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Morphology of Channel-Levee Systems on the Indus Deep-Sea Fan, Arabian Sea

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ABSTRACT

The channel-levee systems of the most recently active part of the Indus deep-sea fan are mapped with GLORIA side-scan sonar, continuous seismic reflection profiling, high resolution (3.5 & 10 kHz) profiling, and other geophysical techniques. The resultant processed sonograph mosaic covers an area of approximately one eighth of the 1,570,000 km^2 of the fan and there are about 12,000 km of new seismic lines. The study is supplemented by 35 new cores recovered from various fan environments. The channel-levee systems have some striking similarities with architectural elements of mature terrestrial fluvial systems. The GLORIA sonographs reveal that the channel-levee systems on the fan are sinuous to highly meandering (sinuosity up to 3). Distributary complexes of large and small channel-levee systems exist on the fan. Distributary complexes of large channel-levee systems develop at the mouth of individual canyons on the upper fan while distributary complexes of small channel-levee systems develop from large channels on the middle fan. Both large and small channel-levee systems show remarkable similarities to each other in their cross-sectional form parameters, dimension of levee (overbank) deposits and degree of meandering etc. Only one channel was active at a time. The process of avulsion is one of the main controls on the development of the large and small channel-levee systems on the fan.

INTRODUCTION

Submarine fans and associated turbidite systems can constitute major hydrocarbon reservoirs. More than 80 sedimentary basins contain major petroleum producing submarine fan deposits, and these reservoirs produce from a variety of structural stratigraphic and combined traps (Weimer & Link, 1991a). The major discoveries of hydrocarbons from turbidite sequences (i.e. Bacoccoli et al., 1980; Bloomer, 1977; Casnedi, 1983; Heritier et al., 1980; Hill and Wood, 1980; Hsu, 1977; Parker, 1975; Sarg & Skjold, 1982; Siemer et al., 1981; Verdos and Visher, 1978) together with the invention of sophisticated geophysical tools (such as GLORIA and SeaMARC side-scan sonars, SeaBeam - a swath bathymetry mapping system and three dimensional multi-channel seismic profiling) led to the start of a new era of submarine fan research in the 1980's. A number of submarine fans were systematically surveyed and many new concepts, which illustrate the future direction of turbidite research, have been introduced and several existing ones have been modified (Bouma et al., 1985; Weimer and Link 1991b). These concepts have important implications for the future exploration for hydrocarbons from turbidite systems. This paper summarizes preliminary findings of the recent mapping on the middle Indus Fan. Emphasis is placed on description of the morphology of channel-levee systems.

INDUS SYSTEM

The Indus system consists of (i) the Indus River and associated small rivers, (ii) the Indus Delta, (iii) the Indus Canyon and (iv) the Indus Fan (Figure 1).

The Indus system is the product of Himalayan orogeny. Many workers have discussed the tectonic origin of the Indian Ocean and the collision of the Indian and Eurasian plates during the Early Oligocene (e.g. Molnar and Tapponnier, 1977; Powell and Conaghan, 1973; Valdiya, 1984; Whitmarsh, 1974). As a result of major and minor orogenic uplifting events two major fluvial systems, the Indus and Ganges, came into existence on either side of the Indian Plate. The Himalayan sediment detritus transported through them created the two largest submarine fans in the world i.e. the Indus and the Bengal Fans.

The Indus River and its associated rivers have been the dominant suppliers of terrigenous sediments to the Indus fan. The Indus river is about 2,900 km long (Coumes and Kolla, 1984). the total drainage area of the river is 970,000 km^2 (Holmes, 1968) and the river has an annual discharge of between 5,550 and 5,700 m^3s^{-1} (Lisitzin, 1972). The mean annual suspended load of the river has been 440 to 450 million tons (Holmes, 1968). However, due to the recent dam building program the mean annual discharge has been drastically reduced to 40 to 55 million tons (Nair, 1984).

The Indus Delta is typically triangular in shape and covers an area of approximately 1,000 km^2 (Kazmi, 1984). As a result of the dam building the delta has now shrunk down to a small triangular area of only 100 km^2.

The present day Indus Canyon is the most pronounced bathymetric feature of the shelf and slope. The general morphology of the Indus Canyon, known as the "swath", was first described by Hayter (1960) and Islam (1959). It reaches

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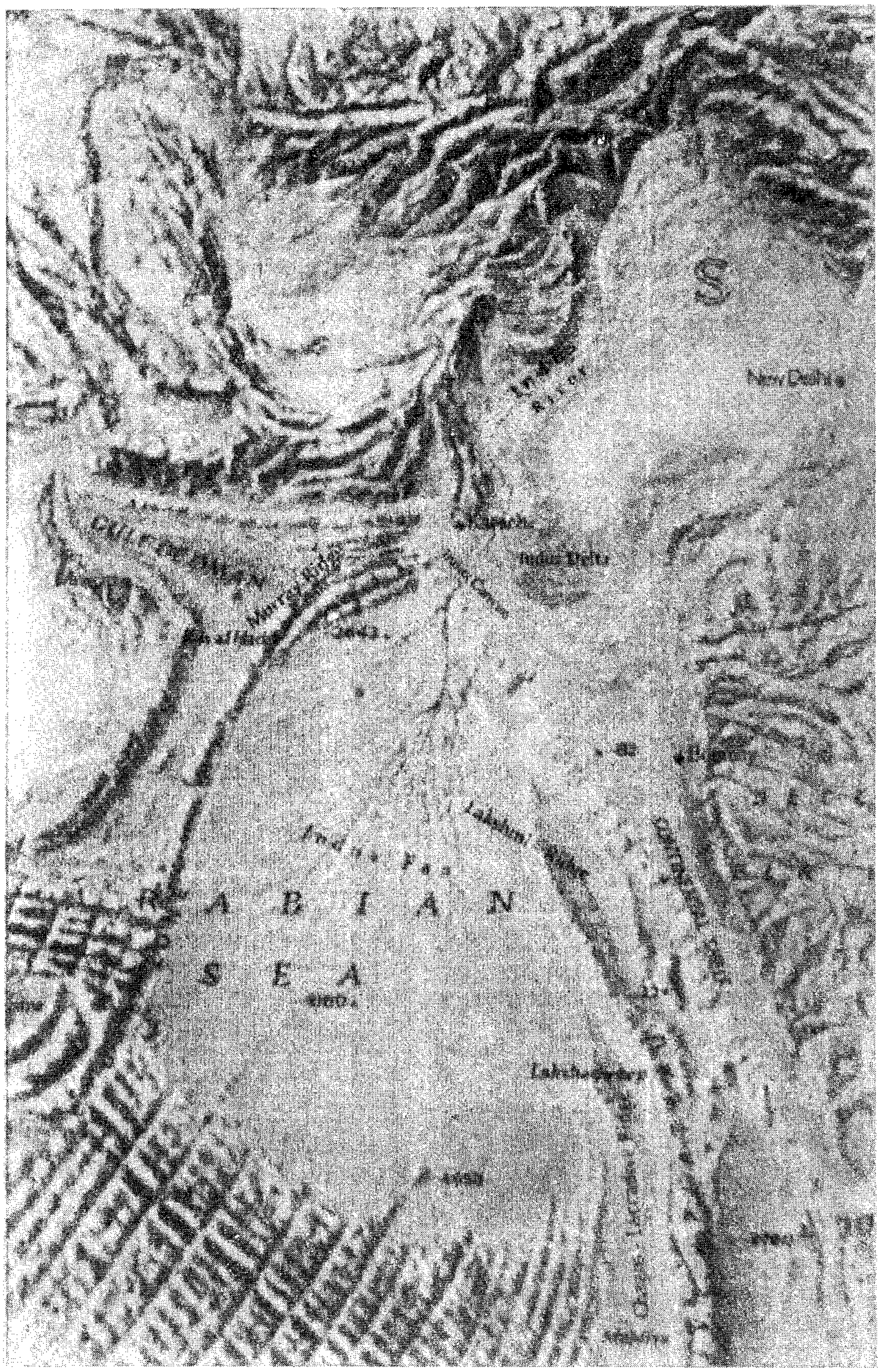

Figure 1- Map showing the location of the Indus Deep-Sea Fan, (modified from Atlas of the World (1981).

an average depth of 800m. Profiling shows that, beside the present-day Indus Canyon, two older buried canyon complexes (or possibly more) exist on the continental shelf of Pakistan (Kolla and Coumes, 1987; McHargue and Webb, 1986).

The Indus Fan developed on the passive continental margins of Indo-Pakistan. The fan is 1950 km in length, 960 km in width and extends from the continental shelf/slope of Pakistan in 1000 m depth, to the flanks of the spreading Carlsberg Ridge, in a water depth of more than 4,500 m (Figure 1). Laterally the body of the fan is bounded by the seismic Laccadive Ridge to the east and by the Owen and Murray ridges to the west. The fan can be divided into several basins of relatively thick sedimentary fill, separated by the Laxmi (Lakshmi) Ridge and its branch, which form a northward continuation of the Chagos-Laccadive Ridge (Naini and Kolla, 1982).

Based on the provenance analysis of the older sediments from sites 220 and 223 (Leg 23), Weser (1974) concluded that the Indus Fan sedimentation in the Arabian Sea began in Late Oligocene to Early Miocene times. The time difference (5 to 7 millions years) between initial uplift and the Indus Fan sedimentation can be ascribed to the time required for development of the Indus drainage system for the transportation of detritus to the fan.

DATA ACQUISITION

This study is part of a collaborative research programme between the National Institute of Oceanography Pakistan, the Institute of Oceanographic Sciences (IOS), UK, and the Department of Earth Sciences, University of Wales College of Cardiff/Swansea, UK.

The survey of the Indus Fan was completed in two separate cruises. On the first cruise, Charles Darwin 20, GLORIA side-scan sonar, 160 in^3 airgun gravimeter, magnetometer, sonobuoy and 3.5 kHz seismic profiling systems were used to map a segment of the middle fan (Figure 2). In a follow up cruise, Charles Darwin 27, a total of 35 cores were recovered from selected study areas of the fan, using various coring techniques (Figure 2).

GLORIA (Geological Long-Range Inclined Asdic) is a long-range side-scan sonar designed and developed at IOS. The system has been described in detail by Somers et al. (1978). It comprises a towed vehicle, an unfaired cable, shipboard amplifiers and procession and display unit. The Vehicle is a 7.75 m long by 0.66 m wide cylinder that is towed at a specific depth, between 40 and 80m, at a speed of 8 to 9 knots. The system operates with frequency of 6.5 to 6.7 kHz. This frequency corresponds to a swath width of about 25-27 km on either side of the vehicle.

GENERAL FAN MORPHOLOGY

The fan can be divided into three parts, the upper, middle and lower fan, based on morphological and acoustic characteristics. Usage of these terms is for purely descriptive purpose and does not have any genetic significance or facies associations.

The upper fan extends from about 1,000 m water depth, at the foot of the continental slope to a depth of more than 3,300 m, where pronounced changes in channel morphology, acoustic character and gradient take place (Figure 3). The upper fan is the steepest part of the fan with an overall gradient of 1:500 (0.11°) (Figure 3). Because of the presence of the large channel-levee systems and their interchannel valleys, which have formed as a result of stacking of the channel-levee systems on top of each other, the upper fan has a characteristically high relief. Approximately 70 percent of the total volume of terrigenous sediment is deposited on the upper fan (Amir, 1992).

The upper boundary of the middle fan leis at the water depth of about 3,300 m and extends to a depth of more than 3,800 m (Figure 3). The average gradient of the middle fan is approximately 1:700 (0.08°). In general the upper section of the middle fan, with an average gradient of 1:550 (0.11°), is steeper than its lower section, where the average gradient is about 1:900 (0.06°) (Figure 3). The entire surface of the middle fan is occupied by small channel-levee systems.

The lower fan, with average gradient of about 1:1,100 (0.05°), is the gentlest slopping part of the fan (Figure 3). The transformation from middle to lower fan takes place between about 3,800 and 3,900m water depth. Little is known about the detailed morphology, acoustic and sedimentary characteristics, because only a small portion of the lower fan was mapped in the present survey. It is believed that most of the lower fan surface contains sandy channel-mouth lobes, resembling classical lobe sequences as defined by Mutti and Ricci Lucchi (1972).

MORPHOLOGY OF CHANNEL-LEVEE SYSTEMS

At least eighteen channel-levee systems have been mapped on the fan (Figure 4). Based upon morpho-acoustic characteristics, channel-levee systems are divided into large and small systems.

(i) Large channel-levee systems.

These are found beyond the mouth of canyon systems and combine to form higher order distributary complexes on the upper fan (Figure 4).

(ii) Small channel-levee systems.

These develop down channel form the large channel-levee systems and also combine to form distributary complexes of a lower order on the middle fan (Figure 4).

Out of eighteen channel-levee systems mapped, six are large channel-levee systems and twelve are small channel-levee systems. The small channel-levee systems form two distributary complexes fed by the two youngest of the large channel-levee systems. It is believed that the other large channel-levee systems may also have had lower order complexes fanning out from a somewhat similar position on the middle fan, but evidence to support this either lies to the

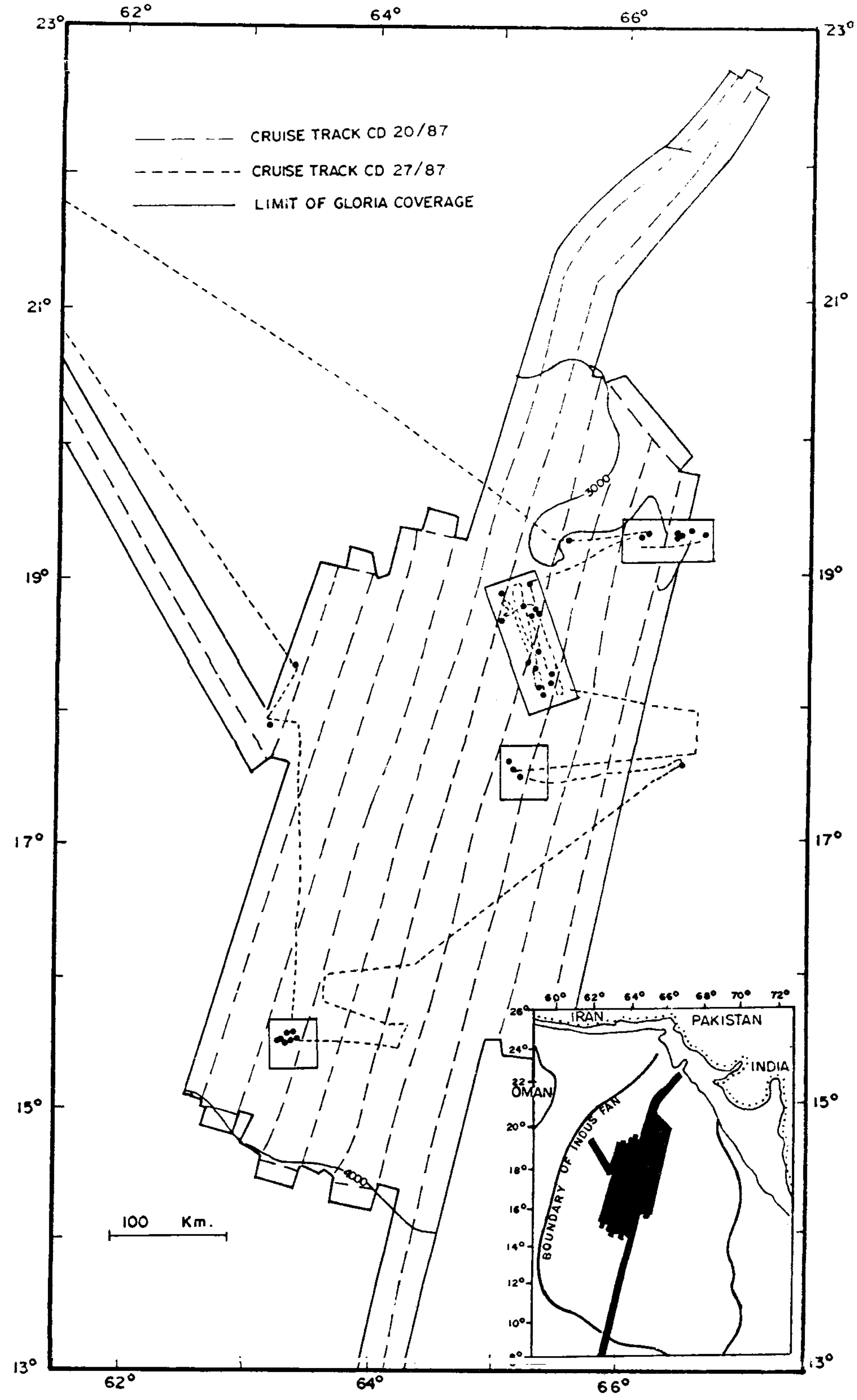

Figure 2- Track chart of the survey area of the Indus Fan. Boxes mark location of sediment sampling sites. Dots marks location of cores. Contours in meters.

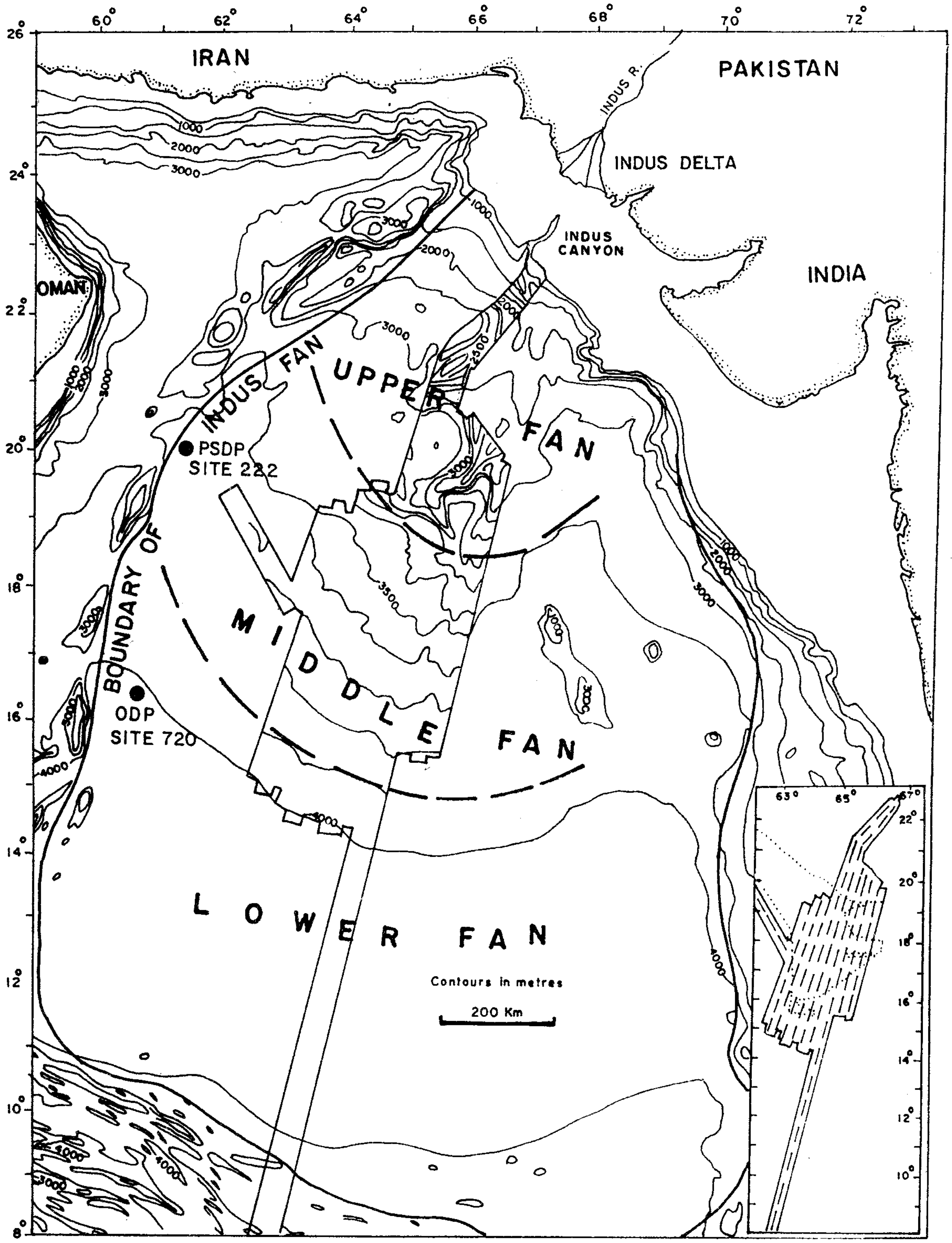

Figure 3- Bathymetry and morphological divisions of the Indus Fan region (modified from Kenyon et al., 1995). The 500m contours are from International Ocean Expedition (1975). Within the area of GLORIA coverage the contour interval is 100m, drawn from data profiles obtained along tracks shown in the insert and in Figure 2. ODP Site 720 (Prell & Niitsuma et al., 1989) and DSDP Site 222 (Whitmarsh et al., 1974) are also shown.

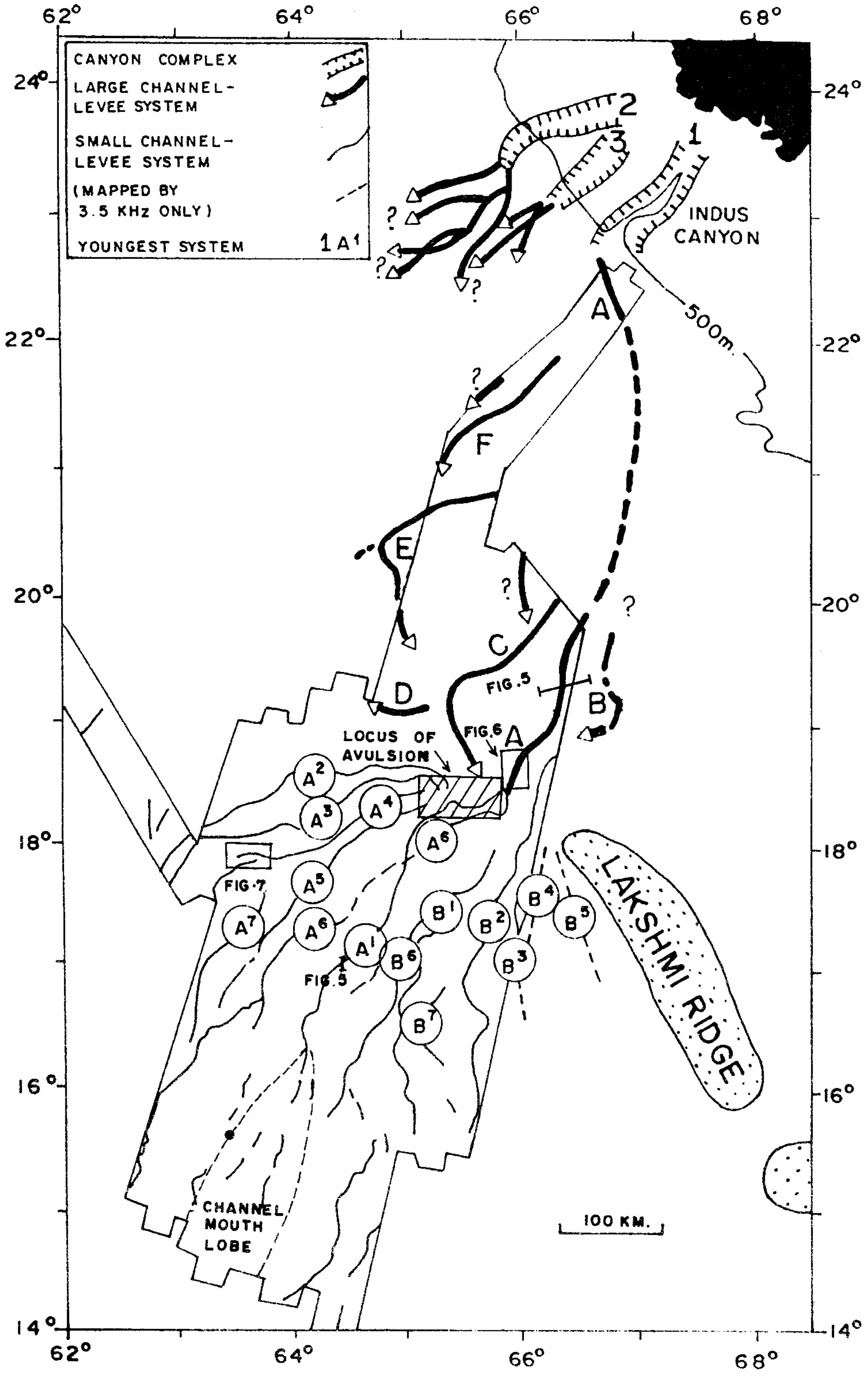

Figure 4- Distributary complexes of large (A is youngest and E is oldest) and small channel-levee systems (A^1 is youngest and B^7 is oldest) on the Indus Fan mapped by GLORIA long-range side-scan sonar and sequence of canyon complexes (1 is youngest and 3 is oldest). Data outside the GLORIA survey is from Droz and Bellaiche (1987), Kolla and Coumes (1987) and McHargue & Webb (1986) (modified from Kenyon et al., 1995).

east of this survey area (an area unmapped by GLORIA), or has been buried by the younger systems.

The channel-levee systems have been named according to nomenclature based on the relative ages of the channel-levee systems within the depositional sequence (Amir, 1992; Kenyon et al., 1995). Large channels are labeled A, B, C, D, etc. while the small channels emanating from A large A^1, A^2, A^3 etc (Figure 4).

Both large and small channel-levee systems show remarkable similarities to each other in channel cross-sectional form parameters, dimension of levee (overbank) deposits and degree of meandering etc. Generally all these parameters change systematically downfan in response to variations in nature and type of sediment load, fan gradient, hydrodynamics of channelized flows, availability of space for sedimentation etc. (Amir, 1992).

The large channels are typically 300 to 400 m deep and 8 to 10 km wide near the foot of the continental slope, and are 100 to 200 m deep and 1.5 to 3 km wide on the upper fan (between 2,900 and 3,300 m water depth) (Figure 5). The individual levee (overbank) deposits on either side of the large channels are about 10 to 30 km wide, up to 1,100 m thick, and rise as high as 800 m above the surrounding fan surface. The total width of large channel-levee systems decreases down fan from about 60 to 20 km (Figure 5). The levee (overbank) deposits of large channels are ornamented with sediment waves (Figure 5).

On the surveyed part of the fan, the large channel A has fed, in turn, at least six small channel-levee systems. The large channel A is considered to be the most recent one as it is part of a channel-levee system that overlies all the others. It is connected to the present day Indus canyon at the shelf break (Figure 4) and has a floor that backscatters sound more strongly than any of the older channels. The greater backscattering strength is thought to be due to the so far unconfirmed, presence of sandy sediments of the channel floor. The large channel starts near the foot of continental slope in about 1,600 m water depth and is traced downslope for a distance of about 500 km (at 3,300 m water depth).

At Lat. 18° 28' and Long. 65° 50', the large channel A spreads out into a distributary complex form a site identified as a "locus of avulsion" and at least six small channel-levee systems originate from this area (Figure 4). This site of avulsion also marks the area where large channel-levee systems gradually transformed to small channel-levee systems. Among the small distributary channel-levee systems only the youngest channel A^1 is presently attached to the large channel. It can be traced for a distance of about 700 km at 3,700m water depth. Beyond this point the high backscattering expression of the channel A^1 merges with the high backscattering pattern of the surrounding fan surface and the channel subtly transforms into a channel-mouth lobe, which is believed to be an area of coarse sandy deposition (Figure 4) (kenyon et al., 1995). The attachment of the large channel A to only one of the small channels suggests that only one channel was active at a time. This is further confirmed by relative age relationships established by superposition seen on air-gun seismic and 3.5 kHz high resolution profiles, by variation in thickness of pelagic/hemipelagic drape and by difference in intensity of backscattering on the sonographs (Kenyon et al., 1995).

As the large channels, the parameters of cross-sectional form and dimension of levee (overbank) deposits of small distributary channels show a progressive decrease downfan. The depth of small channels averages about 50-100 m in the upper reaches of the middle fan and 20-50 m in the lower reaches of the middle and lower fan. The width of the small channels decreases form about 1,800 m to about 600 m. The width of the levee (overbank) deposits decreases downfan form about 20 km in the upper reaches to about 5 km in the middle reaches. The height of the levees decreases from about 60 m to about 5 m. In the extreme lower reaches, the small channels are largely devoid of levees and the channels are entrenched below the fan surface (Figure 5).

At the foot of the continental slope, the large channel is not a truly meandering channel but is a meandering-thalweg channel. The thalweg of the channel is more sinuous than the channel itself. On the upper and middle fan, between 2,900 and 3,700m water depth, both large and small channels are highly meandering. The transition form meandering-thalweg to meandering channel for large channel A occurred in the largely unmapped Indian Exclusive Economic Zone. The sinuosity (which is a quantitative expression of meandering and is the ratio of channel length/valley length) of all channels decreases downfan and varies between 3.0 and 2.0 for the large channels and between 2.7 and 1.3 for the small channels.

One of the most striking features of Indus channel morphology is the presence of abandoned meander loops or oxbow lakes and chute cutoffs. These loops can be observed at several locations on both large and small channels. Figure 6 shows an example of such an abandoned meander loop from the large channel A.

Beside the presence of morphological features which display striking similarities to the architectural elements of typical fluvial systems, the study of acoustic signatures of 3.5 kHz high resolution profiles reveals the presence of possible point bar (s) in the axis of large channel A and other channels (Figure 5). The detailed morpho-acoustic characteristics of point bar(s) observed in the channels will be presented elsewhere (Amir et al., in prep).

Avulsion, the switching of the channel form one part of the valley to another by development of a new course (Schumm, 1977), seems to be a common characteristic of the fan channels. A total of sixteen cases of avulsion are recognized in the surveyed part of the fan, In the example of avulsion seen in the lower reaches of channel A^4 (Figure 7), the old branch appears to be completely abandoned and a new branch developed on the upslope side of the old one. It is believed that the process of avulsion is major control on fan development. Following avulsion a new channel usually develops in one of the two neighboring interchannel deeps (Amir, 1992).

CONCLUSIONS

(1)The mapping of a segment of the middle Indus Fan by GLORIA side-scan sonar shows that distributary channels are highly meandering. The channel-levee systems displays some morphological features which have striking similarities with some of the architectural elements of mature terrestrial fluvial systems. These features include a high degree of meandering

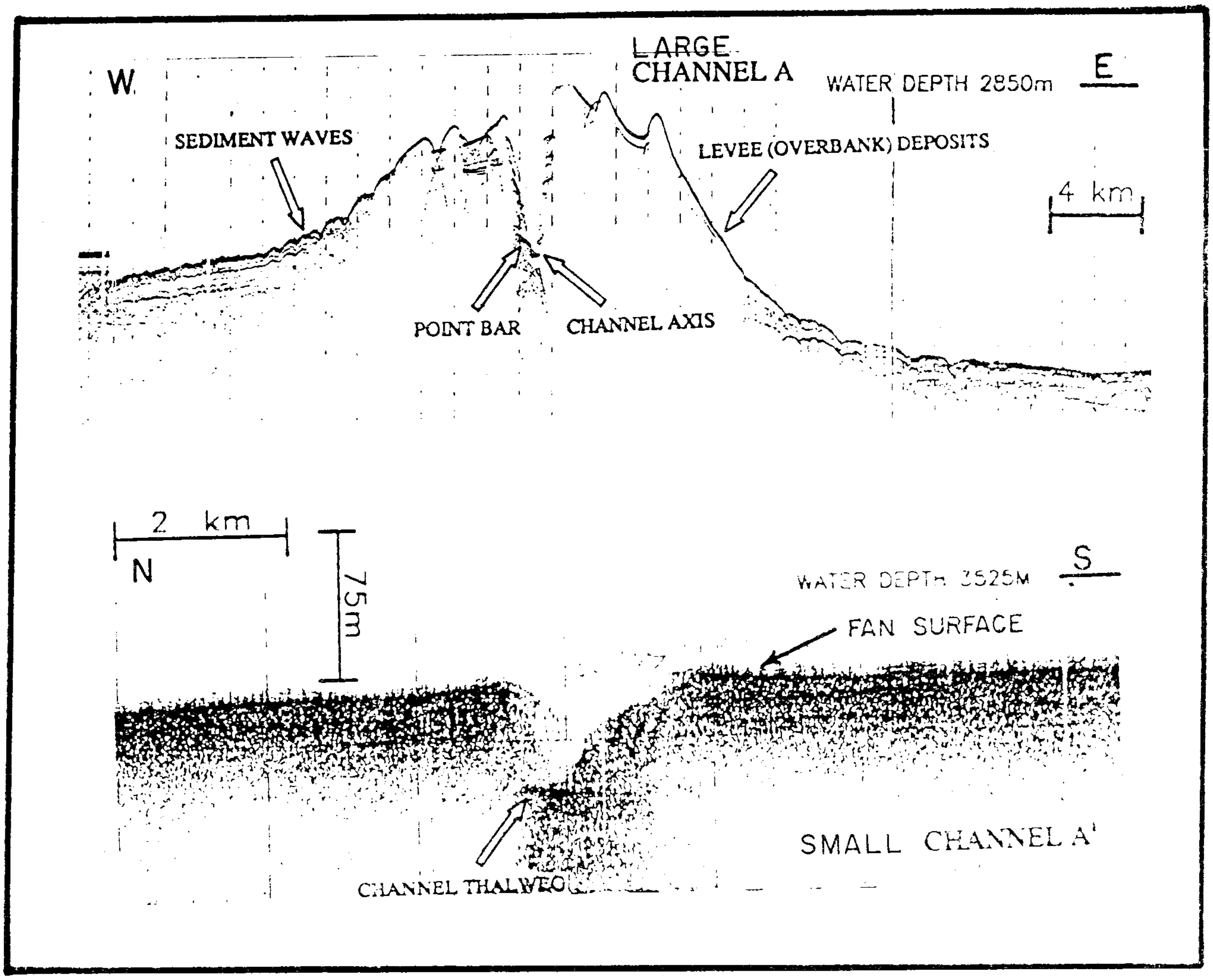

Figure 5- 3.5 kHz high resolution profiles across large and small channels A and A^1 illustrating various morphological features. Location of profiles is shown in Figure 4. Note the entrenching of channel thalweg (about 50m) within the fan surface and levee (overbank) deposits are absent.

accompanied by neck and chute cutoffs, levee (overbank) deposits on the flanks of channels, point bar deposits in the axes of channels etc. Major differences are that marine channel-levee systems decrease regularly in size downslope and that the marine levees can be very much greater in thickness.

(2)Distributary complexes of large and small channel-levee systems exist on the fan. The large channel-levee systems develop at the mouth of canyons on the upper fan while the small channel-levee systems develop from large channels on the middle fan. Both large and small channel-levee systems show similarities to each other in cross-sectional form parameters, dimension of levees, degree of meandering and other parameters. Generally these parameters show a systematic decrease downfan in large and small channels, presumably in response to variations in nature and type of sediment load, hydrodynamics of channelized flows, fan gradient etc.

(3)Each large system has fed in turn a number of small channel-levee systems. Only one channel was active at a time. The process of avulsion is an important control on the overall development of the fan.

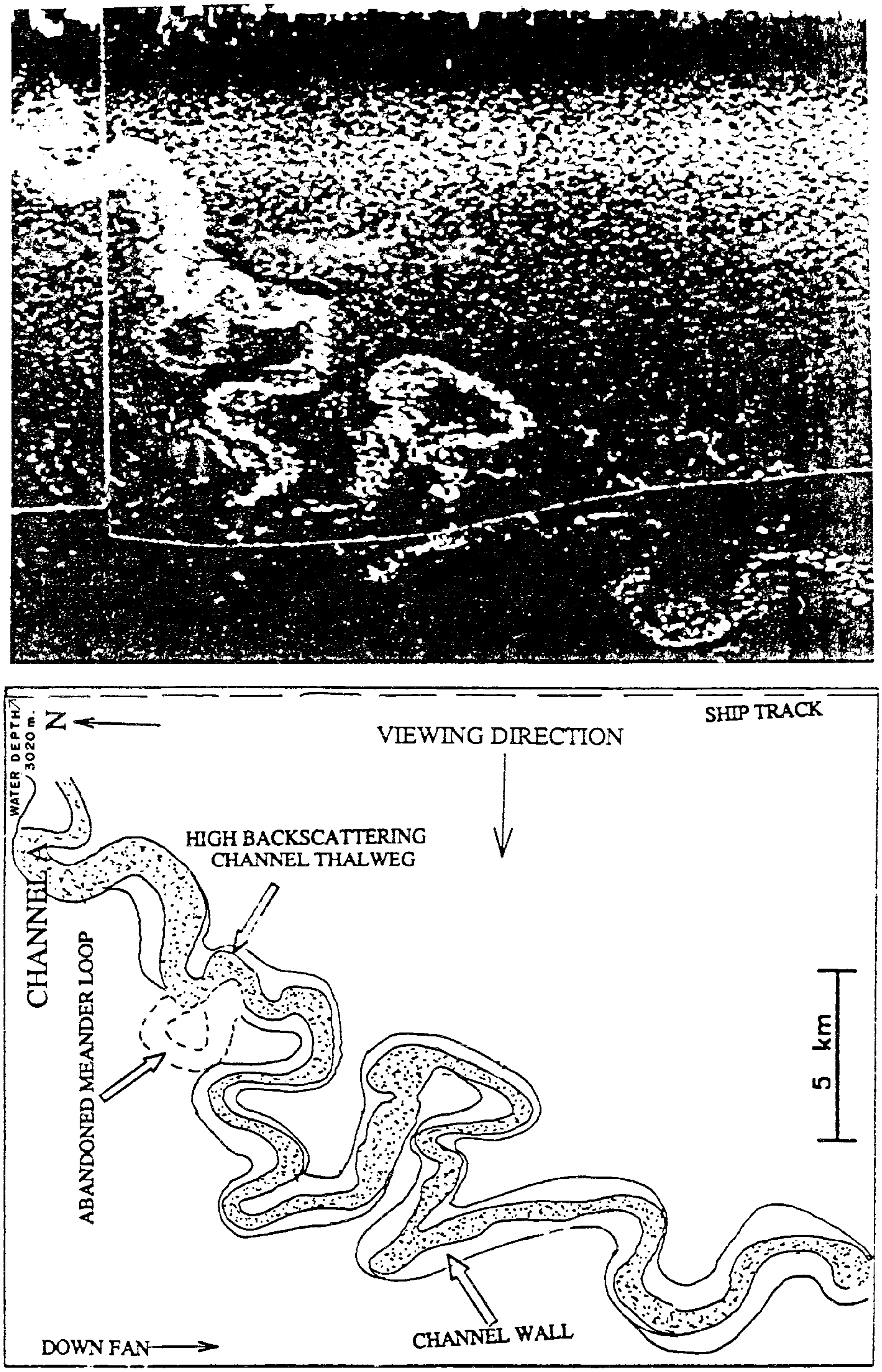

Figure 6- GLORIA sonograph (upper) and interpretation (lower) showing an abandoned meander loop and other morphological features on the large channel A. Scale bar applies in all directions. Location of the sonograph is shown in Figure 4.

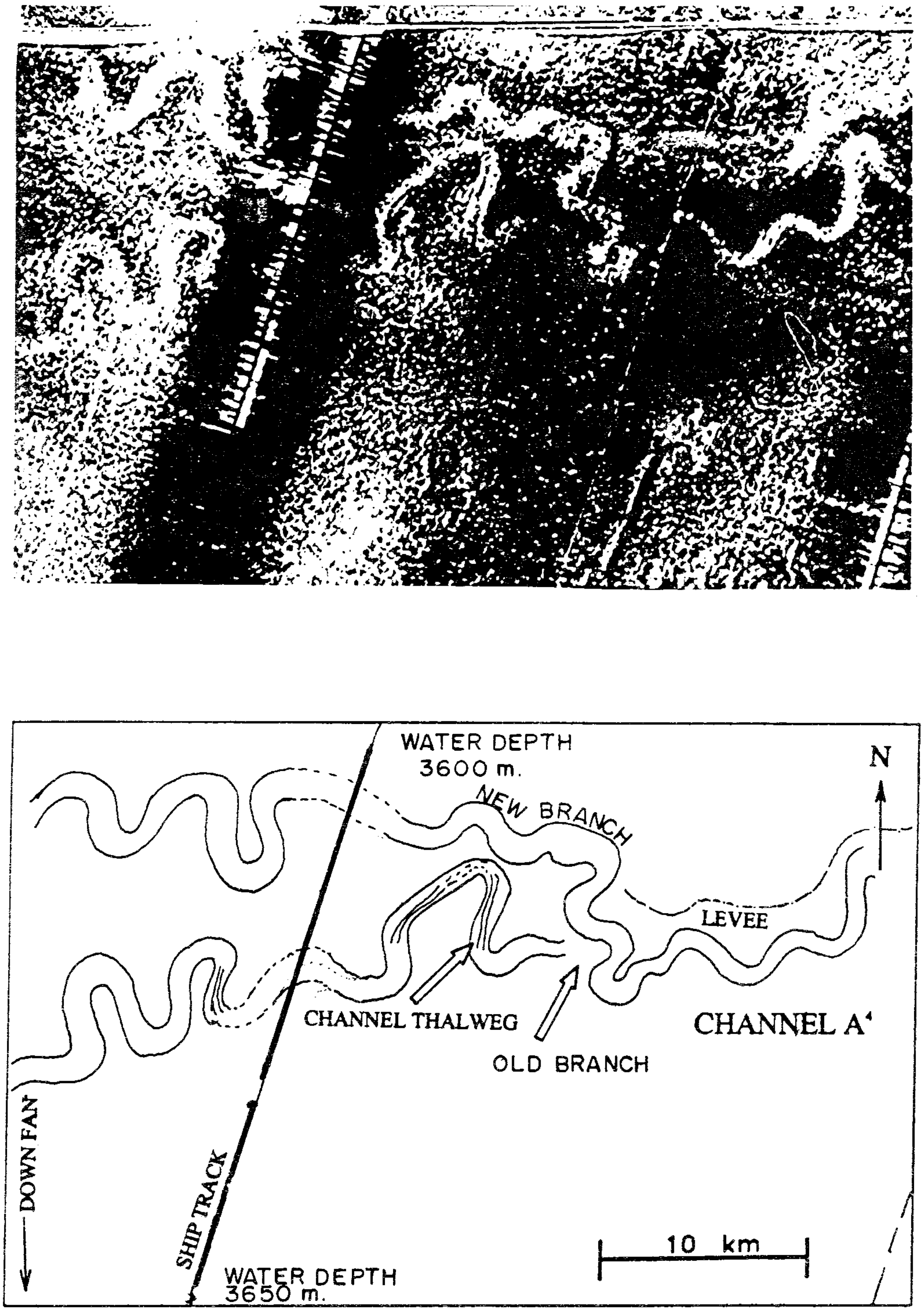

Figure 7- GLORIA sonograph (upper) and interpretation (lower) illustrating an example of channel bifurcation by avulsion of channel A^4. Scale bar applies in all directions. Location of the sonograph is shown in Figure 4.

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