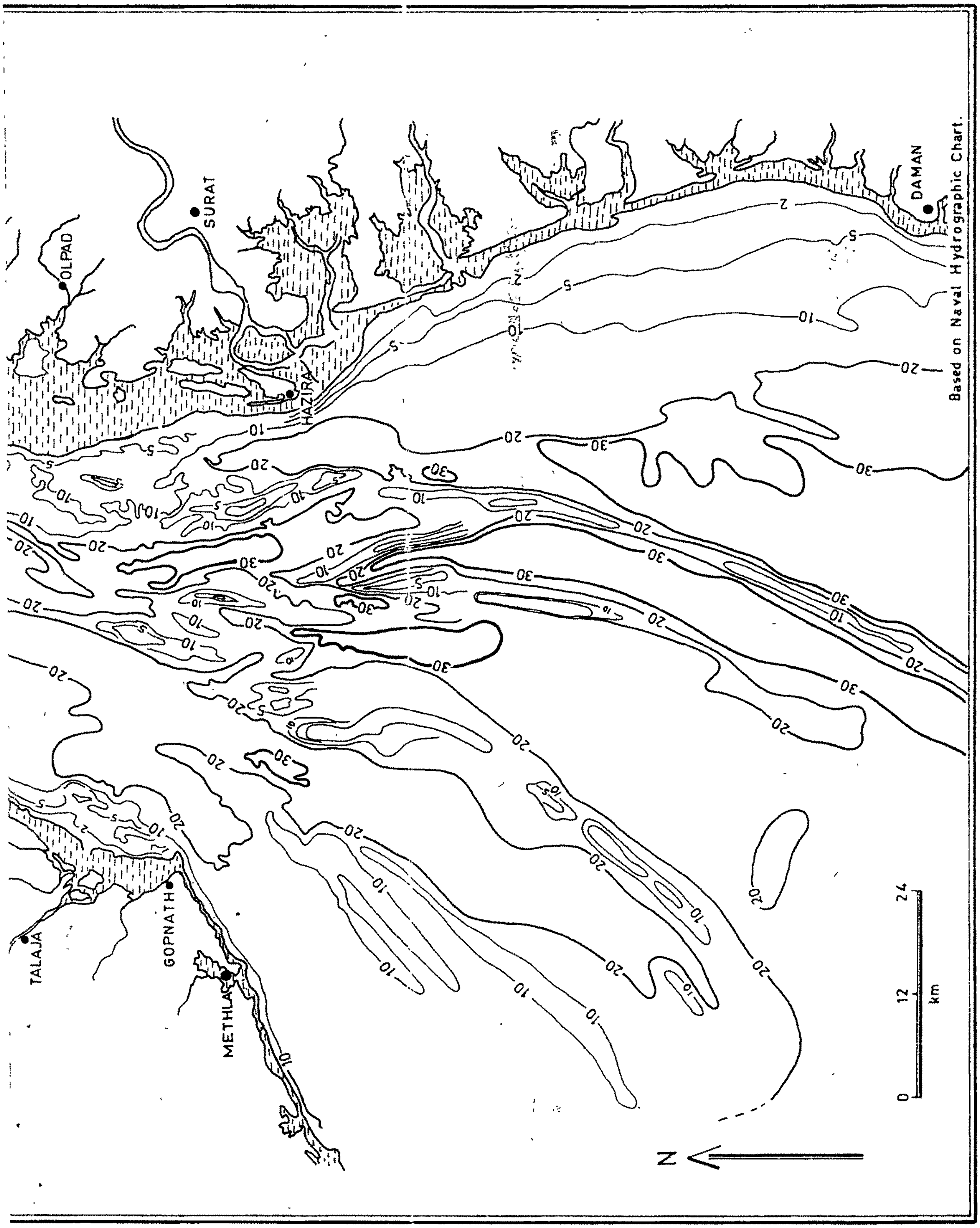
From the bathymetric point of view, the Gulf can be divided into three parts:

(1) Inner Gulf - North of Ghogha Dahej (E-W) line
(2) Outer Gulf - Between Ghogha-Dahej and Gopnath-Surat (E-W) line
(3) Open shelf outside the Gulf - South of the Gopnath-Surat (E-W) line (upto Daman).

<u>Inner Gulf</u>

This part is very shallow, never exceeding in depth beyond 27 m, and is replete with mudbanks and shoals.

FIG. IX.12



BATHYMETRIC MAP OF THE GULF OF KHAMBHAT

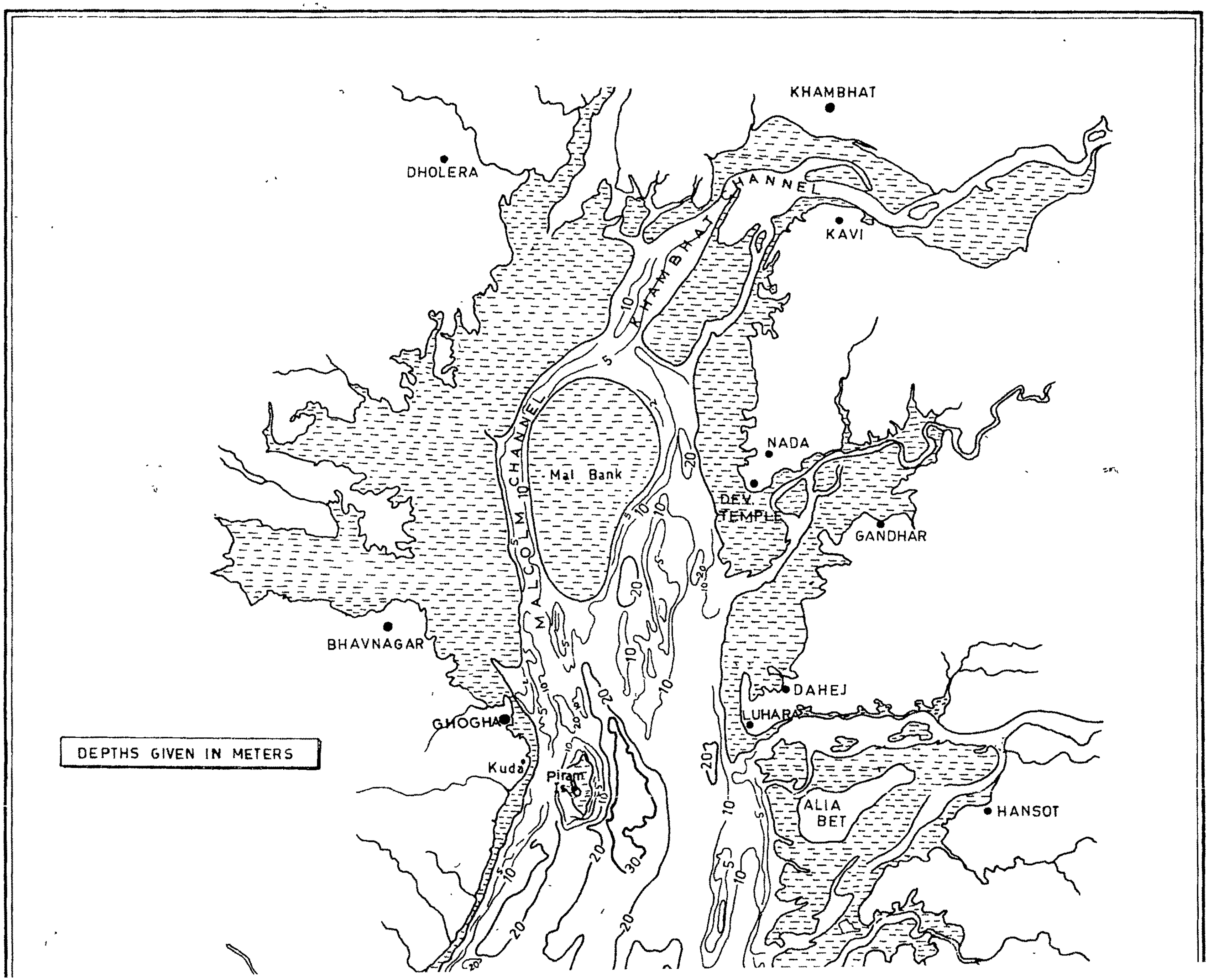
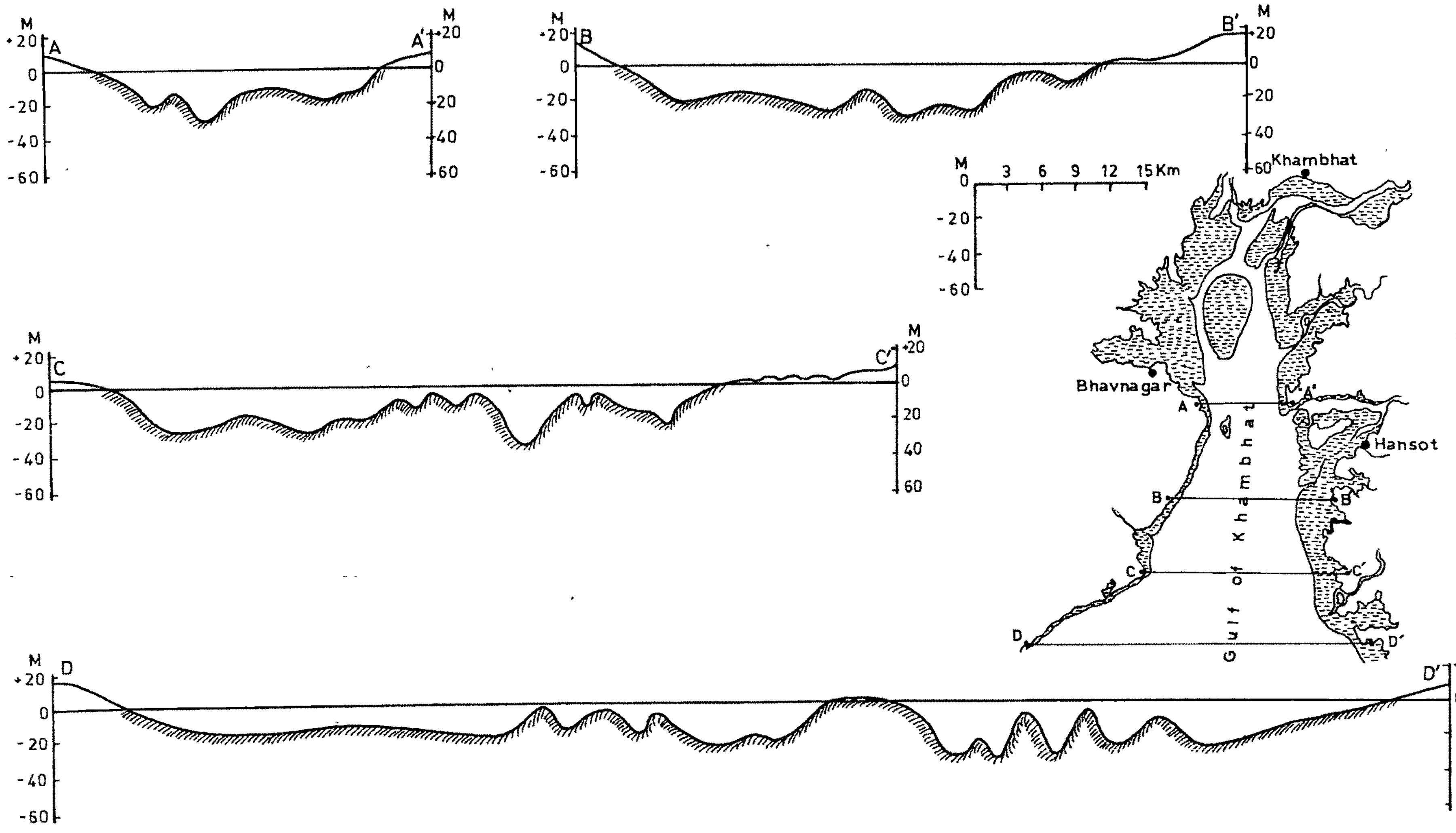

KHAMBHAT
DHOLERA
KAVI
KHAMBHAT CHANNEL
MALCOLM CHANNEL
Mal Bank
NADA
DEV TEMPLE
GANDHAR
BHAVNAGAR
DAHEJ
LUHARA
GHOGHA
Kuda
Piram Is.
ALIA BET
HANSOT
DEPTHS GIVEN IN METERS

FIG IX 13



BATHYMETRIC PROFILES ACROSS THE GULF

Although the Survey of India Toposheets and Naval Hydrographic Charts show an extensive oval-shaped intertidal feature (Mal Bank), the satellite imagery do not show so well defined an existence of such a bank. Muley et al. (1985) on the basis of MKF imagery have instead shown a string of elongated patches of shoals, which they have designated as 'Mal Bank Shoal'. The bottom topography here comprises NS extending banks, underwater shoals with intervening shallow channels (Khambhat channel, Malcolm's channel etc), which are only 10-20 m deep at the most.

Outer Gulf

This part is deeper, broader and has varied floor topography. ~~By and large~~, The Gulf floor is made up of underwater channels and ridges which tend to diverge and open up southward, and some of them rise above the low water line. The channels form the deeper areas in between the various parallel underwater ridges. The deepest portion of the Gulf comprises (i) a median channel as deep as 45 to 49 meters, located to the east of the Piram Island, and (ii) three diverging channels in the southern portion just outside the mouth of the Gulf.

Open Shelf (outside the Gulf)

Study of this portion of the continental shelf which overlooks the Gulf mouth is most vital towards a proper understanding of the offshore processes operating within the Gulf. The author has considered the bathymetric features as far south as the E-W line running across Daman, to explain the phenomenon of the existence of sub-surface ridges several kilometers long (Fig.IX 7). The overall bathymetric features of this part comprise an open flat shelf area averaging from 30 to 35 m deep) dissected by a number of channels with intervening sandy ridges; these ridges tend to converge towards the Gulf mouth. Parts of some of the ridges rise above the low water line. These underwater depositional features provide typical examples of the Linear Rhythmic Tidal Current Ridges of Off (1963). These ridges have considerable bathymetric significance in the gulf environment, because the present day tidal currents and pattern of sediment suspension are closely related to and controlled by the underwater ridges.

Nature and Significance of Tidal Current Ridges

The development of extensive underwater linear sandy ridges of the order of 30 to 80 km long, outside the mouth of the Gulf is typically illustrative of the phenomenon of transport and deposition by tidal currents. According to Off (1963) who studied several gulf areas in different parts of the world, these linear sand bodies are characteristic of shallow gulf areas marked by high tides and strong tidal currents, and their rhythmic disposition simulates the current directions. Hayes'(1979) who has considered areas like the Gulf of Khambhat to mark macrotidal environment, has also shown presence of such ridges. But he has not explained the mode of origin of these linear underwater/intertidal bodies. Off (1963,p.326) has however discussed the tidal current environment capable of forming such ridges in the following words, " Because of the more obvious movement of material by waves and semi-permanent currents, the movement of material by tidal currents has to a large extent been overlooked. The deposition of material by tidal currents has been passed over with statements implying that since there is no net movement of water by tidal currents, there is no net movement of material by them. This is not true for three reasons. First, in any part of the ocean, there is always a net movement of water due to the normal water circulation of the ocean; the presence of local wind driven currents, and the influx of water from rivers and streams. These currents ~~in~~ may not be strong enough to move sand size particles. Second, the nature of tidal currents is such that the ebb and flood do not necessarily follow the same path (e.g., Robinson, 1956). This would result in the movement of sediment landward in the flood path and seaward in the ebb path (e.g., Oomkens, 1960). Third, the ebb and flood currents also generally do not have the same maximum velocity. Particles too large to be moved by one of these currents might be moved by others".

Off (1963) has explained the origin of these rythmic ridges by invoking an anology with river channel development. He writes (1963,p.331)." An analogy with river channels is reasonable and that the origin of tidal current ridges is related to the similar problem of the hydraulic geometry of stream channels. Although empirical formulas have been worked out for the relationship of the various geometric parameters of streams (e.g., Leopold and Maddox, 1953; Simous and Richardson, 1961; Schumm,1960), there is no satisfactory hydrodynamic explanation for these relationships. Possibly a Reynold's number phenomenon is involved. This might cause the setting-up of eddy currents, once a certain critical velocity was exceeded. These eddy currents would be a specific size for a particular water depth and bottom friction; all of this resulting in bands of slower current oriented parallel with the direction of tidal flow. The ridges would tend to form in these bands of slower current. Once the ridges were started in a particular area, they would be self-perpetuating because the resulting irregularity on the bottom of the sea would act as a nucleus for the additional accumulation of sediments".

Though the tidal current ridges occurring at the head of the Gulf of Khambhat, themselves originated by the process of transport and deposition related to the tidal currents, to-day they are now performing an equally important role in controlling the tidal current directions and the pattern of sediment transport and deposition.