4 Riverine Transfer of Particulate Matter to Ocean Systems

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4.1 INTRODUCTION

A few transport modes deliver particulate phases from the continents to world oceans: riverine, wind-borne, and glacial. Although the magnitude of the mass of sediments thus transferred is largely open to speculation, earth scientists have proposed for many years now that rivers are undoubtedly the major suppliers of sediments to world oceans. But only in terms of geological time scales is it correct to assume that the sediment load of world rivers reach deep pelagic plains. Floodplains, coastal marshlands, estuaries, and continental shelves temporarily store most of the detrital load discharged by rivers. Exceptions are those instances where a particular river mouth is close to the shelf break, or where currents (e.g., tidal, longshore) are strong enough to displace suspended particles into submarine canyons. From there, by means of gravity-controlled mass flows (i.e., slumps, slides, turbidity currents), particles are episodically carried down, towards the deep sea platform.

The difficulties inherent to the assessment of global mass transport of sediment are such that estimates on world riverine transport are at best tentative, and subjected to permanent revision (e.g., Clarke and Washington, 1924; Livingstone, 1963; Holeman, 1968; Garrels and Mackenzie, 1971; Martin et al., 1980; Meybeck, 1982; Milliman and Meade, 1983; Degens et al., 1984; Degens et al., 1991; Milliman and Syvitski, 1992). In spite of its debatable nature, riverine sediment transport is presently considered as the best known one of the three modes mentioned above.

Several years ago, scientific evidence indicated that wind-borne dust was effectively transported across oceans, presumably from arid land areas in the jet stream (e.g., Delany et al., 1967; Ferguson et al., 1970). The implications relative to marine sedimentation were obvious, and Windom (1969) suggested that the North and South Pacific, and the Central Atlantic presently receive as much as 25 to 75% of their detrital phases from atmospheric dust fallout. Aeolian transport also determines, for instance, a quartz-rich (> 10%) band in the sediments of the eastern Atlantic, which is unequivocally linked to the expanded arid region

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formed by the Sahara Desert and the Sahel (Kolla et al., 1979). Hence, despite uncertainties, the preponderance of wind-borne input of various elements and compounds to certain oceanic regions is now clearly established, being particularly important in shelf areas and in semi-enclosed seas, such as the Mediterranean (Martin et al., 1989). Additionally, with obvious implications on the global cycling of carbon, recent research stresses the likely significance of dust fallout on the wind-driven biological pump, which sequesters fresh organic matter from the upper ocean to the deep sea (Ittekkot, 1993). A detailed treatment on the biogeochemical significance of the wind-borne flux of particles to world oceans can be found in elsewhere in this volume (this volume, Chapter 3).

Although ice-rafting has been a significant mode of sediment transport in the geological past (e.g., during the last glacial maximum 18 ky B.P.) minera-logical evidence of its present-day effect is limited to high-latitude sea-floor sediments (e.g., Biscaye, 1965; Griffin et al., 1968; Kolla et al., 1979). Bottom current winnowing of relict glacial detritus turns difficult the present-day quantitative assessment of the significance of ice-rafting as a mechanism of sediment transport.

Beyond the fact that there are certain oceanic areas where wind-borne material and ice-rafting attain relevance, in terms of global mass transport rate, rivers are surely the major sediment suppliers to the world ocean. So far, Garrels and Mackenzie's (1971) rough estimate, that rivers supply 90%, ice-rafting an additional 7%, and desert winds and submarine discharges less than 1% of the global sediment transport, still stands essentially unmodified.

4.2 RIVERINE TRANSPORT OF CARBON AND MINERALS

Sediments transported to ocean systems are derived from rocks exposed at the Earth's surface, subjected to ceaseless alteration. Chemical, physical, and biological processes are involved in the weathering of rocks, the first of which has been identified as the most significant (e.g., Garrels and Mackenzie, 1971; Drever, 1988). Continental runoff consists not only of water and inorganic particulate and dissolved phases. It includes the end products of the destruction and decomposition of the vegetation cover, as well as organic matter produced within the boundaries of continental aquatic systems.

Continental denudation is now understood as occurring between two extreme regimes: *transport-limited* and *weathering-limited* (Stallard and Edmond, 1983). In a transport-limited regime, mechanical erosion is less intense, all weatherable minerals would contribute to the dissolved load in proportion to their abundance, and the end-products of weathering would accumulate. In opposition, denudation in a weathering-limited regime is highly selective, with the majority of dissolved phases contributed by the most reactive minerals while the less reactive ones are transported away by physical erosion (e.g., Drever and Zobrist, 1992). Chemical reactions involved in rock-water interactions, however, are now perceived as complex processes, with implications of biogeochemical significance, such as the CO_2 consumption during the global cycling of carbon (e.g., Kempe, 1984; Probst et al., 1994). But weathering will not be treated here beyond these remarks. The following considerations are restricted to the solid residues which, from the moment of their formation, endure dissemination by the main agent of erosion: flowing water.

Rivers transport sediment as bed load and in suspension. The significance of the former is deficiently known at present, mainly due to difficulties inherent to its quantification. It is commonly assumed that most large rivers transport sediment along the river bed in subordinate amounts (typically, < 10% of their total load), although there are indications that some rivers may transport a significantly higher proportion. Not only is the contribution made by bed load to the total sediment load of rivers open to conjecture but also its occurrence, whether bed load transport takes place continuously or primarily during flooding events.

The bed load of large rivers is made up of coarse-fraction sediment, which is deposited in the lower reaches of rivers, in beaches, off the mouths of estuaries, and in continental platforms. Quartz, feldspar, and rock fragments constitute, for example, most of South America’s modern sands (from rivers and beaches). Their quantitative study has allowed Potter (1994) to distinguish three major families of South American sands which, ultimately, are the result of the interaction of climate and the distribution and activity of major continental tectonic elements. Despite wide geomorphic dissimilarities three large groups or families were defined: a) a group of immature lithic arenites that covers about 30% of South America, mostly supplied by Andean volcanic and metamorphic sources; b) a quartz-rich cratonic association that covers about 62% of the eastern side of the continent; and c) a molasse association, reportedly of a transitional nature, which covers about 8% of the continent and occurs as a separation of the previous two groups. Eventually, coarse sediments bypass continental shelves carrying along the signature of their source: the plate tectonic significance of the light mineral fraction found in offshore studies has been put forward by Maynard (1984), and Yerino and Maynard (1984).

Whereas the coarse end product of weathering is mostly retained on or near continents, the fine-grained particles of the suspended load (silt- and clay-size sediments) comprise the bulk of the sediment mass entering the coastal zone. Subjected to very specific processes (Eisma and Cadeé, 1991), these fine-grained particles normally coagulate upon encountering the low salinities of the upper estuary (Kranck, 1981). The resulting flocs are then transported and settled in the middle and lower estuary (e.g., Gibbs et al., 1989). Once river sediment has been deposited in an estuary, it may remain there for hundreds and even thousands of years. Meade (1982) estimated that probably less than 5% of the sediment reaching the coastal zone in the Atlantic seaboard of the United States, is transferred to the continental shelf or to the deep sea.

In the Arabian Sea, where sediment sources were identified several years ago (Goldberg and Griffin, 1970), most of the annual input of lithogenic material of ca. 0.2×10^{15} g remains in estuaries, deltas, and continental shelves. Trap measurements have shown that only 2 to 3% of such flux reaches the deeper parts of the sea (Ramaswamy et al., 1991). At any rate, the transfer of sediments from continents to the deep sea appears to occur mostly in a pulse-like mode. Currents and climatic events (sometimes exceptional) are the main factors ruling such transfer of fine sediments from the continental platform to the continental rise and, eventually, in episodic fashion, to the deep sea platform (e.g., Ittekkot et al., 1991). The sediments thus accumulated in the sea-floor, carry along the distinct biogeochemical signature of their source (e.g., Reemtsma et al., 1990, 1993).

Milliman and Meade (1983) calculated an annual global riverine discharge of 13.5×10^{15} g, by extrapolating average sediment yields over large regions with similar relief. More recently, the international project "Transport of Carbon and Minerals in Major World Rivers" which, with the assistance of SCOPE and UNEP, was carried out under the leadership of Prof. Egon T. Degens (Degens et al., 1991), put forth a global annual figure of ca. 16.0×10^{15} g. A more recent analysis suggests that before the propagation of dam construction which the world has witnessed since the beginning of the second half of this century, rivers probably discharged about 20.0×10^{15} g (Milliman and Syvitski, 1992).

Data gathered in many world rivers, representing most of the global runoff reaching the seas and oceans (Degens et al., 1991), support the estimation that about 0.23×10^{15} g are particulate organic carbon (POC) (Ittekkot and Laane, 1991). Figure 4.1 shows the continental contributions of total suspended solids (TSS) and POC loads. Asiatic rivers are the main TSS and POC suppliers to world oceans whereas African rivers are the least significant sources.

4.3 FACTORS CONTROLLING SEDIMENT YIELD

The sediment load of a river is dependent upon its drainage area (Figure 4.2). Clearly, larger drainage basins deliver higher sediment loads to world oceans. Also, as it has been known for some time, sediment yields exhibit an inverse relationship with drainage areas, with the smaller mountainous basins being the sources of highest yields (Meybeck et al., 1989).

Recently, Milliman and Syvitski (1992) have analyzed data from 280 rivers discharging to the ocean, and have concluded that sediment loads/yields are a log-linear function of basin area and maximum elevation of the river basin. These major controlling variables are followed in order of importance by precipitation and runoff, which affect sediment discharge to a lesser extent.

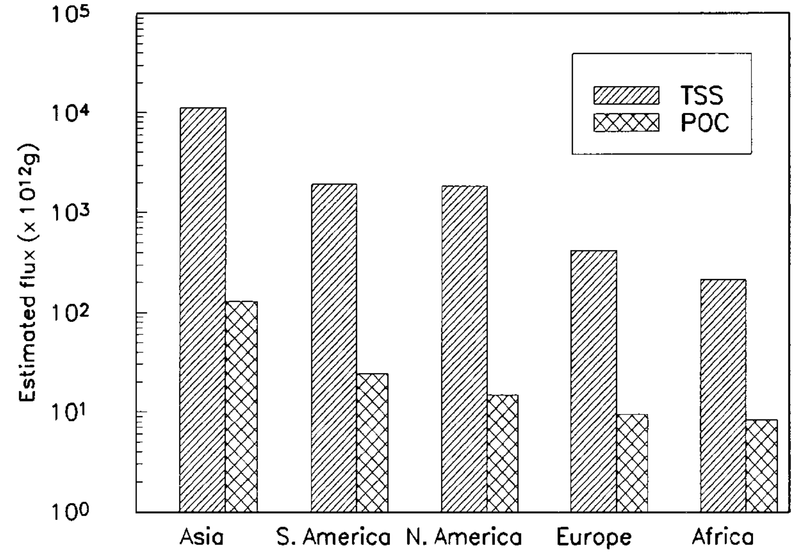

Figure 4.1 Estimated continental flux of total suspended sediments (TSS) and particulate organic carbon (POC). Basic data from Degens et al. (1991).

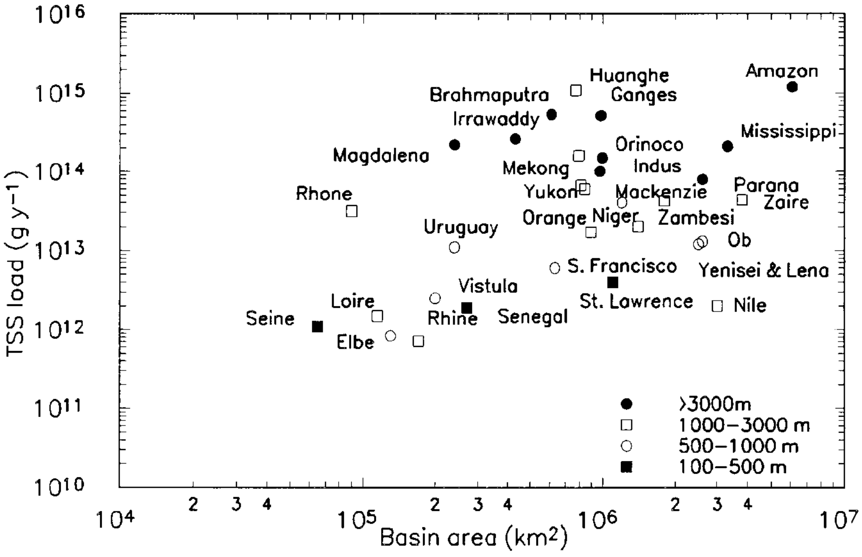

Figure 4.2 Plot of basin area vs. TSS load of some major world rivers. Rivers have been divided into classes according to their relief, following the criteria used by Milliman and Syvitski (1992). Most basic data from Degens et al. (1991).

The total specific exporting capacity of river systems (i.e., sediment yield plus dissolved solids yield) is more difficult to evaluate inasmuch other factors (e.g., geology, climate) attain relevance in the control of the specific yield of dissolved phases. Figure 4.3 shows that some world rivers, whose total specific export is dominated by the dissolved fraction, occur in a wide variety of climates (runoff) and reliefs. Also, it implies that mechanical denudation is not only dominant in high-relief basins (e.g., Ganges, Brahmaputra, Paraná) but also in lowland (e.g., Senegal) or upland drainage basins (e.g., Uruguay).

Milliman and Syvitski (1992) have also stressed the importance of small mountainous rivers, many placed in active continental margins (e.g., western South and North America), whose sediment fluxes may have been grossly underestimated. By virtue of a greater impact of episodic events (i.e., flash floods and earthquakes) during high stands of sea level, and due to the narrow shelves associated with these active margins, the sediment loads from such drainage basins are likely to be transferred to the deep sea. Moreover, a recent study indicated that an ephemeral desert river in Israel (a stream-type which, incidentally, abounds along most of the North and South America active margins) is, on average, as much as 400 times more efficient at transporting very high rates

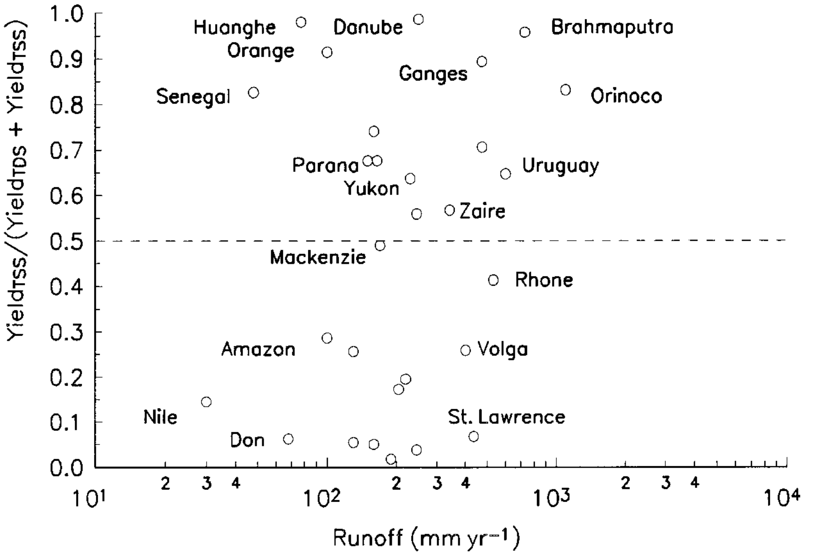

Figure 4.3 Variation of Yield$_{TSS}$/(Yield$_{TDS}$ + Yield$_{TSS}$) as a function of runoff (discharge/basin area) in a group (some labeled) of world rivers. The broken line separates the fields of mechanical denudation dominance (upper) and chemical denudation dominance (lower). Most basic data from Degens et al. (1991).

of coarse sediment bed load than its perennial counterparts in humid zones (Laronne and Reid, 1993).

Obviously climate, along with other factors, such as geology, and human activity have also been identified as important variables controlling sediment load, particularly in certain areas (e.g., southern Asia) where high erosion rates also reflect deforestation and over-farming (Milliman and Syvitski, 1992).

Particulate organic matter in world rivers appears to vary between 1 and 8% of the total suspended matter. Rivers with low TSS concentrations (< 15 mg l^{-1}) exhibit the highest relative POC contents, whereas rivers with a high TSS concentration (500–1500 mg l^{-1}) display the lowest relative POC contents (ca. 1.6 mgC l^{-1}) (Ittekkot and Laane, 1991). It is still difficult to interpret, however, the factors controlling POC yield in world rivers inasmuch as those rivers with a high TSS yield are likely to transport mostly carbon from allochtonous sources (e.g., soil-derived), whereas rivers with a low TSS yield are exporting organic matter which may be mainly produced by autochtonous sources. This can be inferred from the results gathered by the SCOPE/UNEP International Carbon Project, which show that rivers with moderate TSS concentrations have a higher proportion of the so-called labile particulate organic carbon (carbohydrates and proteins) in their POC load than rivers with high TSS concentrations (Ittekkot and Laane, 1991). Turbid waters limit light penetration and thus may hinder primary production, a riverine source of labile particulate carbon.

Although significant progress has been accomplished in the last decade, more research is needed to fully appraise the factors controlling erosion and sediment routing within drainage basins under various climatic conditions and on various rock substrata.

4.4 THE ROLE OF EXCEPTIONAL CLIMATIC EVENTS

In contrast with what appears to be a relatively continuous chemical denudation, the removal of sedimentary materials from the continents is often perceived as mostly occurring in a pulse-like manner. In other words, discrete events, such as earthquakes or unusually intense climatic anomalies may play a major role in removing the bulk of the sediment load from the continents to the oceans. Many references in the scientific literature indicate that this is decidedly the case in small to medium-size drainage basins, where there is unequivocal evidence that occasional, intense events, transport more sediments than years or even decades of normal functioning of the erosive processes.

The response of large river systems to short-lived intense phenomena is more difficult to interpret. The Amazon, for one, being the largest river on Earth, exhibits a peculiar behavior in connection with the yearly flood (Meade et al., 1985). The mean slope of the flood wave on the river surface is smaller during the rising stages than during the falling ones. As a result, the Amazon stores sediment in its lower reaches during rising stages and actually resuspends the previously stored sediment during falling ones. Superimposed on its highly regular hydrograph (Richey et al., 1989), the pattern of storage and remobilization damps out the extreme values of high and low sediment discharge, keeping the mean annual discharge of suspended sediment in the lower Amazon between 1.1×10^{15} and 1.3×10^{15} g. If this mechanism also applies during exceptional positive flow departures from the mean is open to verification. In the Amazon, such deviations mostly occur on a 2- to 3-year time scale and are coupled to the positive phase of the El Niño-Southern Oscillation (ENSO) phenomenon (Richey et al., 1989), the so-called La Niña or cold event (Philander, 1990; Díaz and Kiladis, 1992).

The Paraná River is also coupled to the ENSO phenomenon but, in opposition to the Amazon, its positive discharge anomalies appear to be correlated with ENSO negative (or warm) phases. This teleconnection was originally described by Mossman (1924), and then by Bliss (1928), at the onset of the studies on the general characteristics and mechanisms of remote atmospheric and oceanic responses associated with sea level pressure and sea surface temperature fluctuations in the equatorial Pacific.

The 1982 ENSO event was specially persistent, had an exceptionally large amplitude, and its effects appeared in an unusually large area (e.g., Quiroz, 1983). Heavy rainfall in the upper Paraná drainage basin triggered an exceptional flood which significantly altered the biogeochemical functioning of the River (Depetris and Kempe, 1990). Despite the fact that during the once-in-a-century flood of 1982/83, the Paraná River reached record peak discharges of over 60000 $m^3 s^{-1}$ at Corrientes (the long-term mean is ca. 15700 $m^3 s^{-1}$), TSS transport did not increase significantly and POC transport even seemed to decrease during the ENSO-triggered flood. Although TDS appeared to be subjected to dilution in inverse proportion to the additional discharge, dissolved inorganic and organic carbon (DIC and DOC) experienced marked increases in transport rates which were probably linked to increased remineralization of organic matter in the floodplain, and mobilization of refractory material from the floodplain and from soils upstream.

However, during the receding stage of the 1982/83 flood, TSS concentration increased markedly (Depetris and Kempe, 1993), suggesting remobilization of TSS similar to that described for the Amazon (Meade et al., 1985); i.e., due to changes in the water-surface slope, suspended sediment was apparently stored during the rising stages of the river and resuspended during the falling river stage.

The mean surface slope of the Paraná mainstream in the lower 200 km is ca. 1.2×10^{-5} m m^{-1}. The effect of the flood wave on water surface slope of the Paraná during the 1982/83 ENSO-triggered flood was investigated in a 320 km-stretch of the lower Paraná River (Figure 4.4). The graph represents the variability of the gage height at Paraná (600 km from the mouth) during 1983, and the variation in

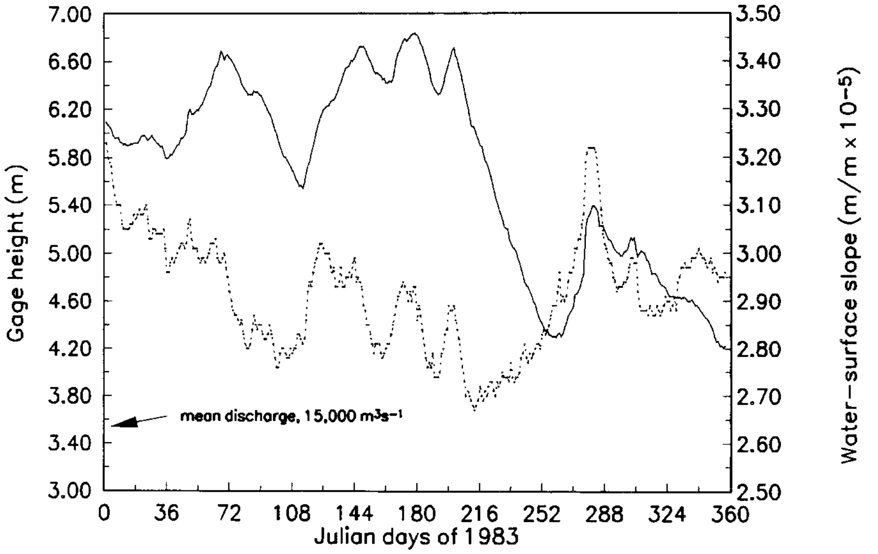

Figure 4.4 Time-dependent variation of gage height (discharge) and water-surface slope (broken line) in the Paraná River during the ENSO-triggered flood of 1982/83. Water-surface slopes were calculated between the cities of Paraná (600 km upstream from the mouth) and San Pedro (280 km upstream from the mouth). The arrow indicates the gage height value corresponding to mean river discharge.

water-surface slopes in the reach comprised between the cities of Paraná and San Pedro (280 km upstream from the mouth). Clearly, increasing discharges (gage heights) generate a decreasing trend in the water-surface slopes and, conversely, decreasing discharges result in higher water-surface slopes. However, the process appears as a complex one, with a clear hysteretic condition (Figure 4.5) which implies that the Paraná River deposits and resuspends sediments in pulses. Lower slopes mean decreasing water velocities and, possibly, sedimentation, whereas slightly steeper slopes denote higher water velocities and resuspension.

In addition to this effect, which is probably common to a number of large world rivers, the Paraná receives most of its water discharge from the upper Paraná drainage basin, which normally contributes a subordinate proportion of the TSS load. Figure 4.6 shows results of TSS load measurements performed in the upper Paraná River, the Paraguay River, in the receiving section of the Paraná which joins both rivers at the City of Corrientes, and at the Paraná-Santa Fe cross-section. The trends of the individual rating curves in the graph suggest that under conditions of high runoff, the TSS flux could in fact decrease with increasing discharge. Such would be the case when the upper Paraná dilutes the Paraguay's

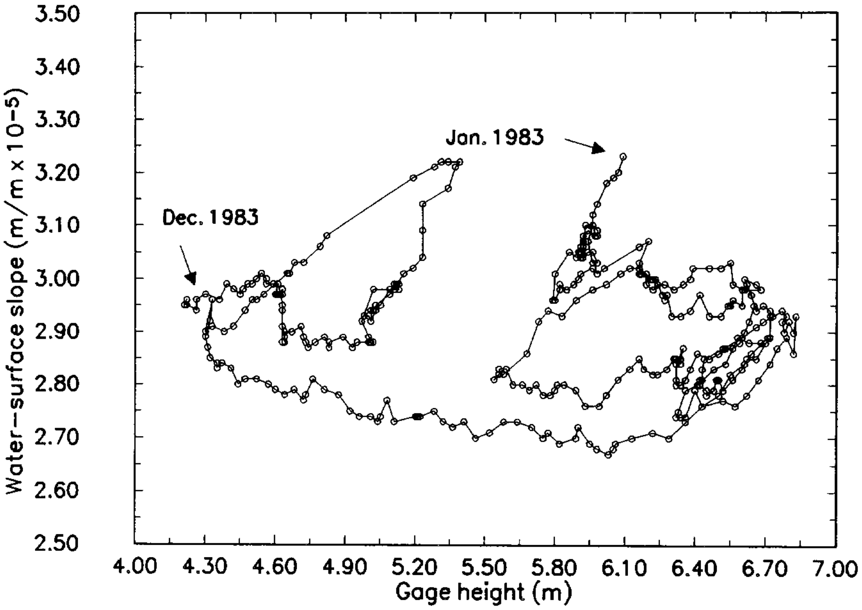

Figure 4.5 Variation of gage height and water-surface slope in the Paraná River during the ENSO-triggered flood of 1982/83 (see Figure 4.4). The hysteretic loop on the right side corresponds to an inverse relationship (sediment deposition?), whereas the one on the left depicts the direct relationship between both variables (sediment resuspension?).

TSS flux by supplying most of the water discharge (e.g., 70 – 80%) entering the Río de la Plata.

Continental sediment fluxes are controlled by global runoff. Discharge fluctuations during this century have been largely related to surface air temperature anomalies (Probst and Tardy, 1989). At any rate, evidence from the recent geological past (a 7000-year geological record for Mississippi River tributaries), indicates that extreme flooding is not necessarily associated to profound changes in climate. Rather, it has been parallel to moderate climatic changes (ca. 1 – 2 °C, and changes in mean annual precipitation of ca. 10 – 20%), which have caused adjustments in both, magnitudes and frequencies of floods (Knox, 1993).

The forecast for a doubled CO_2 climate scenario anticipates significant discharge increases in 25 out of 33 of the world's major rivers (Miller and Russell, 1992) and, most likely, a substantial alteration of the global sediment flux from continents to world oceans.

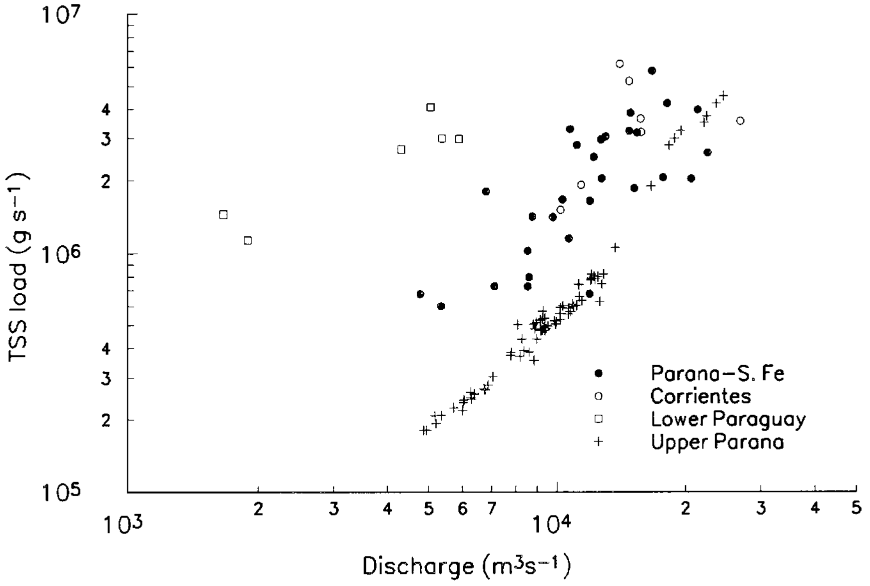

Figure 4.6 TSS depth-integrated measurements at different cross-sections of the Paraná River drainage basin. Note the agreement between the measurements performed at Corrientes (ca. 1200 km upstream from mouth) and those at Paraná-Santa Fe (ca. 500 km upstream from mouth). Also worthy of attention are the high TSS fluxes delivered by the Paraguay River. Data produced by the UNDP/Argentine Government ARG. 31 Project.

4.5 AN ASSESSMENT OF SEDIMENT INPUTS INTO THE SW ATLANTIC: A CASE STUDY

Both, the advent of the revolutionary idea of sea-floor spreading in the early 1960's, and the birth of the broader concept of global plate tectonics by the end of that decade, stimulated studies on the sediment distribution in world oceans (e.g., Ewing and Ewing, 1967). From the onset, the SW Atlantic was particularly amenable to such studies, partly due to the clear climatic signal (Stevenson and Cheng, 1969) exhibited by the carbonate-free, carbon-rich sediments being accumulated in nearly horizontal layers at a significant rate in the abyssal plain of the Argentine Basin (3 to 7 cm ky^{-1}, Turekian and Stuiver, 1964). But mainly because the sedimentary deposits in this region attain thicknesses exceeding 3000 m, and appear as markedly current-controlled (Ewing et al., 1964).

Biscaye (1965) studied the mineralogy and sedimentation of Recent deep-sea sediments in the Atlantic Ocean and concluded that most deep-sea clay is unequivocally detritus from the continents, and a useful indicator of sediment provenance, inasmuch as the component mineral species exhibit relatively restricted loci of continental origin. *In situ* mineral formation on the ocean bottom was qualified as unimportant in the Atlantic.

Among other several meaningful and interesting conclusions, Biscaye (1965) clearly proposed that the fine-fraction mineralogy of the surface sediment of the Argentine Basin, in the western South Atlantic Ocean, was sufficiently diverse from the sediment contiguous to the mouth of the Río de la Plata to eliminate it as a major Recent sediment source for that basin. Further, he proposed the southern Argentine continental shelf, the Scotia Ridge, and the Weddell Sea as more likely sources of fine-fraction sediment transported into the abyssal plain. Moreover, he identified the Antarctic Bottom Water (AABW) as the probable agent transporting fine-fraction sediment from the Weddell Sea, perhaps as far north as the Brazil Basin.

Griffin et al. (1968) studied the distribution of clay minerals in the world Oceans. Using Biscaye's (1965) data they reached essentially the same conclusions for the southwestern Atlantic: the clay-size fraction (illite 40 – 50%, smectite 20 – 30%, kaolinite < 5 – 10%, and chlorite 10 – 30%) appears to be controlled to a large extent by the Antarctic continent, with its chlorite and illite-rich sediments, which are the source of ice rafted material to the southern Atlantic.

More than 20 years passed until the studies performed by Klaus and Ledbetter (1988) in the Argentine Basin by means of high-resolution seismic records (3.5 kHz echograms) revealed that sediment is supplied to the Argentine Basin principally by gravity-controlled mass flows off the mouth of the Río de la Plata, and that the sediment transported by the AABW from higher latitudes is, in fact, a secondary source. Sedimentary material from both sources is winnowed by strong AABW flow along the Argentine continental rise. Earlier works (Ewing et al., 1973) had already suggested that giant ripples and channels are the confirmation of the strong dependence of Argentine Basin sedimentation on moving water masses. As the AABW flow decreases, the fine-grained sediment fraction is deposited in the central abyssal plain as large, migrating mud waves. Klaus and Ledbetter (1988) also found evidence that most land-derived coarse sediment bypasses the continental shelf and rise by means of slides, turbidity currents, etc., and is finally deposited in the adjoining plain. A very extensive mass flow placed east of the Río de la Plata finally suggested that it was a major sediment source to the Argentine Basin.

A comparison is now possible, in light of the above mentioned findings, between the clay-size mineralogy determined in the Argentine Basin, and adjacent areas by Biscaye (1965) and Griffin et al.(1968), with that of possible riverine sediment sources to the SW Atlantic.

Conceivable sources include the Patagonian rivers, and the Antarctic Peninsula and adjacent islands. Along the Patagonian margin, a number of smaller rivers (Colorado, Negro, Chubut, Deseado, Shehuén-Chico, Santa Cruz, Coyle, and Gallegos) supply an additional 63 km^3 y^{-1} of water and an estimated sediment mass of ca. 40.0 x 10^{12} g y^{-1}. The Colorado River supplies a smectite-rich fine-fraction suite, with subordinate proportions of illite, chlorite, and kaolinite, whereas the Negro River delivers an illite-rich clay-size mineralogy, with lower proportions of smectite and chlorite + kaolinite (Irion and Depetris, unpublished data). Recent studies (Yoon et al., 1992) have confirmed the Antarctic Peninsula as a major source of illite-rich sediments. However, other Antarctic sources such as the South Shetland Islands, exhibit ample mineralogical variability in their weathering products.

Through the Río de la Plata, the Paraná and Uruguay drainage basins deliver water and sediment to the SW Atlantic, directly into the Confluence zone where the Brazil and Malvinas currents meet and intense mixing occurs, along the western boundary of the SW Atlantic Ocean. The Río de la Plata discharges ca. 615 km^3 y^{-1} of water and over 90.0 x 10^{12} g y^{-1} of sediment to the adjacent continental shelf (Depetris and Paolini, 1991).

Figure 4.7 compares the mean clay mineralogy for the SW Atlantic as reported by Biscaye (1965) and Griffin et al. (1968), with the mineral suite determined for

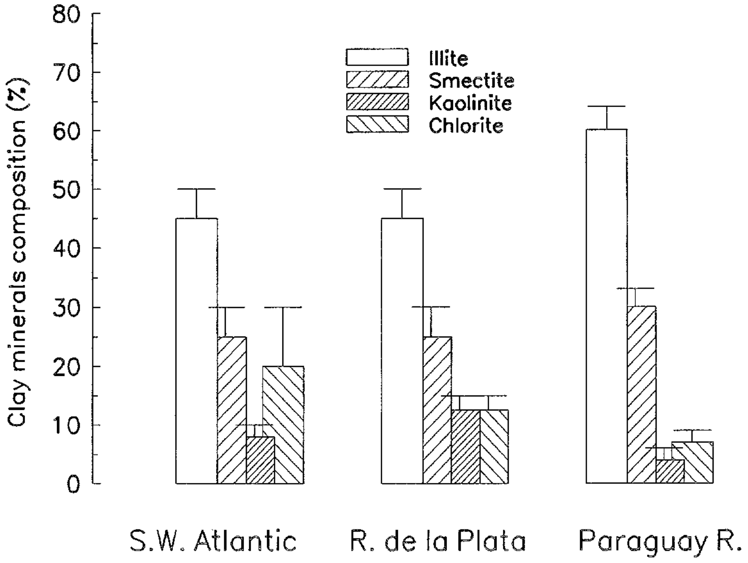

Figure 4.7 Mean clay mineralogy in the SW Atlantic (Biscaye, 1965; Griffin et al., 1968), the Río de la Plata (Depetris and Griffin, 1968), and the Paraguay River (Bertolino and Depetris, 1992). Bars depict estimated variability.

the Río de la Plata and the Paraguay River. The latter, mainly by means of the effect of its Andean tributary, the Bermejo, reportedly supplies about 60% of the Paraná TSS load (i.e., ca. 48 x 10^{12} g y^{-1}). Aside from differences in the chlorite and kaolinite content, it is possible to conclude that the clay mineralogy of the fine fraction of surface sediments from the Argentine Basin and adjacent areas, is closely related to the material supplied by the Río de la Plata, thus adding to the geophysical evidence supplied by Klaus and Ledbetter (1988) in the sense that the Río de la Plata is a major sediment source to the SW Atlantic. The importance of wind-borne particles transported from arid Patagonia to the SW Atlantic remains to be investigated, but may be anticipated as also significant, provided the intense dominant westerlies that sweep the southern portion of South America are considered.

4.6 CONCLUDING REMARKS

Rivers are prominent sources of particles, which transfer their solid load from continents to world oceans. Since most large rivers are located along passive continental margins, a dominant portion of their sediment fluxes is retained at or near continental boundaries. However, there are indications that, subjected to the influence of exceptional events, rivers depart from their "usual" functioning and possibly modify their effect upon coastal seas. These pulses are probably effective ways, accessible to large riverine systems, to increase the transfer of particulate material to deep basins.

Milliman and Syvitski (1992) have pointed out that smaller mountainous rivers, along active margins, are far more likely to by-pass the associated narrow shelves and deliver a larger percentage of their fluxes to deeper ocean basins during both high and low stands of sea level.

Future research directed towards the assessment of the role of world rivers in the transfer of particulate material to the deep sea should address these aspects in more detail.

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