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Dispersal of River Sediments in Coastal Seas: Six Contrasting Cases

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ABSTRACT: The fate of sediment seaward of river mouths involves at least four stages: supply via plumes; initial deposition; resuspension and transport by marine processes; and long-term net accumulation. The processes that operate at each stage, and the relative roles of each stage in governing the long-term accumulation patterns, vary appreciably with river regime and coastal ocean environment. To illustrate the diversity and illuminate the process of dispersal, information is synthesized for six systems: Amazon, Changjiang, Mississippi, Columbia, Purari, and Huanghe. These systems differ markedly in terms of water discharge, sediment discharge, and coastal energy regime and much of the diversity of dispersal patterns is attributed to these differences as well as to the temporal sequencing of river discharge relative to oceanographic transport processes. Although the sediment: water ratio of the discharge of the Mississippi River is 70 times less than that of the Huanghe, both of these systems exhibit rapid deposition and accumulation of sediments near the river mouths. In contrast, sediments dispersed by the other four systems are transported greater distances from the mouths by oceanographic processes, and are accumulating over relatively wide areas.

Introduction

River-borne sediments are dispersed into coastal oceans by a variety of processes operating over a wide range of temporal and spatial scales. From the time that they leave a river mouth until they ultimately become a part of the long-term geological record, the river-derived sediments typically undergo several cycles of transport, deposition, and reactivation. The natures and relative intensities of the processes that dominate these different stages of sediment dispersal are dependent, critically, on such factors as the water and sediment discharge rates of the river system, the physical-oceanographic regimes of the coastal seas into which the sediments are debouched, particle size, and the geometries of the shelves onto which the sediments are deposited.

The "generic" or "archetypical" river-mouth dispersal system remains elusive. Past attempts at systematizing our knowledge of even the most fundamental primary river-mouth processes (e.g., Wright 1977, 1985) have proven to be inadequate for explaining the dispersal of sediment off the mouths of many of the world's rivers, especially the sediment-laden rivers of Asia and the tropics. The difficulty of developing general models results from the multitude of operative mechanisms and the natural variability in the contributions of those mechanisms. We do not propose to correct inadequacies in this paper. Our purpose is, however, to shed light on the suites of environmentally mediated processes that operate at each stage in the transit of sediment parcels from source to sink. To this end, we synthesize existing information on six contrasting dispersal systems: the Amazon (South America), the Changjiang (Asia), the Mississippi (North America), the Columbia (North America), the Purari (Indo-Pacific), and the Huanghe (Asia). Past studies of individual systems have focused on different stages of sediment dispersal. Hence, in order for us to consider all stages, we must examine several systems. Since all stages have not been examined in each of the six cases, we use the different systems to illustrate different aspects of the dispersal process. Table 1 and Fig. 1 summarize some of the distinguishing process-relevant characteristics of these six systems.

Dispersal Stages

We recognize the existence of at least four distinct (but interfingering) stages in the dispersal of

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TABLE 1. Attributes of some major river dispersal systems.

Characteristic	River System					
	Amazon	Changjiang	Mississippi	Columbia	Purari	Huanghe
Latitude	Tropical	Mid-latitude	Mid-latitude	Mid-latitude	Tropical	Mid-latitude
Drainage basin area ($km^2 \times 10^6$)	6.15	1.94	327	0.67	0.03	0.77
Water discharge (km^3/yr)	6,300	900	580	251	84	42
Sediment discharge (10^6 tonnes/yr)	1,200	480	210	12	105	1,060
Sediment/water ratio (kg/m^3)	0.14	0.53	0.36	0.05	1.23	25.24
High/low flow ratio	2.2	4.0	3.3	4.3	1.6	11.0
Interannual flow variability	small	small	moderate	moderate	moderate	large
Dominant coastal winds	southeasterly trades	monsoons	mid-latitude fronts	mid-latitude fronts	southeasterly trades	monsoons
Spring tide range (m)	5.8	3.0	0.4	3.0	3.0	1.4
RMS wave height (m)	1.6	1.5	1.1	1.5	1.3	2.0
Speed of dominant currents (m/s)[a]	1.5	1.0	0.5	0.7	>1.0	1.0

[a] Refers to mean tidal or wind-driven currents over inner shelf.

sediment seaward of a river mouth. These stages are illustrated conceptually in Fig. 2. Although the diagram suggests that the stages are spatially separated and temporally sequential, this is not necessarily the case. In fact, two or more of these stages may exist at the same time and place. Furthermore, the diagram is two-dimensional whereas, in reality, the spatial separations may be more alongshore than across the shelf. In general, however, it is common for a sediment particle to have traveled a considerable distance from the river mouth and to have resided in the sea for decades to millennia before reaching its final resting place with respect to an individual plume (defined here as a burial site for >10^3 yr).

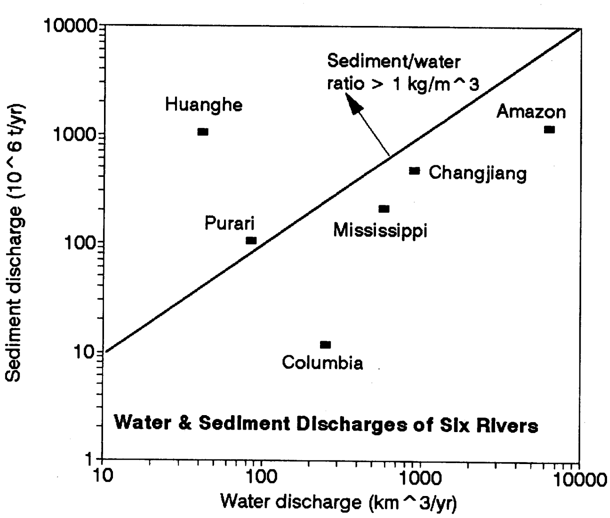

Fig. 1. Water and sediment discharges of six river systems. The relative sediment concentration increases toward the upper left corner of the graph and the relative contribution of positive buoyancy increases toward the lower right corner.

Stages I and II involve those primary processes by which a turbid river-mouth effluent (plume) spreads immediately seaward of the mouth, decelerates, and initially deposits its sediment load. It is these primary processes that have received the most extensive treatment in a generic sense (e.g., Wright 1977; Garvine 1987; Chao 1988; Wright et al. 1990). In Stage III, which may prevail contemporaneous with or subsequent to Stage II, waves, currents, or slope-failure mechanisms cause the resuspension and further transport of the recently deposited sediments. This reactivation stage, which eventually ends in redeposition, may be repeated numerous times before the sediments are permanently accumulated, in Stage IV, beneath an accreting sediment column. A key point, that we hope to demonstrate here, is that the distance- and time-separating the region of initial deposition (Stage II) from the region of final (or penulti-

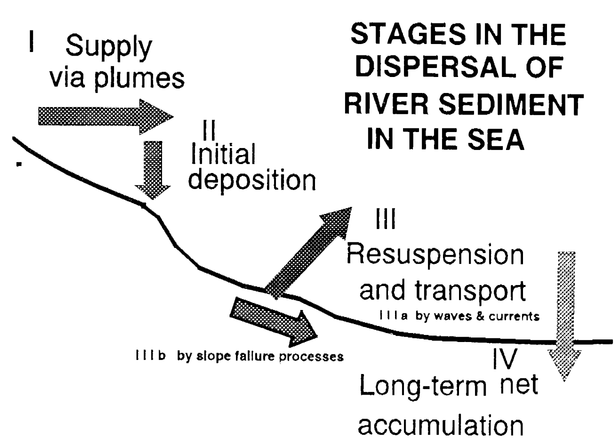

Fig. 2. Conceptual illustration of four major stages in the dispersal of river sediments in the coastal ocean.

mate) accumulation (Stage IV) depends in part on the strengths of the benthic oceanographic flows affecting the inner shelf and in part on the timing between maximum sediment discharge and maximum oceanographic energy.

Plume Dispersal Processes (Stage I)

Immediately upon leaving the confines of a river channel, sediment-laden buoyant plumes spread offshore and alongshore, experience advection and mixing by physical-oceanographic processes, and drop a portion of their sediment resulting in the initial deposition (Stage II). One of the primary determinants of how far sediments are transported from the source prior to their initial deposition is the buoyancy, $\hat{g}$, of the plume. The buoyancy, $\hat{g}$, depends on the difference between the density of ambient seawater and the bulk density of the outflowing river water (e.g., Wright et al. 1990). The plume bulk density is a function of salinity, temperature, and the concentration of suspended solids. The local density contrast depends, additionally, on the degree of tidal and wave-induced mixing between the river effluent and the sea. Hence, $\hat{g}$ and the resulting initial plume behavior, depend on the ratio of sediment to water discharge and on mixing factors such as wind stress, tide range, and wave height (Table 1).

The plumes issuing from most modern river mouths are positively buoyant ($\hat{g} > 0$), because the suspended-sediment concentration in the plumes is seldom high enough to offset the density differentials caused by salinity contrasts. Exceptions exist in cases like that of the Huanghe (Table 1), where concentrations in excess of 25 kg m^{-3} (e.g., Qin and Li 1983) cause even freshwater effluents to be negatively buoyant ($\hat{g} < 0$) in "clear" seawater. Negative buoyancy also occurs in cases where tidal currents, surface waves, or estuarine fronts significantly increase the concentration of suspended sediment relative to the salinity-induced density differential (e.g., Amazon, Kineke et al. 1991). We may thus conceive of both positively and negatively buoyant plumes as illustrated in Fig. 3.

In general, where the input of positive buoyancy to the coastal ocean is large relative to the amount of sediment in suspension and where the settling velocities of the suspended sediments are small, the sediment can be expected to be dispersed relatively far from the source before being initially deposited. The overall slope of the shelf also influences the offshore reach of positively buoyant plumes. Chao (1988) shows that, over steeply sloping shelves, the seaward extent of a plume is significantly reduced by vorticity. Plumes can, theoretically, extend farther seaward over flat shelves. The importance of vorticity in these studies also implies a latitudinal effect.

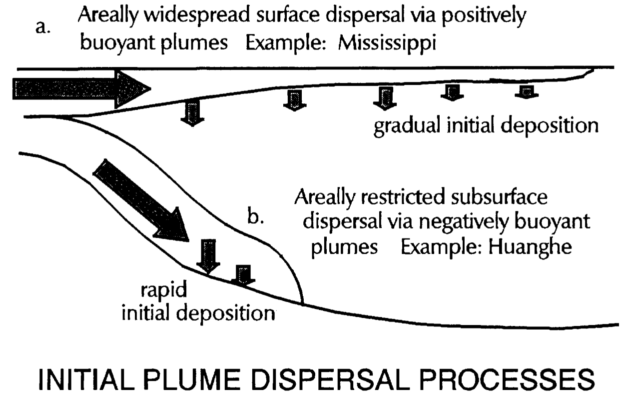

Fig. 3. Conceptual illustration of positively and negatively buoyant river-mouth plumes.

Initial Deposition (Stage II)

The rate at which sediment is initially deposited seaward of a river mouth in the region of spreading and decelerating effluents depends in part on the rate of effluent deceleration and in part on the settling velocities of the sediment particles. The primary processes of effluent-ocean interaction have been reviewed by Wright (1977, 1985) and more recently by Hoekstra (1988). Those studies have concluded that the most rapid deposition takes place immediately off the mouths of shallow rivers that transport sandy loads and is related to the rapid spreading and deceleration of turbulent frictionally dominated plane jets. Examples include the Jaba Delta of Bougainville, Papua New Guinea (Wright et al. 1980), and the Porong Delta of Indonesia (Hoekstra 1988). This type of river-mouth condition is rare for larger systems, and it does not prevail in any of the six cases discussed in this paper. It is, however, likely to characterize the mouths of many of the small mountainous rivers that Milliman and Syvitski (1992) consider to be most important in supplying sediment to the sea. Wave breaking near the river mouth enhances mixing and momentum exchange between buoyant effluents and the sea and promotes more rapid initial deposition close to the mouth (Wright et al. 1980). Deposition is also very abrupt in the case of negatively buoyant plumes that have been observed to undergo abrupt termination because of a combination of pronounced bottom friction, seaward-diminished bed slope, and detrainment of plume momentum by interactions between coastal currents and the plume (e.g., Wright et al. 1990).

Initial deposition by falling from positively buoyant effluents is a more common process, at least off the mouths of larger, low-gradient rivers, and has been widely invoked to explain the seaward fining of deltaic sediments and, particularly, the deposition of laminated prodelta shelf sediments (e.g., Adams et al. 1987). For river systems without well-developed coastal-plain estuaries (such as our six cases), flocculation over the continental shelf can be a significant process for increasing particle settling velocities and favoring more rapid particle deposition near the mouth (e.g., Amazon; Gibbs and Konwar 1986).

At rapidly prograding river mouths in particular and over fine-grained subaqueous deltas in general, bulk transport by slope-failure and gravity-driven processes of various sorts takes place penecontemporaneously with initial deposition (e.g., Prior and Coleman 1978, 1982; Prior et al. 1989; Adams and Roberts 1993). These processes have the net effect of shifting the locus of secondary deposition seaward of the region of initial deposition and may carry sediments off the shelf. A simple model for the long-term progradation of subaqueous deltaic deposits by bulk-transport processes, including landslides, is offered by Kenyon and Turcotte (1985). Adams and Roberts (1993) have developed a model for predicting the sedimentation rates necessary to initiate slope failure.

Resuspension and Transport (Stage III)

Except for rivers entering semi-enclosed seas or estuaries, many large river systems debouch into the energetic environment of the inner continental shelf. Normally, these are frictionally dominated realms where surface and bottom boundary layers overlap and usually occupy the entire water column (e.g., Mitchum and Clarke 1986). This situation becomes somewhat more complicated in the neighborhood of river effluents where stratification may reduce the thickness of the surface boundary layer and isolate the bed from the direct effects of local wind stress (e.g., Adams et al. 1987). Nevertheless, the combination of wave-induced bottom agitation, wave-induced and wind-induced nearshore currents, and tidal currents creates strong bed shear stresses that resuspend sediments off many river mouths. As a result, sediments are redistributed alongshore, usually producing smoother shoreline and submarine topography (e.g., Wright 1985).

In situations where the inner-shelf region remains energetic throughout the year or where high-energy conditions coincide with maximum river discharge, resuspension may take place simultaneous with initial deposition or deposition may be delayed. Adams et al. (1987) refer to an expression that shows the rate of sedimentation to be proportional to

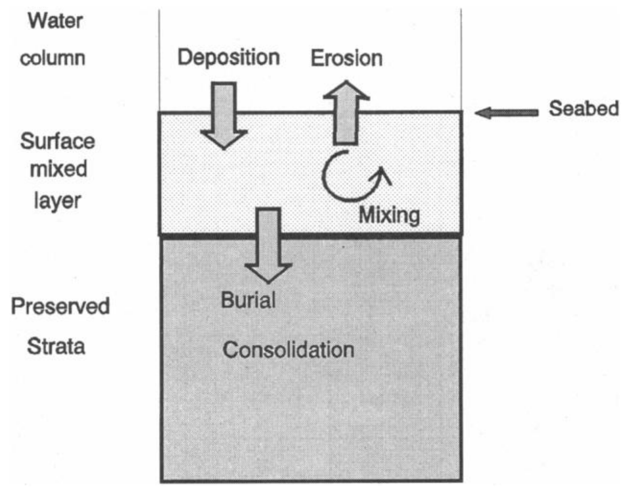

Fig. 4. Conceptual illustration of the surface mixed layer of the seabed and its relationship to sediment accumulation.

$$C_b w_s \left[1 - (\tau_o/\tau_d)\right]$$

where C_b is the average concentration of suspended sediment near the bed, w_s is particle settling velocity, τ_o is bed shear stress, and τ_d is the critical shear stress above which no deposition takes place; Adams et al. (1987) took τ_d to be about 0.04 Pascals. Where, on the other hand, bed stresses are acting to resuspend previously deposited sediments, the important quantity is $\tau_o - \tau_{cr}$ (with τ_{cr} being the critical shear stress required for sediment to be resuspended). In the case of fine sand and silt, τ_{cr} is in the neighborhood of 0.16 Pascals but for consolidated cohesive sediments it becomes much larger (e.g., Dyer 1986). In any event, $\tau_{cr} > \tau_d$ which means, simply, that it is easier for inner-shelf flows to retard initial deposition than it is for them to erode previously deposited and consolidated muds. Thus, one would expect accumulation near the river-mouth source to be generally favored in cases where the maximum sediment discharge and maximum wave activity (or bed stress) occur in different seasons of the year, because τ_{cr} usually increases with time following deposition.

Long-term Net Accumulation (Stage IV)

Stages III and IV are linked through the surface mixed layer (SML) of the seabed (Fig. 4). Within the SML, particles are actively reworked by physical and biological processes (Rhoads 1974; Nittrouer and Sternberg 1981; Rhoads and Boyer 1982; Jumars and Nowell 1984; Sanford 1992). Wave-induced and current-induced shear stresses erode, transport, and redeposit particles. Benthic organisms ingest particles at depth in the seabed and defecate them at the surface; some species expel fecal material directly into the water column

(Rhoads 1974; Rhoads and Boyer 1982; Jumars and Nowell 1984). Other organisms move particles laterally through mechanisms of locomotion and feeding. The net effect is to control the presence of particles within the upper few centimeters, where subsequent physical processes will erode and transport the particles during the next high-shear-stress event. The SML is the region of the seabed in which particles still interact with ambient oceanographic processes.

The difference between erosion and deposition through time determines whether net accumulation (and therefore burial of particles below the base of the SML) occurs. Accumulation rates (A) found within fluvial dispersal systems range from millimeters to tens of centimeters per year. The thickness (L) of the SML is largely dependent on the type and intensity of physical and biological processes. Typical thicknesses are about 10 cm (Nittrouer et al. 1979), but SMLs can extend in excess of 100 cm where intense physical processes or deep-burrowing organisms (e.g., *Callianassa* shrimp) occur (Kuehl et al. 1986), or can be nonexistent in quiescent, anoxic basins (Bruland 1974). The mixed layer depth divided by the accumulation rate equals the average residence time (R) for particles within the mixed layer ($R = L/A$) (Nittrouer and Sternberg 1981).

The residence time for the surface mixed layer determines how long physical and biological processes operate on particles before they are buried at a site. This is important because the processes operate selectively, moving some particles upward and other particles downward depending on characteristics of the particles (e.g., size, shape, mineralogy). Longer residence times allow these sorting mechanisms to be more effective. Particles moved upward can be transported laterally to more distal portions of the dispersal system. Particles moved downward have a higher probability of being buried at a site. Consequently the nature of a sediment dispersal system changes with distance from a river mouth. For example, the particle size typically becomes finer with distance (Nittrouer and Sternberg 1981).

In the marine environment, a fluvial dispersal system is represented by a tongue of sediment on the sea floor of the continental shelf. Dispersal systems extend away from river mouths in the direction of predominant sediment transport (usually with an alongshelf trend), and demonstrate the fate of the particulate portion of river effluent (e.g., Chin 1979; Nittrouer et al. 1979; Kuehl et al. 1986; Alexander et al. 1991). The seabed portion of the dispersal system represents the long-term (10^3 yr time scale) path of the particulate plume, and this path may be very different than that for the short-term water-column plume. For example, the turbid plume of the Changjiang River is carried northeastward during peak discharge (Beardsley et al. 1985), but the dispersal system extends southward (Chin 1979). Other rivers (e.g., the Columbia and Zaire) reveal similar reversals. The composition and long-term trajectory of river sediments are strongly influenced by stage IV processes.

The Amazon Dispersal System

The Amazon offers an example of a large tropical river, with a gentle gradient lower course, and with relatively intense oceanographic processes at its mouth. Sediments are distributed over wide areas of the shelf and alongshore before finally coming to rest. The immense freshwater discharge of the Amazon (6,300 $km^3\ yr^{-1}$; Oltman 1968) is derived from a tropical drainage basin that occupies an area of $6.15 \times 10^6\ km^2$ and extends from the Andes to the Atlantic. This drainage basin also supplies the Amazon with the world's second largest sediment discharge, 90% of which is silt and clay (Gibbs 1967). Despite the high suspended load, the large water discharge results in an extremely dilute sediment to water ratio of only 0.14 (Table 1) and the input of positive buoyancy to the tropical Atlantic is insignificantly affected by turbidity.

The Amazon plume extends far seaward and along the coast (Curtin and Legeckis 1986; Geyer et al. 1991; Fig. 5). Although tide range is large and mixing processes are relatively intense, the great volume of the outflow causes the effluent to fill the entire water column beyond the mouth before ascending above the seawater (Fig. 5b). It then continues to expand as a distinct buoyant plume 5–10 m thick. This plume reaches more than 300 km offshore over the wide, flat shelf and about 1,000 km to the northwest entrained by the North Brazil Current (Geyer et al. 1991). However, plume expansion is not a steady process even though the Amazon's discharge exhibits relatively little temporal variability. Geyer et al. (1991) observed that the northward transport of fresh water over the Amazon shelf averaged 180,000 $m^3\ s^{-1}$ but had a standard deviation of 140,000 $m^3\ s^{-1}$. They speculate that these large fluctuations might be attributable to wind forcing or tidal variations (in bottom drag and vertical mixing).

Although the water discharge of the Amazon remains high all year, there is some seasonality and the maximum discharge of May–June is more than twice the minimum of October–November (Nittrouer et al. 1991a). In addition, the peak sediment discharge precedes the peak water discharge by about a month or more (Meade et al. 1985). The shelf energy regime exhibits subdued season-

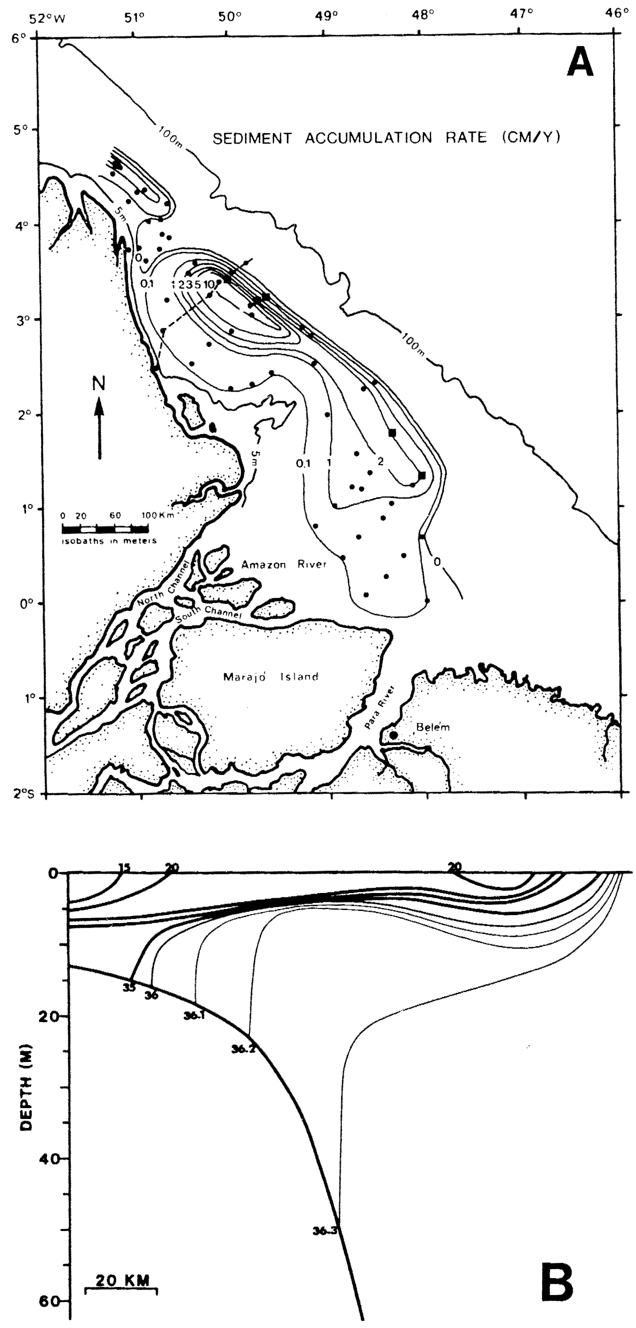

Fig. 5. The Amazon dispersal system. (A) Bathymetry and setting of the Amazon shelf and sediment accumulation rates (from Kuehl et al. 1986); (B) salinity structure of the Amazon plume seaward from the mouth (from Curtin 1986).

ality and is dominated by strong tidal currents and moderate waves generated by the easterly trade winds.

Kineke et al. (1991) found that intense reworking of sediment over the inner shelf allows only temporary sediment deposition. Once resuspended, the transport of sediments is facilitated by net mean flows, the most important of which is the North Brazil Current that carries sediment far to the northwest. Accumulation of sediments along the shore is retarded by high bed stress for the first few hundred kilometers of this northwestward path, where erosion is occurring despite the high alongshore sediment flux (Nittrouer et al. 1991b). Only after entering a regime of reduced tidal amplitude at about 3.5°N latitude does the rapid accumulation of sediment occur as prograding mudflats. Most of the accumulation, however, takes place over the mid shelf (depth 30–50 m) seaward and northwestward of the mouth in a region of seaward-dipping foreset beds; Pb-210 measurements from cores indicate accumulation rates there of about 10 cm yr^{-1} (Fig. 5a; Kuehl et al. 1986). On century time scales, roughly 50% of the Amazon's sediment discharge appears to be accumulating on the mid shelf (Kuehl 1986) and about 10% is transported to the northwest (Allersma 1971; Allison et al. 1995). Most of the remainder is probably sequestered within the tidal reaches of the lower river. The formation and movement of fluid mud on the inner shelf is a critical factor in determining the location of sediment accumulation (Kineke and Sternberg in press).

The Changjiang Dispersal System

The Changjiang (Fig. 6) is the world's fourth largest river in terms of both water and sediment discharge. The peak discharge of these components occurs during July–September (Shi et al. 1985), and the discharge reveals a bifurcation near the river mouth (Beardsley et al. 1985). A low-salinity plume about 10 m thick (defined by the 26‰ salinity contour) extends northeastward, and a band of fresh water also hugs the coast south of the river (extending into Hangzhou Bay; Jilan and Kangshan 1989). During the winter, cold-air outbreaks from Siberia create storms with winds predominantly blowing southward. The plume is carried southward (Beardsley et al. 1985); however, water and sediment discharge are at a minimum during this period. The summer is the time of peak discharge and the plume enters the East China Sea when winds are weak. A portion of the plume extends to the bottom, and the combination of plume inertia and sloping bottom cause a turn to the left, which conserves vorticity (Beardsley et al. 1985). The strong winds control the trajectory of the plume during winter.

Although seasonal fluctuations of the river have the dominant control over discharge, tidal phase (spring versus neap) also plays an important role (Milliman et al. 1985). Approximately 40% of the annual sediment supply is trapped in the river mouth. The remainder of the sediment escapes

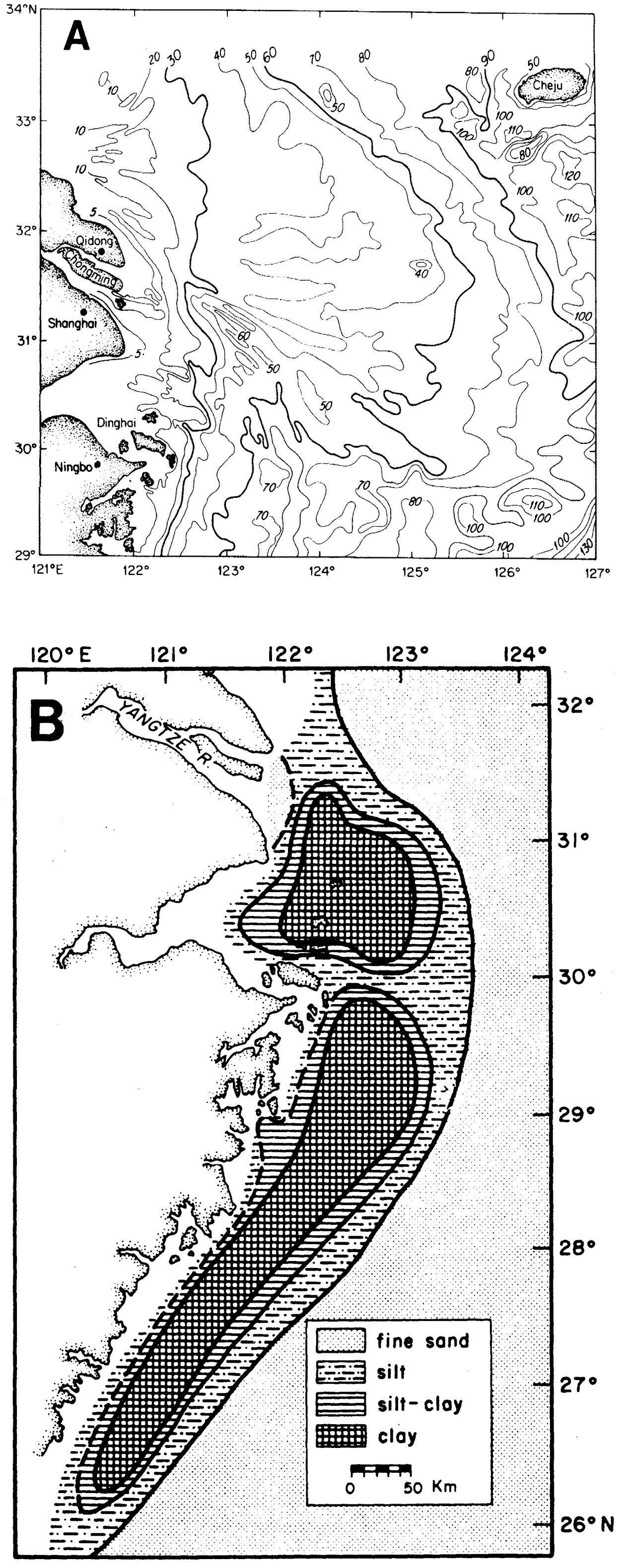

Fig. 6. The Changjiang dispersal system. (A) Setting and bathymetry (from Butenko 1982); (B) distribution of Changjiang (Yangtze River) sediments on the continental shelf (from Chin 1979).

seaward, and forms a subaqueous delta (Chen et al. 1985) similar to that for the Amazon. Maximum accumulation rates are about 5 cm yr^{-1} (McKee et al. 1983; DeMaster et al. 1985), and decrease abruptly northward and eastward (across-shelf) and gradually southward (along-shelf). These trends have a significant effect on the character (sedimentary structure) of buried sediment. Strong ambient currents from tides (Larsen et al. 1985; Sternberg et al. 1985) and winter storms produce laminations by means of physical transport and deposition. In areas of high accumulation rate, the residence time of particles within the surface mixed layer is reduced. Also, the high accumulation rates (>2 cm yr^{-1}) inhibit habitation by benthic organisms (Rhoads et al. 1985), allowing physical laminations to dominate sedimentary structure. In areas of slower accumulation, the effects of bioturbation become more significant and physical sedimentary structures are destroyed. This trend is generally observed with distance along sediment dispersal systems, and specifically within the Changjiang and Huanghe systems (Nittrouer et al. 1984).

Another important observation from the Changjiang regarding dispersal systems is the relative timing of sediment discharge, deposition, and transport. The peak discharge occurs during summer months when winds and along-shelf (southward) currents are weak. Most sediment is deposited near the river mouth, and short-term deposition rates (time scale 3 mo) as high as 5 cm mo^{-1} have been measured at the same locations where net long-term (order 100 yr) accumulation rates are only 5 cm yr^{-1} (McKee et al. 1983). This observation indicates that much sediment is deposited on the shelf near the Changjiang River mouth during the summer, but only a fraction (< a third) remains as net accumulation. The bulk of this sediment is eroded by winter storms and transported southward along the dispersal system (Fig. 6b). Ironically, the period of minimum sediment input (winter) is the period of peak sediment dispersal. Consequently the direction of the long-term sediment plume (southward) is decoupled from the direction of the predominant water-column plume (northeastward). The southerly transport ultimately contributes to the sequestering of a significant fraction of the sediment in Hangzhou Bay (south of river mouth).

The Mississippi Dispersal System

The Mississippi provides an example of a system with a low oceanographic energy regime and minimal resuspension following initial deposition. The water and sediment discharges of the Mississippi (580 km^3 yr^{-1} and 2.1 × 10^{11} kg yr^{-1}; Milliman and

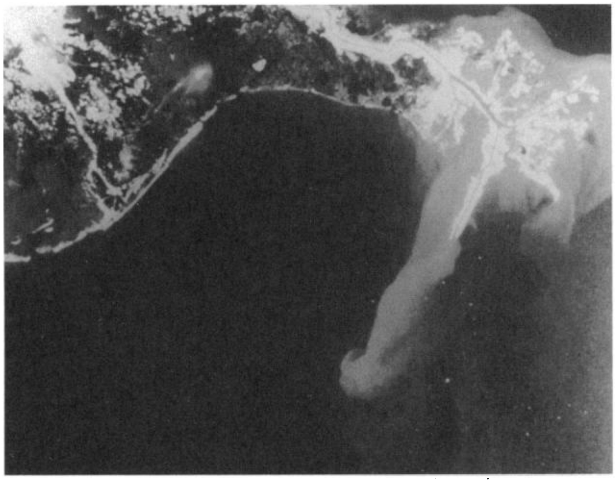

Fig. 7. Satellite image of the Mississippi dispersal system showing the protruding "bird's-foot" delta and elongated buoyant plumes.

Meade 1983) are respectively an order of magnitude and a factor of five less than those of the Amazon (Table 1; Fig. 1). Like the Amazon, the Mississippi carries its sediment load, 80% of which is fine silt and clay, predominantly in suspension. Because the tidal range over the Louisiana-Texas shelf is very low, tide-induced mixing and flow velocities in distributary channels are minimal. This, together with the fine-grained cohesive character of the sediment, permits the distributary channels to remain narrow and relatively deep. The mouth of the Mississippi therefore represents a classic salt-wedge estuary for most of the time (Wright 1971) and the effluent approximates a discrete freshwater plume overlying relatively undiluted seawater near the mouth (Wright and Coleman 1971, 1974; Fig. 7).

Initial deposition of the coarsest material (fine sand, coarse silt) takes place roughly four channel widths seaward of distributary mouths to produce prograding distributary-mouth-bar deposits (Wright and Coleman 1974). Downslope transport of bar deposits by gravity-driven slope-failure processes occurs episodically to move the deposits into deeper water (e.g., Prior and Coleman 1978, 1982; Adams and Roberts 1993). Finer material that remains in suspension is transported farther seaward and is spread more uniformly along isobaths by the thin, expanding buoyant plumes. This material falls from suspension to produce the laminated prodelta muds (Coleman 1981; Adams et al. 1987). In more distal parts of the prodelta region where accumulation rates are slower, Moore and Scruton (1957) recognized bioturbated muds. Measurements of near-bottom currents over the prodelta deposits at a depth of 60 m by Adams et al. (1987) show that bed shear stresses tend to be less than the critical value at which deposition occurs. Hence, oceanographic flows do not significantly retard deposition and cannot resuspend previously deposited sediments. Other measurements of shelf currents over the Mississippi Delta front by Wiseman and Dinnel (1988) also show that flows are minimal under normal conditions. This favors a relatively high accumulation rate. Coleman (1981) estimates an average prodelta value of 20 cm yr^{-1}.

Probably the most distinguishing features of the dynamic regime affecting the Mississippi dispersal system are the low bed stresses and relative weakness of along-shelf flows (Adams et al. 1982; Wiseman and Dinnel 1988). This sets the Mississippi apart from the other five systems discussed in this paper. Because of this mild regime, most of the sediment apparently remains near the loci of initial deposition and is not dispersed far afield, although slope failure processes cause additional postdepositional downslope transport (e.g., Adams and Roberts 1993). For this reason, river-mouth deposits surmounted by distributaries have succeeded in prograding across the shelf as elongated "fingers" (Fisk 1955; Fig. 7). Wiseman and Dinnel (1988, p. 1287) point out that "The bird-foot delta of the modern Mississippi River extends nearly completely across the Mississippi–Louisiana continental shelf, blocking the shelf to significant east-west flow." Thus, on the time frame of centuries to millennia, significant alongshore (east–west) dispersal is effected by episodic lobe switching rather than by oceanographic forcings. In Holocene time, the Mississippi has built five major deltas comprising at least 16 lobes (Kolb and VanLopik 1966; Frazier 1967). At the present time, Mississippi sediments are reaching coastal waters well to the west of the modern delta by way of the Atchafalaya River, a primary distributary of the Mississippi that has only recently begun to build a new delta lobe (VanHeerden and Roberts 1980; Adams et al. 1982).

The Columbia Dispersal System

The sediment discharge of the Columbia River is smaller than that of the other systems discussed here, but the associated sedimentation closely approximates the classic models of Holocene processes put forth by Curray (1965) and Swift (1970). A high energy coastal oceanographic regime precludes significant inner shelf deposition and promotes deposition and accumulation of fines primarily on the mid shelf. On a global basis, the Columbia River (Fig. 8) is of moderate size (Table 1) and represents a good example of a river plume responding to the unique processes (e.g., upwelling) associated with an eastern ocean boundary. Winds at the mouth of the Columbia fluctuate with

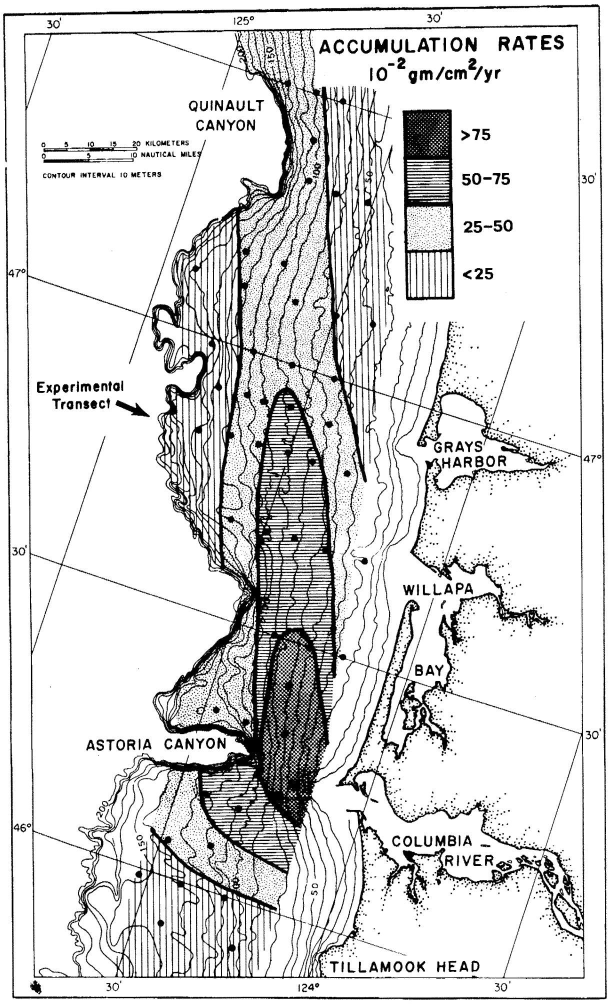

Fig. 8. The setting, shelf bathymetry, and sediment accumulation rates associated with the Columbia dispersal system (from Nittrouer 1978).

synoptic-scale atmospheric conditions in the North Pacific. A low-pressure system in the Gulf of Alaska provides intense northward winds during winter (Nelson 1977), and a high-pressure system in the central North Pacific causes southward winds during summer months (Beardsley et al. 1987). The prevailing surface currents undergo similar seasonal variation (Smith and Hopkins 1972; Hickey 1989). However, event-scale fluctuations (e.g., associated with storms) are of the same order as seasonal means, allowing currents and winds to reverse for short periods throughout the year. The Columbia plume (defined by the 32‰ salinity contour) is typically 5–20 m thick (Hickey 1989). During winter when currents are northward, Ekman transport is directed onshore, and the plume flows northward along the Washington shelf hugging the coast. During summer when prevailing currents are southward, Ekman transport is offshore, and the plume flows southwestward across the Oregon shelf and slope. Baroclinic and barotropic responses to the winds (e.g., upwelling or downwelling; water surface slope) are largely responsible for the above patterns (Smith and Hopkins 1972).

The Columbia dispersal system is similar to the Changjiang with respect to the seasonal divergence of the plume trajectory. However, the Oregon–Washington shelf is much narrower than the East China Sea (40 km versus 400 km) and the seaward extension of the plume during the summer apparently allows some of the finest terrestrial sediment to escape the shelf. Clay-mineral signatures in continental-slope sediment (found near and south of the river mouth) indicate a modern Columbia River origin (Karlin 1980). However, the vast majority of the Columbia sediment is deposited on the shelf near the river mouth (forming ephemeral layers of mud) during relatively quiescent summer months (Nittrouer and Sternberg 1981). Bottom shear stresses sufficient to erode and transport sediment are generally limited to winter storms (Smith and Hopkins 1972; Sternberg and McManus 1972; Kachel and Smith 1989). A distinct tongue of Columbia River sediment extends northward along the mid shelf (Nittrouer and Sternberg 1981) with a slight offshore component (probably due to turning in the bottom Ekman layer; Smith and Long 1976).

The modest size of the Columbia River sediment discharge precludes accumulation rates on the shelf from exceeding 1 cm yr^{-1}. The highest rates are about 7 mm yr^{-1} on the mid-shelf near the river mouth; they decrease northward to about 2 mm yr^{-1} and result in a progressive thinning of the tongue of modern sediment (Nittrouer et al. 1979). Approximately two-thirds of the Columbia sediment discharge annually accumulates within the mid-shelf portion of the dispersal system (Nittrouer 1978). The remainder is resuspended and transported seaward during (winter) storms, and is supplied to the continental slope as an intermediate-depth nepheloid layer (Baker and Hickey 1986). Several other progressive changes are observed along the dispersal system as a result of mechanisms operating within the surface mixed layer. Sedimentary structure becomes homogeneous with distance from the river mouth as accumulation rates decrease (Nittrouer and Sternberg 1981), similar to the changes described for the Changjiang and Huanghe dispersal systems. Sediment grain size becomes finer with distance due to selective sorting by physical and biological processes.

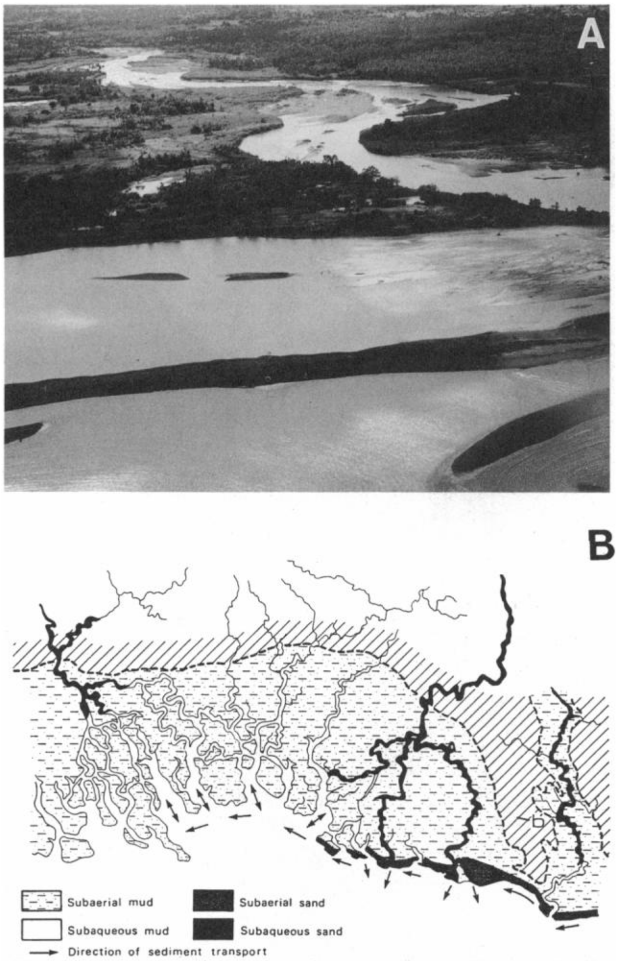

Fig. 9. The Purari dispersal system. (A) wave-built longshore bar adjacent to the mouth of the Purari River; (B) sediment dispersal patterns alongshore and into estuaries of the northern portion of the Gulf of Papua (from Thom and Wright 1983).

The Purari Dispersal System

The importance of small mountainous rivers as sources of sediment to the coastal ocean has been emphasized by Milliman and Syvitski (1992). Prominent examples of such systems are the Purari, Kikori, and Fly rivers that drain the highlands of Papua New Guinea and flow into the Gulf of Papua (Fig. 9). These rivers, along with several smaller ones, are estimated to supply roughly 410 km^3 of fresh water to the Gulf of Papua annually (Wolanski et al. 1984). About 84 $km^3\ yr^{-1}$ are contributed by the Purari and its major tributary, the Aure River (Petr 1983). Although the Purari has by far the smallest drainage basin of the six systems examined here, over 8,000 mm of rain annually falls into its catchment (Pickup and Chewings 1983); locally, even higher rates of rainfall occur. In addition, the catchment is high and relief is rugged: the peak elevation in the Bismarck Range, 200 km from the coast, is 4510 m. Consequently, the Purari has a high sediment discharge of 105×10^6 t yr^{-1} (Pickup and Chewings 1983) and a sediment:water discharge ratio of 1.23 (Table 1). The sediment load delivered to the upstream limit of the active delta consists of 6% sand, 48% silt, and 46% clay (Pickup 1980).

Some of the Purari's sediment load is trapped within the active delta plain, which is heavily vegetated with mangrove forests and crossed by a complex network of interconnecting channels (Thom and Wright 1983). The remaining sediment that reaches the sea does so by way of three main distributary channels: Purari, Ivo-Urika, and Wame-Varoi; the Ivo-Urika channel carries most of the high-discharge flow (Thom and Wright 1983). Saltwater intrusion is largely excluded from the lower distributary channels by shallow and mobile shoals at the entrances combined with the high river flows. Sand is deposited within and immediately seaward of the energetic, wave-influenced river mouths. Fines are carried into the inner-shelf environment as muddy, low-salinity plumes that are disseminated by the coastal oceanographic regime (Thom and Wright 1983).

The coastal energy regime is dominated by the onshore-directed southeast trade winds for much of the year. The wind regime is made somewhat more complicated, however, by the existence in summer (December–March) of a northwesterly airflow (Evesson 1983). On an annual basis, the southeasterlies dominate and cause the north shore of the gulf to be subjected to moderate waves and a westward-setting littoral drift (Thom and Wright 1983). As a consequence, much of the effluent water remains trapped relatively close inshore as a turbid band and is advected alongshore, especially during the period April–October (similar, on a smaller scale, to the Amazon). Plumes advected to the west inshore ultimately enter funnel-shaped tidal estuaries on flooding tides. Much of the suspended material is deposited on intertidal flats and some contributes to siltation of the upper ends of the estuaries. Seaward of the nearshore zone, however, evidence suggests that sediments are migrating toward the east (Wolanski et al. 1984). Some significant but undetermined amount of the suspended sediment probably also is transported directly offshore, especially during summer when the southeasterly winds are weakened or reversed. Wolanski et al. (1984) report that satellite imagery (from rare occasions when cloud cover is not complete) show Purari plumes extending directly into the Gulf of Papua. The ultimate sink for this sediment is not known, although it is probably the Coral Sea. Waves and tidal currents clearly are effective in dispersing sediments along the shelf, precluding the digitate progradation of the Mississippi River.

The Huanghe Dispersal System

The Huanghe has the lowest water discharge rate of the six systems compared here: two orders of magnitude separate the Huanghe from the Amazon (Table 1). However, the sediment discharges of the Huanghe and Amazon are approximately the same. Consequently, the Huanghe contributes a huge amount of sediment and a very small amount of positive buoyancy to the compartmentalized epicontinental sea (Huanghai-Bohai) into which it debouches (Fig. 10a). In contrast to most modern river-mouth systems, effluents from the Huanghe mouth tend to possess considerable negative buoyancy. On average, the suspended sediment concentration along the lower course of the river is roughly 25 kg m^{-3}; during high flow it exceeds 200 kg m^{-3} (Ren and Shi 1986).

The Huanghe sediments are predominantly carbonate silts eroded from the loess plateau of interior China (the Mongolian Plateau). Most of the sediment (86%) is discharged during the summer monsoon period of July–October (Qin and Li 1983). Low precipitation and low discharge accompany the strong winds and high wave activity of the dry winter monsoon (December–February). At present (and since 1855), the Huanghe discharges into the Bohai, the shallow innermost compartment of the compound epicontinental sea, north of the Shandong Peninsula. However, the large sediment load and consequent rapid aggradation and deltaic progradation has caused the river's course to be unstable and the location of the mouth to shift frequently (Ren and Shi 1986). Between 1128 and 1855 the river flowed directly into the Huanghai (Yellow Sea; Ren and Shi 1986) south of the Shandong Peninsula and about 500 km south of the present mouth (Fig. 10C).

Field measurements of effluent processes off the modern mouths of the Huanghe show the existence of both positively and negatively buoyant plumes, but with the bulk of the sediment being transported within the negatively buoyant underflows (Fig. 10b; Wright et al. 1990). Strong isobath-parallel tidal currents with speeds on the order of 1 m s^{-1} act to mix ambient and effluent waters and maintain high suspended-sediment concentrations over the upper part of the delta front. However, as they descend over the delta front slope, the gravity-driven turbid underflows terminate abruptly and deposit their sediment loads near the mouth. As sediment discharge diminishes during the autumn months, the newly deposited sediments undergo partial consolidation and become more resistant to

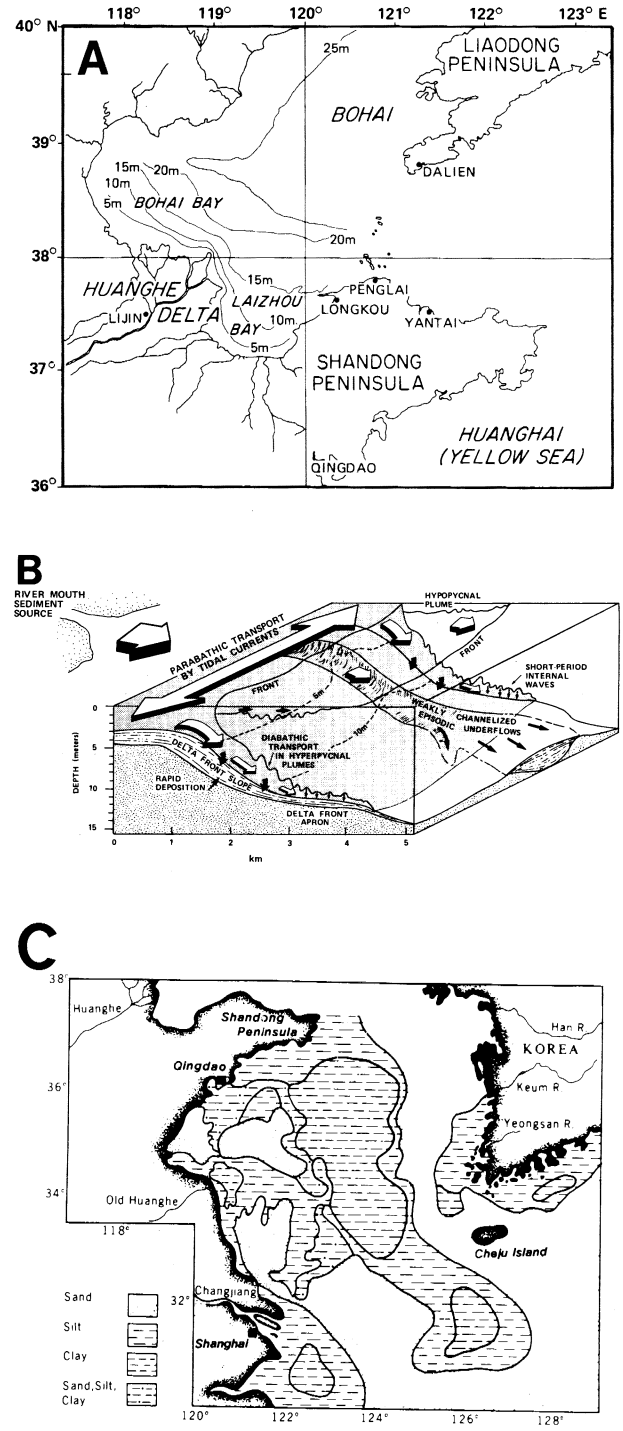

Fig. 10. The Huanghe dispersal system. (A) Location map showing the active Huanghe delta (from Wright et al. 1990); (B) diagram illustrating the dispersal and deposition of sediment by way of negatively buoyant plumes over the Huanghe delta front (from Wright et al. 1990); (C) distribution of Huanghe muds in the Huanghai (Yellow Sea) (from Alexander et al. 1991).

resuspension by tidal currents (Wright et al. 1990). The net result is that about 90% of the sediment discharged by the Huanghe into the Bohai since 1976 has remained within 30 km of the mouth (Bornhold et al. 1986), leading to rapid deltaic progradation rates that are estimated to range from 0.5 km yr^{-1} regionally (Ren and Shi 1986) to as much as 1.0 km yr^{-1} locally (Yang and Lu 1987).

Limited observations indicate that the high waves and strong wind-driven currents generated by the prolonged storms (Siberian outbreaks) of autumn and winter are highly effective in resuspending previously deposited delta-front sediments and advecting them to the south and north as highly concentrated fluid-mud layers (Wright et al. 1990). These severe storms also cause slope failure and downslope transport by way of submarine landslides (Prior et al. 1989). Despite the intensity of these storm-driven processes, only about 10% to 15% of recently debouched sediments are leaving the neighborhood of the river mouth (Bornhold et al. 1986; Alexander et al. 1991). (It should be noted that 10% of the Huanghe's sediment load is equivalent to one half of the Mississippi's load.) The fractions that do leave the active delta region are apparently transported out of the Bohai and are accumulating west and south of the Shandong peninsula as an extensive subaqueous delta lobe (Fig. 10c). Subbottom profiles of this lobe, combined with ^{210}Pb and ^{14}C geochronologies, indicate that roughly 40 m of Huanghe sediment has accumulated vertically in Holocene time (Milliman et al. 1987; Alexander et al. 1991). Modern accumulation rates on the topset, foreset, and bottomset deposits of the lobe are respectively 1–2 mm yr^{-1}, 4–9 mm yr^{-1}, and 2–4 mm yr^{-1} (Alexander et al. 1991). Although these rates are lower than those observed for the Amazon subaqueous delta, the relative trends are similar (i.e., the foreset beds accumulate the most rapidly; Alexander et al. 1991).

Discussion and Conclusions

Many general conclusions can be distilled from intercomparisons of the six dispersal systems described above. In two of our examples—Huanghe and Mississippi—it is the initial plume dispersal and initial deposition processes that appear to govern the bulk of the longer-term accumulation patterns. In the Amazon and Purari cases, oceanic processes that resuspend and transport sediment act contemporaneously with maximum plume outflow and cause sediment to be dispersed farther from the mouths before accumulating. Divergent plumes and rapid initial deposition followed by intense resuspension and transport by oceanic processes characterize the Changjiang and Columbia systems.

The Mississippi and Huanghe differ dramatically in several respects: the sediment : water ratio of the Huanghe is 70 times larger than that of the Mississippi; the Mississippi plume is strongly positively buoyant, whereas the predominant Huanghe plume (for transporting sediment) is negatively buoyant; and the waves, tidal currents, and wind-driven currents over the Huanghe delta front are much stronger than those affecting the Mississippi. Despite these differences, sediments are rapidly depositing and accumulating near the mouths of both systems. In the case of the Mississippi, this is because benthic flows are almost always too weak to entrain and transport sediment. Off the mouth of the Huanghe, accumulation occurs because an immense amount of sediment is delivered to the inner shelf a few months before storm conditions occur, allowing partial consolidation of sediment. Rapid accumulation near the mouths of these two systems probably accounts for some other important features that the Huanghe and Mississippi have in common: protruding subaerial deltas; subaqueous slope-failure processes; and river-mouth avulsions and delta-lobe switching.

Sediments dispersed by the other four systems are accumulating over relatively wide areas that extend considerable distances from the mouths. Neither the Amazon nor the Columbia has constructed a major subaerial delta, and the subaerial deposits of the Changjiang and Purari are not extensive and do not protrude significantly beyond the regional coastline trend. In addition, the positions of the Amazon and Columbia mouths have remained relatively stable.

Alongshore dispersal of sediments issuing from the Amazon, Changjiang, and Purari takes place primarily over the inner shelf. In contrast, fine sediments debouched by the Columbia are initially deposited, abruptly, on the inner shelf near the mouth and subsequently resuspended by winter storms and dispersed over the mid shelf, where they are accumulating in an along-shelf band. Much of the material transported alongshore from the Changjiang and Purari rivers becomes sequestered within nearby tidal estuaries. Amazon muds that are transported alongshore ultimately accumulate as mudflats hundreds of kilometers to the northwest of the mouth.

The Amazon and Huanghe systems are characterized by accumulations of sediments as subaqueous-delta deposits at relatively large distances ($>$ 100 km) from their mouths. In both cases, these deposits exhibit classic bottomset-foreset-topset sequences. These deposits account, respectively, for 50% and 10–15% of Amazon and Huanghe sediments. The fact that a large fraction of Amazon sediments reaches this distal sink is attributable to the energetic currents and waves that sustain the sediments in suspension until they reach relatively deep water. In the Huanghe case, the sediment is initially deposited—and partly consolidated—near the mouths. Only a fraction of this sediment is subsequently resuspended and transported out of Bohai and into the Huanghai (Yellow Sea) by storm-driven processes. We can postulate that if the time of maximum Huanghe discharge coincided with the time of maximum marine energy, a much larger fraction of the total sediment load would end up outside of Bohai and in the Yellow Sea subaqueous delta.

Much of the observed diversity in the patterns of sediment dispersal and accumulation that distinguish the six systems is attributable to variations in coastal energy regime and to the temporal sequencing of river discharge relative to oceanographic transport processes. There are some important temporal and spatial factors that must be considered when attempting to explain the dispersal patterns of any particular system.

In the time dimension, we must keep in mind that, from a geological perspective, sediment "plumes" involve integration over scales of many years rather than hours or days. This means simply that the mechanisms that dominate the short-term spreading and mixing of a river effluent may differ significantly from the mechanisms that determine the longer term dispersal of the sediment. In fact, differences in plume direction are often recognized when plumes are examined at different time scales (e.g., Changjiang, Columbia, Purari). The timing of sediment discharge in relation to seasonally-variable oceanographic processes is an important temporal consideration.

Among the spatial factors, latitude is obvious but not trivial; it determines the strength of the Coriolis parameter (nearly zero in the case of the Amazon) as well as the relative importance of seasonal effects. Shelf width, which depends fundamentally on tectonic setting, is a determinant of the extent to which sediment escapes the shelf or accumulates on the shelf. Finally, the absolute size of the river systems cannot be ignored.

Where continental geography forms large drainage basins, river discharge is much more regular and less influenced by unusual events. As shown by Milliman and Syvitski (1992), however, it is the small, mountainous rivers, particularly those in the humid tropical regions of Oceania, that are probably the most important sources of river sediment to the sea at the present time.

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