

$\delta^{13}\text{C}$ of organic carbon in the Bengal fan: source evolution and transport of C3 and C4 plant carbon to marine sediments

Christian France-Lanord(1) & Louis A. Derry(2)

(1) Centre de Recherches Pétrographiques et Géochimiques - CNRS, BP20
54501 Vandœuvre-les-Nancy - France
cfl@crpg.cnrs-nancy.fr
Tel (33) 83 51 22 13 - Fax (33) 83 51 17 98

(2) Cornell University, Dept. of Geological Sciences, Ithaca, NY 14853,
USA.

Revised manuscript published in:

France-Lanord C. and Derry L. A. (1994) $\delta^{13}\text{C}$ of organic carbon in the Bengal Fan: Source evolution and transport of C3 and C4 plant carbon to marine sediments. *Geochimica et Cosmochimica Acta* 58, 4809-4814.

DOI: 10.1016/0016-7037(94)90210-0

Abstract - Carbon isotopic measurements on organic carbon in sediment cores from the Bengal Fan (ODP Leg 116) show a dramatic 10 ‰ increase beginning ca. 7 Ma ago, and a rapid decrease after 0.9 Ma. These shifts reflect changes in the mixing ratio of terrigenous carbon derived from C3 and C4 plants. The rapid increase in $\delta^{13}\text{C}$ of Bengal Fan OC at 7 Ma show that C4 expansion already documented in the Siwaliks was widespread overall the Himalayan foreland. After 7 Ma, relations of $\delta^{13}\text{C}$ with sedimentological parameters show that C4 plants dominates in the foreland whereas C3 plants remain in the mountain range. Variations in the source of the sediments and of the OC appear to be sensitive to climate-hydrologic conditions in the basin. Major changes in the isotopic composition of the carbon flux in one of the largest river system modify the isotopic budgets of both marine dissolved carbon and the sedimentary carbon mass.

Introduction

The Bengal Fan is one of the largest sedimentary units in the world, containing ca. 3×10^{19} kg of sediment, primarily derived from the erosion of the Himalayan orogen (Curry, 1991; Curry and Moore, 1971; Rea, 1992). The rate of sediment delivery appears to have increased markedly in early Miocene time (ca. 21 Ma (Cochran, 1990; Lindsay, et al., 1991), and again at 10-11 Ma (Rea, 1992), implying an average sediment delivery rate of ca. 1.5×10^{12} kg/yr during the late Neogene. This mean rate is similar to estimates of the modern rate (Milliman and Syvitski, 1992). Measurements obtained from drill core of early Miocene to Quaternary age in the distal portion of the fan (ODP Leg 116) have an average total organic carbon (TOC) content of 0.85 wt % (n=155) (Cochran et al., 1989) and this study). A smaller number of analyses (n=12) from Quaternary sediments in the submarine portion of the proximal Bengal delta are similar (=0.90wt %, (Bouquillon, 1987)). If these results are representative of the fan as a whole, the mean burial rate of OC in the Bengal Fan since early the Miocene has been, $\approx 1.1 \times 10^{12}$ mol/yr. Recent published estimates for global OC burial are from 4 to 10×10^{12} mol/yr (Lasaga, et al., 1985; Smith and Hollibaugh, 1993), thus the Bengal Fan may account for 10 to 25% of the total global OC burial flux during the Neogene. If the Indus Fan, Indo-Gangetic Plain and Ganga-Yamuna delta are included, the estimate of OC burial in Neogene sediments derived from the Himalaya increases by a factor of roughly 1.5. It is evident that the global OC burial budget may have been significantly perturbed by rapid erosion of the Himalayan region.

The fraction of biologically labile particulate organic carbon (POC) in the Ganga river is low, which suggests (Ittekkot, 1988) that deep sea sediments in the Indian Ocean are an important sink for OC derived from terrestrial plants. Data from ODP Legs 116 and 117 support this hypothesis. Gas chromatograph and pyrolysis data show that OC in the Bengal Fan is dominated by organic matter derived from terrigenous sources (Bertrand, et al., 1991; Meyer and Dickens, 1992; Party, 1989; Poynter and Eglinton, 1990). Carbon isotopic analyses ($\delta^{13}\text{C}$) of paleosol carbonates, organic matter and fossil teeth (Cerling, et al., 1993; Morgan, et al., 1994; Quade and Cerling, in press; Quade, et al., 1989) show evidence of a major shift in terrestrial vegetation patterns in the

Himalayan foreland in late Miocene time. A terrestrial plant community dominated by C4 plants appears to replace a C3-dominated community between 7 and 6 Ma. The stable isotopic results (Cerling, et al., 1993; Morgan, et al., 1994; Quade and Cerling, in press; Quade, et al., 1989) suggest several questions. Was the expansion of C4 plants confined to a relatively small area in the foreland, or was it of general importance in the northern Indian subcontinent? What caused the shift in the dominant photosynthetic pathway? What effects did the expansion of C4 biomass have on the budget of OC exported to the ocean and buried in marine sediments? Since the bulk of the OC preserved in the Bengal Fan is derived from the Ganga and Brahmaputra river basins, $\delta^{13}\text{C}$ analyses of sedimentary OC provide insight into this question.

The Bengal Fan

Sedimentation of the fan can be illustrated by variations in rate of deposition, clay mineralogy, grain size and TOC (Fig 1). Bengal Fan sediments older than 7 Ma or younger than 0.9 Ma are dominantly silts with an illite-rich clay fraction, TOC content usually < 0.5 wt %, show relatively little chemical weathering, and were deposited at high sedimentation rates. In contrast, between 7 and 0.9 Ma, sedimentation rates of mostly smectite-rich muds and fine silts were lower, the degree of chemical weathering was much more intense, and TOC > 1 wt %. However Nd, Sr, O and H isotopic data show that these variations were not caused by changing sediment sources, but rather by changing continental alteration histories (Bouquillon, et al., 1990; France-Lanord, et al., 1993). Comparable variations in sedimentation rate and weathering intensity are also observed in the Siwalik Himalayan foreland sequence (Burbank, et al., 1993; Quade and Cerling, in press). These variations have been interpreted to reflect a change in the rate of sediment supply and the residence time of sediment in the foreland basin (Burbank, et al., 1993; France-Lanord, et al., 1993). According to this hypothesis, between 7 and 0.9 Ma sediments were stored longer and weathered more intensely in the Indo-Gangetic Plain. The beginning of this interval follows oceanographic evidence for the intensification of the Asian monsoon ca. 7-8 Ma (Kroon, et al., 1991; Prell, et al., 1992)

Methods and Results

Total Organic Carbon has been analyzed on whole rock sediments. Samples were first acidified with 2N HCl at 100°C to eliminate carbonate, rinsed, collected on a silica filter and dried at 80°C. The sample on its filter was then oxidized under vacuum at 950°C with CuO/Cu₂O. The CO₂ released was purified at -140°C, manometrically measured for TOC content, and analysed on a VG602D mass spectrometer. Reproducibility is better than 0.2% and $\delta^{13}\text{C}$ of NBS-22 was measured at -29.7 ± 0.1 relative to PDB.

$\delta^{13}\text{C}$ on total organic carbon (TOC) was analyzed for twenty eight samples from ODP Holes 717C and 718C (Table 1, Fig 2). Together, these two holes provide a continuous 18 Ma record of turbidite sedimentation (Stow, et al., 1990). Prior to ca. 7 Ma, $\delta^{13}\text{C}$ values in TOC are -27 to -25‰, typical of C3 plants. The $\delta^{13}\text{C}$ data show a dramatic positive shift of 10‰ beginning near 7 Ma. $\delta^{13}\text{C}$ values in Pliocene sediments of the

Bengal Fan reach -15 to -17‰. In late Quaternary sediments $\delta^{13}\text{C}$ values decrease rapidly to -24‰. Limited $\delta^{13}\text{C}$ data from OC at DSDP Hole 218 show comparable values with the exception of one sample (Erdman, et al., 1974). Mixing of carbon from terrestrial C3 plants with OC derived from marine primary production ($\delta^{13}\text{C} \approx -20$ ‰) is unlikely to account for the observed shifts because its relative abundance in Bengal Fan sediments is low (Bertrand, et al., 1991; Meyer and Dickens, 1992; Party, 1989; Poynter and Eglinton, 1990). Rather, we interpret these variations as primarily resulting from changing mixing ratios of terrigenous C3 and C4-derived OC. Between 7 Ma and ca. 0.9 Ma, OC burial in the fan appears to have been dominated by material derived from C4 biomass. In agreement with paleosol studies in the Himalayan foreland (Quade and Cerling, in press; Quade, et al., 1989), we find no evidence for a significant C4 component in Bengal Fan OC prior to 7 Ma. The timing and magnitude of the 7 Ma $\delta^{13}\text{C}$ shift in both carbonates and OC in the Siwalik paleosols is very similar to that observed in the Bengal Fan OC. This remarkable agreement implies that the expansion of C4 plants was widespread and rapid across the G-B basin.

Discussion

C3/C4 plants distribution

$\delta^{13}\text{C}$ of TOC recorded in the Bengal Fan reflects the C3/C4 abundance in the Himalaya-Ganga-Brahmaputra system. However, in order to interpret the observed variations correctly, we must first consider the processes of carbon export and transport. Net organic carbon export from a variety of ecosystems is roughly proportional to net primary productivity (Kaplan and Newbold, 1993), and productivity of C4 plants is known to be significantly higher than that of C3 plants (Jones, 1992). Therefore, the C4 /C3 ratio recorded in Bengal Fan OC can be amplified with respect to the ratio of C4 to C3 plants in the whole catchment area. $\delta^{13}\text{C}$ of Bengal OC after 7 Ma is variable and is closely related to the other sedimentological variables such as TOC and water content of the sediments (Fig. 3). The increase of TOC in sediments younger than 7 Ma (Fig. 1) likely results from the decrease of the mean grain size (and increase of specific surface area) of the particles delivered to the fan, as has recently been shown for other marine clastic sediments (Keil, et al., 1994). Whole rock water contents (H_2O^+) reflect the relative proportion of hydrous supergene minerals (mainly smectite and vermiculite) derived via weathering in the Indo-Gangetic Plain versus less-hydrated minerals produced by physical erosion in the Himalaya (quartz, feldspars, micas, illite) (France-Lanord, et al., 1993). The relation between $\delta^{13}\text{C}$ and H_2O^+ implies that the secondary mineral assemblage is associated with OC derived from a C4-dominated ecosystem, while the "primary" mineral assemblage carries carbon from a C3-dominant ecosystem. Thus the relationship for post-7 Ma samples shown in Fig. 3 can be interpreted as a mixing line between coarse, relatively unaltered sediments associated with C3 carbon, and fine-grained, weathered sediments carrying mostly C4 carbon. The $\delta^{13}\text{C}$ variability of Bengal Fan OC contrasts with the relatively constant $\delta^{13}\text{C}$ of Siwalik paleosol carbonate and OC through this interval (Cerling, et al., 1993; Quade and Cerling, in press; Quade, et al., 1989). This suggests that, after 7 Ma, OC $\delta^{13}\text{C}$ values were

primarily controlled by changes in the source of particulate organic matter rather than by C3/C4 change over the whole source region. The coarser-grained, less weathered sediments, which we interpret to have been derived more or less directly from the Himalayan hinterland during intervals of rapid transport, may have derived more of their OC from C3-dominated forests upstream. Sediments which became incorporated into soils in the C4-dominated foreland and were weathered during intervals of slower transport carry C4 carbon. We propose that, once C4 plants became established in the G-B basin at 7 Ma, $\delta^{13}\text{C}$ variations in Bengal OC result from changes in the dynamics of the river transport system leading to changes in the source region of river POC. Essentially, under different hydrologic conditions the rivers appear to "sample" different parts of the drainage basin. For example, two mid-Pliocene samples show a brief return to low $\delta^{13}\text{C}$ values indicative of increased C3 plant carbon. These samples are illite-rich silts, associated with an interval of increased sedimentation rate and grain size. The post-0.9 Ma shift to lower $\delta^{13}\text{C}$ values is also associated with a return to rapidly deposited, coarse, illite-rich sedimentation.

The increase in the ratio of chemical weathering to physical erosion appears to be synchronous with the expansion of C4 biomass recorded both in the Bengal Fan and the Siwalik foreland. Oceanographic evidence indicates a more pronounced monsoonal climate in the region beginning 7-8 Ma (Kroon, et al., 1991; Prell, et al., 1992). Increased seasonality should favour C4 plants, and the expansion of C4 vegetation in the Siwaliks could be a consequence of the development of the monsoon (Quade, et al., 1989). More recent work has raised the possibility that the late Miocene expansion of C4 plants was a global event, perhaps driven by falling atmospheric CO_2 levels (Cerling and Quade, 1993; Ehleringer, et al., 1991), but African evidence (Morgan, et al., 1994) suggests a diachronous history. Similarly, changes in the weathering regime could reflect either climatic or tectonic control (Burbank, et al., 1993). We argue that the close coupling of the shifts in both vegetation and weathering in the Himalayan foreland can only be reasonably explained by climate change. The marked change in sediment supply beginning near 0.9 Ma correlates with a significant cooling of global climate and ice volume expansion, and the beginning of the strong 100 kyr periodicity in the marine $\delta^{18}\text{O}$ record (Ruddiman, et al., 1986). The corresponding decrease in $\delta^{13}\text{C}$ in Bengal Fan OC could indicate lower abundance or productivity for C4 plants in the G-B basin precipitated by a cooler and/or wetter climate. However, the relationship between sediment source and $\delta^{13}\text{C}$ for post-0.9 Ma samples (Fig. 3) suggests that the light carbon was primarily derived from higher in the G-B drainage system. This relationship further suggests that the hydrology and transport dynamics of the G-B river system exert first-order control over the type of OC exported to the oceans after 7 Ma.

Implications for the marine and sedimentary carbon isotope budget

The present day Ganga, Brahmaputra and Indus rivers carry 3 to 5% of the river dissolved inorganic carbon (DIC) flux (Meybeck, 1979), and > 10% of the river TOC flux (Subramanian and Ittekkot, 1991). Although the

Bengal Fan records only refractory POC from the G-B river system, it is likely that DOC and labile POC were isotopically similar (In the Amazon, for example, $\delta^{13}\text{C}_{\text{DOC}} - \delta^{13}\text{C}_{\text{POC}}$ usually $<2\%$ (Quay, et al., 1992)). Because the G-B river system is such an important source of OC, it is thus very likely that the mean global $\delta^{13}\text{C}$ of the riverine TOC input to the ocean increased significantly ca. 7 Ma. The mean $\delta^{13}\text{C}$ of the inorganic carbon input to the ocean was probably similarly affected. A large fraction of DIC in rivers is derived from respiration of organic matter, which results in river DIC with low $\delta^{13}\text{C}$ values relative to the atmosphere (Hitchon and Krouse, 1972; Longinelli and Edmond, 1983). Since isotopically heavy carbon derived from C4 plants began to contribute significantly to the carbon load of the G-B rivers at ca. 7 Ma, the mean $\delta^{13}\text{C}$ of marine DIC should also have increased. A 5% increase in the $\delta^{13}\text{C}$ of 10% of the global river TOC flux would be sufficient to change the mean $\delta^{13}\text{C}$ of marine bicarbonate by $+0.5\%$. The $\delta^{13}\text{C}$ record of marine carbonates is complex during this interval, and not all records agree (Broecker and Woodruff, 1992). We note that $\delta^{13}\text{C}$ of bulk marine carbonate, which has been proposed to be the best estimate of the global ocean carbon budget, increases by ca. 0.5% near 7 Ma (Shackleton and Hall, 1984), as do several foraminiferal records from both the Atlantic and Pacific e.g. (Wright, et al., 1991).

The expansion of C4 photosynthetic plants in the terrestrial environment has implications for interpreting the Late Cenozoic carbon isotope record as well. As noted above, the Neogene OC burial flux in the Bengal and Indus Fan, associated deltas and foreland basins probably represents $\sim 15\%$ of the global total. From ca. 7 to 1 Ma, the OC buried in the Bengal Fan was 7-10% less depleted in ^{13}C than it had been prior to 7 Ma. Consequently, the global ^{13}C depletion of sedimentary organic carbon relative to carbonate, $\delta^{13}\text{C}_{\text{carb}} - \delta^{13}\text{C}_{\text{org}} = \Delta\text{B}$ (Hayes, et al., 1989), must have decreased by 1-2%. If C4 plant-derived carbon was an important component of OC burial in other regions (Cerling, et al., 1993) this effect would have been correspondingly greater. Carbon isotope depletion produced by marine algae appears to have decreased by 5-7%, mostly by early Neogene time (Popp, et al., 1989). The value of ΔB at any given time depends on the relative proportions of marine and terrestrial organic carbon burial as well as the depletion associated with each. Because of the large changes in carbon isotope depletion associated with photosynthesis in both the marine and terrestrial habitats models of the Cenozoic sedimentary carbon isotope mass balance must take these effects into account (Derry, 1993; Kump, 1989).

Acknowledgements - The authors are grateful to Todd Dawson and Jay Quade for helpful discussions. This study was carried out under the auspices of the CNRS program "Dynamique et Bilan de la Terre - Erosion et Hydrogéologie". CNRS-INSU-DBT contribution # 715 and CRPG-CNRS contribution # 1069.

REFERENCES

Bertrand P., Lallier-Verges E. and Grall H. (1991) Organic petrology of Neogene sediments from North Indian ocean (Leg 117): amount, type,

- and preservation of organic matter. In Proc. ODP Sci. Res. (ed. W. L. Prell et al.), Vol. 117, pp. 587-594. Ocean Drilling Program.
- Bouquillon A. (1987) Influence continentales et marines dans les sédiments Cénozoïques de l'océan Indien Nord Oriental.. thesis, Université de Lille Flandres-Artois.
- Bouquillon A., France-Lanord C., Michard A. and Tiercelin J.-J. (1990) Sedimentology and isotopic chemistry of the Bengal fan sediments: the denudation of the Himalaya. In Proc. ODP Sci. Res. (ed. J. R. Cochran et al.), Vol. 116, pp. 43-58.
- Broecker W. S. and Woodruff F. (1992) Discrepancies in the oceanic carbon isotope record for the last fifteen million years? *Geochim. Cosmochim. Acta* 56, 3259-3264.
- Burbank D. W., Derry L. A. and France-Lanord C. (1993) Reduced Himalayan sediment production 8 Myr ago despite an intensified monsoon. *Nature* 364, 48-50.
- Cerling T. E. and Quade J. (1993) Stable carbon and oxygen isotopes in soil carbonates. In *Climate Change in Continental Isotopic Records* (ed. P. K. Swart et al.), Vol. 78, pp. 217-231. AGU.
- Cerling T. E., Wang Y. and Quade J. (1993) Expansion of C4 ecosystems as an indicator of global ecological change in the late Miocene. *Nature* 361, 344-345.
- Cochran J. R. (1990) Himalayan uplift, sea level, and the record of Bengal fan sedimentation at the ODP Leg 116 Sites. In Proc. ODP Sci. Res. (ed. J. R. Cochran et al.), Vol. 116, pp. 397-414. Ocean Drilling Program.
- Cochran et al. (1989) Initial Reports Sites 717-718-719 Distal Bengal Fan. In Proc. ODP Init. Rep. Vol. 116, Ocean Drilling Program.
- Curray J. R. (1991) Postcollision sediments in the Bay of Bengal. *EOS* 72, 250.
- Curray J. R. and Moore D. G. (1971) Growth of the Bengal Deep-Sea Fan and denudation in the Himalayas. *Geol. Soc. Amer. Bull.* 82, 563-572.
- Derry L. A. (1993) Interpreting the Neogene $\delta^{13}\text{C}$ record: the effect of variable isotopic fractionation. *EOS* 74, 328 (abstr.).
- Ehleringer J. R., Sage R. F., Flanagan L. B. and Pearcy R. W. (1991) Climate change and the evolution of C4 photosynthesis. *Trends Ecol. Evol.* 6, 95-99.
- Erdman J. G., Schrono K. S. and Scalan R. S. (1974) Geochemistry of carbon: Legs 22,24,26,27, and 28. In *Init. Repts. DSDP*, Vol. 24, pp. 1169-1176. U.S. Gov. Printing Office.
- France-Lanord C., Derry L. and Michard A. (1993) Evolution of the Himalaya since Miocene time: isotopic and sedimentologic evidence from the Bengal Fan. In *Himalayan Tectonics* (ed. P. J. Treloar and M. Searle), Vol. 74, pp. 603-621. *Geol. Soc. Lond.*
- Gartner S. (1990) Neogene calcareous nannofossil biostratigraphy, Leg 116 (Central Indian Ocean). In Proc. ODP Sci. Res. (ed. J. R. Cochran et al.), Vol. 116, pp. 165-187. Ocean Drilling Program.
- Hayes J. M., Popp B. N., Takigiku R. and Johnson M. W. (1989) An isotopic study of biogeochemical relationships between carbonates and organic carbon in the Greenhorn Formation. *Geochim. Cosmochim. Acta* 53, 2961-2972.
- Hitchon B. and Krouse H. R. (1972) Hydrogeochemistry of the surface waters of the Mackenzie River drainage basin, Canada-III. Stable isotopes of oxygen, carbon and sulfur. *Geochim. Cosmochim. Acta* 36, 1337 - 1357.
- Ittekkot V. (1988) Global trends in the nature of organic matter in river suspensions. *Nature* 332, 436-438.
- Jones H. G. (1992) *Plants and Microclimate: a quantitative approach to environmental plant physiology.* Cambridge U. Press.

- Kaplan L. A. and Newbold J. D. (1993) Biogeochemistry of dissolved organic carbon entering streams. In *Aquatic Microbiology: An Ecological Approach* (ed. T. Ford), pp. 139-165. Blackwell Scientific.
- Keil R. G., Tsamakis E., Bor Fuh C. B., Giddings J. C. and Hedges J. I. (1994) Mineralogical and textural controls on the organic composition of coastal marine sediments: hydrodynamic separation using SPLITT-fractionation. *Geochim. Cosmochim. Acta* 58, 879-894.
- Kroon D., Steens T. and Troelstra S. R. (1991) Onset of monsoonal related upwelling in the western Arabian Sea as revealed by planktonic foraminifers. In *Proc. ODP Sci. Res.* (ed. W. L. Prell et al.), Vol. 117, pp. 257-263.
- Kump L. R. (1989) Alternative modeling approaches to the geochemical cycles of carbon, sulfur, and strontium isotopes. *Amer. J. Sci.* 289, 390-410.
- Lasaga A. C., Berner R. A. and Garrels R. M. (1985) An improved model of atmospheric CO₂ fluctuations over the past 100 million years. In *The Carbon Cycle and Atmospheric CO₂: Natural Variations Archean to Present* (ed. E. T. Sundquist and W. S. Broecker), pp. 397-410. American Geophysical Union.
- Lindsay J. F., Holliday D. W. and Hulbert A. G. (1991) Sequence Stratigraphy and the Evolution of the Ganges-Brahmaputra Delta Complex. *AAPG Bull.* 75, 1233-1254.
- Longinelli A. and Edmond J. M. (1983) Isotope geochemistry of the Amazon basin : a reconnaissance. *J. Geophys. Res.* 88, 3703-3717.
- Meybeck M. (1979) Concentrations des eaux fluviales en $\delta^{13}C$ majeurs et apports en solution aux océans. *Rev. Géol. Dyn. Géogr. Phys* 21, 220-227.
- Meyer P. A. and Dickens G. R. (1992) Accumulation of organic Matter in sediments of the Indian Ocean: A synthesis of results from scientific deep sea drilling. In *Synthesis of Results from Scientific Drilling in the Indian Ocean, Geophysical Monograph* (ed. R. A. Duncan et al.), Vol. 70, pp. 295-309. American Geophysical Union.
- Milliman J. D. and Syvitski P. M. (1992) Geomorphic/Tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. *J. Geol.* 100, 525-544.
- Morgan M. E., Kingston J. D. and Marino B. (1994) Carbon isotopic evidence for emergence of C₄ plants in the Neogene from Pakistan and Kenya. *Nature* 367, 162-165.
- Popp B. N., Takigiku R., Hayes J. M., Louda J. W. and Baker E. W. (1989) The post-Paleozoic chronology and mechanism of ¹³C depletion in primary marine organic matter. *Amer. J. Sci.* 289, 436-454.
- Poynter J. and Eglinton G. (1990) Molecular composition of three sediments from Hole 717c: the Bengal Fan. In *Proc. ODP Sci. Res.* (ed. J. R. Cochran et al.), Vol. 116, pp. 155-161. Ocean Drilling Program.
- Prell W. L., Murray D. W. and Clemens S. C. (1992) Evolution and variability of the Indian Ocean Summer Monsoon: Evidence from the Western Arabian Sea Drilling Program. In *Synthesis of Results from Scientific Drilling in the Indian Ocean, Geophysical Monograph* (ed. R. A. Duncan et al.), Vol. 70, pp. 447-469. American Geophysical Union.
- Quade J. and Cerling T. E. (in press) Expansion of C₄ grasses in the Late Miocene of Northern Pakistan: Evidence from stable isotopes in paleosols. *Paleo. Paleo. Paleo.*

- Quade J., Cerling T. E. and Bowman J. R. (1989) Development of Asian monsoon revealed by marked ecological shift during the latest Miocene in northern Pakistan. *Nature* 342, 163-166.
- Quay P. D., Wilbur D. O. and Richey J. E. (1992) Carbon cycling in the Amazon River: implications from the ^{13}C compositions of particles and solutes. *Limnol. Ocean.* 37, 857-871.
- Rea D. K. (1992) Delivery of Himalayan sediment to the Northern Indian Ocean and its relation to global climate, sea level, uplift, and seawater strontium. In *Synthesis of Results from Scientific Drilling in the Indian Ocean, Geophysical Monograph* (ed. R. A. Duncan et al.), Vol. 70, pp. 387-402. American Geophysical Union.
- Ruddiman W. F., Shackleton N. J. and McIntyre A. (1986) North Atlantic sea-surface temperature for the last 1.1 million years. *Geological Society Special Publication* 21, 155-173.
- Shackleton S. J. and Hall M. A. (1984) Carbon isotope data from Leg 74 sediments. In *Initial Reports of the Deep Sea Drilling Program* (ed. T. C. Moore et al.), Vol. 74, pp. 613-619. U.S. Govt. Printing Office.
- Smith S. V. and Hollibaugh J. T. (1993) Coastal metabolism and the oceanic organic carbon balance. *Reviews of Geophysics* 31, 75-89.
- Stow D. A. V., Amano K., Balson P. S., Brass G. W., Corrigan J., Raman C. V., Tiercelin J.-J., Townsend M. and Wijayananda N. P. (1990) Sediment facies and processes on the distal Bengal Fan, Leg 116. In *Proc. ODP Sci. Res.* (ed. J. R. Cochran et al.), Vol. 116, pp. 377-396. Ocean Drilling Program.
- Subramanian V. and Ittekkot V. (1991) Carbon transport by the Himalayan rivers. In *Biogeochemistry of Major World Rivers, SCOPE* (ed. E. T. Degens et al.), Vol. 42, pp. 157-168. Jhon Wiley & Sons Ltd.
- Wright J. D., Miller K. G. and Fairbanks R. G. (1991) Evolution of modern deepwater circulation: evidence from the Late Miocene southern ocean. *Paleoceanography* 6, 275-290.

Table 1 - Total Organic Carbon contents and $\delta^{13}\text{C}$ data from Holes 717C and 718B

Sample	#depth (m)	Age* (Ma)	TOC (wt %)	$\delta^{13}\text{C}$ (‰)
Hole 717C				
2 H 2 - (60-61)	15.6	0.1	0.22	-24.0
4X2 - (9-10)	28.6	0.2	0.47	-22.3
5X1 - (51-52)	37.0	0.2	1.75	-20.8
6X3 - (22-23)	49.2	0.3	0.19	-24.4
7X2 - (20-21)	57.2	0.3	0.13	-23.1
8X1 - (50-51)	65.5	0.4	0.21	-21.3
15XCC - (6-7)	114.8	0.7	0.18	-24.8
21X3 - (145-146)	164.5	1.1	2.26	-18.3
22X5 - (25-26)	175.8	1.3	1.58	-16.6
30X2 - (8-9)	247.1	2.4	1.72	-15.5
31X2 - (10-11)	256.6	2.5	1.68	-15.5
36X5 - (77-78)	309.3	3.4	1.66	-19.4
37X1 - (79-80)	312.8	3.4	0.31	-23.1
40X4 - (105-106)	346.1	3.9	0.53	-21.9
41X1 - (36-37)	350.4	4.0	1.81	-17.1
51X5 - (13-14)	451.1	5.6	1.82	-18.3
53XCC - (32-33)	473.5	5.9	1.45	-19.7
55X2 - (95-96)	485.5	6.1	1.92	-19.0
61X2 - (50-51)	542.0	6.9	0.46	-26.0
66X4 - (7-8)	592.1	7.4	1.19	-25.1
71X3 - (99-100)	639.0	7.9	0.38	-25.4
81X1 - (49-50)	730.5	8.5	0.48	-24.9
91X1 - (70-71)	819.4	8.9	0.40	-24.8
Hole 718C				
60X1 - (100-101)	570.8	13.0	0.15	-24.8
68X1 - (67-68)	646.5	14.2	0.40	-25.8
78X5 - (34-35)	747.1	15.9	0.21	-25.5
86X1 - (89-90)	817.7	17.1	0.59	-25.8
95X1 - (59-60)	897.6	18.4	0.35	-25.0

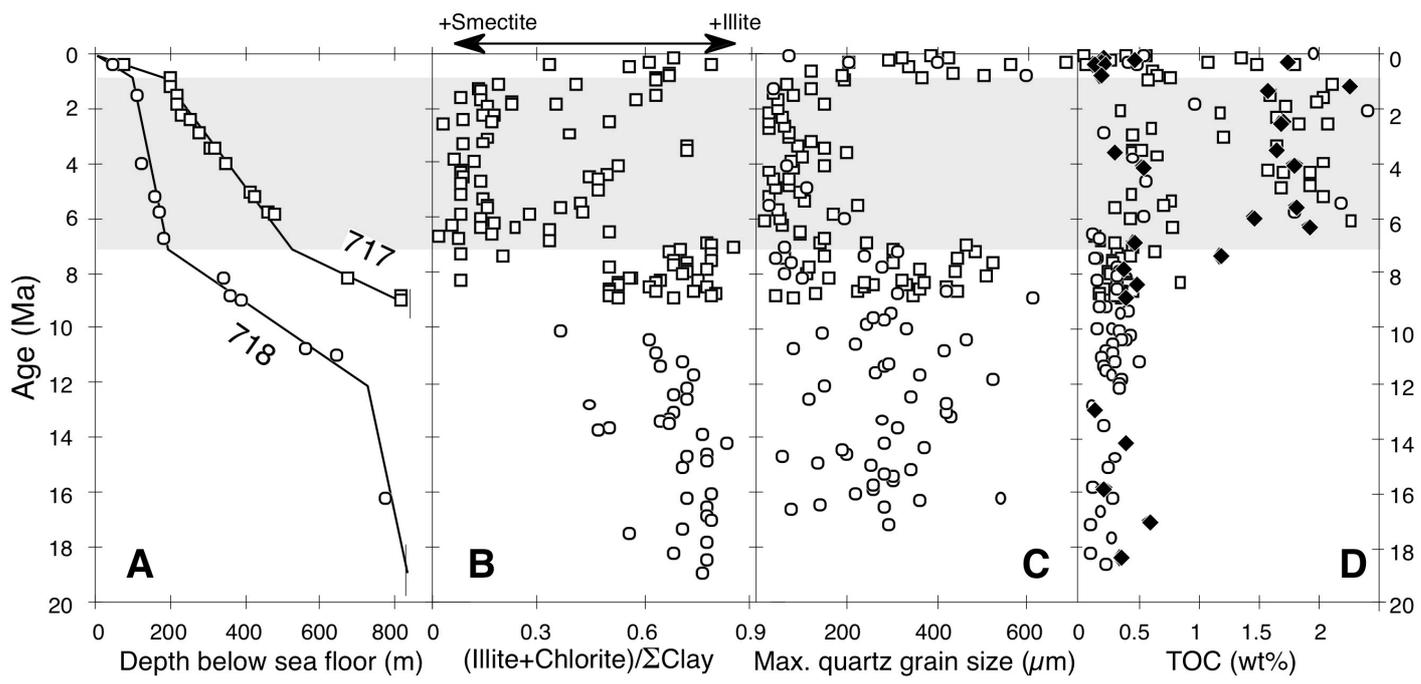
*Ages are estimated from biostratigraphic data (Gartner, 1990).

Figure captions

Fig. 1. Age dependence with (A) sediment thickness (Gartner, 1990), (B) clay mineralogy (Bouquillon, et al., 1990), (C) maximum quartz grain size and (D) TOC content (Cochran et al., 1989) at ODP Sites 717 (\square) and 718 (o) and data in this study(\blacklozenge). A : lower slopes correspond to higher sedimentation rates. B : (Illite+chlorite)/ Σ clay ratios are measured on $<2\mu\text{m}$ fractions. They mostly reflect the relative abundance of illite versus smectite. In the Bengal Fan, illite and chlorite are derived from metamorphic precursors by physical erosion whereas smectite is primarily derived from weathering of the same material (France-Lanord, et al., 1993). %TOC appears to reflect grain size/specific surface area of sediments (Keil et al. 1994).

Fig. 2. $\delta^{13}\text{C}$ of TOC in Bengal Fan sediments plotted against age in Holes 717C and 718B. The increase of $\delta^{13}\text{C}$ values at ca. 7 Ma reflects the increase of the C4/C3 plant ratio in the source of the organic matter. The $\delta^{13}\text{C}$ increase near 7 Ma closely parallels that observed in paleosol studies in the Himalayan foreland (e.g., Cerling, et al., 1993), but the decrease after 0.9 Ma is not observed in the paleosol data. Variations in $\delta^{13}\text{C}$ are correlated with variations in sedimentation rate, grain size and clay mineralogy (Fig. 1).

Fig. 3. Variations of $\delta^{13}\text{C}$ of TOC with (A) TOC content, and (B) H_2O^+ content for sediments of Holes 717C and 718B. H_2O^+ is calculated from loss on ignition of whole rock analysis corrected for carbonate and TOC contents, after drying at 110°C for 24 hours. Symbols: \square samples > 7 Ma; \bullet = 7 to 0.9 Ma; Δ < 0.9 Ma. In samples < 7 Ma, the relationships between $\delta^{13}\text{C}$, TOC and H_2O^+ suggest that Bengal Fan OC contains a mixture of C3-derived material associated with coarser, unweathered sediments and C4-derived carbon associated with weathered, fine-grained sediments.



France-Lanord & Derry
Fig 1

France-Lanord & Derry
Fig 2

