

ON THE POSSIBILITY OF HIGH-VELOCITY TIDAL STREAMS AS DYNAMIC BARRIERS TO LONGSHORE SEDIMENT TRANSPORT: EVIDENCE FROM THE CONTINENTAL SHELF OFF THE GULF OF KUTCH, INDIA

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ABSTRACT

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Differences in the bathymetry, bottom topography and the abundance of mica and clay minerals on the continental shelf north and south of the Gulf of Kutch, a macro-tidal bay, indicate the presence of two distinct sedimentary environments. The northern part is characterised by accumulation of sediments (prograding sediments of the Indus delta) and higher concentrations of mica and clay minerals, whereas the southern part is deprived of sediments and has relatively lower concentrations of mica and clay minerals. The distinct differences have resulted because the high-velocity (2 to 2.5 knots) tidal stream at the gulf mouth acts as a dynamic barrier inhibiting sediment transport across the mouth. Differences in the distribution of sand-size and clay-size sediments further indicates that it acts as a selective filter that is more effective against the coarser end of the size spectrum.

INTRODUCTION

The influence of tides on sedimentation on beaches, estuaries, bays and on the continental shelf has been established in numerous studies. The greater the tidal range, the stronger the currents and the clearer the signature of the tide on the sediment. Macrotidal regions (tidal range > 4 m) most clearly demonstrate the influence of the tides and frequently result in the formation of linear sand bars, sand waves and allied bed forms. Unusual regimes such as the Bay of Fundy, with its extremely high tidal range of 11.7 m, result in 60% of floor of the Bay being covered with coarse pebble and gravel (Pelletier and McMullen, 1972). However, differences in the sedimentation pattern result as a consequence of the association of high tidal ranges with variation in the geometry of the basin, its geographic location, climate, and the source and amount of sediment contributed to it. The differences in the sedimentation pattern in the basin in turn influence the sedimentation processes on the neighbouring continental shelf to varying degrees.

This paper documents some of the influences on the transport of sediments on the continental shelf at the mouth of the Gulf of Kutch, a macrotidal environment, on the northwest coast of India. The Gulf of Kutch is one of the regions around the coast of India that has been identified as having potential for tidal-power generation and since sedimentation processes play a key role in the planning of such engineering ventures, gaining some insight into them is of importance. Sediment samples and echo-sounding data were collected during the various cruises by RV "Gaveshani" as part of the geological exploration of the western continental margin of India.

The Gulf of Kutch

The Gulf of Kutch is a 7300 km² east-west-oriented indentation north of the Saurashtra peninsula (Fig.1). Depth ranges from a maximum of about 60 m at the mouth to less than 20 m at the head of the gulf. The climate is semi-arid and the maximum rainfall is of the order of 50 cm/yr. It has therefore little run-off from land and no major river flows into it.

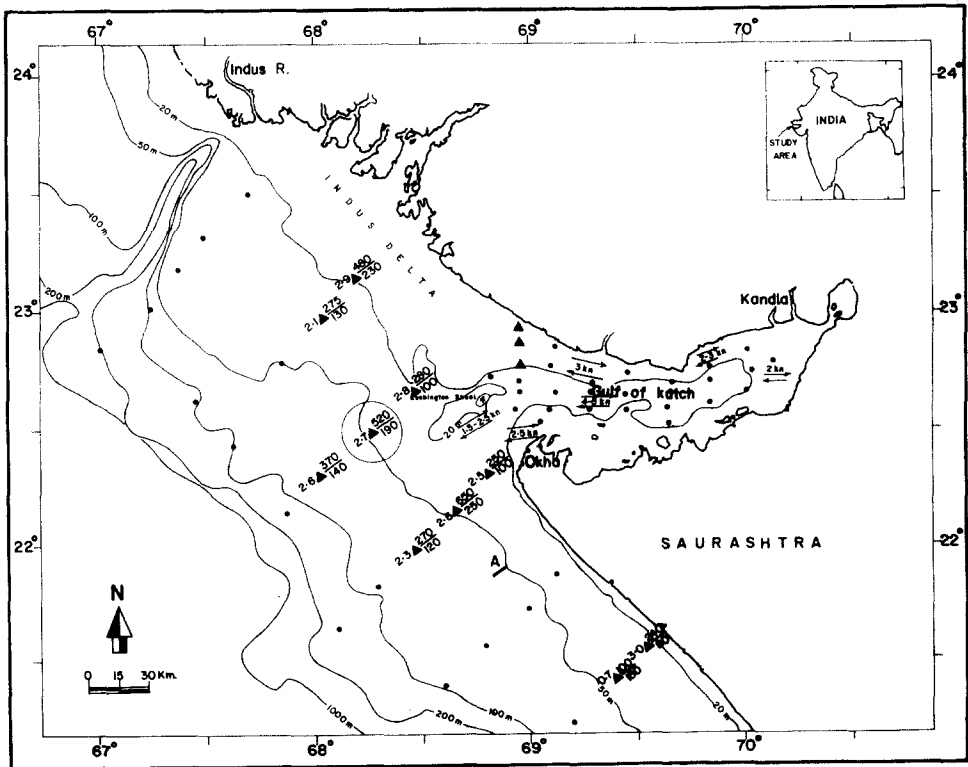


Fig.1. Sample location and bathymetry. Number at the left of triangle shows the kaolinite/muscovite ratio and number at the right shows the individual values of the same minerals. A indicates the location of the bottom profile shown in Fig.5. Tidal current data from N.H.O. chart no.L(D2) 203.

Located about 100 km northwest of the gulf is the mouth of the river Indus, one of the major rivers of the world. It is 3200 km in length, discharges an annual suspended load of 435 million tons and has a delta about 8500 km² in area which is prograding the shelf. This makes the Indus about the sixth largest river in the world in terms of suspended load discharge. Tongues of exceptionally high-suspended sediment concentrations extend from the Ganges and Indus mouths for distances of 1000 to 1500 km, much farther out to sea than any of the river outflows in the northern parts of either the Atlantic or Pacific oceans (Lisitzin, 1972). The river is also the source of the thick pile of sediments in the Arabian Sea called the Indus Cone.

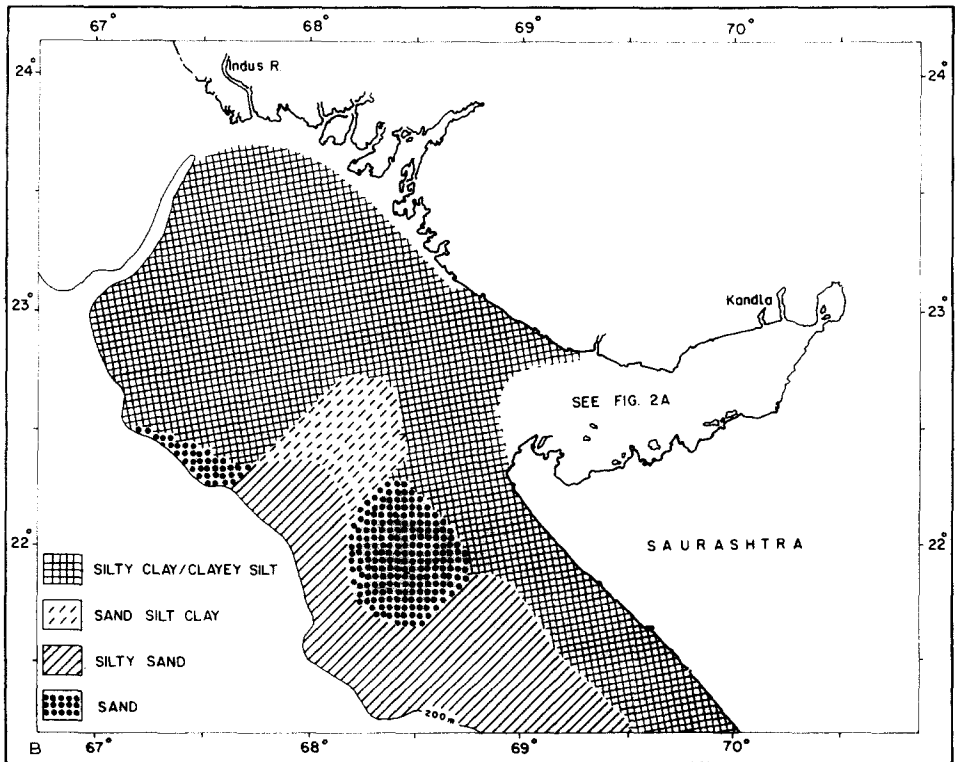
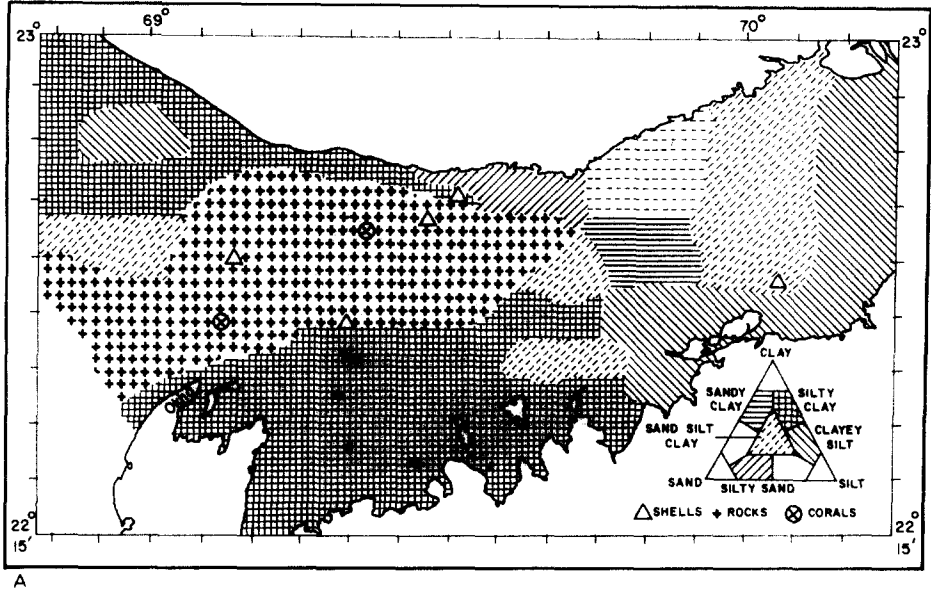
Tides of the gulf

The gulf has an average tidal range of 4 m. It varies from 3.06 m at Okha at the mouth to 5.89 m at Kandla at its head (Fig.1), and has a spring tide range of 6.2 m at its head.

Surface currents vary from 1.5 to 2.5 knots at the mouth to 3 to 5 knots in the central portions of the gulf (Naval Hydrographic chart no.L(D2) 203; Fig.1). Currents measured at Gurur Shoal at the mouth of the gulf on the southern side gave values of 1.59 m/s (~ 3 knots) (Srivastava and John, 1977) comparable to the value of 2.5 knots shown for the place in chart notations. Because of the high tidal range, low runoff from land and the irregular topography of the gulf, its waters as expected, are homogenous in terms of salinity and temperature (Varkey et al., 1977). This behaviour of the gulf is in sharp contrast to the estuaries on the west coast of India, which show seasonal stratification associated with the monsoon.

Topography and sediments

The topography is very irregular at the mouth and the central part of the gulf and consists of pinnacles and scarps ranging in height from 6 to 32 m. Towards the head the relief is subdued due to the covering of fine-grained sediments. A large area of the floor of the mouth of the gulf, at depths greater than 20 m, is covered with algal limestones, aragonite cemented sandstones and dead corals. On the low-energy margin of the gulf, especially on the southern side, wide tidal flats with patches of coral in the intertidal zone are present. The remainder of the gulf consists of silt and clay with patches of fine sand. Silt-size materials (5–8 ϕ) are found at the mouth, fine silt (6–8 ϕ) and medium silt (5–6 ϕ) occur at the southern side of the gulf at its head (Hashimi et al., 1978). A generalised sediment distribution map of the gulf is shown in Fig.2A and of the neighbouring continental shelf in Fig.2B. Sediment sources are likely to be due to wave erosion of the rocks bordering the shores of the gulf and those derived, as discussed below, from the Indus.



RESULTS AND DISCUSSIONS

Distribution of mica

The distribution of mica in sediments has been advanced as a qualitative measure of the energetics of the depositional environment (Doyle et al., 1968). Regions of high energy are characterised by low mica contents and vice versa. The Gulf of Kutch, despite being a high energy environment, as is evidenced by the high tidal range and strong currents, has a high mica content (Fig.3). For the purposes of this paper the term mica includes muscovite, biotite and chlorite. The mica content ranges from 50 to as high as 75% (estimated in the sand fraction by counting 300 grains under a binocular microscope) in the silty clays and clayey silts at the northern part of the mouth and at the head of the gulf. On the continental shelf north of the gulf, heavy-mineral studies (Mallik et al., 1976) show a distinct heavy-mineral province consisting of muscovite, biotite and chlorite ranging in concentration between 40 and 60%. In sharp contrast, in the sediments south of the gulf on the Saurashtra shelf these minerals occur at 5% or less (Fig.3). In general, the concentration gradient of mica increases towards the Indus and a reasonable inference from this distribution of mica is that the Indus is its source and that part of it is carried into the gulf by the flood tide and flushed out again by the ebb tide.

A significant outcome of the above-postulated process is that very little mica is transported along the shelf across the mouth of the gulf to the south of it. It may be added here that bathymetric features such as topographic highs are absent on the shelf in the area; even if present, these would influence the transport of material carried as bed load rather than mica and clay minerals which tend to be transported in suspension. Current velocities of the order of 1.5 to 2.5 knots are present at Lushington shoal at the mouth of the gulf (Fig.1) where it is about 75 km wide and such velocities in the offshore—onshore direction on the shelf may approximate the high-velocity jets that emanate from certain estuary inlets. We believe that it is this high-velocity jet that prevents the sediments carried by the coastal currents, usually weaker than the tidal stream, from being transported onto the inner continental shelf to the south of the gulf.

Distribution of clay minerals

In order to determine if the clay minerals also show variation similar to that of mica, thirteen selected samples from the north, south and at the

Fig.2. A. Sediment distribution map, based on analysis of samples shown in Fig.1. Note extensive outcrop of rock at the mouth of the gulf.

B. Generalised texture of sediment on the shelf off the Gulf of Kutch, based on analyses of samples shown in Fig.1. Off Saurashtra inner shelf (less than 50 m depth) the sediments are modern, low-carbonate, terrigenous facies and on the outer shelf they are calcareous relict sands. Off the Indus the modern terrigenous sediments extend to the shelf edge (100–120 m).

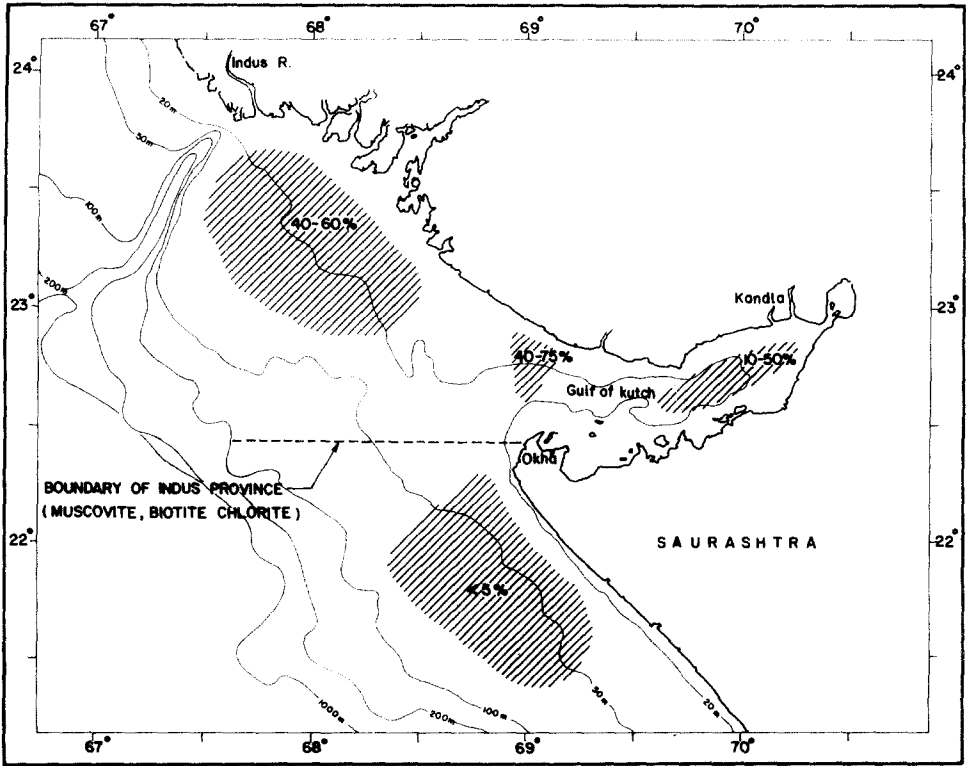


Fig. 3. Distribution of mica in the sand fraction.

mouth of the gulf (Fig.1) were analysed by X-ray diffraction. Analytical methods consisted of preparing oriented aggregates of the $< 2 \mu$ fraction by pipetting on glass slides which were scanned at $2^\circ 2\theta/\text{min}$ from 4 to $30^\circ 2\theta$. To distinguish chlorite from kaolinite, another batch of the same samples were treated with 1 N HCl at 80°C for one hour and scanned from 8 to $30^\circ 2\theta$, under the same instrumental conditions as the untreated samples. Relative variations in abundance of kaolinite and muscovite were estimated by measuring the area of their principal reflections, 7.1 and 10\AA respectively, by a polar planimeter. The results are expressed as ratios of the areas (Fig.1). The minerals identified are montmorillonite (smectite), kaolinite, muscovite, chlorite, quartz and feldspar in all the samples (Fig.4A). After acid treatment the kaolinite/chlorite peak is reduced in intensity and the chlorite peak at 4.7\AA does not disappear (Fig.4B). These results indicate that the chlorite is a well-ordered form (Carrol, 1970). Acid treatment also intensifies the 10\AA (it becomes asymmetrical to low angle), 5 and 3.5\AA peaks of muscovite (Fig.4B), indicating that it is a polymorph in mixture with other components (Thorez, 1975). Differences in the abundance of kaolinite and muscovite occur between samples at the mouth of the gulf and those south of it (Fig.1). The variation in the abundance of the individual minerals is more pronounced in the samples close to the coast than those further away. The ratios are

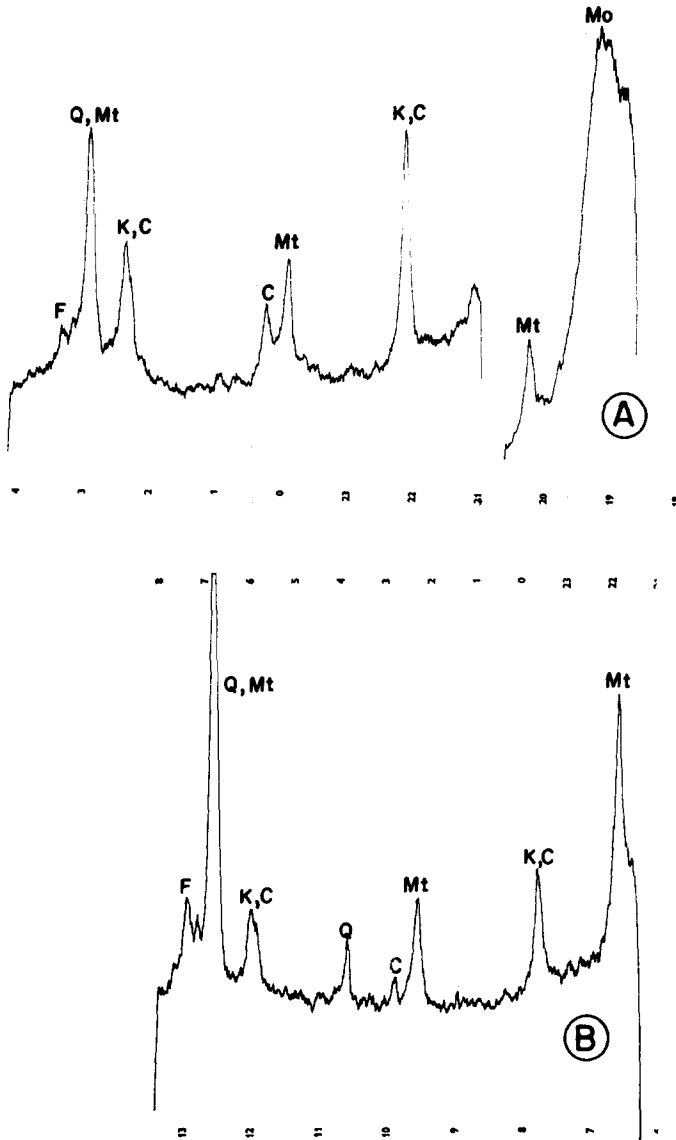


Fig. 4. X-ray diffractogram of representative sample (circled value in Fig. 1 shows the location).

A. Untreated, 4 to $30^\circ 2\theta$; B. Acid treated. 8 to $30^\circ 2\theta$.

Mo = Montmorillonite, *Mt* = Muscovite, *K* = Kaolinite, *C* = Chlorite, *Q* = Quartz, *F* = Feldspar.

smaller south of the mouth than those directly off the mouth. Unlike the distribution of mica, which was determined from the coarse fraction and which shows a marked variation in abundance north and south of the gulf; the distribution of clay-size minerals ($< 2\mu$) is not pronounced. This is

because the tidal stream is a more effective barrier to the transport of coarsed-grained sediments. In other words, the tidal stream acts as a filter permitting some of the fine-grained sediments to pass through but preventing the coarse grained sediments.

Bathymetry data and bottom profile

More importantly, the long-term integrated result of the transport and accumulation of sediments on the inner continental shelf is depicted by the 20 and 50 m isobaths (Fig.1) and they considerably strengthen the arguments based on the distribution of mica. Progradation of the sediments of the Indus delta has resulted in the pronounced seaward shift of the 20 m isobath whereas, in sharp contrast, off the Saurashtra coast the same isobath lies close to the coast, indicating that this part of the shelf is deprived of sediment, even though it is close to the Indus delta. Echo-sounding profiles south of the gulf also reveal that even small-scale topographic features of the order of 1 to 3 m in height are not covered by modern sediments (Fig.5). Thus despite the fact that the Indus sediments are transported as far as 1500 km in the pelagic regions of the Arabian Sea and result in the accumulation of as much as 2500 m of unconsolidated sediments on the Indus Cone (Ewing et al., 1969), the sedimentary contribution on the continental shelf by the Indus 100 km south of its mouth remains highly restricted.

The situation is all the more unusual when one considers the fact that during the southwest monsoon season (June to September) when the discharge of the Indus is at its peak, a southerly to southeasterly flowing current on the continental shelf is generated in response to the monsoon winds. Under these conditions, one would expect the river-borne sediments to be carried in the down-current direction. That this takes place only on the shelf north of

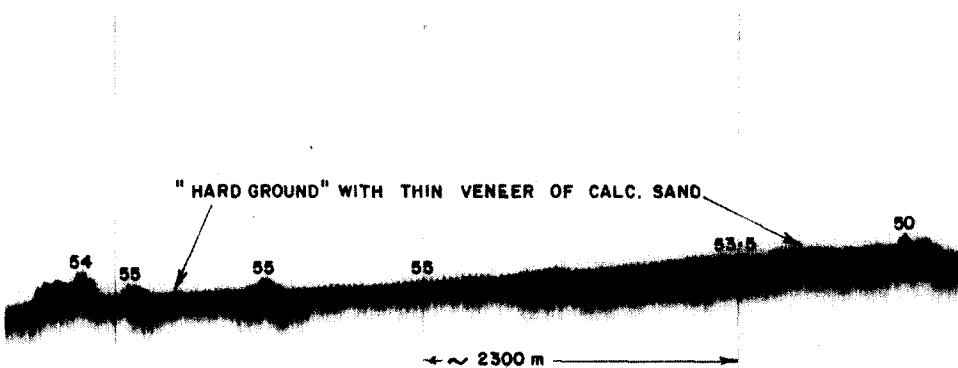


Fig.5. Bottom profile (location in Fig.1) showing small-scale topographic features uncovered by sediments. Depths in metres.

the gulf is seen from the description of the distribution of mica. Had the along-shore drift on this shelf not been interrupted by the tidal currents of the gulf, the distribution of mica would tend to be more uniform on either side of its mouth. Since its distribution shows sharp gradients and since the 20 and 50 m isobaths also show large differences in distance from the coast north and south of the mouth of the gulf, the hydraulic barrier effect of the high-velocity tidal stream is apparent. The distribution of clay minerals on the inner shelf demonstrates that the tidal stream is less effective as a barrier or filter for the fine-grained sediments than for the coarse-grained ones. This behaviour of the tidal stream is analogous to that of an electronic pulse-height discriminator which transmits only pulses above a certain amplitude.

The tentative physical explanation is as follows: the suspended sediment plume of the Indus river must be a relatively fresh water plume. Therefore, it may override the tidal jet of normal salinity and higher density. At 150 km from the source, the sediments in suspension would be only clays with no sands hence the clays will by-pass the jet but not the sands. Sand-size material, if present, will be carried as bed load and appreciable quantities of bed load transport can occur, as shown by many studies, under strong unidirectional tidal currents.

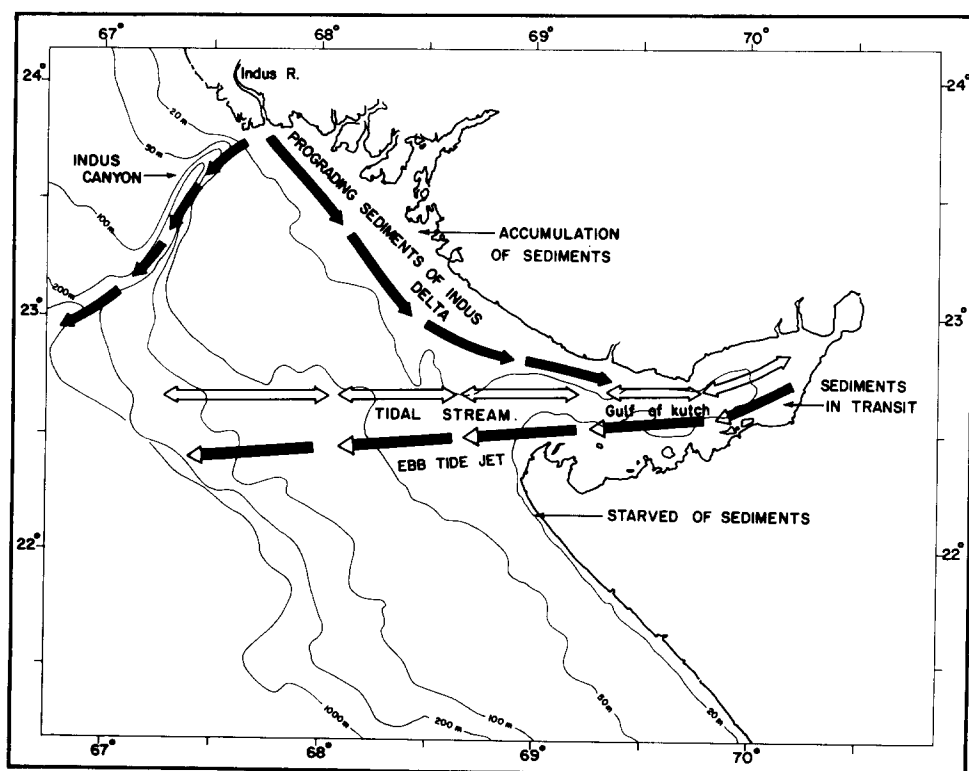


Fig.6. Inferred sediment transport direction.

The inferred sediment transport directions in the region are shown schematically in Fig.6. This is necessarily a simplified regional picture and the effect of local factors like interaction of the tidal stream with the waves on the shelf, the generation of eddies and other matters have been ignored.

By analogy with the behaviour of other rivers associated with submarine canyons, the bulk of the river-borne sediment is probably funneled by the canyon head to the depths of the Arabian Sea, giving rise to the Indus Cone. Lesser amounts of sediment are deposited on the delta and some of it is carried along in a southeasterly direction into the Gulf of Kutch. Within the gulf the sediments are in transit under the action of the high-velocity tidal currents. The ebb-tide jet transports them to slope depth (> 200 m). South of the gulf, on the Saurashtra shelf, the sediment input is considerably reduced, thereby accelerating coastal retreat by wave erosion.

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