Suspended-Sediment Dispersal Patterns of River Deltas Photographed by ASTP

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ABSTRACT

Orbital photographs of five major river deltas reveal the presence of distinctive suspended-sediment plume patterns that can be related to models of sedimentation in a deltaic environment. By using both delta geometry and plume pattern, the relative effects of river inertia, buoyancy of suspended matter, and turbulent bed friction can be evaluated. Although long-term delta development is affected by numerous factors, the study of plumes from orbital photographs indicates the short-term processes that dominate deltaic sedimentation. Photographs of the Fraser and Rhône Rivers suggest river-inertia domination, whereas those of the Orinoco and Yangtze Rivers suggest the importance of both frictional turbulence and buoyancy. The major process operating at the mouth of the Danube River is buoyancy.

INTRODUCTION

As part of the Earth Observations and Photography Experiment of the Apollo-Soyuz Test Project (ASTP), several sites of present-day deltaic sedimentation were chosen for visual observations and photography. Information on cameras, film types, and photographic support data are in reference 1. The intent of this study is to investigate the sediment plume patterns emanating from deltas with respect to (1) shore morphology, (2) deltaic pattern of the river, and (3) models of deltaic sedimentation.

Much of the world's supplies of oil and gas has been found in ancient deltaic sediments and, consequently, many studies have been made of both recent and ancient deltas (reviewed in refs. 2 and 3). These studies have dealt mainly with the distribution of sediments and the depositional environment, and only recently have they made use of aerial photographs and space images to define the distribution of suspended sediment plumes (refs. 4 and 5). Recent studies of Landsat images have shown the importance of longshore currents, prevailing winds, and turbulence in distributing the sediment input by rivers. However, the relationship of color zones within the plumes can be studied only through the use of a continuous-tone color film, such as that used on ASTP.

Five major river deltas were photographed during the mission: the Danube, Fraser, Orinoco, Rhône, and Yangtze (fig. 1). Although numerous photographs of the Nile Delta were taken, there are no pronounced sediment discharge plumes and, consequently, the Nile is not included in this study. Sediment plumes are visible at the mouths of all the other. rivers studied, and may be classified according to the relative effects of river and receiving-basin energy levels. Plume patterns of the Orinoco and Yangtze are most affected by longshore currents and by the effects of wave and tidal energy, whereas patterns of the Rhône and Fraser Rivers are influenced by outflow inertia (ref. 6). Based on present models of deltaic deposition, it may be possible to estimate the geometry of subaqueous bar development based on plume pattern. Consequently, this paper will first review

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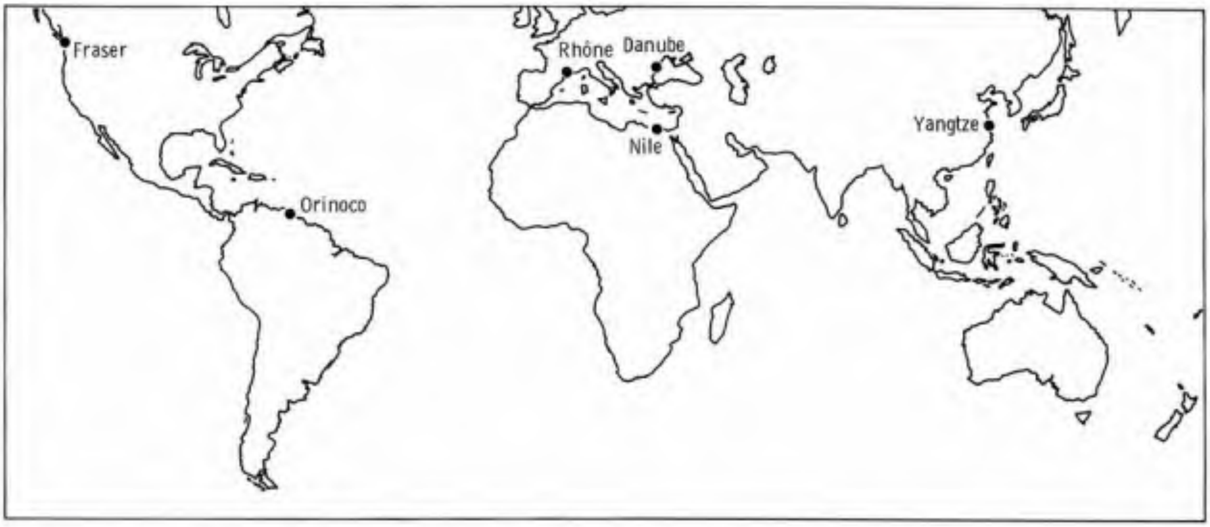

FIGURE 1.—Locations of major deltas photographed by ASTP crewmembers.

models of distributary-mouth bar development, and then discuss plume patterns photographed by ASTP in terms of their dominant controlling mechanisms.

CONTROLS OF SEDIMENT DISTRIBUTION PATTERN

Although long-term deposition and delta evolution are controlled by climate more than by any other single factor (ref. 3), the instantaneous nature of sediment plumes revealed in space photographs is more a function of short-term daily (or even hourly) weather and tidal conditions. However, the deltaic processes that give the plume its characteristic shape are time-independent, and the study of plumes can therefore be used to estimate the relative importance of each process. The significance of each process is subject to daily variations in weather, tides, discharge, and receiving-basin conditions; therefore, detailed interpretations cannot be made on the basis of a single photograph. However, for purposes of this study, the basic factors of delta and shore geometry will be considered static.

Based on a synthesis of deltaic studies, three dominant processes have been proposed for the evolution of sediment dispersal patterns (refs. 3, 6, and 7). With the exception of coastal processes, sediment discharge can be viewed as a function of (1) outflow inertia, (2) turbulent bed-friction seaward of the mouth, and (3) outflow buoyancy (ref. 7). Depositional patterns resulting from these three mechanisms are summarized in figure 2. Although these processes were proposed partially on the basis of depositional patterns, they are also applicable to sediment plumes in ASTP photographs. The following summary of river mouth processes is based on studies by Coleman and Wright (refs. 3 and 7).

River inertia effects on sediment dispersal take place through turbulent jet diffusion at the boundary of the river and receiving basin (fig. 2, sketch A). This process is enhanced by steep river gradients, the lack of bottom interference, and small differences in buoyancy between the river and basin water. A river mouth dominated by this process is characterized in plan view by a lunate bar that is further distinguished by sediment sorting; the coarsest material is deposited at the landward margin of the bar. With this process dominating, the sediment plume would have relatively sharp margins with the basin water, and its length would be the direct result of river velocity.

When continuous deposition at the mouth of the river results in decreased water depth, an increase in the dominance of bed friction occurs. High bed friction contributes to increased deposition. Eventually, channelization will occur, localized by subaqueous levees, and a triangular-shaped bar will develop at the mouth of the river (fig. 2, sketch B). The resulting plume pattern will be broader than an inertia-dominated river mouth, although a subaqueous channel may be marked by a concentrated zone of suspended sediment.

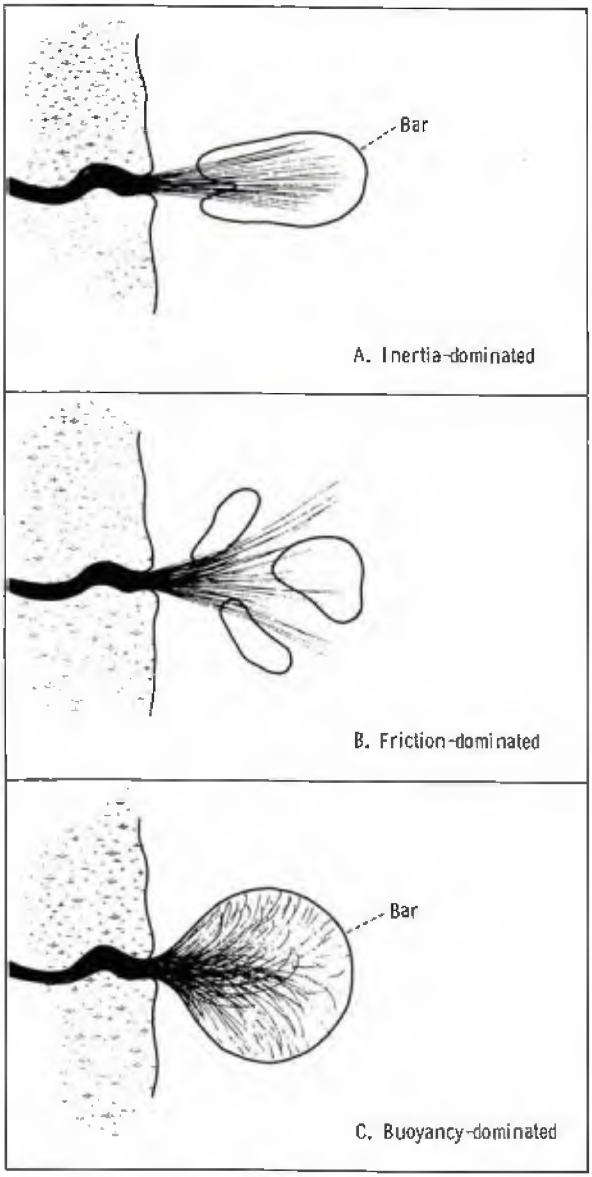

FIGURE 2.—Patterns of sediment dispersal and distributary-mouth bar formation for three processes of sedimentation (modified from Coleman, ref. 3).

Because the density of seawater is greater than that of river water (even with admixed sediment), the suspended sediment of a coastal delta will be buoyantly supported. The process of turbulent diffusion is not as significant as is the spreading of the river water above the more dense basin water. Consequently, the bar of the river mouth extends radially away from the mouth, and sediment deposits will be laterally sorted. Depending on the magnitude of discharge and the difference between river and basin water density, this process may also occur within the river, where straight distributaries would be flanked by subaqueous levees (fig. 2, sketch C). The sediment plumes resulting from this mechanism will appear more symmetrical than those of inertial or frictional processes.

Although these factors are the primary controls on the outflow pattern of sediments, forces active in the receiving basin will redistribute suspended matter. Active wave and tidal regimes will produce rapid mixing of the sediment, and may offset the effects of buoyancy through vertical mixing of freshwater and seawater (ref. 7). Because these processes can fluctuate rapidly with local tidal and weather conditions, interpretation of plumes seen in ASTP photographs will be considered only with respect to the primary depositional processes.

PLUME CHARACTERISTICS

Danube River

The Danube Delta occupies an area of 2740 km^2 (ref. 3) on the western margin of the Black Sea. Sediment plumes emanate from all three major branches of the river, although the central and northern branches (Sulina and Chilia) join at the coast and together are responsible for the most dense portion of the plume (fig. 3(a)). North of these river mouths, sediment is distributed uniformly along the coast, but it has a sharp boundary with clearer basin water approximately 8 km from the shore.

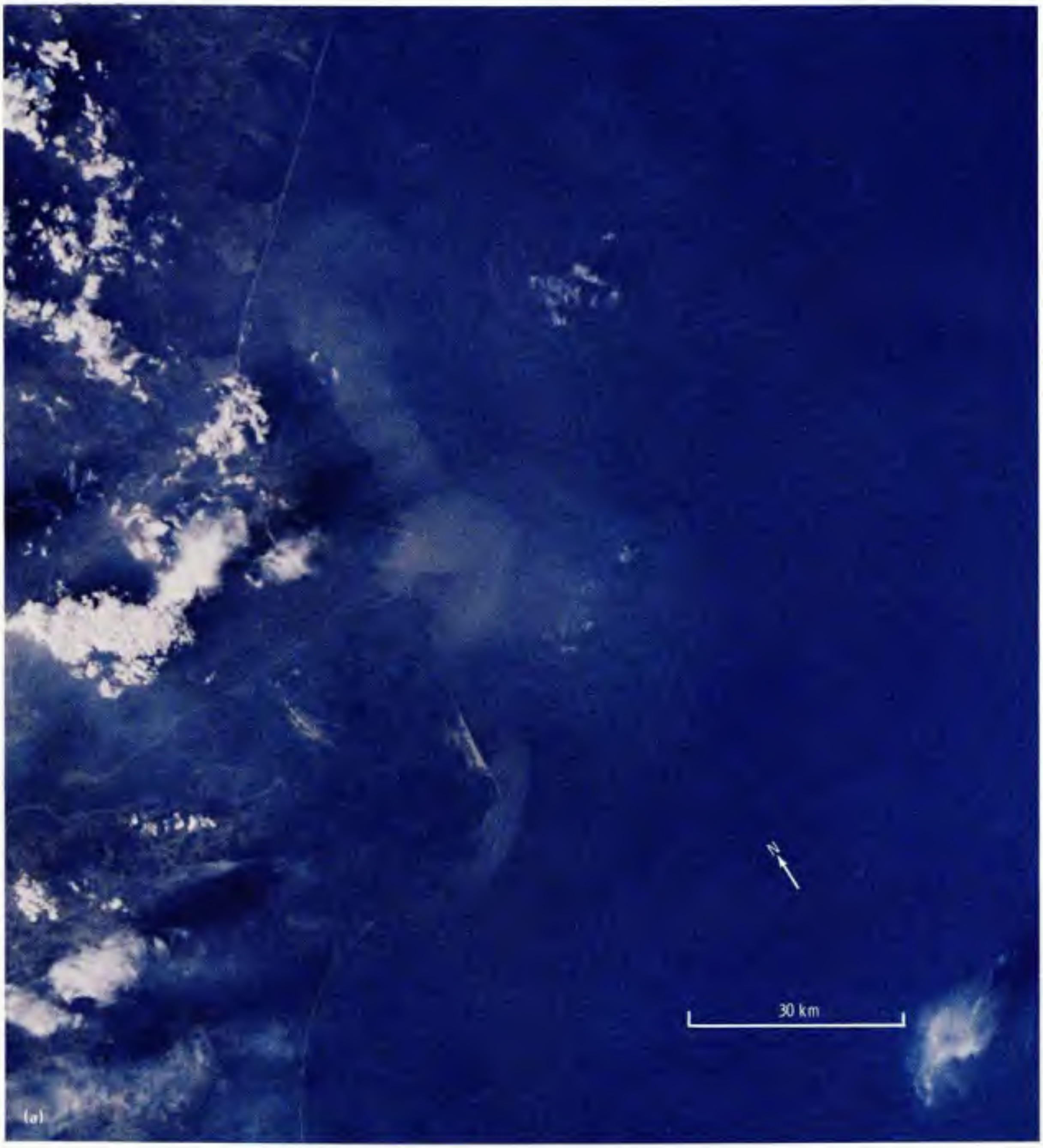

FIGURE 3.—The Danube Delta on July 24, 1975. (a) On this ASTP photograph, the northern distributary indicates redistribution by longshore currents, but the southern distributary indicates effects of buoyancy (AST-24-1965). (b) The Landsat band 5 image, taken on same day as figure 3(a), shows change of drift direction, although the basic patterns are similar (E-2183-08071).

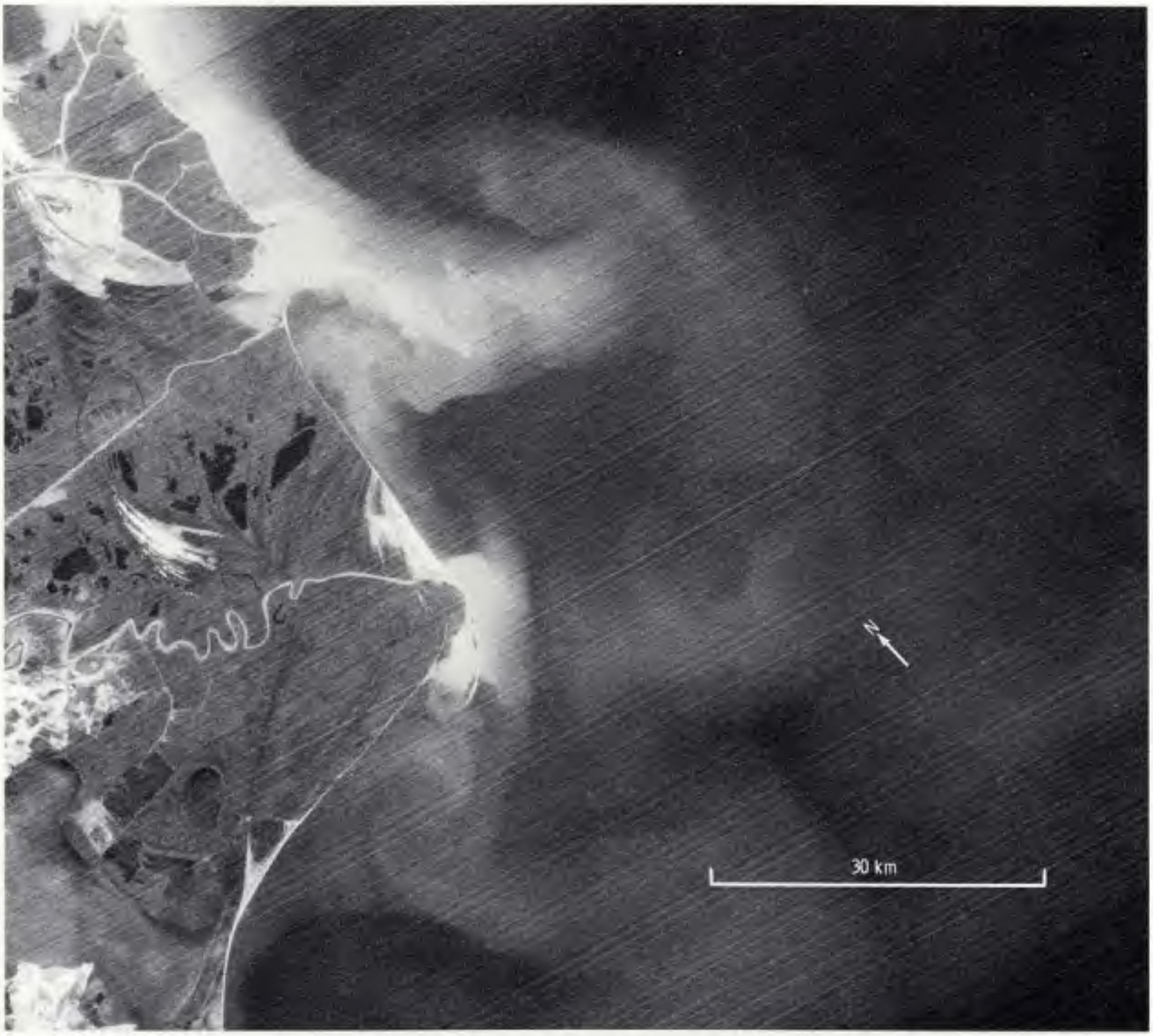

FIGURE 3.—Concluded.

Although offshore wave and current activity has distributed sediment along the coast, the effect of buoyant support of river sediment has previously been noted for the Danube Delta (ref. 6). The southern mouth of the river shows the sediment distribution pattern that is expected from a buoyancy-dominated system (fig. 3(a)). Both the large extent and color of the Danube effluent were observed by Apollo crewmembers (ref. 8): "Coming up to the Danube Delta, there's tremendous sediment plumes there . . . . Man, that's really flooding out into the Black Sea; turning it brown. , It looks like the Danube's . . . water running right across the Black Sea."

The extension of the plume to the south shows the effect of local longshore currents; however, the variability in both size and pattern of sediment distribution within the same day is emphasized by figure 3(b). Although the major plume pattern remains the same, the plume seen on the Landsat image extends farther into the basin, and is influenced more by the southward current.

FIGURE 4.—The Fraser River Delta, near Vancouver, British Columbia. The straight, jetlike appearance of the sediment plume indicates the dominance of river inertia (AST-19-1538).

Fraser River

The mouth of the Fraser River is in a more protected environment than that of the Danube. As expected, therefore, the sediment plume is less diffuse. It extends 18 km into the Strait of Georgia, approximately 75 percent of the width of the strait (fig. 4). The main part of the plume is light brown and extremely dense, as is the nearshore water to the south.

As a result of the sheltered receiving basin, inertial force of the river is the dominant cause of

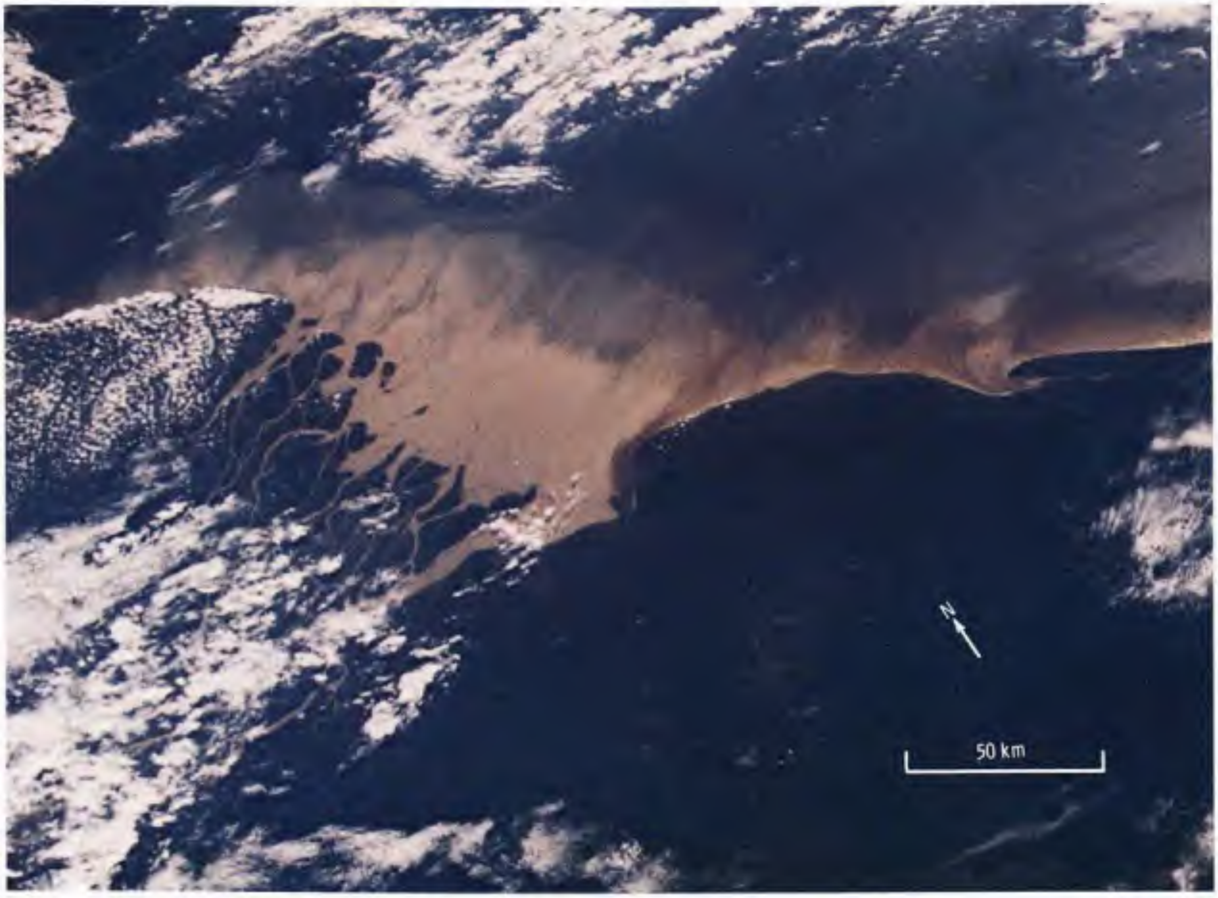

FIGURE 5.—Three distinct zones of sediment density are present in this ASTP view of the Orinoco Delta. Note longshore drift to the east (AST-21-1683).

the plume pattern. Although some southward drift has occurred, the more diffuse parts of the plume do not occur next to the shore as is the case with deltas open to the ocean. The lack of effective longshore redistribution of sediment has resulted in protrusion of the present delta into the strait. Consequently, it is likely that river inertia has played the dominant role throughout formation of the delta.

Orinoco River

On the basis of field studies, Van Andel (ref. 9) has shown that the Orinoco Delta is a zone of rapid coastal accretion, with a large volume of sediment contributed by longshore transport from nearby rivers. The nearshore pattern of sediment seen in ASTP photographs, however, suggests that the major contribution of suspended sediment comes from the Orinoco River itself.

Three distinct zones of sediment density are present in the Orinoco plumes (fig. 5). The zone nearest the distributary mouths has the highest sediment concentration. It is light tan in color, similar to the water of the Orinoco distributaries. Approximately 30 km from the distal end of the delta, there is a sharp boundary with darker basin water. In this zone (30 to 55 km), the dark tan color of the effluent matches the color of nearshore water along the coast. A third zone of brown-tinted seawater occurs in a band 5 to 17 km wide at the outmost edge of the sediment plume. This color zone is present elsewhere on the coast

FIGURE 6.—The delta pattern of the Rhône River indicates the result of inertia-dominated formation, which is also reflected in the faint sediment plumes (AST-23-1945).

where it is gradational with the dark tan nearshore sediment; however, this zone is most clearly delineated at the outer Orinoco plume.

Both the depth and slope of the sea floor are shallow at the mouth of the Orinoco (ref. 9); therefore, frictional processes of sedimentation would be expected to dominate. Within 40 km from the delta, the depth of seawater is less than 10 m, which corresponds to the most dense portion of the sediment plume. However, studies of bottom topography reveal no major subsequent channels; this may be due to either redistribution by longshore currents or to buoyant support of sediment. Consequently, the major primary processes of sediment support in the Orinoco Delta region are a combination of both frictional turbulence and buoyancy. The effects of longshore currents, although evident elsewhere along the coast, are not prominent in ASTP photographs.

Rhône River

The delta pattern of the central Rhône distributary is geometrically similar to models of delta growth presented by Komar (ref. 10) in which river sediments were provided to an initially straight shoreline with waves moving directly onshore. The slight curvature of the shoreline on either side of the distributary mouth, and the larger-scale irregular nature of the shoreline both suggest that longshore sediment transport and redistribution have not been active processes in development of the Rhône Delta. Consequently,

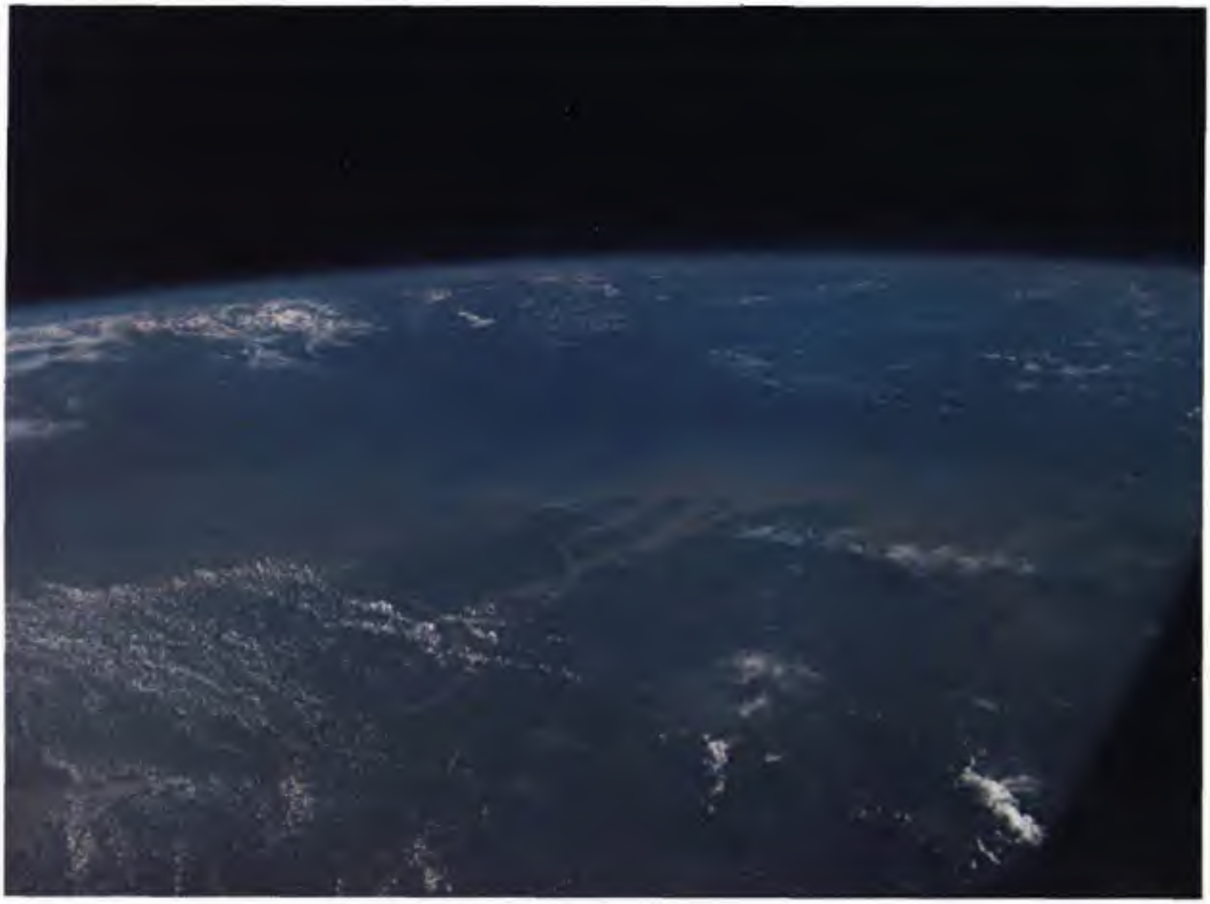

FIGURE 7.—High-oblique view of the Yangtze River Delta (AST-21-1738). Light tan suspended sediment is distributed along the coast, indicating the prevalence of longshore drift.

delta growth is primarily the result of accretion of river sediments to form beaches, and the consequent formation of intervening strand flats (ref. 9).

As would be expected from the delta pattern, a river-dominated sediment plume is generated at the mouth of the Rhône. This faint plume extends 12 to 15 km into the Gulf of Lions, and is only slightly affected by a current to the east (fig. 6). Although river inertia is the dominant factor controlling the shape of the sediment plume, the low density of the effluent can be attributed to a lack of fine-grained sediment entrained by the river. Consequently, the interpretation of a river-dominated sediment plume for the Rhône River can be made equally on the basis of deltaic and effluent patterns.

Yangtze River

High-oblique ASTP photographs of the Yangtze River Delta indicate the presence of both nearshore and fluvial suspended sediment. Nearshore surface water is lighter tan than that of the river mouth, although considerable reworking of river sediment is suggested by streaks of brown-tinted water in the coastal zone (fig. 7). The dark tan color of Yangtze River water is continuous in tone from the upper reaches of the river (within the delta) to the mouths of the distributaries. Although these photographs are too oblique to indicate well-defined zones of sediment density, the mixing of river water with basin water is not gradational. A light blue zone of mixed sediment and basin water occurs continuously along the coast.

Because several distributary channels are responsible for the influx of suspended sediment, the effects of either bed friction or effluent buoyancy dominate over river inertia, and these effects are most likely responsible for the plume pattern. Turbulent bed friction is the most probable mechanism, on the basis of the mixing pattern, but the influence of other factors is difficult to judge because of the effective longshore redistribution.

CONCLUSIONS

On the basis of three models for deltaic deposition, the use of orbital photographs from ASTP allows classification of plumes and deltas as a function of the dominant sedimentary process. River-inertia-dominated plumes are represented by the Fraser and Rhône Rivers, and buoyant support of suspended sediment is represented by the Danube River. Both the Orinoco and Yangtze Rivers owe their characteristic sediment patterns to a combination of frictional turbulence and buoyancy.

Because of rapidly changing coastal conditions (as indicated by comparison of the ASTP photograph and Landsat image of the Danube Delta), these observations of delta development are valid only for short-term investigations of the deltaic environment. For longer-term observations of delta development, the effects of tides, currents, and local weather conditions on plume patterns should be related.

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