Available online at www.sciencedirect.com
ScienceDirect
Continental Shelf Research 26 (2006) 1668–1684
CONTINENTAL SHELF RESEARCH
www.elsevier.com/locate/csr

Recent morphodynamics of the Indus delta shore and shelf

Liviu Giosan[a,*], Stefan Constantinescu[b], Peter D. Clift[c], Ali R. Tabrez[d], Muhammed Danish[d], Asif Inam[d]

[a]*Department of Geology and Geophysics, Woods Hole Oceanographic Institution, 360 Woods Hole Road, Woods Hole, MA 02543, USA*
[b]*Department of Geography, University of Bucharest, N. Balcescu No.1, Bucharest, Romania*
[c]*Department of Geology and Petroleum Geology, University of Aberdeen, Aberdeen AB24 3UE, UK*
[d]*National Institute of Oceanography, ST-47 Block 1, Clifton, Karachi 75600, Pakistan*

Received 29 June 2005; received in revised form 7 April 2006; accepted 11 May 2006
Available online 10 July 2006

Abstract

In natural conditions, the Indus River had one of the largest sediment loads in the world, building an extensive delta on the high-energy coast of the Arabian Sea. However, water and sediment discharge have been drastically altered in the Indus since the early 1960s, when several barrages were built along the river to feed the world's largest irrigation system. A digital terrain model based on detailed 19th century surveys has been constructed to assess the morphology of the Indus shelf. Comparison of the digital terrain model to a 1950s Pakistani bathymetric survey allowed an estimation of the natural sedimentation regime before extensive human-induced changes. Digital analysis of the Indus delta coastline based on satellite imagery was used to explore the effects of the drastic decrease in sediment delivery following extensive dam building.

The Indus Canyon is a dominant feature of the region dissecting the shelf to within 20 m water depth and 3.5 km of the coast. Theoretical considerations based on estimates of the relative importance of wave energy vs. fluvial sediment delivery suggest that the Indus delta should develop a mid-shelf subaqueous clinoform. Instead, the Indus shelf exhibits a compound clinoform morphology. A shallow *delta front clinoform* extends along the entire delta coast from the shoreline to the 10–25 m water depth. A mid-shelf clinoform developed probably as a *prodelta clinoform* between ~30 and 90 m water depth. The advanced position of the mid-shelf clinoform east of the Indus Canyon might reflect either a prolonged sediment delivery from the Indus River in that area compared to the shelf west of the canyon or the presence of a relict pre-Holocene mid-shelf delta. A distinct lobe of the mid-shelf clinoform developed along the Kutch (Kachchh) coast probably as sediment advected alongshore was redeposited on the mid-shelf by strong offshore-directed tidal currents at the Gulf of Kutch mouth.

Accumulation and erosion between 1895/96 and 1952/54 occurred primarily on the delta front clinoform, but also on the prodelta clinoform sector covered by both the surveys. During that time period, at the active Indus mouths, the delta front clinoform has built directly into the Indus Canyon, where sedimentation rates exceeded 50 cm/year. A sediment budget for the shelf for the 1895/96–1952/54 period suggests that the previous estimate of an Indus sediment discharge rate of 250 million tons per year in natural conditions is probably a minimum estimate. For the same time interval, the shoreline advanced along most of the delta coast. The progradation rate at the active mouths along the central delta coast surpassed 100 m/year. Following the 80% reduction in sediment discharge after the late 1950s, the deltaic shoreline along the central delta coast started to recede at average rates of ~50 m/year. The abandoned delta shore (southeastern and northwestern sectors of the delta coast) remained largely progradational over the same period, with the southeastern sector prograding

*Corresponding author. Tel.: +1 508 289 2257.
E-mail address: lgiosan@whoi.edu (L. Giosan).

0278-4343/$ - see front matter
doi:10.1016/j.csr.2006.05.009

at an even greater rate than before. This differential behavior of the delta shoreline suggests a significant role for delta front sediment transfer processes in the evolution of abandoned deltaic coast.

Keywords: River discharge; Coastal erosion; Subaqueous delta; Clinoform; Pakistan; Arabian Sea

1. Introduction

Construction of dams for flood control, water consumption, and power generation has resulted in significant reductions of water and sediment discharged to coastal regions by rivers (Vörösmarty et al., 1997; Walling and Fang, 2003). Over 40% of the river water discharge and close to 30% of the sediment discharge on a global scale are intercepted by large man-made impoundments (Vörösmarty et al., 1997; Syvitski et al., 2005). Changes in fluvial freshwater discharge can drastically impact coastal ecosystems, while reduction in river-supplied sediment can lead to coastal retreat. Deltaic coasts, where the sediment budget is dominated by river supply, exhibit low relief that renders them especially vulnerable to retreat. In many cases, the morphological effects of recent, often dramatic, human-induced reductions in sediment discharge of delta-building rivers remain to be quantified. A prominent example is the Indus River, which is one the largest rivers that is intensively impounded (Milliman et al., 1984). Furthermore, the Indus delta has a high wave energy coast that is susceptible to erosion (Wells and Coleman, 1984) and rapid sea encroachment due to sea level rise (Haq, 1999).

The Indus River drains the western Himalaya and Karakoram Mountains, crossing the semi-arid to arid regions of the Indus Plain toward the Arabian Sea (Fig. 1). The water discharge of the river ranked 20th in the world with ~90 km^3/year before the extensive damming started in 1950s. Although this discharge was modest compared to other rivers with drainage basins of similar size, the Indus used to be one of the most important sediment-producing rivers in the world that built an extensive alluvial plain and delta as well as the world's second largest submarine fan (Milliman and Meade, 1983). The Indus River feeds the world's largest irrigation system, which has been developed over the last ~150 years (Fahlbusch et al., 2004). Several large dams and barrages were built on the Indus River (Sukkur Barrage in 1932, Kotri Barrage in 1961, Mangla Dam in 1967, and Tarbela Dam in 1971), leading to dramatic reductions in water and sediment discharge after 1950s (more than 70% and 80%, respectively; Milliman et al., 1984; Fig. 2). Over the last few years, water flow below Kotri, which is the last barrage before the delta (Fig. 2), has been effectively cut down to approximately 2 months a year of active flow (August–September; Asianics, 2000; Inam et al., 2004).

In a seminal paper on the Indus delta morphology, Wells and Coleman (1984) advanced a scenario for the evolution of the Indus delta coast under the current loss of water and sediment. They predicted a cessation of subaqueous and subaerial delta front deposition, followed by the establishment of transgressive beaches along the delta coast dominated by eolian activity.

The objective of our study was to examine the morphodynamics of the Indus coast and shelf in natural conditions, before any significant reductions in fluvial sediment discharge occurred due to river damming. We used detailed historical charts to assess the morphology of the Indus shelf and analyzed changes along the deltaic coast in natural discharge conditions (pre-1960). Satellite imagery was then employed to provide initial estimates of the impact of the post-1960 Indus discharge reduction on shoreline changes along the Indus delta coast.

2. Background

2.1. Water and sediment discharge

The Indus is the oldest river in the Himalayan region, with the location of its upper reaches remaining stationary within the Indus Suture Zone since early Eocene (>54.6 Ma; Clift, 2002). In spite of its age, the Indus River used to deliver to the Arabian Sea the fifth largest sediment load in the world (Wells and Coleman, 1984), because it drains barren, unconsolidated glacial and fluvially reworked detritus (Milliman et al., 1984) eroded from high-relief, rapidly uplifting tectonic units of the western Tibetan Plateau, Karakoram and the Indus Suture Zone (Clift, 2002). Aridity in the basin leads

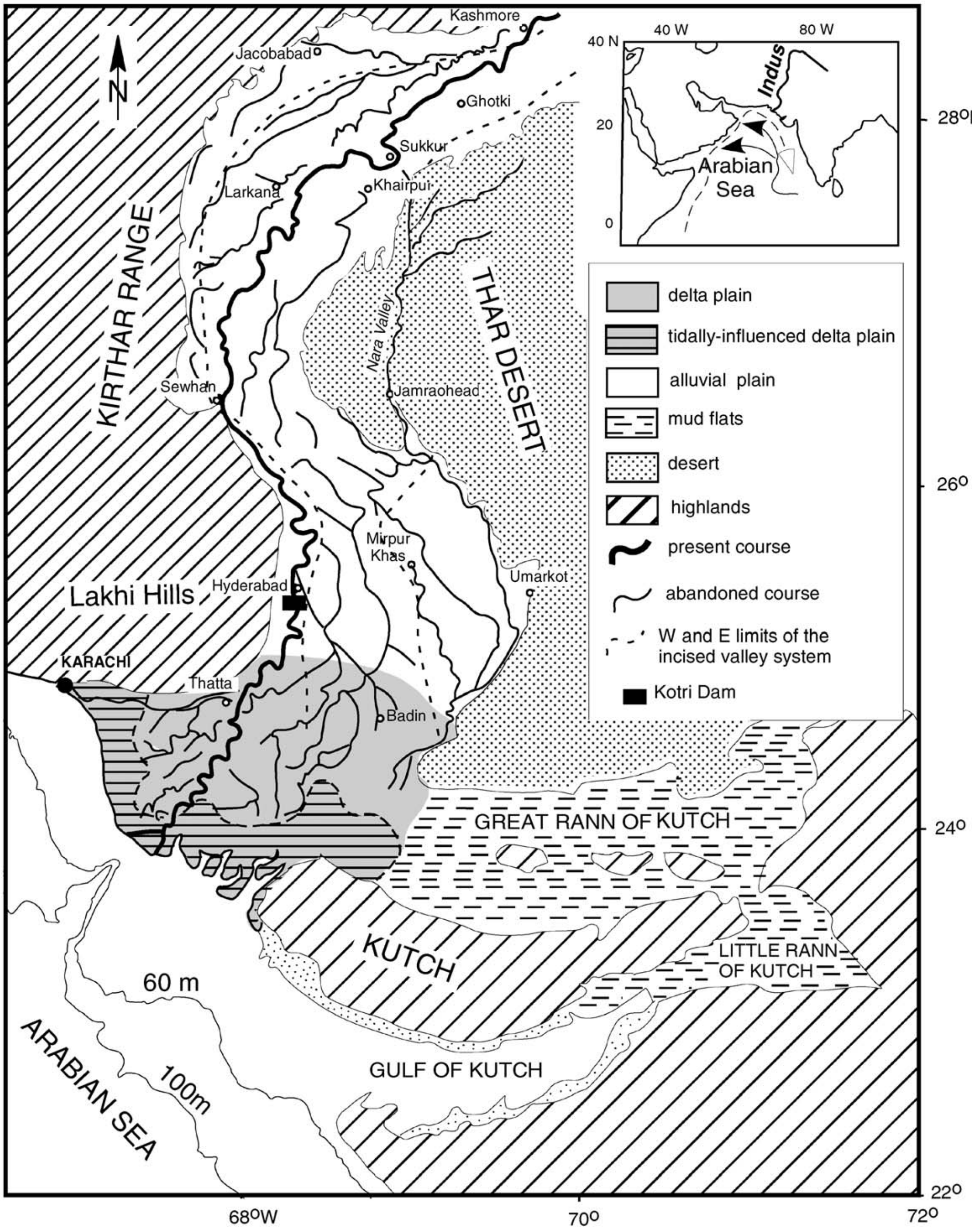

Fig. 1. Location map of the lower Indus basin and Indus delta showing the general physiography, former river courses (after Holmes, 1968), and postulated location of the late Pleistocene incised-valley system (after Kazmi, 1984). Inset in the upper right corner shows the geographical location of the Indus River and the surface currents in the Arabian Sea during the summer monsoon (dashed arrowed line) and winter monsoon (continuous arrowed lines; after Staubwasser et al., 2002).

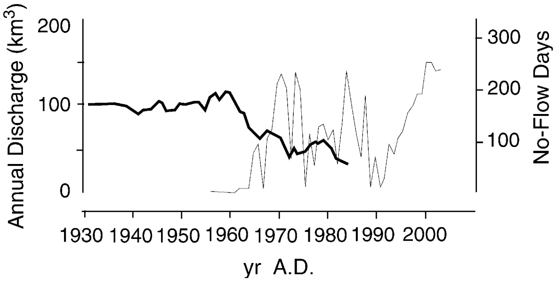

Fig. 2. Mean annual discharge of the Indus River at Kotri near Hyderabad (thick line; after Jorgensen et al., 1993; Karim and Veizer, 2002) and days with no river flow below Kotri barrage (thin line; data from Asianics, 2000 and Inam et al., 2004). A dramatic reduction in discharge and a consequent increase of in the number of days without river flow occurred after 1950s after the construction of major barrages and dams on the Indus River at Kotri in 1961, Mangla in 1967, and Tarbela in 1971.

to a low annual water discharge when compared to rivers that have similar sediment loads (cf. Milliman and Meade, 1983; Meade, 1996), averaging ~3000 m^3/s in natural conditions. However, water discharge is extremely variable during the year with summer monsoonal discharge occasionally reaching ~30,000 m^3/s (Wells and Coleman, 1984). Most of the water flow occurs between May and October (>80%) following the melting of snow in the headwaters of the basin and augmented by summer monsoon rains (Milliman et al., 1984; Karim and Veizer, 2002). The sediment discharge is similarly erratic with suspended sediment concentrations reaching 3 g/l during floods (Holmes, 1968). The annual sediment discharge has been estimated to be between 300 and 675 million tons (Milliman et al., 1984 and references therein), before the large-scale human regulatory intervention in the 1960s. Milliman et al. (1984) argued that only 250 million tons of sediment reached the Indus delta in natural conditions, with a remainder of ~350 million tons of sediment being deposited in the alluvial plain.

2.2. *Indus alluvial plain*

The large sediment load of the Indus River led to the formation of a broad alluvial valley (~150 km wide on average) in the lower basin between the hills of Kirthar Range in the west and sand dunes of the Thar Desert in the east (Fig. 1). In natural conditions, the sediment reaching the delta and continental shelf was composed predominantly of silt (between 60% and 70% on average) with variable quantities of sand and clay (Kazmi, 1984; Khan et al., 1993). Micas are typical of Indus sediment and could add up to 60% of the sand fraction in shelf sediments (Nair et al., 1982).

Abandoned older courses of the Indus River (Fig. 1) were identified by Holmes (1968) based on soil surveys (WPWPDA, 1966; Holmes and Western, 1969) and aerial photographs taken in 1953 (WPWPDA, 1966), before large-scale agricultural development started to obliterate natural landforms on the alluvial plain. Holmes's inventory of old river channels shows that major avulsions of the river took place well above the delta, preferentially around Kashmore and Sehwan (Fig. 1). Jorgensen et al. (1993) linked these avulsion loci to tectonically controlled differential uplift and subsidence. Within the delta, historical accounts document avulsions by levee breaching during extreme flood events (Holmes, 1968). The relatively coarse grade of the sediment load probably favored formation of new channels rather than reoccupation of older small channels that silted up quickly to function as secondary spillways (Holmes, 1968).

2.3. *Oceanographic regime*

Although the Indus delta receives the highest deep water wave energy of all deltas globally (Wells and Coleman, 1984), after being attenuated on the wide, shallow shelf, wave energy at the coast is lower than for typical wave-dominated deltas (Wells and Coleman, 1984). However, Wells and Coleman (1984) observed that the Indus coast receives in a day as much wave energy as the Mississippi coast in year. Wave measurements offshore Karachi at 20 m water depth reported by Rizvi et al. (1988) show that the mean significant wave height during the summer southwest monsoon (May–September) is ~1.8 m with a mean period of 9 s. During the winter offshore-directed monsoon winds (October–April), the significant wave height is ~1.2 m with a period of 6.5 s (Rizvi et al., 1988). Wells and Coleman (1984) suggested that wave-driven sediment transport is effective in redistributing of river-delivered sediments along the deltaic coast.

Dispersal of sediments is also accomplished by tidal and wind-driven currents; however, their role in sediment transport is unknown at present as no systematic measurements are available. Tides are semidiurnal with a tidal range at the Karachi gauge of 2.7 m. The mean current along the coast switches from southwesterly during the summer monsoon to northeasterly during the winter monsoon (Rizvi et al., 1988). Further southeast on the coast of India, Nair et al. (1982) proposed that strong cross-shore tidal currents up to 1.6 m/s offshore the Gulf of Kutch (or Kachchh; Fig. 1) act as a dynamic barrier preventing dispersal of Indus sediments past the mouth of the Gulf to southeast (see also Chauhan et al., 2000).

2.4. Indus delta

During the Holocene, the Indus has built an extensive lobate delta (Figs. 1 and 3). The delta apex was proposed to be located somewhere between Hyderabad and Sehwan (Holmes, 1968; Kazmi, 1984; Wells and Coleman, 1984). Kazmi (1984) postulated that much of the alluvial plain from the modern delta coast to north of Sukkur (Fig. 1) was formed during the last deglacial period and the Holocene, when the Indus River filled its own valley system that was incised during the last sea level lowstand. Several remnants of the pre-deltaic relief composed of Eocene limestone crop out within the delta (Ganjo Takar at Hyderabad, Makli Hill at Thatta; Aban Shah Hill in the lower delta plain; Fig. 3). The delta extends to the east into the Great Rann of Kutch (Fig. 1), a vast mudflat area that is invaded by storm surges during the summer monsoon. The Rann is probably a former gulf of the Arabian Sea that has been filled by deltaic deposition (Malik et al., 1999; Rajendran and Rajendran, 2001 and references therein). The hills of the Kutch Mainland (Fig. 1 and 3) are composed of Jurassic and Cretaceous rocks and border the Great Rann to the south and several "islands" of similar rocks outcrop within the Rann (Merh, 1995). It is not clear if the Rann was filled by the early Indus deltaic deposition and/or by one or several independent river systems (Malik et al., 1999; Rajendran and Rajendran, 2001).

Several contradicting reconstructions have been proposed for Indus delta development (Lambrick, 1964; Wilhelmy, 1967; Holmes, 1968; Kazmi, 1984; Flam, 1999), but lack of any chronostratigraphic information makes it impossible to validate one model over another. The strongest indication that the Indus delta first started to develop in the east near the Rann of Kutch comes from the distribution of archeological findings of the Harappan (Indus Valley) culture (Flam, 1999). The only delta plain sites of this ancient culture were discovered south of Badin (Fig. 1) and they are part of its mature phase, which suggests that the delta plain in that region was already developed between 4600 and 3900 years BP.

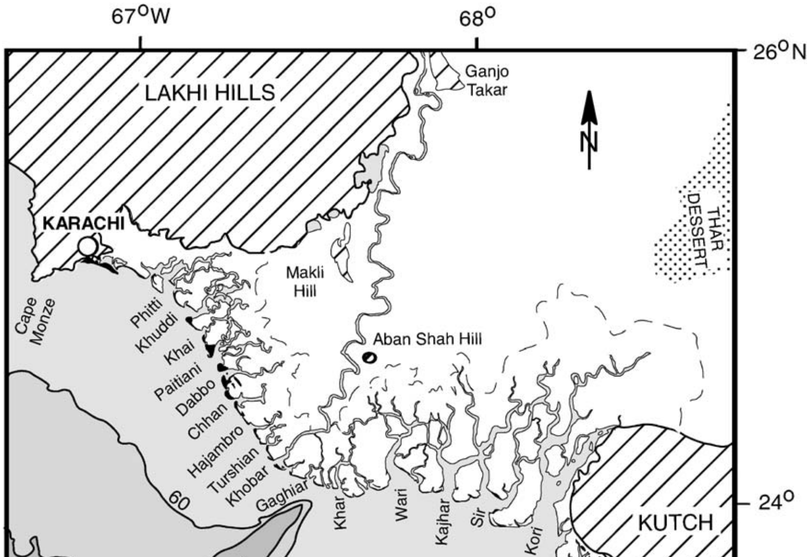

Fig. 3. Map of the Indus delta region with the names of the main tidal creeks along the delta coast are shown. Several sandy barrier islands front the delta coast (black-filled pattern). The landward limit for the tidal penetration within the delta is indicated by the dashed line.

During the recent historical period, a major avulsion of the Indus from east to west of Hyderabad was recorded in 1758–59 and resulted in the establishment of the present river course within the delta (Wilhelmy, 1967; Holmes, 1968). As previous distributaries were progressively abandoned following this event (Wilhelmy, 1967), direct fluvial sediment delivery to both the eastern and western sectors of the delta coast probably declined (i.e., between the Phitti and the Dabbo mouths and between the Wari and the Sir mouths, respectively). Abandoned Indus delta channels have been reworked by tides all along the coast into dendritic tidal creeks (Fig. 3). The tidal creek network is most extensive and appears more mature east of the present Indus mouths (Khobar, Gaghiar) towards Kutch, where the coast has a dissected appearance typical of tide-dominated deltas. The wide channels of this eastern delta plain (Khar, Wari, Kajhar, Sir, and Kori) penetrate deep inland, leading to flooding of wide areas of the lower delta plain and the Rann of Kutch during the summer monsoon (Fig. 3). The deltaic coast from Karachi to the active river mouths exhibits a dense, less-mature tidal channel network. A stronger wave influence along this part of the coast compared to further east is suggested by the development of drumstick-shaped barrier islands (Fig. 3), typical of island systems significantly influenced by both waves and tides (e.g., Stutz and Pilkey, 2002).

2.5. *Indus shelf*

The shelf of the Indus delta remains largely unstudied. Its most prominent feature is the Indus Canyon or "The Swatch", a relic feature of the pre-Holocene relief (Fig. 3), which dissects the shelf to within 20 m water depth at 3.5 km offshore the Khobar mouth of the Indus delta. Wells and Coleman (1984) assumed that the subaqueous delta extends to the 10 m isobath only, which would place the Indus delta within the category of largely subaerial deltas. The relatively coarse caliber of the river sediments and the fact that most sediment is delivered in phase with summer monsoon wind setup that promotes retention of sand close to the shore was proposed to have favored rapid expansion of the subaerial delta (Wells and Coleman, 1984). However, high silt and low carbonate contents in surface sediments on the modern Indus shelf (Nair et al., 1982; Khan et al., 1993) show that sediments from the Indus River are probably dominant to depths of ~70 m. On the outer shelf (deeper than ~90 m), geophysical and core data near the Indus Canyon show only patches of a thin veneer of Holocene sediments (Von Rad and Tahir, 1997). Southeast of the Gulf of Kutch, micas make up less than 5% of the shelf sands, confirming that a limited amount of coarse Indus sediment escapes past the gulf's mouth to the southeast (Nair et al., 1982). The Indus Canyon is also presumed to have played a role in preventing the subaqueous delta from developing by capturing and funneling sediment towards the Indus submarine fan (Islam, 1959; Nair et al., 1982; Wells and Coleman, 1984).

3. Methods

Early detailed charts of the Indus delta coast from the 19th century were based on surveys of the Marine Survey of India. To visualize the morphology of the Indus shelf in natural conditions, we chose the most detailed single survey performed in 1895–96 under the direction of Commander C.F. Oldham (Fig. 4 and 5a; British Admiralty, 1897a, b). The survey was published by the British Admiralty in 1897 in two separate sheets covering the coast from Cape Monze (or Ras Muari) west of Karachi to the Turshian (or Kediwari) Creek on the delta coast and further from Turshian mouth to Nirani Creek on the Kutch coast, respectively (see Fig. 3 for locations). To construct a more complete digital terrain model of the shelf, we added soundings from the survey performed by L.A.M. Grieve in 1848–50 (Fig. 4; British Admiralty, 1915) for areas outside the Oldham survey (i.e., the offshore part of the shelf located east of the Indus Canyon and the shelf in front of the Gulf of Kutch). The final DTM consists of 21,707 individual soundings of which 15,642 from the Oldham survey; to these we added the digitized bathymetric contours of the original charts.

The only available single-survey chart in the 20th century is based on the 1952–54 data (Fig. 5b) of the Hydrographic Office of Pakistan (1955). This later chart consists of 5497 soundings and covers Pakistani waters only. We compared this chart to the Oldham survey to study the bathymetric changes in the region of the Indus shelf covered by both the surveys. No similar single-survey bathymetric data were available for the coast east of Sir Creek. Soundings on the 1952–54 chart are presented reduced to the Karachi datum, which is 0.2 m above the Mean Lower Low Water and 1.2 m

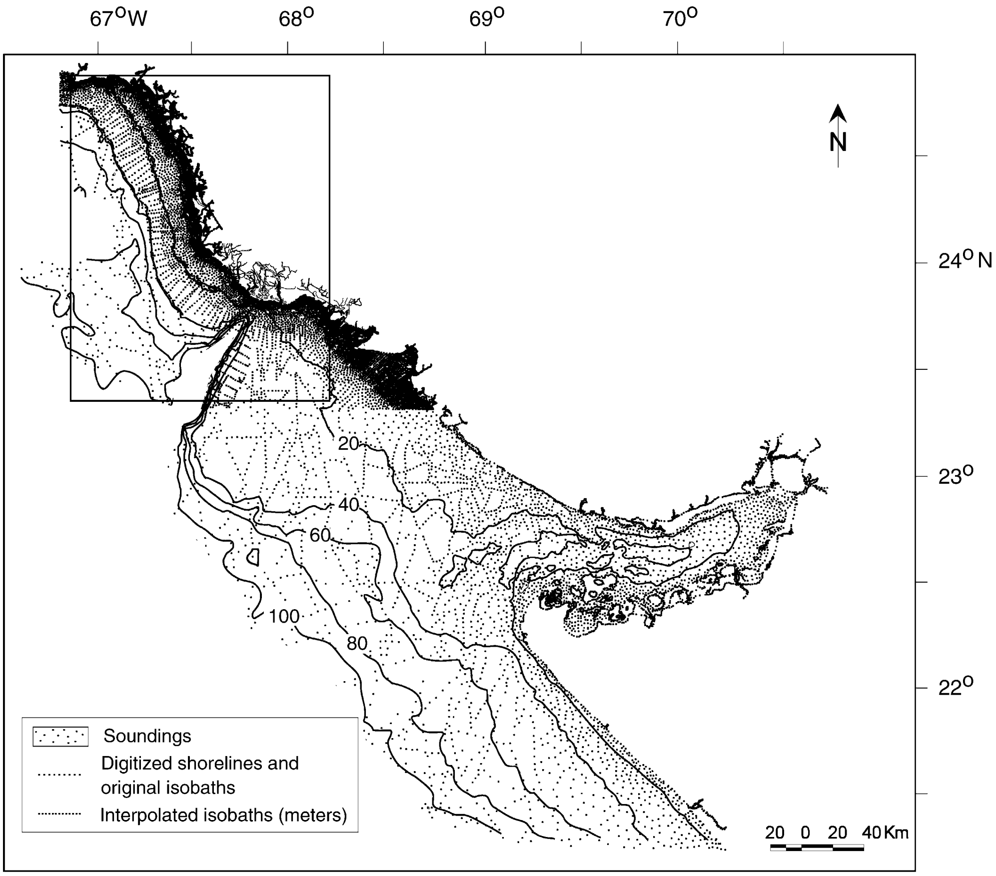

Fig. 4. Digitized bathymetric surveys and shorelines used for generating the DTM for the Pakistani Indus coast in the 19th Century. The surveys include the 1848–50 Grieve survey (British Admiralty, 1915) and the 1895–96 Oldham survey (British Admiralty, 1897a, b). The box indicates the region of overlap between the Oldham survey and the 1952–54 Pakistani survey (Hydrographic Office of Pakistan,1955).

below the Mean Higher Low Water measured at the Karachi gauge. Although no direct information is provided on the Oldham map, the inundability pattern along the coast described on the map suggests that the data have been reduced to a datum close to low tide level. The vertical error when comparing the two maps should therefore be between −0.2 and 1.2 m. Sea level rise at the Karachi gauge is ~1.1 mm/year (Khan et al., 2002); the cumulative rise between the dates of the two surveys used for bathymetric comparisons is thus ~6.5 cm, which is within the potential errors resulting from using different datums for the two surveys. Given the constraints on datum accuracy, only bathymetric changes that were larger than ±2 m were considered in our interpretations. Similarly, given the density of points on the 1952–54 chart, only areally extensive (larger the 10 km^2) bathymetric changes were considered in our analysis.

Shoreline change rates were computed based on the digitized shorelines of 1895–96 and 1952–54 for interfluves of the deltaic coast between Karachi and Sir Creek mouth (i.e., segments of coast located between tidal creeks/river mouths in both the surveys). Shoreline changes for the post-1971 period, when the large-scale damming of the Indus was completed, were calculated using shorelines digitized from satellite photos (LANDSAT MSS, from Global Land Cover Facility, http://glcf.umiacs.umd.edu/index.shtml) taken on October 11, 1978 and on November 3, 2000. Both photos were taken when the tide stage at Karachi was 1.6 m. The coverage area of the satellite-derived shorelines extended only between Khudi and Sir Creeks (Fig. 3).

Prior to digitizing, all charts and satellite photos used in this study were georeferenced and transformed to a common UTM projection (Zone 42N) with Global Mapper 6.0 (http://

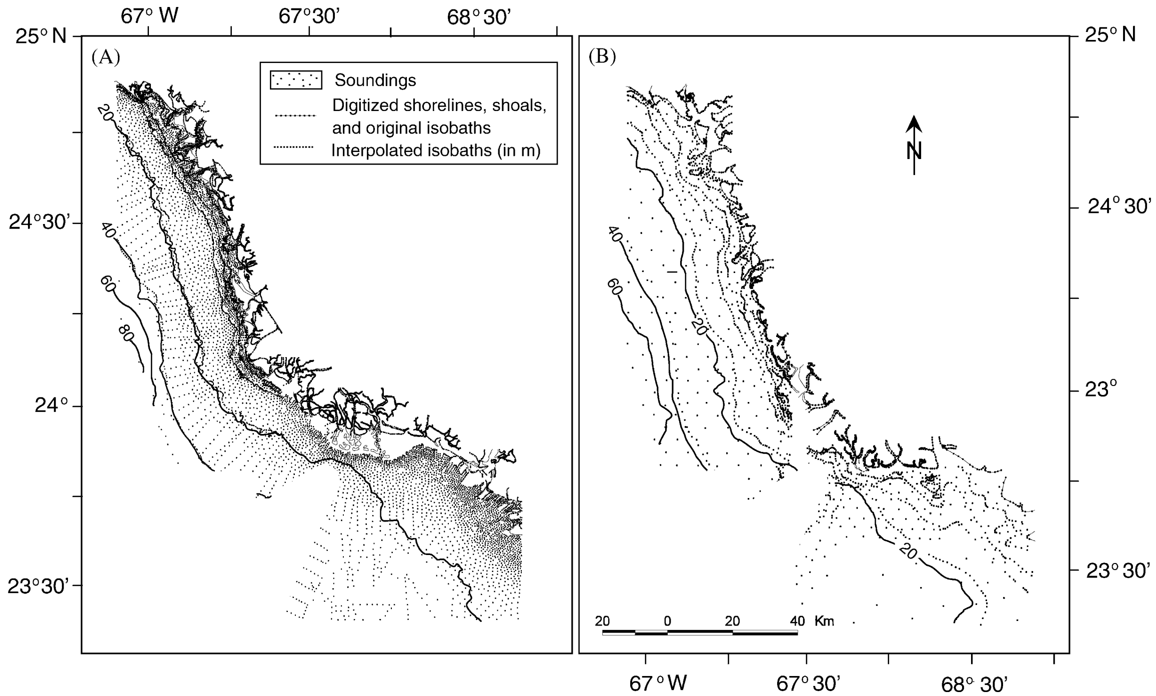

Fig. 5. Digitized bathymetric surveys and shorelines for the Pakistani Indus coast: A. the 1895–96 Oldham survey (British Admiralty, 1897a, b); B. the 1952–54 Pakistani survey (Hydrographic Office of Pakistan, 1955).

www.globalmapper.com/) using 24 control points for each chart or photo. DTMs at a 100 m resolution were generated from digitized soundings with Surfer 8.0 software (http://www.goldensoftware.com/). The "natural neighbor" algorithm was chosen for interpolation because it is suitable for a variable density of data across the interpolation domain and does not extrapolate depth values beyond the range of existing data.

4. Results

4.1. Morphology of the Indus shelf based on the 19th century charts

The digital terrain model based on the 19th century charts shows the front of the Indus delta extending down to 10–15 m water depth (Fig. 6), along the abandoned part of the delta plain. Close to the active river mouths, the delta front extended significantly deeper down to 20–25 m water depth. Part of the delta front appears to have built directly into the head of the Indus Canyon. The delta front slope ranged between 0.2° and 0.3°, whereas the shelf gradient offshore the delta front was typically less than 0.1°. The front was steepest close to the canyon head (0.3–0.4°) and the gradient increased to 0.5–0.6° into the canyon at less than 10 km from the Indus coast. Perched upon the delta front, there were tidal ebb shoals with shallow subaqueous channels associated to the large deltaic tidal creeks (Fig. 6). These shoals typically extended less than 10 km offshore, except for the larger ones (i.e., in front of the Kori and Sir Creeks), which extended 20–25 km away from the coast.

Outside the prominent trough of the Indus Canyon, the most conspicuous morphological feature of the Indus shelf was not the delta front discussed above, but a clinoform feature on the mid-shelf (Fig. 6).[1] The clinoform foreset is defined by two breaks in seafloor slope occurring at ~30–40

[1]The term "clinoform" (see e.g., Walsh et al., 2004) has been used to describe either the morphology of a feature (i.e., sigmoidal in cross-section) or its sedimentary dynamics (i.e., aggradational–progradational feature of a sigmoidal shape). In the latter, process-based, accept of the term, the clinoform is composed of topset, foreset, and bottomset beds. For simplicity, we use this terminology to describe the mid-shelf clinoform on the Indus shelf. Our choice of terminology is justified by the fact that bathymetric changes suggest that the mid-shelf clinoform located northwest of the Indus Canyon is actively prograding (see Subsection 4.2).

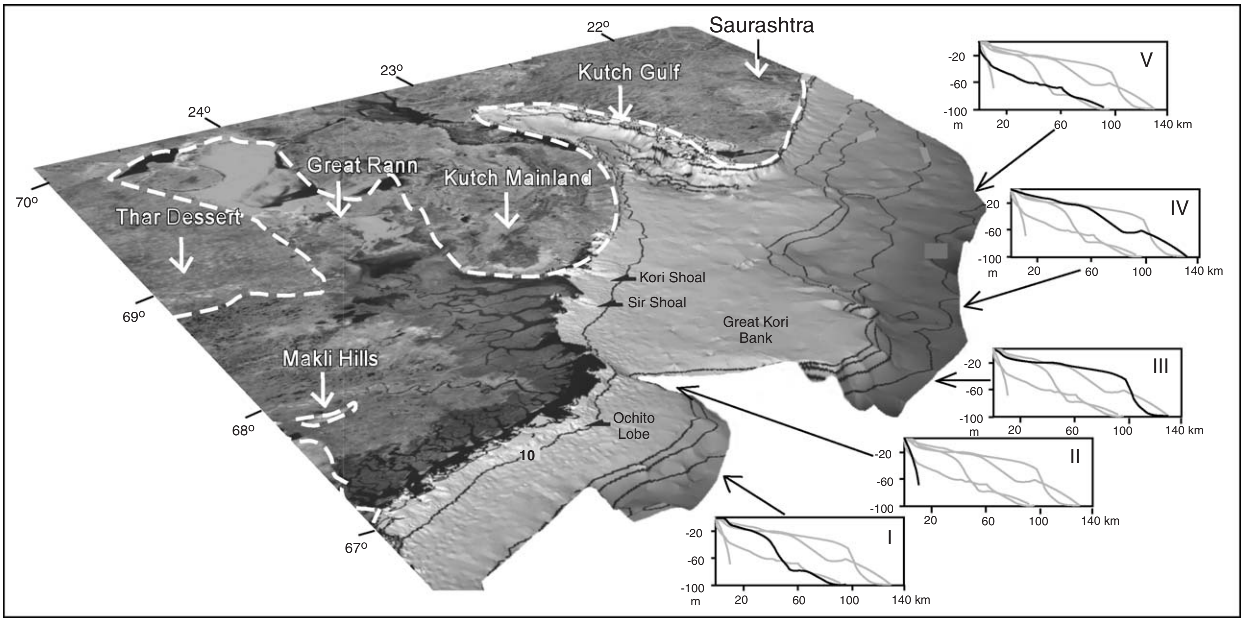

Fig. 6. Digital terrain model for the Indus shelf based on 19th century surveys (British Admiralty, 1897a, b; British Admiralty, 1915). Typical bathymetric profiles across the Indus delta and Saurashtra coast (i.e., I—northwestern shelf clinoform; II—Indus Canyon; III—southeastern shelf clinoform; IV—Kutch clinoform; V—Saurahstra shelf) are also presented (in black is the profile at the location indicated by the arrow; in gray are the other profiles for comparison). Inland geography is visualized on a LANDSAT image from 2000.

and ~80–90 m water depth, respectively, and it is characterized by relatively large and constant gradients between 0.3° and 0.4°. The mid-shelf clinoform is continuous along the delta coast, but is much more advanced toward the shelf edge on the east side of the Indus canyon (~60 km closer to the shelf edge at the level of the −40 m isobath) vs. the west side of the canyon (Fig. 6). A somewhat distinct lobe of the mid-shelf clinoform is apparent in front of the Kutch mainland and the entrance to the Gulf of Kutch, but it is less steep and extends only between ~30 and 70 m water depth (Fig. 6). Along the Saurashtra coast, on the other side of the Gulf of Kutch's entrance, the shelf displayed a concave up profile with a steep nearshore with no mid-shelf clinoform present (Fig. 6).

4.2. Morphological changes on the Indus shelf between the 1895–96 and 1952–54 surveys

At the time of the 19th century survey, the active Indus river mouths included the Turshian, the Khobar, the Gaghiar, and the Khar. For descriptive purposes, we define a central (active river mouth) sector of the coast (named A in Fig. 7), a northwestern sector (sector B in Fig. 7), and a southeastern sector for the abandoned delta plain coast on either side of the active mouths (sector C in Fig. 7). Bathymetric changes between the late 19th century and 1950s show that the delta front prograded along most of the delta coast (Fig. 7). The main depocenter of the delta front developed in front of the active river mouths (sector A; Fig. 7); the seabed there shoaled 6 m on average, with a maximum accumulation of over 35 m in the head of the Indus Canyon. Using a sediment bulk density value of 1500 kg/m^3, we estimate that over 190 million tons of sediment had accumulated per year on the delta front in sector A between 1895–96 and 1952–54 (Fig. 7).

Offshore the abandoned delta plain coast, ~24 million tons of sediment per year accumulated on the delta front in the northwestern sector B that was balanced by the same amount of sediment eroded. This corresponds to rates of 6 cm/year average accumulation and erosion, respectively. About 30 million tons of sediment accumulated in the southeastern sector C to the Sir Creek alone (Fig. 7), corresponding to an average accumulation rate of 5 cm/year. In contrast to the arealy continuous delta front deposition east of the active mouths, sediment accumulation in the northwest sector appears to have been more localized, with a large erosional area between the Turshian and Hajambro mouths

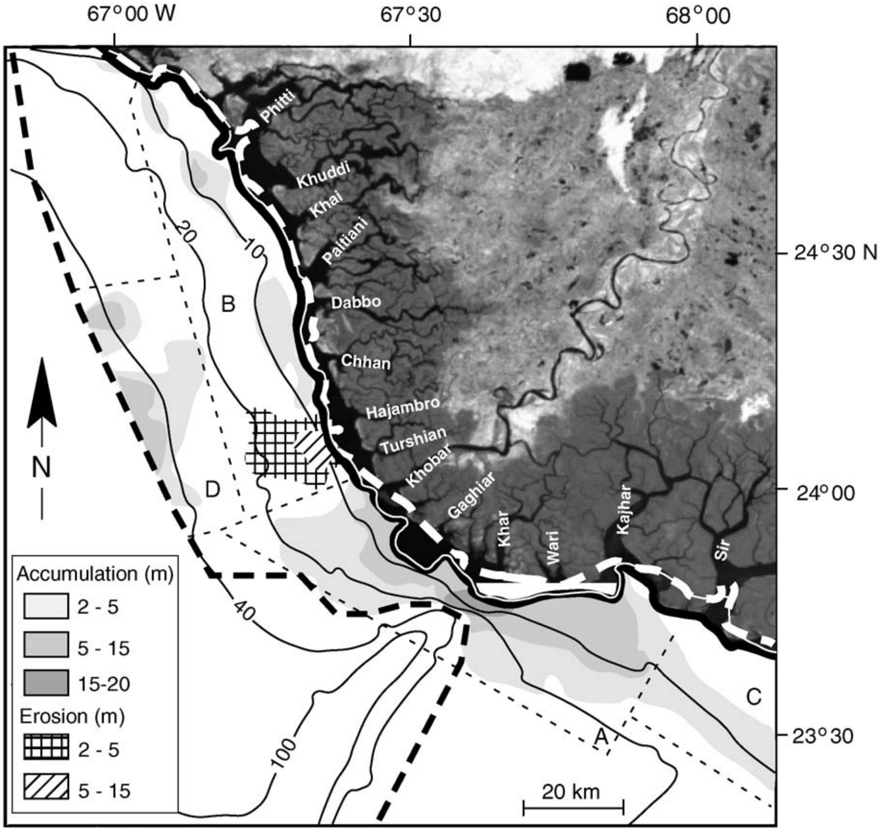

Fig. 7. Bathymetric changes between the 1895–97 and 1952–54 surveys of the Indus shelf for the region of common coverage shown over the simplified 1895–97 bathymetry. The offshore limit of coverage is indicated by the bold dashed black line. Yearly values for erosion and accumulation of sediment and sedimentation rates are discussed in the text for several areas noted A through D. Shorelines from 1895–97 (thick white dashed line) and 1952–54 (thin white continuous line) are shown overlapped on a 2000 satellite photo of the Indus delta.

(Fig. 7). This erosional area appears to be related to the early 20th century abandonment of the Ochito distributary that discharged through the Hajambro mouth (Holmes, 1968). This generally accumulative character of the delta front in areas outside the direct influence of the active river mouths (Fig. 7: areas B and C) suggests a strong, bidirectional alongshore dispersal of sediments from the mouth region via waves as well as reversing tidal and monsoon wind currents. The change in the direction of the delta shoreline in the vicinity of the active mouths relative to the dominant southwestern summer monsoon waves favors a bidirectional wave-driven longshore sediment transport system.

The close proximity of the Indus Canyon to the active river mouths has led to a focused deposition within the canyon's head (area A in Fig. 7), with accumulation rates in excess of 50 cm/year. The rapid increase in depth along the thalweg of the canyon indicates that sediments accumulated in the canyon are effectively removed from the energetic dispersal system of the delta front zone. Most of the sediment has probably accumulated in the upper Indus Canyon, although a core in the middle reaches of the canyon at ~1012 m water depth shows that turbidity currents have been active in recent times depositing thin silty–sandy turbidites along the axial valley of the canyon (Prins et al., 2000). Turbidite deposition ceased only very recently, sometime in the last 150 years (Prins et al., 2000), possibly after the dramatic reduction of the Indus River sediment discharge in the 1960s.

The only sector of the mid-shelf clinoform covered by both the Oldham and the 1952–54 Pakistani surveys is between the Turshian and the Khai Creeks (area D in Fig. 7), where the upper foreset of the clinoform shoaled ~4 m on average. Sediment accumulation on the foreset suggests that the clinoform is actively prograding at this location. In total, 63 million tons of sediment accumulated between 1895–96 and 1952–54 in sector D.

4.3. Shoreline changes

Between 1895–96 and 1952–54, the delta shoreline advanced at an average rate of ~45 m/year. Several erosion areas occurred on the coast northwest of the Turshian mouth (Fig. 8a and c), but the sector between Paitiani and Chhan was strongly progradational (~70 m/year). The shoreline advanced much faster near the active river mouths between the Khobar and the Wari mouths at an average rate of ~150 m/year (Fig. 8a and c). All shoreline advance rates calculated using the Oldham chart and the modern Pakistani chart should be considered as minimal estimates until a low tide datum for the earlier map is confirmed (conversely the erosion rates probably represent maximum values).

In contrast to the largely progradational coast in unaltered river sediment discharge conditions that characterized the Indus between 1895–96 and 1952–54, shoreline changes during the post-damming period (1978–2000; Fig. 8b and c) show that extensive sectors of the Indus delta coast have become erosional after damming. The shoreline retreat was greatest in front of the formerly active river mouths between Khobar and Wari Creeks, reaching rates of ~50 m/year. On the northwestern coast between the Khobar Creek mouth and Karachi the retreat rates were significantly lower at ~10 m/year, with the sector between Paitiani Creek and Karachi even prograding at an average

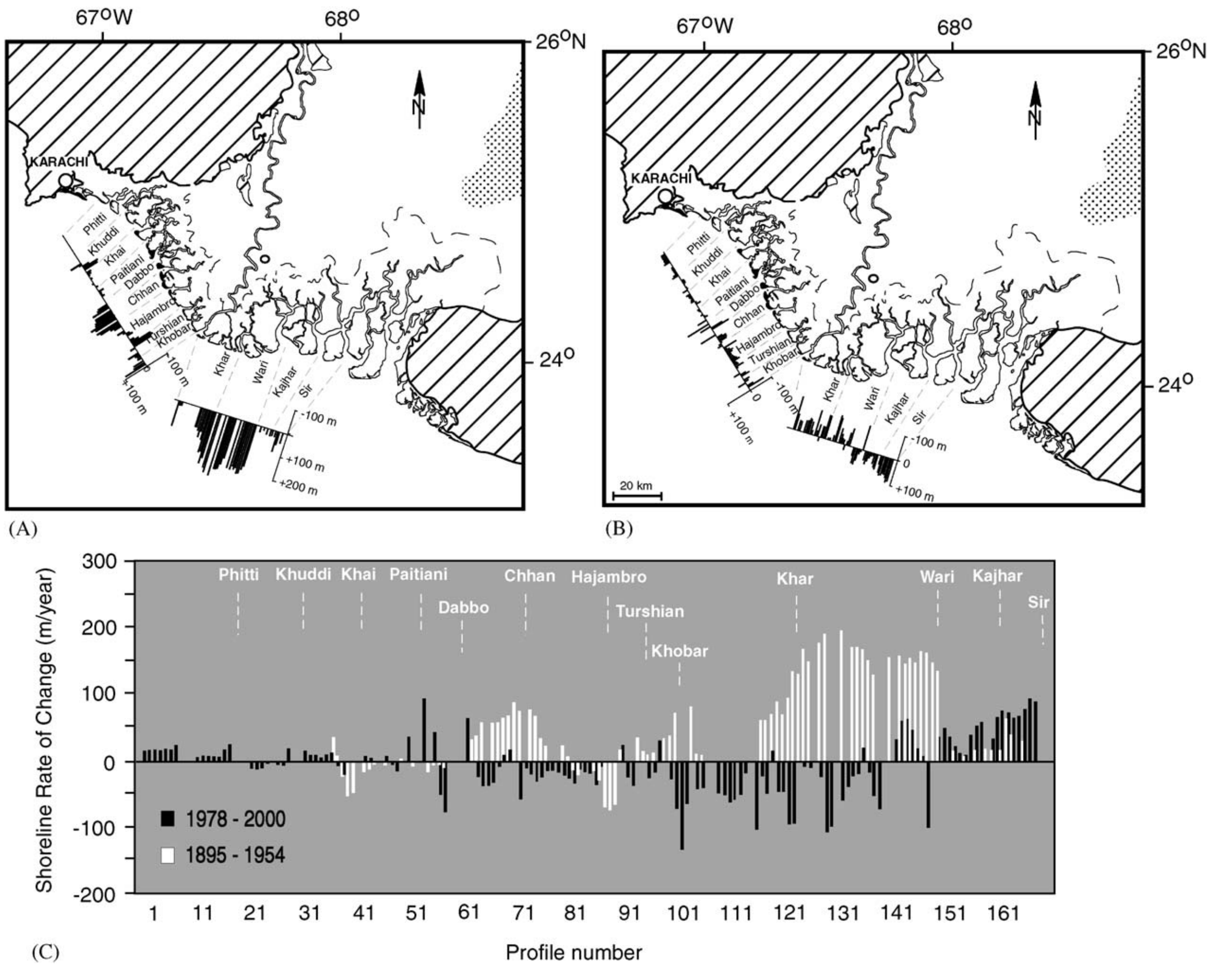

Fig. 8. Shoreline change rates for the Indus delta coast for: A. the pre-damming period between 1895–97 and 1952–54; B. the post-damming conditions (1978–2000); and C. a comparison between shoreline change rates of the two intervals. Locations of largest tidal creek mouths are indicated.

rate of ~10 m/year. The abandoned deltaic coast east of the Wari mouth to Sir Creek continued to prograde during the post-damming period (Fig. 8b and c) at ~70 m per year was on average, a rate greater than the ~45 m per year advance rate between 1895–96 and 1952–54 for the same sector.

Neither the Oldham, nor the Pakistani charts extend far enough inland to allow us to analyze long-term changes in the morphology of the tidal channel network. Comparing the 1978 and 2000 satellite images, we have not been able to detect any systematic widening or narrowing of the tidal channels.

5. Discussion

5.1. Delta front vs. prodelta clinoforms

The morphological components of a river delta have been traditionally considered to include the flat, mostly subaerial, delta platform continuing with the completely submerged, relatively steep delta slope that extends further offshore into the low-gradient prodelta (Reading and Collinson, 1996). Process-based terminology equates the delta platform with the delta plain that is dominated by fluvial processes and the delta slope with the delta front, the zone of continuous interaction between marine and fluvial processes. On the low-gradient prodelta, sedimentation from suspension has been assumed to be dominant (Reading and Collinson, 1996). The dip profile of a delta has a clinoform shape with a wedge-like regressive stratigraphy (Scruton, 1960; Reading and Collinson, 1996). In this classic framework, the subaqueous delta has been considered to consist of the delta front and the prodelta.

Recent studies on supply-dominated shelves near abundant sources of fluvial sediment (Swift and Thorne, 1991) show that strictly subaqueous clinoforms (also called sometimes "subaqueous deltas") can develop on high-energy deltaic shelves largely within the prodelta region exhibiting a sigmoidal regressive pattern (Nittrouer et al., 1996; Kuehl et al., 1997, 2005). To avoid confusion introduced by using parallel terminologies, we propose the terms *delta front clinoform* and *prodelta clinoform* to distinguish between the two types of regressive units that characterize subaqueous deltas. In both cases, the clinoform foresets have the highest accumulation rate, whereas the topset and bottomset, where intense physical processes occur and/or sediment supply is low are characterized by lower accumulation rates (Walsh et al., 2004 and references therein).

Development of a prodelta clinoform can be concurrent with the progradation of the delta front clinoform, leading to compound clinoform morphologies (e.g., Nittrouer et al., 1996), as in the case of the Ganges–Brahmaputra (Allison, 1998; Kuehl et al., 2005). In other cases, like the Amazon, the development of the delta front clinoform could be drastically diminished or spatially offset alongshore (Nittrouer et al., 1996). Conversely, deltas developing on low-energy shelves would not develop a prodelta clinoform (e.g., the Mississippi—Wright and Nittrouer, 1995). The tridimensional architecture of the clinoforms is also a function of the shelf energy regime (Driscoll and Karner, 1999). For example, Cattaneo et al. (2003) showed that even if the Po River builds a typical delta front clinoform (e.g., Correggiari et al., 2005), it also contributes sediment to a mid-shelf prodelta clinoform that is far offset alongshore from the river mouths due to an advection-dominated regime along the Adriatic coast.

5.2. The delta front clinoform of the Indus

The Indus shelf exhibits a clear compound clinoform morphology (Fig. 6). In the nearshore, on the delta front clinoform, sediment accumulation was highest close to the active river mouths at an average rate of 10 cm/year (Fig. 7—area A), which is comparable to accumulation rates estimated for other river-mouth proximal depocenters of the Rhone (Sabatier, 2001), the Red River (van Maren and Hoekstra, 2005), or the Yellow River (Li et al., 1998). Between 1895–96 and 1952–54, the active river mouth depocenter alone stored the equivalent of ~75% of the 250 million tons of sediment discharged annually by the Indus River (Milliman et al., 1984). Our analysis indicates that the delta front clinoform along the abandoned delta coast has stored sediment equivalent to at least another 10% of the annual river discharge. At least part of this sediment was probably advected from the mouth region by the alongshore wave dispersal system as well as by reversing tidal and monsoon wind currents. This estimate does not include potential accumulation and/or erosion of the delta front between the Sir Creek mouth and the Gulf of Kutch.

Cannibalization of the subaerial delta through the development of a tidal channel network could have provided some sediment for accumulation on the delta front clinoform as suggested by the development of ebb shoals at the mouth of the largest tidal creeks (Fig. 6). Sediment dispersal on tide-dominated deltaic coasts has a strong on–offshore component, leading to extensive development of elongate tidal shoals (Off, 1963; Willis, 2005). Although ebb shoals are present at the mouth of the largest Indus tidal creeks, they are limited in extent. In contrast, similar shoals along the coast of the Ganges–Brahmaputra delta extend 80 km offshore, imparting a digitate aspect to that delta front (Allison, 1998).

At the shoreline, the extensive retreat after late 1950s contrasts with the almost general advance typical for the delta shore during the 1895/96–1952/54 period, when the discharge was less affected by fluvial engineering (Fig. 8). However, even under a drastically reduced sediment discharge of the Indus River after the 1950s, the southeastern and northwestern coasts of the abandoned delta continued to advance (Fig. 8). If the longshore drift is a major source of sediment for the coast as expected in a wave-dominated environment, the post-damming shoreline changes suggest that reworking of the depocenter in front of the active river mouths of Khobar, Gaghiar, and Khar Creeks supplies sediments to the abandoned delta coast.

5.3. The prodelta clinoform of the Indus

For the offshore sector located northwest of the Indus Canyon that was covered by both the surveys used in this study, bathymetric changes indicate that the prodelta clinoform had been actively prograding between the surveys (Fig. 7—area D). The average accumulation rate on the upper foreset of the northwestern clinoform was 7 cm/year, a value that is similar to other prodelta clinoform foresets (see Walsh et al., 2004 and references therein). The net amount of sediment accumulated on the upper foreset of the northwestern clinoform lobe accounts for 13% of the Indus sediment discharge.

Assuming that the prodelta clinoform has been active on the eastern side of the Indus Canyon, its advanced position can be explained by a longer progradation time span. If the main discharge of the Indus River occurred at a position east of the canyon as postulated by Kazmi (1984), via either an early course or dominant distributary of the river, the prodelta clinoform could have built for a longer period there compared to the shelf west of the canyon. In such a configuration, the Indus Canyon would have effectively prevented westward dispersal of sediments leading to either clinoform development strictly on the eastern side of canyon or to an asymmetric advance rate for the clinoform on opposite sides of the canyon. An alternative explanation for the advanced position of the clinoform could be that it is, at least in part, a relict pre-Holocene mid-shelf delta (e.g., Porebski and Steel, 2003).

The distinct clinoform lobe developed along the Kutch coast (Fig. 6) may be genetically linked to an Indus sediment source. Mid-shelf redeposition of sediment advected alongshore from the Indus delta coast by the strong on–offshore tidal currents at the Gulf of Kutch mouth (Nair et al., 1982) is a likely mechanism for the clinoform lobe development as an extensive tidal shoal. Further, this "tidal barrier" proposed by Nair et al.'s at the Gulf of Kutch mouth appears to significantly block the dispersal Indus sediments further to the southeast, along the Saurashtra coast.

5.4. Theoretical considerations on the Indus clinoforms

An analytical model developed by Friedrichs and Wright (2004) for gravity-driven, wave-supported sediment transport predicts the equilibrium bathymetric profile on supply-dominated shelves offshore river mouths as a function of the wave climate and fluvial sediment supply. Wave- or tide-suspended hyperpycnal flows or "fluid muds" (e.g., Trowbridge and Kineke, 1994; Cacchione et al., 1995) are thought to be the dominant mechanisms supplying sediment for the prodelta clinoform (e.g., Walsh et al., 2004). Deeper and broader profiles correspond to higher wave energy relative to river supply (i.e., higher ratio between the cube of the wave height H and the riverine sediment discharge per unit length along the shelf, Q_r). If we consider the seasonal wave height values for the Indus shelf (i.e., where H is the wave height taken as $2^{-1/2}$ H_{sig}, and where H_{sig} is the measured significant wave height of Rizvi et al., 1988), the H^3/Q_r ratio for the Indus coast can vary between ~2 and 14. When considering a short dispersal system (i.e., ~50 km) that is equivalent to the length of the active river mouths depocenter, H^3/Q_r equals 14, suggesting that the Indus delta should have developed a clinoform anywhere between 40 and 100 m water depth. The depth of this clinoform would increase further, if the dispersal system for the Indus sediments is taken to extend along the abandoned coast, as more wave energy is available to move less sediment. The H^3/Q_r during the winter monsoon is between 2 and 4, typical for a low-energy situation leading to a clinoform shallower than 40 m.

The model of Friedrichs and Wright (2004) is consistent with the observation that the Indus is able to build a deep prodelta clinoform, but raises the question on how a shallow delta front clinoform develops simultaneously. Because most of the sediment is discharged by the Indus River during the summer monsoon months, when the wave energy is highest, the development of the deep prodelta clinoform should be the favored equilibrium profile. Instead a delta front clinoform with a significant storage capacity builds near the active river mouths. The gravity flow mechanism considered by Friedrichs and Wright (2004) is envisioned to feed a deep clinoform, which is dependent on the availability of fine particles to generate fluid mud within the wave boundary layer. If a significant portion of a sediment load is coarse (silt or coarser), like it is the case for the Indus's load, particles would probably settle too fast to form such fluid muds.

Swenson et al. (2005) developed a model for compound clinoform development assuming wave-current-driven transport of suspended, non-cohesive sediments. This exploratory modeling study suggests that prodelta clinoforms could develop with strictly non-cohesive sediments, thus in locations where hyperpycnal flows are not a viable mechanism for offshore sediment transport. The delta front clinoform develops preferentially under a decreased frequency and/or magnitude of coastal storms, increased river discharge and/or flood frequency, and larger sediment grain sizes (Swenson et al., 2005). The Indus provides a test case for theoretical studies as its sediment discharge is apparently dominated by sediments coarser than clay, which is the critical component for fluid muds. It remains to be explored how the Indus delta developed as a compound clinoform with a combination of a highly energetic wave and current regime as well as a short flood season that all favor the development of a prodelta rather than delta front clinoform, together with a high river sediment discharge and coarse grain size, which both favor the preferential development of a delta front clinoform (cf. Swenson et al., 2005). In this context, it is not clear what role is played by the in-phase relationship between Indus River floods and summer monsoon setup. Wells and Coleman (1984) argued that this overlap could lead to high accumulation rates within the river channels, ultimately leading to the expansion of a river-mouth proximal depocenter. However, in the same time, dispersal of sediment offshore and alongshore should be more intense under the energetic waves of the monsoon.

6. Conclusions

- Detailed 19th Century bathymetric surveys show that the Indus shelf exhibits a compound clinoform morphology with separate nearshore delta front and mid-shelf clinoforms.
- The mid-shelf clinoform has developed asymmetrically about the Indus Canyon, which dissects the shelf to within 20 m water depth and 3.5 km of the coast. The clinoform front (foreset), located between ~30 and ~90 m water depth is much more advanced toward the shelf edge on the eastern vs. the western side of the canyon. A distinct lobe of the mid-shelf clinoform occurs in front of the Kutch coast and mouth of the Kutch Gulf.
- The mid-shelf clinoform has probably developed as a *prodelta clinoform* of the Holocene Indus delta. This is suggested by recent active progradation of the feature west of the Indus Canyon, in a sector re-surveyed in the 1950s. The advanced position of the clinoform east of the canyon might reflect either a prolonged sediment delivery from the Indus river in that region compared to the shelf west of the canyon or the presence of a relict pre-Holocene mid-shelf delta on the shelf east of the canyon. The distinct clinoform lobe developed along the Kutch coast appears to be an extensive tidal shoal formed by mid-shelf redeposition of sediment advected alongshore the Indus delta coast by strong offshore-directed tidal currents at the Gulf of Kutch mouth.
- In pre-damming conditions, the *delta front clinoform* stored ~85% of the 250 million tons of sediment estimated to be discharged annually by the Indus River. Additionally, only in the region of the prodelta clinoform covered by both 1895–96 and 1952–54 surveys, sediment storage amounted to another 13% of the estimated annual sediment discharge. Considering that

our analysis does not cover the entire shelf, it is likely that in natural conditions the Indus River discharged more sediment to the coast than previously estimated.

- In natural conditions, before significant damming along the Indus River, the shoreline advanced along most of the delta coast. Following the reduction in sediment discharge after the late 1950s, the deltaic shoreline along the central part of the delta coast started to recede whereas the southeastern and northwestern coast sectors remained largely progradational, with the southeastern sector advancing at an even greater rate than before. This differential behavior of the delta shoreline suggests a significant role for delta front sediment transfer processes in the evolution of abandoned deltaic coast.
- An analytical model based on wave climate and river discharge characteristics predicts a mid-shelf clinoform for the Indus shelf instead of the compound clinoform identified in the bathymetric data. One potential explanation for this discrepancy is the relatively coarse sediment discharged by the Indus that promotes rapid settling of a significant part of sediment load near the coast.
- Assuming that the sediment load of Indus River has been dominated by non-cohesive sediments that are not suitable to generate hyperpycnal flows, the mechanisms involved in the prodelta clinoform development remain to be identified. In this context, it is important to explore the modern sediment dispersal on the Indus shelf as well as the internal architecture, sedimentology, and chronostratigraphy of the mid-shelf clinoform of the Indus shelf.

Acknowledgments

Many thanks go to Dr. M.M. Rabbani, Director General of the National Institute of Oceanography, Pakistan, for his lasting support. We thank John Creaser from the library of the University of California at Berkeley and the personnel from the British Library for their indefatigable search for charts. Thorough reviews provided by Antonio Cattaneo and Carl Friedrichs were insightful and helped shape the final form of the paper. Funding for this study was provided by the National Science Foundation through award OCE-0324837 to Clift and Giosan. Part of S. Constantinescu's financial support came from a WHOI Mary Sears award to Giosan.

References

Allison, M.A., 1998. Historical changes in the Ganges–Brahmaputra delta front. Journal of Coastal Research 14 (4), 1269–1275.

Asianics Agro-Dev. International (Pvt.) Ltd., 2000. Tarbela Dam and related aspects of the Indus River Basin, Pakistan, A World Commission on Dams case study, Cape Town, www.dams.org

British Admiralty, 1897a. Delta of the Indus. Cape Monze to Kediwari Mouth. Approach to Karachi. Admiralty Chart, London.

British Admiralty, 1897b. Delta of the Indus. Kediwari Mouth to Nirani Creek. Approach to Karachi. Admiralty Chart, London.

British Admiralty, 1915. India. West Coast. Chart of the coasts of Sind and Kutch, including the Gulf of Kutch. Admiralty Chart, London.

Cacchione, D.A., Drake, D.E., Kayen, R.W., Sternberg, R.W., Kineke, G.C., Kate, G.B., 1995. Measurements in the bottom boundary layer on the Amazon subaqueous delta. Marine Geology 125, 235–257.

Cattaneo, A., Correggiari, A., Langone, L., Trincardi, F., 2003. The late-Holocene Gargano subaqueous delta, Adriatic shelf: sediment pathways and supply fluctuations. Marine Geology 93 (1–2), 61–91.

Chauhan, O.S., Almeida, F., Suneethi, J., 2000. Influence of sedimentation on the geomorphology of the northwestern continental margin of India. Marine Geodesy 23 (4), 259–265.

Clift, P.D., 2002. A brief history of the Indus River. In: Clift, P.D., Kroon, D., Craig, J., Gaedicke, C. (Eds.), The Tectonics and Climatic Evolution of the Arabian Sea Region, vol. 195. Geological Society of London Special Publication, pp. 237–258.

Correggiari, A., Cattaneo, A., Trincardi, F., 2005. Depositional patterns in the late Holocene Po delta system. In: Giosan, L., Bhattacharya, J.P. (Eds.), River deltas—Concepts, models, and examples, SEPM—Society for Sedimentary Geology, vol. 83. Special Publication, pp. 363–390.

Driscoll, N.W., Karner, G.D., 1999. Three-dimensional quantitative modeling of clinoform development. Marine Geology 154 (1–4), 383–398.

Fahlbusch, H., Schultz, B., Thatte, C.D., 2004. The Indus Basin: History of Irrigation, Drainage and Flood Management. International Commission on Irrigation and Drainage, New Delhi, India.

Flam, L., 1999. The prehistoric Indus river system and the Indus Civilization in Sindh. Man and Environment 24 (2), 35–69.

Friedrichs, C.T., Wright, L.D., 2004. Gravity-driven sediment transport on the continental shelf: implications for equilibrium profiles near river mouths. Coastal Engineering 51 (8–9), 795–811.

Haq, B.U., 1999. Past, present and future of the Indus delta. In: Meadows, A., Meadows, P.S. (Eds.), The Indus River, Biodiversity, Resources, Humankind. Linnaean Society of London, Oxford University Press, Oxford, UK, pp. 231–248.

Holmes, D.A., 1968. The recent history of the Indus. Geographical Journal 134 (3), 367–382.

Holmes, D.A., Western, S., 1969. Soil texture patterns in the alluvium of the lower Indus plains. Journal of Soil Science 20 (1), 23–37.

Hydrographic Office of Pakistan, 1955. Pakistan Sind coast: Churna Island to Wari Creek chart.

Inam, A., Khan, A.T.M., Amjad, S., Danish, M., Tabrez, A.R., 2004. Natural and man made stresses on the stability of Indus deltaic ecoregion. Extended Abstract, The Fifth International Conference on Asian Marine Geology, Bangkok, Thailand (IGCP475/APN). http://www.megadelta.ecnu.edu.cn/main/upload/Asifpaper1.pdf

Islam, S.R., 1959. The Indus submarine canyon. Oriental Geography 3, 101–104.

Jorgensen, D.W., Harvey, M.D., Schumm, S.A., Flam, L., 1993. Morphology and dynamics of the Indus River: implication for the Mohenjo Daro site. In: Schroder, Jr., J.F. (Ed.), Himalaya to the Sea. Routledge, London, UK, pp. 288–326.

Karim, A., Veizer, J., 2002. Water balance of the Indus River Basin and moisture source in the Karakoram and western Himalayas: implications from hydrogen and oxygen isotopes in river water. Journal of Geophysical Research 107 (D18), 4362.

Kazmi, A.H., 1984. Geology of the Indus Delta. In: Haq, B.U., Milliman, J.D. (Eds.), Marine Geology and Oceanography of Arabian Sea and Coastal Pakistan. Van Nostrand Reinhold, New York, pp. 65–70.

Khan, A.A., Memon, M.G., Danish, M., Inam, A., 1993. Distribution of surface sediments off Indus delta on the continental shelf of Pakistan. Pakistan Journal of Marine Sciences 2 (1), 33–39.

Khan, T.M.A., Razzaq, D.A., Chaudhry, Q.-U.-Z., Quadir, D.A., Kabir, A., Sarker, M.A., 2002. Sea level variations and geomorphological changes in the coastal belt of Pakistan. Marine Geodesy 25 (1–2), 159–174.

Kuehl, S.A., Levy, B.M., Moore, W.S., Allison, M.A., 1997. Subaqueous delta of the Ganges–Brahmaputra river system. Marine Geology 144 (1–3), 81–96.

Kuehl, S.A., Allison, M.A., Goodbred, S.L., Kudrass, H., 2005. The Ganges–Brahmaputra delta. In: Giosan, L., Bhattacharya, J.P. (Eds.), River Deltas—Concepts, Models, and Examples, SEPM–Society for Sedimentary Geology, vol. 83. Special Publication, pp. 411–432.

Lambrick, H.T., 1964. Sind: A General Introduction. Sindhi Adabi Board, Hyderabad, 289pp.

Li, G., Wei, H., Yue, S., Cheng, Y., Han, Y., 1998. Sedimentation in the Yellow River delta: Part II. Suspended sediment dispersal and deposition on the subaqueous delta. Marine Geology 149 (1–4), 113–131.

Malik, J.N., Merh, S.S., Sridhar, V., 1999. Palaeo-delta complex of Vedic Sarasvati and other ancient rivers of northwestern India. Geological Society of India Memoirs 42, 163–174.

Meade, R.H., 1996. River-sediment inputs to major deltas. In: Milliman, J., Haq, B.U. (Eds.), Sea-Level Rise and Coastal Subsidence. Kluwer, London, pp. 63–85.

Merh, S.S., 1995. Geology of Gujarat. Geological Society of India, Bangalore, 222pp.

Milliman, J.D., Meade, R.H., 1983. World-wide delivery of sediment to the oceans. Journal of Geology 91 (1), 1–21.

Milliman, J.D., Quraishee, G.S., Beg, M.A.A., 1984. Sediment discharge from the Indus River to the ocean: past, present and future. In: Haq, B.U., Milliman, J.D. (Eds.), Marine Geology and Oceanography of Arabian Sea and Coastal Pakistan. Van Nostrand Reinhold, New York, pp. 65–70.

Nair, R.R., Hashimi, N.H., Purnachandra Rao, V., 1982. 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. Marine Geology 47 (1–2), 77–86.

Nittrouer, C.A., Kuehl, S.A., Figueiredo, A.G., Allison, M.A., Sommerfield, C.K., Rine, J.M., Faria, L.E.C., Silveira, O.M., 1996. The geological record preserved by Amazon shelf sedimentation. Continental Shelf Research 16 (5–6), 817–841.

Off, T., 1963. Rhythmic linear sand bodies caused by tidal currents. AAPG Bulletin 47 (2), 324–341.

Porebski, S.J., Steel, R.J., 2003. Shelf-margin deltas: their stratigraphic significance and relation to deepwater sands. Earth-Science Reviews 62 (3–4), 283–326.

Prins, M.A., Postma, G., Cleveringa, J., Cramp, A., Kenyon, N.H., 2000. Controls on terrigenous sediment supply to the Arabian Sea during the Late Quaternary: the Indus Fan. Marine Geology 169 (3–4), 327–349.

Rajendran, C.P., Rajendran, K., 2001. Characteristics of deformation and past seismicity associated with the 1819 Kutch earthquake, Northwestern India. Bulletin of the Seismological Society of America 91 (3), 407–426.

Reading, H.G., Collinson, J.D., 1996. Clastic coasts. In: Reading, H.G. (Ed.), Sedimentary Environments: Processes, Facies, and Stratigraphy. Blackwell, Oxford, 688pp.

Rizvi, S.H.N., Ali, A., Naeem, S.A., Tahir, M., Baquer, J., Saleem, M., Tabrez, S.M., 1988. Comparison of the physical properties of seawater offshore the Karachi coast between the northeast and southwest monsoons. In: Thompson, M., Tirmizi, N.M. (Eds.), Marine Science of the Arabian Sea. Proceedings of an International Conference, American Institute of Biological Sciences, Washington, DC.

Sabatier, 2001. Fonctionnement et dynamiques morpho-sedimentaires du littoral du delta du Rhone, Ph.D. Thesis, Université Aix-Marseille III, unpublished.

Scruton, P.C., 1960. Delta building and the deltaic sequence. In: Shepard, F.P., Phleger, F.B., Van Andel, T.H. (Eds.), Recent Sediments, Northwest Gulf of Mexico. American Association of Petroleum Geologists, Tulsa, OK, pp. 82–102.

Staubwasser, M., Sirocko, F., Grootes, P.M., Erlenkeuser, H., 2002. South Asian monsoon climate change and radiocarbon in the Arabian Sea during early and middle Holocene. Paleoceanography 17, 1063.

Stutz, M.L., Pilkey, O.H., 2002. Global distribution and morphology of deltaic barrier island systems. Journal of Coastal Research (Special Issue 36), 694–707.

Swenson, J.B., Paola, C., Pratson, L., Voller, V.R., Murray, A.B., 2005. Fluvial and marine controls on combined subaerial and subaqueous delta progradation: morphodynamic modeling of compound-clinoform development. Journal of Geophysical Research 110, F02013.

Swift, D.J.P., Thorne, J.A., 1991. Sedimentation on continental margins; I, A general model for shelf sedimentation. In: Swift, D.J.P., Oertel, G.F., Tillman, R.W., Thorne, J. (Eds.), Shelf Sands and Sand Bodies, vol. 14. Special Publication of the International Association of Sedimentologists, pp. 3–31.

Syvitski, J.P.M., Vörösmarty, C.J., Kettner, A.J., Green, P., 2005. Impact of humans on the flux of terrestrial sediment to the global coastal ocean. Science 308, 376–380.

Trowbridge, J.H., Kineke, G.C., 1994. Structure and dynamics of fluid muds on the Amazon continental shelf. Journal of Geophysical Research 99, 865–875.

Van Maren, D.S., Hoekstra, P., 2005. Dispersal of suspended sediments in the turbid and highly stratified Red River plume. Continental Shelf Research 25, 503–519.

Von Rad, U., Tahir, M., 1997. Late Quaternary sedimentation on the outer Indus shelf and slope (Pakistan); evidence from high-resolution seismic data and coring. Marine Geology 138, 193–236.

Vörösmarty, C.J., Sharma, K.P., Fekete, B.M., Copeland, A.H., Holden, J., Marble, J., Lough, J.A., 1997. The storage and aging of continental runoff in large reservoir systems of the world. Ambio 26, 210–219.

Walling, D.E., Fang, D., 2003. Recent trends in the suspended sediment loads of the world's rivers. Global and Planetary Change 39 (1–2), 111–126.

Walsh, J.P., Nittrouer, C.A., Palinkas, C.M., Ogston, A.S., Sternberg, R.W., Brunskill, G.J., 2004. Clinoform mechanics in the Gulf of Papua, New Guinea. Continental Shelf Research 24 (19), 2487–2510.

Wells, J.T., Coleman, J.M., 1984. Deltaic morphology and sedimentology, with special reference to the Indus River delta. In: Haq, B.U., Milliman, J.D. (Eds.), Marine Geology and Oceanography of Arabian Sea and Coastal Pakistan. Van Nostrand Reinhold, New York, pp. 85–100.

Wilhelmy, H., 1967. The shifting river; studies in the history of the Indus valley. Universitas 10, 53–68.

Willis, B.J., 2005. Deposits of tide-influenced river deltas. In: Giosan, L., Bhattacharya, J.P. (Eds.), River Deltas—Concepts, Models, and Examples, SEPM—Society for Sedimentary Geology, Special Publication 83, pp. 87–132.

WPWPDA (West Pakistan Water and Power Development Authority), 1966. Lower Indus Report: Hunting Technical Service. M. MacDonald & Partners, Lahore, 2 vols.

Wright, L.D., Nittrouer, C.A., 1995. Dispersal of river sediments in coastal seas: six contrasting cases. Estuaries 18, 494–508.