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## Os-Sr-Nd results from sediments in the Bay of Bengal: Implications for sediment transport and the marine Os record

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**Abstract.** Sr, Nd, and Os isotopic data are presented for sediments from diverse locations in the Bay of Bengal. These data allow the samples to be divided into three groups, related to their sedimentary contexts. The first group, mainly composed of sediments from the shelf off Bangladesh and the currently active fan, has Sr and Nd characteristics consistent with a dominantly Himalayan source. Their  $^{187}\text{Os}/^{188}\text{Os}$  ratios (~1.2-1.5) show that the average detrital material delivered by the Ganga-Brahmaputra (G-B) river system is not unusually radiogenic. A large difference in  $^{187}\text{Os}/^{188}\text{Os}$  ratio exists between these Bengal Fan sediments and Ganga bedloads ( $^{187}\text{Os}/^{188}\text{Os}$  ~2.5, Pierson-Wickmann *et al.* [2000]). This difference mainly reflects addition of a less radiogenic Brahmaputra component, though mineralogical sorting and loss of radiogenic Os during transport may also play some role. The second sample group contains sediments from elsewhere in the Bay, particularly those located on the continental slope. They display Os isotopic compositions (0.99-1.11) similar to that of present seawater and higher Os and Re concentrations. These characteristics suggest the presence of a large hydrogenous contribution, consistent with the lower sedimentation rate of these samples. Sr and Nd ratios indicate that a significant fraction of these sediments is derived from erosion of non-Himalayan sources, such as the Indo-Burman range. These observations could be explained by the deflection of sediments from the G-B river system by westward currents in the head of the Bay. The third group contains only one sample, but shows that in addition to a Himalayan source, sediment discharge from Sri Lanka may influence the detrital component in the distal part of the fan. The similarity between the isotopic compositions of the group I R/V *Sonne* samples and those of Ocean Drilling Program Leg 116 [France-Lanord *et al.*, 1993; Reisberg *et al.*, 1997] suggests that the material eroding in the Himalayas has been roughly constant since the Miocene. The high Os isotopic ratios of leachates of both *Sonne* group I and Miocene Leg 116 sediments imply that much of the leachable highly radiogenic Os component was conserved during transport through the estuary or interaction with seawater. In contrast, samples with lower, but still relatively high, sedimentation rates (*Sonne* groups II and III and Pliocene Leg 116) seem to have significantly adsorbed or exchanged Os and Re with seawater. This suggests that in some cases the Os isotopic ratios of leachates of detrital sediments can be used to constrain the ancient marine Os record, or conversely, to date unfossiliferous sediments.

### 1. Introduction

Os isotopes provide a powerful tool for reconstructing past variations in crustal and mantle inputs to the world's oceans. The great utility of this tracer comes from the extreme contrast between the Os isotopic composition of the continental crust and that of the mantle and meteorites. The mean osmium isotope composition of seawater reflects the balance between the input of osmium released during the chemical weathering of continental rocks ( $^{187}\text{Os}/^{188}\text{Os} > 1.2$ ) and that of osmium derived from the dissolution of cosmic

dust and/or hydrothermal alteration of oceanic crust ( $^{187}\text{Os}/^{188}\text{Os} \sim 0.12$ ). In marine sediments, Os is carried by three different phases: (1) hydrogenous material ( $^{187}\text{Os}/^{188}\text{Os}$  of seawater), (2) micrometeoritic dust ( $^{187}\text{Os}/^{188}\text{Os} \sim 0.12$ ), and (3) terrigenous material ( $^{187}\text{Os}/^{188}\text{Os}$  of source, typically  $> 1.2$ ).

The  $^{187}\text{Os}/^{188}\text{Os}$  ratio of the oceans has increased greatly during the Cenozoic era, changing from 0.2 at the Cretaceous-Tertiary boundary [Pegram *et al.*, 1992; Peucker-Ehrenbrink *et al.*, 1995] to 1.06 at present [Sharma *et al.*, 1997; Levasseur *et al.*, 1998]. The rapid evolution of the seawater Os isotopic composition over the past 15 Ma has been attributed by some authors [Pegram *et al.*, 1992; Peucker-Ehrenbrink *et al.*, 1995; Turekian and Pegram, 1997] to Himalayan erosion, in analogy with the evolution of oceanic  $^{87}\text{Sr}/^{86}\text{Sr}$  over the same period. They stressed the potential importance of the weathering of black shales, which are generally highly radiogenic and Os-rich [Ravizza, 1991]. The Lesser Himalaya

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black shales have radiogenic Os isotopic compositions, with  $^{187}\text{Os}/^{188}\text{Os}$  ratios from 1 to 14.5 and high Os concentrations relative to other Himalayan bedrocks ([Os] from 40 parts per trillion (ppt) to 13.5 ppb) [Singh *et al.*, 1999; Pierson-Wickmann *et al.*, 2000]. As a consequence, both dissolved loads and particulates carried by many Himalayan rivers display highly radiogenic Os compositions [Levasseur *et al.*, 1999; Sharma *et al.*, 1999; Pierson-Wickmann *et al.*, 2000]. Nevertheless, these river data show a large range of variation. Bulk analyses and leachates of sediments or Fe/Mn oxide nodules taken from the Ganga river and its Himalayan tributaries have high  $^{187}\text{Os}/^{188}\text{Os}$  ratios [Pegram *et al.*, 1994; Chesley *et al.*, 1998; Pierson-Wickmann *et al.*, 2000]. On the other hand, not all Himalayan rivers have radiogenic Os compositions. Indeed, the Os signatures are much less radiogenic in both sediments and water from the other major Himalayan river, the Brahmaputra [Chesley *et al.*, 1998; Pierson-Wickmann *et al.*, 1998; Sharma *et al.*, 1999; Pierson-Wickmann *et al.*, 2000; Singh *et al.*, 2000].

Os isotopic results spanning 16 Ma are available from Ocean Drilling Program Leg 116, located in the distal part of the Bengal Fan [Reisberg *et al.*, 1997]. These results show that bulk sediments have relatively low  $^{187}\text{Os}/^{188}\text{Os}$  ratios, comparable to those of the Brahmaputra bedloads, while leachates almost always have higher ratios. The  $^{187}\text{Os}/^{188}\text{Os}$  ratio of the leachate of the shallowest Ocean Drilling Program (ODP) Leg 116 sample is indistinguishable from that of seawater, which was thought to imply that the radiogenic leachable Os carried by Ganga river particles [Pegram *et al.*, 1994] may be completely removed prior to

sediment deposition in the fan. The  $^{187}\text{Os}/^{188}\text{Os}$  ratios of the leachates increase with depth, which was interpreted to result from the addition of  $^{187}\text{Os}$  brought in by thermoconvective circulation in the sedimentary pile. In order to test these hypotheses we have analyzed recent sediments from R/V cruise *Sonne* SO93 for Os, Sr, and Nd isotopic compositions. These new results provide information both on how material sources vary with time and position in the fan and on the behavior of Os and Re during sediment deposition. These data also allow us to examine the conditions under which detrital sediment leachates can be used to reconstruct past variations in the seawater Os isotopic composition.

## 2. Study Area and Samples

### 2.1. Study Area

The Bengal Fan represents the largest reservoir of terrigenous sediments in the world and provides a very important tool for reconstructing the history of Himalayan erosion and its relationship to orogenic processes. The Bengal Fan is dominated by detrital turbidite sediments [Bouquillon *et al.*, 1990; Kudrass, 1996; Weber *et al.*, 1997] deposited at variable sedimentation rates [Kudrass, 1996]. The Bangladesh shelf is located in the northern part of the Bengal Fan, at the mouth of the estuary of the Ganga-Brahmaputra (G-B) river system. This shelf is cut by the head of the submarine canyon called "Swatch of No Ground". This canyon, characterized by the world's highest rate of sediment supply to the oceans [Milliman and Meade, 1983], is in fact a channel transporting

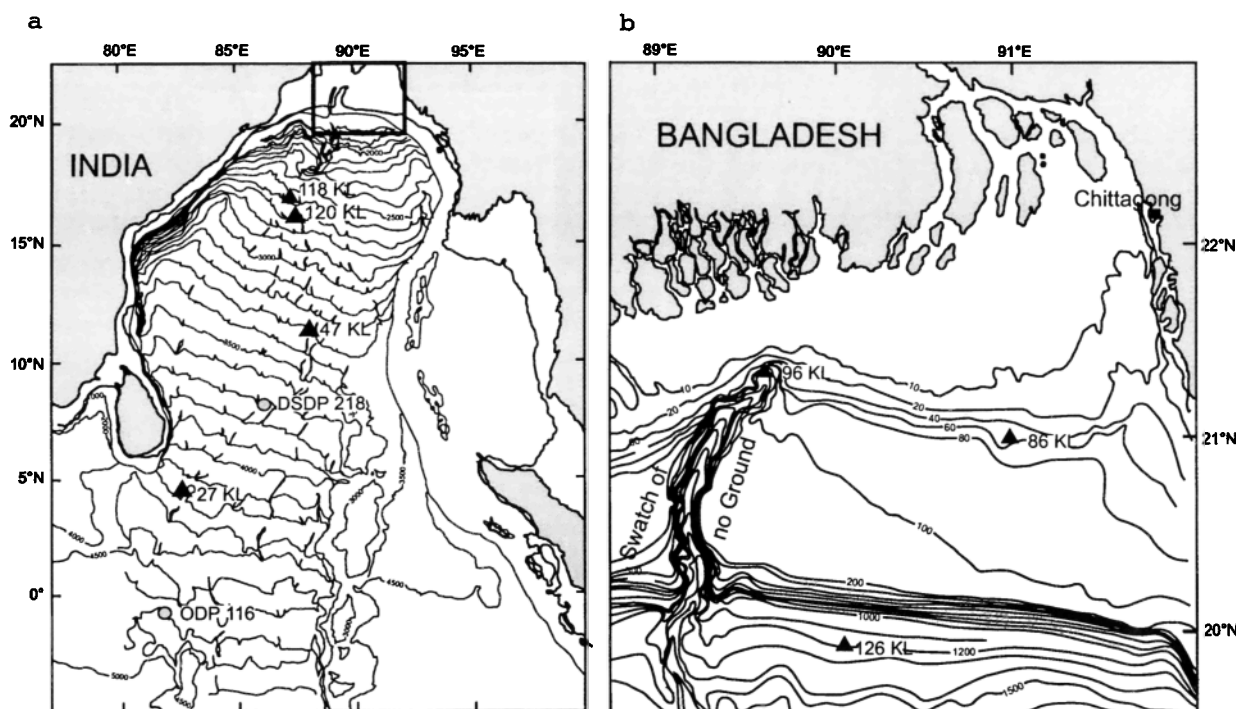


Figure 1 (a and b). Schematic map of sample locations from the *Sonne* cruise SO93 in the Bengal Fan. Triangles represent the different cores of samples analyzed in this study. Circles indicate the position of the DSDP Leg 218 and ODP Leg 116 cores. Rectangle indicates map area of Figure 1b. BGP samples from the Ganga and Brahmaputra were analyzed for Os, Sr and Nd in previous studies [Galy, 1999; Pierson-Wickmann *et al.*, 2000].

turbiditic sediments to the deep-sea fan. The principal function of this canyon is to channel particulate material toward the deep ocean during the high fluvial discharge of the monsoon [Weber *et al.*, 1997].

Previous studies based on Sr, Nd, and Os isotope compositions of marine sediments from the distal Bengal Fan (ODP Leg 116) have shown that the source of detrital sediment was essentially constant since the early Miocene and dominantly Himalayan [Bouquillon *et al.*, 1990; France-Lanord *et al.*, 1993; Derry and France-Lanord, 1996; Galy *et al.*, 1996]. Nevertheless, a small part of the particulate budget is thought to be derived from a non-Himalayan component, such as the Indian continent, the eastern part of the Deccan Traps or Sri Lanka [France-Lanord *et al.*, 1993; Derry and France-Lanord, 1996; Galy *et al.*, 1996]. A recent study based on sediments from throughout the Bay of Bengal [Colin *et al.*, 1999] suggests that isotopic compositions show a geographic dependence. Sediments from the western part of the Bay of Bengal are essentially from the G-B system, whereas in the eastern part, sediments represent a mixture between those derived from the G-B river, the Irrawady River and the Arakan coast [Colin *et al.*, 1999].

## 2.2. Samples

The samples in this study were taken with a piston corer at seven different locations (Figure 1), drilled during cruise SO93 with R/V *Sonne* in the Bengal Fan, from the shelf off Bangladesh to the distal part of the Fan. These cores extend over a time period of ~300 kyr, which covers the last eight oxygen isotopic stages. The core 86 KL is located on the Bengal Shelf, where two major Himalayan rivers (Ganga and Brahmaputra) join and enter the Indian Ocean. It is characterized by a sedimentation rate of 5 cm/yr [Michels *et al.*, 1998]. Core 96 KL corresponds to the head of the shelf canyon, named "Swatch of No Ground" [Weber *et al.*, 1997; Kudrass *et al.*, 1998]. It is considered to be a trap for sediments, with a very high sedimentation rate estimated at more than 30 cm/year [Michels *et al.*, 1998]. Core 126 KL is located ~150 km south of 86 KL and 150 km east of the canyon, and corresponds to the upper continental slope of Bangladesh. It accumulated at a sedimentation rate of 0.01 cm/yr, which is high for hemipelagic conditions. Cores 120 KL and 118 KL were drilled in an active canyon levee, in the midfan area [Weber *et al.*, 1997]. These cores correspond to outer and inner levees, respectively. Core 47 KL represents an ancient levee, to the east of the active canyon. Core 27 KL is in the distal part of the fan, in the modern active channel, between Deep Sea Drilling Project Hole 218 and ODP Leg 116 sites. The sediment ages have been determined using Accelerator Mass Spectrometry  $^{14}\text{C}$  dating, oxygen isotope stratigraphy and two tephra layers from Toba eruptions [Kudrass, 1996].

## 3. Analytical Procedures

### 3.1. Sr and Nd isotopic analyses

Sediment samples were washed with distilled water (Milli-Q) in order to remove marine chlorides. Sediments were decarbonated by leaching with 5% acetic acid for 30 min in an

ultrasonic bath. Leachate and residue were separated by centrifuging, and the residue was rinsed repeatedly with distilled water to eliminate any trace of carbonate solution. Spiked samples were dissolved in an HF-HNO<sub>3</sub>-HClO<sub>4</sub> mixture, dried down, and redissolved in HCl. Sr and light rare earth elements were separated by standard procedures using AG50-X8 cationic exchange resin in quartz columns. Nd and Sm were isolated by reverse-phase chromatography on HDEHP-coated Teflon powder. Sr and Nd isotopic compositions and concentrations were determined by isotope dilution mass spectrometry with a Finnigan MAT 262 in static mode. Sr isotopic ratios were normalized to  $^{86}\text{Sr}/^{88}\text{Sr}=0.1194$ . The mean value of  $^{87}\text{Sr}/^{86}\text{Sr}$  for NBS-987 was  $0.710195 \pm 36$  during the period of analysis. Nd isotopic ratios were normalized to  $^{146}\text{Nd}/^{144}\text{Nd}=0.7219$ , and the mean  $^{143}\text{Nd}/^{144}\text{Nd}$  ratio of the Johnson Matthey standard was  $0.511110 \pm 27$ . Sr blanks were 300 pg, with a  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of 0.710. Nd blanks were 150 pg. These Nd and Sr blank levels are negligible.

### 3.2. Re-Os isotopic analyses

Re and Os were extracted by two methods: The first method is hydrogen peroxide-sulfuric acid washing to separate the leachable component. The H<sub>2</sub>O<sub>2</sub> leaching technique used was the same as that of Reisberg *et al.* [1997] and nearly identical to that developed by Pegram *et al.* [1992, 1994]. Leaching may allow the Os composition of the hydrogenous portion of the sediment to be determined when the detrital fraction of the sediment is high. The peroxide leaching method used here was initially developed by Pegram *et al.* [1992] in order to selectively leach the hydrogenous Os component (derived from river water or seawater) thought to be bound to Fe-Mn oxyhydroxides. Though it is possible that this technique may also liberate some Os held by nonhydrogenous phases [Peucker-Ehrenbrink *et al.*, 1995], we used this technique to allow direct comparison with previous studies. Os was extracted from the leachate by distillation. The second method is an acid digestion followed by liquid Br extraction using the procedure developed by Birck *et al.* [1997] to obtain the bulk rock composition. In both procedures,  $^{185}\text{Re}$  and  $^{190}\text{Os}$  tracers were added before sample digestion to allow Re and Os concentrations to be determined by isotope dilution. These methods were also used for the determination of the Os isotopic compositions and Os and Re concentrations of Himalayan samples [Pierson-Wickmann *et al.*, 2000], allowing a direct comparison with these results. Total blank levels were ~0.3 pg and 30 pg for Os and Re, respectively, for ~2 g of sample powder. Os was analyzed by negative thermal ionization [Creaser *et al.*, 1991; Völkening *et al.*, 1991] using a Finnigan MAT 262 mass spectrometer. Os isotopic ratios were normalized to  $^{192}\text{Os}/^{188}\text{Os}=3.08271$ . Our standard value was  $0.17387 \pm 0.00025$  over the course of this study. Re concentrations were calculated by isotope dilution after measurement of the  $^{187}\text{Re}/^{185}\text{Re}$  ratio by Inductively Coupled Plasma Mass Spectrometry (Elan 6000).

## 4. Results

The Nd, Sr (silicate fraction), and Os (bulk and leachate) isotopic data are listed in Table 1.  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\epsilon_{\text{Nd}}$  values

Table 1. Sr, Nd and Os Isotopic Data From Marine Sediments From the Sonne SO93 Piston Cores.

Sample	Age	Isotopic Stage	Group	Average Sedimentation Rate, cm/yr	$^{87}\text{Sr}/^{86}\text{Sr}$	[Sr], ppm	$\epsilon_{\text{Nd}}$	[Nd], ppm	$^{187}\text{Os}/^{188}\text{Os}$ (b)	[Os] (b), ppt	[Re] (b), ppt	$^{187}\text{Re}/^{188}\text{Os}$ (b)	$^{187}\text{Os}/^{188}\text{Os}$ (l)	[Os] (l), ppt	[Re] (l), ppt	$^{187}\text{Re}/^{188}\text{Os}$ (l)	Os (l) Fraction (%)	Re (l) Fraction (%)
27 KL 052-055	Holocene	1	III	0.005	0.72748	84	17.8	31.0	1.086	90	2909	175	1.042	32	2175	364	35.7	74.8
47 KL 728-732	270 kyr	8	I	Dead channel	0.74507	110	15.5	34.6	1.218	46	479	57	1.320	20	233	62	42.6	48.6
86 KL 038-041	5-10 years	1	I	5	0.73994	102	14.0	36.7	1.267	24	279	64	1.356	7	121	97	28.7	43.4
86 KL 817-820	250-300 years	1	I	5	0.74192	96	12.0	34.5	1.242	27	192	39	1.429	6	86	79	22.4	44.8
96 KL 077-080	0 year	1	I	37	0.74393	112	14.1	35.8	1.341	25	181	40	1.553	8	99	73	30.7	54.7
96 KL 1107-1111	30 years	1	I	37	0.74425	96	14.9	38.5	1.296	46	225	27	1.721	15	150	61	31.9	66.7
118 KL 029-032	<1000 years	1	I	0.03	0.74040	109	14.3	36.3	1.166	56	435	43	1.316	13	334	138	24.2	76.8
120 KL 348-349	6000 years	1	I	0.06	0.74467	99	14.5	37.5	1.351	74	645	49	1.819	20	412	124	26.4	63.9
120 KL 579-582	10 kyr	1	I	0.06	0.74723	100	15.3	32.0	1.515	43	787	104	1.596	12	580	273	28.3	73.7
120 KL 787-789	10.5 kyr	1	I	0.06	0.74129	128	14.4	32.1	1.506	43	828	109	1.597	14	565	225	33.3	68.2
120 KL 1071-1072	14.8 kyr	2	II	0.06	0.72989	94	9.4	33.5	0.969	57	1355	127	1.014	18	954	279	32.2	70.4
120 KL 1114-1117	15 kyr	2	I	0.06	0.73811	144	14.6	35.8	1.443	36	815	127	1.806	9	510	343	24.2	62.6
126 KL 039-041	5800 years	1	II	0.007	0.72936	93	11.7	27.4	1.110	93	9667	564	1.055	41	8385	1090	44.6	86.7
126 KL 178-180	last glacial period	2	II	0.007	0.72400	101	10.9	32.5	0.980	109	2230	109	0.994	37	1801	261	33.9	80.8
126 KL 601-603	stage 4	4	II	0.007	0.72452	105	11.1	32.0	0.982	107	4669	233	0.999	39	3683	510	36.1	78.9
126 KL 801-802	stage 5	5	II	0.007	0.72527	93	10.6	29.0	0.997	128	11108	465	1.010	44	6310	775	34.1	56.8

Sr and Nd isotopic data were determined on silicate fraction and Os on bulk sediment (b) and leachate (l). Isotopic stages 5 and 1 are considered as interglacial periods and isotopic stages 8, 4 and 2 are considered as glacial periods. Typical errors were 0.0002 for  $^{87}\text{Sr}/^{86}\text{Sr}$ , 0.4 units for  $\epsilon_{\text{Nd}}$ , and 0.3 % for  $^{187}\text{Os}/^{188}\text{Os}$ . Sedimentation rates represent averages over the core length and do not necessarily reflect instantaneous rates.

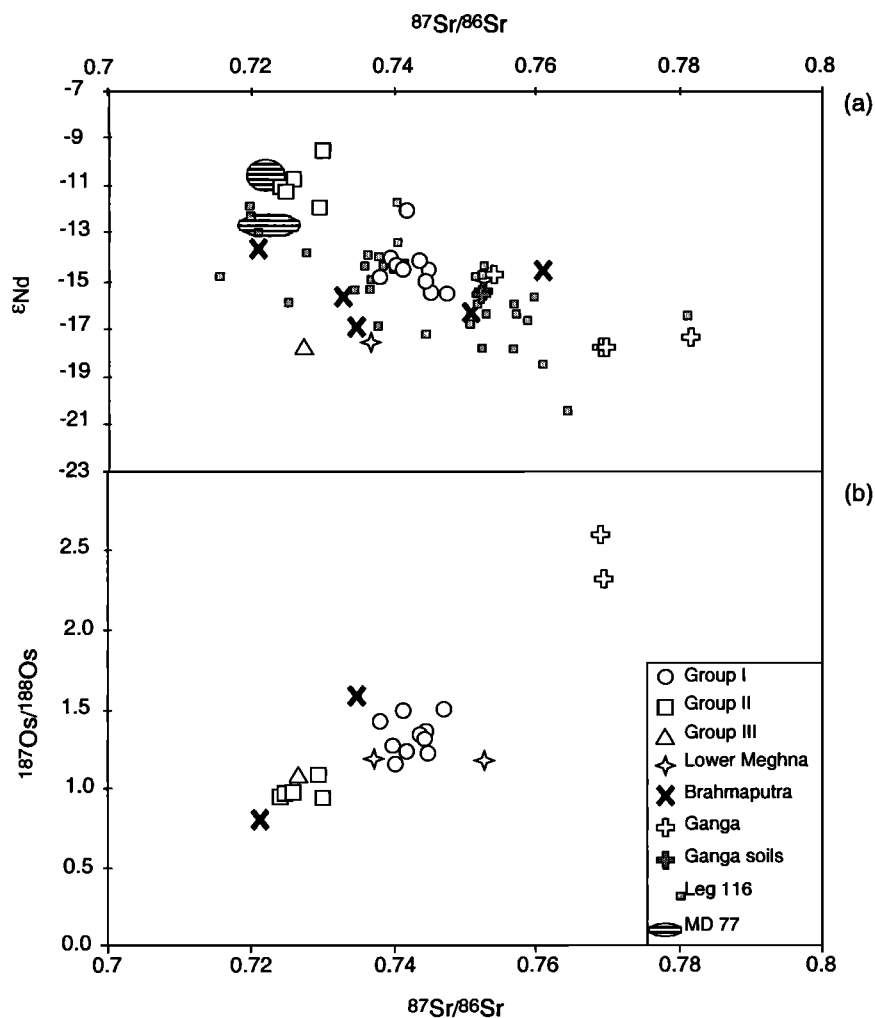


Figure 2. Os, Sr, and Nd isotopic compositions of marine sediments from the *Sonne* cruise SO93. Sr and Nd were determined on silicate fractions of sediments and Os were determined on bulk sediments. MD 77 data are from Colin *et al.* [1999].

of SO93 sediments vary between 0.724 and 0.747 and  $-9.4$  and  $-17.8$ , respectively (Figure 2a). The ranges of Nd and Sr concentrations, 27-38 ppm for Nd and 84-144 ppm for Sr, are similar to those of previously published Ganga-Brahmaputra and Bay of Bengal data [Goldstein and Jacobsen, 1988; Bouquillon *et al.*, 1990; France-Lanord *et al.*, 1993; Colin *et al.*, 1999]. The sediments may be separated into three groups on the basis of their Sr and Nd isotopic compositions. The first group (group I) includes the majority of the samples, with  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of 0.740-0.750 and  $\epsilon_{\text{Nd}}$  of  $-15.5$  to  $-14.0$ , which are similar to the ratios of the High Himalayan Crystalline series rocks [France-Lanord *et al.*, 1993]. This group corresponds to turbidites (47 KL, 86 KL, 96 KL, 118 KL and 120 KL) sampled near the active canyon and shelf off Bangladesh. The second group (group II), defined by a  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of 0.725-0.730 and  $\epsilon_{\text{Nd}}$  of  $-9.4$  to  $-11.7$ , is composed mainly of sediments from 126 KL on the continental shelf, but also includes one sample (120 KL 1071-1072) from the canyon levee. The third group (group III) is represented by a single sample (27 KL) in the active channel in the distal part of the Bengal Fan, combining a low  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio and a very low  $\epsilon_{\text{Nd}}$  value ( $-17.8$ ).

Os concentrations of bulk sediments range from 24 to 128 ppt, and the leachable fraction represents between 22 and 44% of the total Os. The Re concentrations are more variable, ranging from 86 ppt to 11 ppb. The leachable Re fraction remains quite high relative to the total Re fraction, between 44 and 87%. These Os and Re concentrations are comparable with those found in ODP Leg 116, in the distal part of the Bengal Fan [Reisberg *et al.*, 1997]. The Os concentrations of bulk sediments are higher than those of bedloads of the feeding rivers [Pierson-Wickmann *et al.*, 1999]. As was found in ODP Leg 116 samples [Reisberg *et al.*, 1997], the  $^{187}\text{Os}/^{188}\text{Os}$  ratio of the bulk fraction, ranging from 0.97 to 1.51, is always less radiogenic than that of the leachable fraction (from 0.99 to 1.82), except in the case of the most distal sample (27 KL) and one of the 126 KL samples. The Os isotopic ratios of the bulk samples can be divided into the same three groups defined by the Sr and Nd data. The first group has radiogenic Os ratios (1.17-1.52 for bulk and 1.32-1.81 for leachate), while the second and third groups have Os isotopic ratios (0.97-1.11 for bulk and 0.99-1.06 for leachate) comparable to the present seawater value (1.06; Sharma *et al.* [1997]; Levasseur *et al.* [1998]). The SO93 samples are less

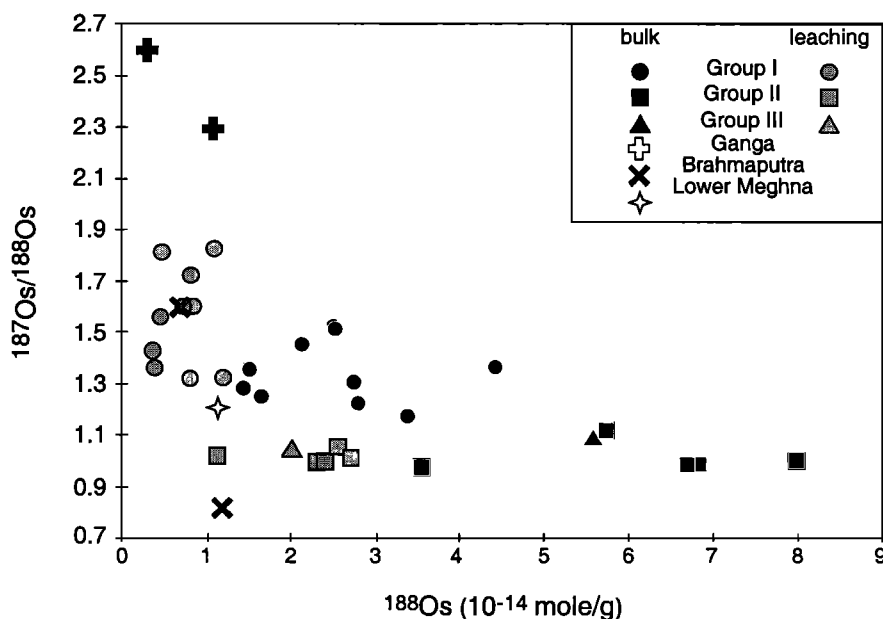


Figure 3. Os isotopic composition ( $^{187}\text{Os}/^{188}\text{Os}$ ) of *Sonne* sediments versus  $^{188}\text{Os}$  abundance. The  $^{187}\text{Os}/^{188}\text{Os}$  ratios of bulk and leachate sediments plot between those of Ganga and Brahmaputra river bedloads. Note that the Os concentration of bulk fan sediment is sometimes much higher than that of continental bedloads. The sediments with the highest Os isotopic ratios have also the lowest Os concentrations.

radiogenic than the Ganga bedloads and have  $^{187}\text{Os}/^{188}\text{Os}$  ratios close to those of the Brahmaputra river bedloads [Chesley *et al.*, 1998; Pierson-Wickmann *et al.*, 2000; Singh *et al.*, 2000]. When  $^{187}\text{Os}/^{188}\text{Os}$  is plotted against  $^{188}\text{Os}$  concentration (Figure 3) a trend toward less radiogenic Os compositions at increasing Os concentration is observed. The samples with the highest Os concentrations and lowest  $^{187}\text{Os}/^{188}\text{Os}$  ratios are those of groups II and III. These samples, which come from areas of relatively low sedimentation rate, also have Re concentrations (2–11 ppb) much higher than those of typical continental rocks and sediments. Taken together, these observations suggest a large hydrogenous contribution to groups II and III.

The variations of the Nd, Sr, and Os isotopic compositions are not related to sample age but rather to geographic location. No conclusion concerning glacial-interglacial variations can be drawn, because of the small number of samples available from each period. The sudden change in the Nd, Sr and Os isotopic composition of core 120KL raises the question of the time resolution of the sediment profiles, since over a few centimeters the isotopic compositions can change greatly.

## 5. Sediment Sources

The Sr, Nd, and Os isotopic data (Figure 2) can be interpreted in terms of sources of material deposited in the Bengal Fan. The potential source regions include the Himalayan range, whose erosional products are carried by the Ganga and Brahmaputra rivers, and non-Himalayan areas such as the Deccan Traps, eastern India, Sri Lanka to the west, and the Arakan coast to the east of the Bay of Bengal. The isotopic compositions of Ganga and Brahmaputra particles are known from studies of the modern river system and soils of the delta

[Goldstein and Jacobsen, 1988; Pegram *et al.*, 1994; Derry and France-Lanord, 1996; Galy and France-Lanord, 1999; Pierson-Wickmann *et al.*, 2000]. These compositions are rather variable, with a tendency toward more radiogenic Sr and Os isotopic ratios for the Ganga material compared to that of the Brahmaputra. One sample of the Lower Meghna (BGP 34), representing a mixture of the G-B inputs before entering the ocean, is characterized by a bulk  $^{187}\text{Os}/^{188}\text{Os}$  ratio of 1.20 and [Os] of 29 ppt,  $^{87}\text{Sr}/^{86}\text{Sr}=0.73790\text{--}0.75305$  and  $\epsilon\text{Nd}$  from  $-17.8$  to  $-14.8$  [Galy, 1999]. Soils from Bangladesh have very similar Sr-Nd signatures.

### 5.1. Group I

Bengal Fan samples belonging to group I have Sr, Nd, and Os isotopic signatures very similar to those of the Lower Meghna which suggests that most material deposited in the submarine delta and the main Channel levee system is almost exclusively supplied by the G-B river system. These data, derived from different parts of the Bengal Fan with ages between 0 and 300 kyr, imply that the riverine detrital mixture has been remarkably stable over that time interval. The Bengal Fan sediments have isotopic signatures very similar to that of a Brahmaputra sediment sampled during the monsoon (BGP 14; Pierson-Wickmann *et al.* [2000]) and are less radiogenic in Sr and Os than are Ganga sediments. At first glance, this might suggest that Ganga sediments are almost absent in the Fan, but this interpretation is ruled out by the presence of 1 to 3 wt % of detrital calcite and dolomite in fan sediments, which is characteristic of the Ganga flux [Höhndorf *et al.*, 2001]. Ganga sediments carry from 4 to 7 wt% of detrital carbonates, whereas the Brahmaputra is almost free of carbonate [Galy *et al.*, 1999].

Three nonexclusive hypotheses can be proposed to explain the apparent low proportion of Ganga material in the fan

sediments. First, Ganga and Brahmaputra end-members, as defined by the current data set, could be nonrepresentative. In particular, the average Brahmaputra input could be less radiogenic in Sr and Os as observed in one sample collected during the dry season (BGP 82; Pierson-Wickmann *et al.* [2000]). Recent data from Singh *et al.* [2000] strongly support this possibility. Alternatively or additionally, mineralogical sorting could produce river bedloads with Sr and Os isotopic compositions more radiogenic than those of fan sediments. The main carrier phases of Os in sediments are still unknown, but its isotopic distribution is not homogeneous as shown by the systematically higher ratio of the leachable Os compared to the corresponding bulk Os. This, however, does not provide a simple explanation for a possible isotopic fractionation of Os with mineralogical sorting. A third hypothesis is that the fan sediments have lost radiogenic Os and perhaps Sr during river and marine transport or after deposition. A decrease in  $^{187}\text{Os}/^{188}\text{Os}$  is observed between bedloads from Himalayan mountain rivers and those from the Ganga [Pierson-Wickmann *et al.*, 2000], which might argue in favor of this possibility. The fact that the leachable, and presumably more mobile, Os fractions of group I sediments are always more radiogenic than the corresponding bulk sediments is also in accord with this suggestion. However, even if radiogenic Os loss has occurred, it cannot explain the higher Os concentrations of the fan sediments. Some mineralogical concentration of Os-rich phases must also have taken place.

## 5.2. Group II

Group II samples are characterized by distinctly less radiogenic Os and Sr isotopic compositions and higher  $\epsilon_{\text{Nd}}$  values than those of group I. These compositions are not compatible with known values for the G-B rivers and imply that another source of detrital particles is mixed with the G-B flux. The group II Sr-Nd values are very similar to those observed by Colin *et al.* [1999] among low accumulation rate sediments of the northeastern Bay of Bengal. On the basis of both the distribution of isotopic data and the current dynamic in the Bay of Bengal, Colin *et al.* proposed that the additional source could be the erosion of the Indo-Burman range through the drainage of the Arakan coast. The isotopic composition of this end-member is unknown, which makes it impossible to assess the proportion of mixing with the G-B particle flux.

Most samples of group II belong to core 126 KL, which consists of hemipelagic muds with sedimentation rates around 0.007 cm/yr, which is 10 to 1000 times lower than those of cores of the nearby submarine delta. Detailed study of this zone shows that accumulation rates decrease very rapidly toward the south of the shelf [Michels *et al.*, 1998]. Sr and Nd isotopic data indicate that the G-B flux does not dominate the sedimentation in core 126 KL, despite the fact that this core is located just 250 km south of the river's outflow. Thus westward currents at the mouth of the G-B system are strong enough to divert most of the G-B particle flux [Michels *et al.*, 1998]. Sample 126 KL 39-41, with an age of 5800 years, is marked by a higher proportion of the G-B end-member. This is consistent with the observed slight increase in detrital carbonate abundance in the core during the Holocene [Höhndorf *et al.*, 2001].

Another group II sample is found at 1.07 m depth in core 120 KL, which was taken in the east outer levee of the active channel [Weber *et al.*, 1997]. The rest of the samples from this core are in group I. This short-lived change in isotopic composition implies that pelagic intervals, which are abundant in the lower part of the core, correspond to periods where the flux of Himalayan material in the channel is temporarily stopped or diverted.

The lower sedimentation rates of the group II samples imply that a significant component of the chemical signature of the sediments may be hydrogenous in origin. This suggestion is supported by the Re-Os data. The Os isotopic compositions of these samples approach the seawater value, and the leachates all approach this value more closely than do the corresponding bulk sediments. In addition, the Re concentrations (1.4-11 ppb) are much higher than those of typical detrital sediments. This suggests that in regions where the G-B particle flux is minor, a large fraction of the Os and Re is derived from seawater. Nevertheless, the lower Os isotopic ratios of the group II sediments also reflect their original detrital signatures. The low  $^{187}\text{Os}/^{188}\text{Os}$  ratios of these samples, and the even lower ratios that can be inferred for most of their detrital fractions, suggest that this detritus was derived mainly from sources with fairly young crustal residence ages or with a significant mantle-derived component. This inference is in agreement with the lower Sr and higher Nd ratios of these samples.

## 5.3. Group III

Group III, which consists of a single sample (27 KL sediment), has Sr and Os compositions comparable to those of group II. Here again the Os isotopic ratio is very close to that of seawater, the Re and Os concentrations are high, and the sedimentation rate is low, suggesting that much of the Re and Os is of hydrogenous origin. On the other hand, the  $\epsilon_{\text{Nd}}$  value (-17.8) is very low, much lower than those of Group II. This difference may be related to the sediment source. Considering the location of Core 27KL (Figure 1), southeast of Sri Lanka, the source of this material could be G-B sediments mixed with old crustal material with low  $\epsilon_{\text{Nd}}$ . The Highland Complex, in the meridian part of Sri Lanka, has the required Sr-Nd signatures [Milisenda *et al.*, 1994]. Of course, further analyses of sediments from this region are required to verify this hypothesis.

## 6. Comparison With ODP Leg 116 Sediments

The ranges of variation in Os, Sr, and Nd isotopic data are similar for sediments from Sonne cruise SO93 and ODP Leg 116. A detailed comparison between these studies is not possible, as no data set including Sr, Nd, and Os data on the same samples exists for Leg 116, but several observations can be made. The higher than marine Os isotopic ratios of the Leg 116 sediment leachates were explained by the addition of excess  $^{187}\text{Os}$  from the sedimentary pile [Reisberg *et al.*, 1997], through thermoconvective circulation in the distal part of the Bengal Fan [Ormond *et al.*, 1995]. However, the presence of similarly radiogenic Os sediments in leachates of recent sediments in the active channel and also in an abandoned channel of the deep fan (47 KL) indicates that such diagenetic



processes are not required. Instead, in both the Leg 116 and the Sonne samples the leachable radiogenic Os was probably an original component, carried by the detrital particles derived from Himalayan erosion. The similarity of Os compositions between the group I Sonne and ODP Leg 116 samples implies that Himalayan erosion has been a source of radiogenic Os since the early Miocene. This implies in turn that rocks analogous to the highly radiogenic Lesser Himalaya black shales were exposed during the Miocene.

The section of Leg 116 between 7.4 and 0.9 Ma is characterized by fine-grained smectite and organic carbon-rich sediments. In this section, the leachate  $^{187}\text{Os}/^{188}\text{Os}$  ratios, though still higher than that of seawater, are closer to the marine value than are those of the Miocene section [Reisberg *et al.*, 1997]. Sr-Nd-Os isotopic data imply that the source of these sediments remained dominated by the Himalaya and therefore that it was essentially the erosional regime that changed during this period [Derry and France-Lanord, 1996]. The lower Os isotopic ratio could then reflect a change in the distribution of Himalayan erosion, with, for instance, less erosion of the Lesser Himalaya black shales, which are the main source of radiogenic Os [Singh *et al.*, 1999; Pierson-Wickmann *et al.*, 2000]. There is however no evidence from the Siwalik record to support this hypothesis (Huyges *et al.*, manuscript in preparation). Alternatively, two processes that could modify the initial radiogenic signature of the G-B material can be proposed to explain the somewhat lower Os isotopic ratios of leachates of the middle to late Pliocene section. First, as proposed above, mineralogical sorting could produce a finer grain fraction with lower  $^{187}\text{Os}/^{188}\text{Os}$  ratios. Since the distribution of Os in the sediment is unknown, this hypothesis is difficult to test. Second, seawater Os could be absorbed on the sediment and overprint the radiogenic signature. Such a process could be enhanced by the clay and organic-matter-rich character of the Pliocene sediments and by the lower sedimentation rate at that time. In this case, the leachable Os component would represent a mixture between Os derived from seawater and more radiogenic Os, ultimately derived from Himalayan erosion, carried by the detrital particles. Interestingly, one Leg 116 sample (57X CC 33-35) has an extremely high Re concentration (11 ppb) and an Os ratio equal to the contemporaneous seawater value. This sample may be analogous to the groups II and III Sonne samples. The other samples from the post-7.4 Ma Leg 116 section have Re-Os characteristics intermediate between those of the group I and Group II Sonne samples.

## 7. Implications for the marine Os record

The results obtained on recent Bay of Bengal sediments have several implications concerning the effect of Himalayan erosion on the seawater Os isotopic budget, and more generally, the exchange of Os between seawater and sedimentary particles. First, the average Os isotopic composition of the G-B sediments ( $1.33 \pm 0.12$ ) is lower than that of Ganga bedloads (2.3 and 2.6; Pierson-Wickmann *et al.* [2000]) and river waters sampled in the same location (2.94; Levasseur *et al.* [1999]). This difference is due primarily to mixing with Brahmaputra sediments, which have much less radiogenic Os ratios (0.8 and 1.5) [Pierson-Wickmann *et al.*, 2000; Singh *et*

*al.*, 2000]. It is thus likely that the average dissolved Os delivered by the G-B system is less radiogenic than that of the Ganga water. This is supported by the only known measurement of Brahmaputra water ( $^{187}\text{Os}/^{188}\text{Os}=1.07$ ; Sharma *et al.* [1999]), which is less radiogenic than that of the Ganga ( $^{187}\text{Os}/^{188}\text{Os}=2.94$ ; Levasseur *et al.* [1999];  $^{187}\text{Os}/^{188}\text{Os}=1.59$ ; Sharma *et al.* [1999]). The effect of Himalayan erosion on seawater Os is therefore lower than what could be expected from the Ganga data alone. Second, both modern (Sonne group I) and ancient (Leg 116 and pre-7.4 Ma section) high sedimentation rate samples have leachate  $^{187}\text{Os}/^{188}\text{Os}$  ratios that are higher than those of the corresponding bulk sediments and much higher than that of seawater. This suggests that much of the radiogenic Os contained in labile phases is retained during sediment passage through the estuary or interaction with seawater. In lower sedimentation rate samples (Sonne groups II and III and Leg 116 post-7.4 Ma section) this radiogenic component is partly or completely masked by the presence of Os derived from seawater. Additionally, the presence of highly radiogenic Os in leachates of modern sediments removes the need for the hydrothermal redistribution of Os suggested by Reisberg *et al.* [1997] to explain the Miocene Leg 116 results.

The mechanisms of Os exchange and adsorption on detrital sediments remain to be clarified, but our data suggest that sedimentation rate plays a critical role. Leachates of group I sediments display a strong detrital Os isotopic composition, while those of groups II and III sediments suggest an exchange of Os and Re with seawater. There is clear evidence that groups II and III sediments have adsorbed Re and possibly Os. Re concentrations in groups II and III sediments are much higher than in typical crustal rocks. While there is no obvious difference in bulk geochemistry between the group I samples and those of the other two groups, they were deposited in very different contexts within the megafan. The groups II and III samples formed on the continental slope (group II), or in the distal part of the channel (group III), at accumulation rates that are moderately high relative to most hemipelagic sediments. In contrast, the group I samples, deposited in the channel levee, accumulated at rates that were much higher still, among the most rapid in the world, thus limiting the time available for sediment interaction with seawater. This may indicate that time of direct contact with seawater is one of the main parameters controlling efficient exchange/sorption of Re and Os. This seawater-derived Re and Os seem to be incorporated into preexisting phases, as there is no evidence for higher proportions of hydrogenous phases, such as ferromanganese oxides, in groups II and III than in group I.

The similarity between the Os compositions of leachates of the groups II and III sediments and the recent seawater Os ratio suggests that leaching of detrital sediments may provide a means of reconstructing the marine Os isotopic record in the past. The detrital accumulation rates of these sediments ( $\sim 0.01$  cm/yr), while much lower than those of the Group I samples, are still high compared to those of most hemipelagic sediments. While detrital sediment leachates are probably unsuitable for determining the details of the ancient Os record, because of possible contributions from nonmarine Os, the broad outlines of the Os record may still be obtainable in

some cases, given the wide variations in the Os ratio of seawater that have occurred. This in turn could help to constrain the crustal/mantle inputs to ancient seawater. Conversely, the Os isotopic compositions of sediment leachates could perhaps be used as a dating tool in unfossiliferous sediments.

## 8. Summary and Conclusion

The Sr, Nd, and Os isotopic compositions of sediments from the Bay of Bengal show a geographic dependence which reflects source variations, caused by both sediment transport processes and location in the Bay. Sediments from the submarine delta or belonging to the active channel are dominated by Himalayan particles. Immediately to the south of the shelf the Himalayan contribution is much more limited, allowing the effects of other detrital contributions, such as the Indo-Burman range, to be observed. These mixed sediments are present in zones of the fan which are not influenced by the turbiditic deposition associated with the channel levee system. The intense particle flux of the Ganga and Brahmaputra is therefore very efficiently channeled and overprints the background deposition in the Bay of Bengal. This background detritus appears to be derived from a source with a relatively young crustal residence age or a large mantle-derived component.

Reconstructing the past flux of riverine Os from the sedimentary record remains difficult because the carrier phases of

Os in the sediment remain unknown, precluding definitive interpretation of observed variations. The systematic difference between leachable and bulk Os shows that the isotopic signature of Os is not homogeneous in these sediments and therefore that processes of mineralogical sorting may control part of the isotopic signature of the samples. The Os isotopic composition of the leachates is controlled by the  $^{187}\text{Os}/^{188}\text{Os}$  ratio of the detrital material in very high sedimentation rate samples (group I), while a seawater-derived component is apparently important in samples with lower sedimentation rates (groups II and III). Thus time of direct exposure to seawater appears to be one of the critical parameters determining the efficiency of Re and Os adsorption by sedimentary particles. The observation that leachates of detrital sediments with even moderately high accumulation rates reflect the seawater Os value suggests that such samples can sometimes be used to reconstruct the ancient marine Os record. This record can in turn provide information on continental versus mantle contributions to the oceans in the distant past.

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