Organic carbon exhumation and global warming during the early Himalayan collision

Richard A. Beck
Douglas W. Burbank
Department of Earth Sciences, University of Southern California, Los Angeles, California 90089-0740
William J. Sercombe
Thomas L. Olson
Amoco Production Company, 501 Westlake Boulevard, Houston, Texas 77253
Asrar M. Khan
Hydrocarbon Development Institute of Pakistan, Sector 18, H/9, P.O. Box 1236, Islamabad, Pakistan

ABSTRACT

Organic carbon eroded and oxidized from marine sediments on the passive and active neo-Tethyan margins during the early Indian-Asian collision may have been sufficient to shift the carbon isotopic ratios of late Paleocene–early Eocene marine carbonates toward lighter values, and may have contributed to coeval global warming via the greenhouse effect. New limits on the timing of collision and the organic carbon content of Himalayan sedimentary sources and sinks allow us to estimate the net Paleogene flux. Our calculations suggest that continental collisions play a fundamental role in the global carbon cycle and climate through the exhumation as well as burial of organic carbon.

INTRODUCTION

Evaluation of recent hypotheses for feedback mechanisms between climate, biospheric chemistry, metamorphism, and collisional orogenesis (Fischer and Arthur, 1977; Molnar and England, 1990; Edmond, 1992; Burbank, 1992; Kerrick and Caldeira, 1993; Raymo, 1994; Selverstone and Gutzler, 1993) requires knowledge of both the nature and timing of continent-continent collisions. One logical place to investigate tectonic-climatic hypotheses for global change is the Himalayan-Tibetan region, because of its scale and the continually improving chronology data about its history. The present topographic and climatic expression of the region is easily appreciated, if not well understood (Molnar and England, 1990; Raymo, 1994). The possible isotopic and climatic effects of oceanic closure and initial continent-continent contact are controversial and less-well appreciated (Kerrick and Caldeira, 1993; Selverstone and Gutzler, 1993).

Following a review of global carbon sources and sinks, Kerrick and Caldeira (1993) proposed that volatilization of carbonate rocks during regional metamorphism in the Himalayan orogen may have been responsible for the marked early Cenozoic increase in temperature and, by inference, atmospheric CO_2. Selverstone and Gutzler (1993) challenged the notion that significant quantities of CO_2 are volatilized from carbonates during collisional metamorphism. They postulated that subduction of as little as 10^{16} to 10^{17} mol of carbon over 125 m.y. (flux $\sim 10^{14}$ to 10^{15} mol/m.y.) and its storage in metamorphic rocks during the Alpine-Himalayan orogeny have had a damping effect on global surface temperature during the Late Cretaceous and Cenozoic (Selverstone and Gutzler, 1993).

HYPOTHESIS

It is evident that a consensus regarding the net effect of early continental collision on the CO_2 content of the atmosphere and global temperature does not yet exist. Nonetheless, any tectonic mechanism for climate change involving the carbon cycle must be reconciled with the carbon isotopic composition of marine carbonates ($\delta^{13}C_{carb}$) (Shackleton, 1987) either directly or through additional, possibly independent, mechanisms. We investigate one of the more immediate consequences of continent-continent collisions: the exhumation of *organic* carbon (C_{org}) from strata at colliding active and passive margins.

We present evidence that (1) the timing of early Himalayan thrusting and exhumation of C_{org} (kerogen, bitumen, and mobile hydrocarbons including methane) from neo-Tethyan strata above the north Indian shelf coincides with and is quantitatively compatible with the rapid decrease of $\delta^{13}C_{carb}$ near the Paleocene-Eocene boundary, and (2) collision-related C_{org} fluxes are comparable to those of competing carbon-generating hypotheses for late Paleocene–early Eocene global warming (Kerrick and Caldeira, 1993; Selverstone and Gutzler, 1993; Beck et al., 1994).

The cause of the early to late Paleocene increase of $\delta^{13}C_{carb}$ (Fig. 1) is not known (Zachos et al., 1992). Organic carbon is strongly enriched in ^{12}C by photosynthesis. Approximately 99.95% of all C_{org} is stored in the sedimentary and metasedimentary reservoirs (Tissot and Welte, 1978). An increase in the size of the lithospheric C_{org} reservoir would increase the $^{13}C/^{12}C$ ratio of the minute oceanic and atmospheric reservoirs (Shackleton, 1987). Rapid fluctuations in sea level or erosion of the Trans-Himalayan arc (e.g., Raymo, 1994) during earliest collision that may have increased the nutrient flux and oceanic productivity, increased sedimentation rates and focused deposition (e.g., modern Mediterranean), and restricted circulation resulting in anoxia are all possible contributors to an increase in the apparent rate of C_{org} burial (e.g., Calvert, 1987).

Conversely, a relative increase in the flux of C_{org} to the biosphere could be responsible for the observed decrease in $\delta^{13}C_{carb}$ during isotopically and paleofloristically inferred late Paleocene to early Eocene increases of temperature (T) and the partial pressure of carbon dioxide (PCO_2) (Wolfe and Poore, 1982; Zachos et al., 1992; Sloan et al., 1992) (Fig. 1). If the C_{org} source was imbricated Asian and Indian active- and passive-margin strata, a decline in $\delta^{13}C_{carb}$ should have begun after collision. As predicted by this hypothesis, the Cenozoic $\delta^{13}C_{carb}$ maximum that occurred during the

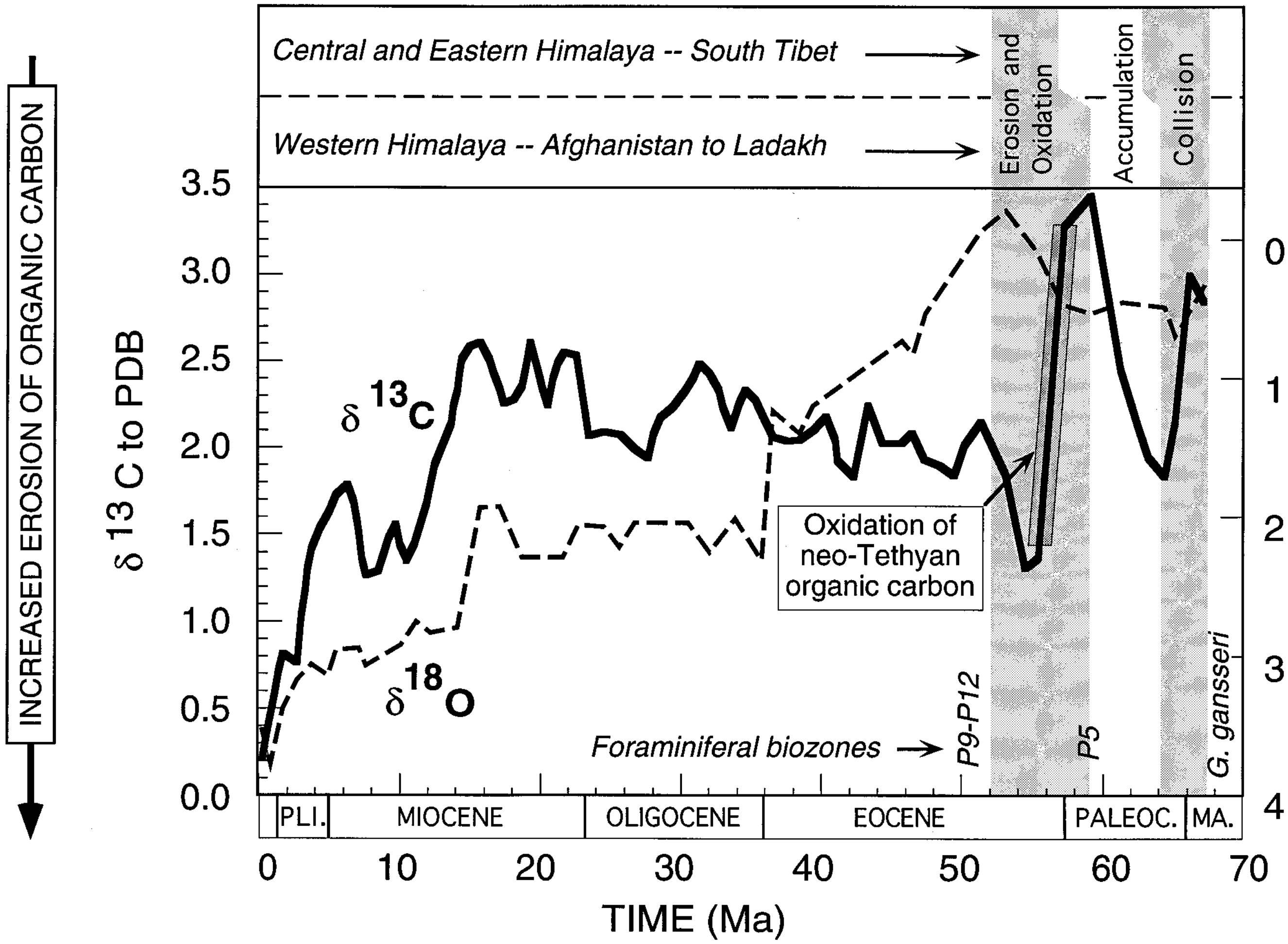

Figure 1. Values of $\delta^{18}O$ and $\delta^{13}C$ for marine Cenozoic carbonate strata (Shackleton, 1987) vs. timing of initial Indian-Asian collision with consequent erosion of organic carbon-bearing north Indian slope, outer shelf, south Asian fore arc and accretionary prism. Initial collision is determined as postdating *G. ganserri* and being prior to end of P5 foraminiferal biozones (Beck et al., 1995). PLI.—Pliocene, PALEOC.—Paleocene, MA.—Maastrichtian.

P5 *Morozovella velascoensis* subbiozone (Shackleton, 1987) preceded massive exhumation during early Indian-Asian collision (Fig. 1) (Beck et al., 1995). The subsequent decrease in $\delta^{13}C_{carb}$ lasted ~4 m.y. (Shackleton, 1987) and coincided with vigorous erosion and oxidation of neo-Tethyan strata prior to deposition of overlying shallow-marine upper lower Eocene limestones and shales in northwestern Pakistan (Beck et al., 1995). The contemporaneous late Paleocene to middle Eocene positive excursion of $^{187}Os/^{186}Os$ values in marine clays has also been attributed to the erosion of Himalayan shales (Pegram, 1992).

Erosion and oxidation of sedimentary C_{org} to CO_2 at the lithosphere-biosphere interface avoids the subducted carbonate volatilization controversy (Kerrick and Caldeira, 1993; Selverstone and Gutzler, 1993) and has previously been postulated to occur during eustatic sea-level falls (Broecker, 1982). However, the general upward trend of late Paleocene–early Eocene sea levels (Hallam, 1992) suggests that the apparent increase of C_{org} erosion was not driven by eustatic sea-level fall.

FLUX ESTIMATES

Changes in the sedimentary C_{org} reservoir must be compatible with the $\delta^{13}C_{carb}$ record. Shackleton's (1987) carbon isotope mass-balance calculations for the late Paleocene–early Eocene negative shift in $\delta^{13}C_{carb}$ values (~2.2‰) (Fig. 1) suggest a net decrease in the rate of C_{org} burial of $\sim 1.6 \times 10^{18}$ mol/m.y., which was sustained for ~4 m.y. Thus, we have a standard against which to measure the feasibility of our hypothesis for the exhumation of C_{org} during the Indian-Asian collision.

We used a simple sediment budget in combination with measured total C_{org} (TOC) values from sedimentary sources and sinks to estimate the net quantity of early Himalayan C_{org} exhumed. Our sediment/C_{org} budget (Table 1) assumes that geometric cross sections of the Sumatran active margin (Hamilton, 1988) and the modern Atlantic passive margin (Grow, 1981) are reasonable analogs for the Himalayan segment of the neo-Tethyan accretionary prism and fore arc (Hamilton, 1988) and north Indian passive margin (e.g., Brookfield, 1993). We also assume that TOC values for shales of the Asian active margin and north Indian passive margin (Table 2) are representative of analogous strata along the suture (Meyers and Dickens, 1992; Karunakaran and Rao, 1976). Early erosion of most of the former Asian active and Indian outer passive-margin strata along the Himalaya is also a core assumption of our hypothesis. This assumption is supported in northwestern Pakistan by large quantities of reworked Jurassic pollen and dinoflagellates and Cretaceous chert and ultramafic clasts in late Paleocene–early Eocene strata that are securely dated on the basis of foraminifera as well as by

TABLE 1. ESTIMATES OF THE ORGANIC CARBON FLUX DURING THE INITIAL COLLISION OF INDIA AND ASIA

Sedimentary organic carbon source	Cross-sectional area (km^2)	Density (10^{15} g/km^3)	Fraction deformed and eroded	Shale fraction of strata	TOC values of pre-collisional strata (wt%)	Duration of erosion (m.y.)	Fraction of sediment redeposited as red beds	TOC values for sediments re-deposited as red beds (wt%)	Fraction of sediment redeposited as marine sediments (not red beds)	TOC values sediments redeposited in marine shale (wt%)	Net flux of organic carbon released to atmosphere and hydrosphere (10^{15} mol/m.y.)	Net flux of organic carbon from prism and passive margin (less eclogite sink) (10^{15} mol/m.y.)
Himalayan prism	1600	2.0	0.9	0.75	0.3	4	0.25	0.06	0.75	0.2	63	
Himalayan fore arc	450	2.4	0.9	0.75	1.5	4	0.25	0.06	0.75	0.2	477	
N. Indian slope and rise	1400	2.4	0.9	0.85	1.0	4	0.25	0.06	0.75	0.2	1050	
N. Indian outer shelf	250	2.4	0.2	0.65	1.5	4	0.25	0.06	0.75	0.2	9	
Totals											1600	1550

Note: Length of orogen = 2500 km. TOC--total organic carbon.

TABLE 2. TOTAL ORGANIC CARBON DATA FOR PRECOLLISIONAL STRATA

Lithosome	Period, epoch or stage	No. of samples	Avg. TOC (wt%)	Location	Reference
Prism	Middle - Upper Cretaceous	51	0.3	Pakistan	This study
Slope	Neocomian	n.a.	1.0	NW Australia	Meyers and Dickens (1992)
Outer shelf	Carnian-Rhaetian	n.a.	1.5	NW Australia	Meyers and Dickens (1992)
	Oxfordian-Tithonian	n.a.	1.5	NW Australia	Meyers and Dickens (1992)
	Berraisian-Valenginian	n.a.	1.5	NW Australia	Meyers and Dickens (1992)
	Mid-Jurassic - Lower Cretaceous	n.a.	1.5	Nepal	Thurow et al. (1992)
Inner shelf	Jurassic-Cretaceous	42	0.82	Pakistan	This study
Flysch	Paleocene - early Eocene	68	0.18	Pakistan	This study
Molasse	Paleocene-Miocene	n.a.	0.06	India	Karunakaran and Rao (1976)

Note: Source of variables discussed in text. TOC--total organic carbon.

upper lower Eocene strata, which unconformably overlie klippen of Indian slope and Asian accretionary-prism strata (Beck et al., 1995). Remnants of the active and passive margins provide lower limits on their original C_{org} contents (Thurow et al., 1992; Gaetani and Garzanti, 1991).

To determine the magnitude of the precollisional C_{org} source, we subdivided two-dimensional cross sections of the active- and passive-margin analogs to estimate more precisely the relative proportion of shale and nonshale rocks, their densities, and respective TOC values. The cross-sectional areas were multiplied by the length of the Himalayan mountain chain (2500 km) to estimate their precollisional volumes. Representative densities were taken from analogs determined by seismic, well-bore, and gravity data (Hamilton, 1988; Grow, 1981). Average shale contents were estimated from published data on Himalayan outcrops (Sinha and Upadhyay, 1990; Meissner et al., 1975) or analogous strata from similar tectonic environments (Seuss et al., 1987) (Table 1). We multiplied the resulting mass of shale in each subdivision (Table 1) by average TOC values from Himalayan strata, strata with which they were once continuous, or analogous strata (Table 2) to obtain the mass of C_{org} stored in each subdivision.

The north Indian passive margin and the northwest Australian margin with which it was once continuous are remarkable for the abundance of C_{org}-rich strata they contain (Gaetani and Garzanti, 1991; Meyers and Dickens, 1992; Thurow et al., 1992). Permian, Triassic, Jurassic, and Cretaceous outer shelf shales in northern India (Gaetani and Garzanti, 1991) and Nepal contain 1–2 wt% TOC or more (Meyers and Dickens, 1992), despite at least low-grade metamorphism (Gaetani and Garzanti, 1991). We included only shale-dominated strata of the active margin, the north Indian slope, and 20% of the outermost shelf in our C_{org} source estimates. The constant Paleogene carbonate compensation depth (CCD) (Rea, 1993) suggests that calcium and magnesium carbonates were redeposited with little or no effect on oceanic carbon isotope ratios or atmospheric CO_2 (e.g., Shackleton, 1987). TOC values for sandstones in the Indian shelf and slope and the molasse are low (<0.2 wt%, this study). Thus, for the sake of simplicity, we made the conservative assumption that the nonshale fraction of pre- and postcollisional sedimentary material had a TOC value equal to 0 wt%.

TOC data (Table 2) were also used to estimate the magnitude of the syndeformational sedimentary C_{org} sink. We assumed that 25% of all the eroded sediment (shale and nonshale fractions) was redeposited in the $\leq$8-km-thick Paleogene red-bed facies (Karunakaran and Rao, 1976) (average TOC = 0.06 wt%) and the remaining 75% in the green-shale–rich marine flyschoid facies. New TOC analyses ($n = 68$) distributed vertically through the Paleocene to middle Eocene marine flysch facies yield an average TOC value of 0.2 wt%. Accordingly, our budget suggests that ~30% of the total C_{org} in the active and passive margins was reburied by its own detritus (Table 1).

The rate of India-Asia convergence and the geometry of the colliding margins will determine the rate at which sedimentary C_{org} is uplifted and eroded. To estimate C_{org} fluxes, we must know the duration of this presumably diachronous process. Initial collision is determined as pre–earliest Eocene (pre–56 Ma) (Beck et al., 1995) for the western one-third of the Himalayan suture, and recent field work in south Tibet indicates that contraction commenced in the Paleocene, and it is attributed to the approach of the Indian continental margin (Burg and Chen, 1984; Einsele, et al., 1995).

We estimate a duration of 4 m.y. (~60–56 Ma) for the closure of the Himalayan segment of neo-Tethyan remnant ocean basins and the initial stages of Indian-Asian collision. Between 600 and 800 km of convergence would have occurred during this interval (Dewey et al., 1989). This implies a sediment flux of 1.97 km^3/yr, which is similar to the modern Himalayan value of 1.06 km^3/yr (Summerfield and Hulton, 1994), and a C_{org} flux of $\sim 1.6 \times 10^{18}$ mol/m.y., which is comparable to the apparent decrease in C_{org} burial predicted by Shackleton (1987). We conclude that organic carbon exhumed from the early Himalayan active and passive margins may have depressed late Paleocene–early Eocene $\delta^{13}C_{carb}$ values and may have driven Paleogene global warming by increasing the atmospheric concentrations of the greenhouse gases CH_4 and CO_2.

ACKNOWLEDGMENTS

Supported by grants (to Burbank) from Amoco, the National Science Foundation, and the National Geographic Society and by Fulbright Fellowships and Achievement Rewards for College Scientists (to Beck). We thank P. Molnar, M. Raymo, J. Edmond, B. C. Burchfiel, J. Hedges, M. Pasley, L. Stott, D. Hammond, R. Ku, W. Berelson, A. Fischer, R. Douglas, D. Kerrick, K. Caldeira, and A. Sinha for providing valuable reviews and references. Beck and Burbank thank staff of the Department of Earth, Atmospheric, and Planetary Sciences at the Massachusetts Institute of Technology for their hospitality during preparation of this manuscript.

REFERENCES CITED

Beck, R. A., Burbank, D. W., Sercombe, W. J., Olson, T. L., and Khan, A. M., 1994, Organic carbon exhumation and climate change during the early Himalayan collision: Geological Society of America Abstracts with Programs, v. 26, no. 7, p. A162.

Beck, R. A., and 13 others, 1995, Stratigraphic evidence for an early collision between northwest India and Asia: Nature, v. 373, p. 55–58.

Broecker, W. S., 1982, Glacial to interglacial changes in ocean chemistry: Progress in Oceanography, v. 11, p. 151–197.

Brookfield, M. E., 1993, The Himalayan passive margin from Precambrian to Cretaceous times: Sedimentary Geology, v. 84, p. 1–35.

Burbank, D. W., 1992, Causes of Himalayan uplift deduced from depositional patterns in the Ganges basin: Nature, v. 357, p. 680–683.

Burg, J. P., and Chen, G. M., 1984, Tectonics and structural zonation of Tibet, China: Nature, v. 311, p. 219–223.

Calvert, S. E., 1987, Oceanographic controls on the accumulation of organic matter in marine sediments, *in* Brooks, J., and Fleet, A. J., eds., Marine petroleum source rocks: Geological Society of London Special Publication 26, p. 137–153.

Dewey, J. F., Cande, S., and Pitman, W. C., III, 1989, Tectonic evolution of the India/Eurasia collision zone: Eclogae Geologicae Helvetiae, v. 82, p. 717–734.

Edmond, J. M., 1992, Himalayan tectonics, weathering processes, and the strontium isotope record in marine limestones: Science, v. 258, p. 1594–1597.

Einsele, G., and 11 others, 1995, The Xigase forearc basin: Evolution and facies architecture (Cretaceous, Tibet): Sedimentary Geology (in press).

Fischer, A. G., and Arthur, M. A., 1977, Secular variations in the pelagic realm, *in* Cook, H. E., and Enos, P., eds., Deep water carbonate environments: Society of Economic Paleontologists and Mineralogists Special Publication 25, p. 19–50.

Gaetani, M., and Garzanti, E., 1991, Multicyclic history of the northern India continental margin (Northwestern Himalaya): American Association of Petroleum Geologists Bulletin, v. 75, p. 1427–1446.

Grow, J. A., 1981, The Atlantic margin of the United States, *in* Bally, A. W., ed., Geology of passive continental margins: American Association of Petroleum Geologists Education Course Note Series 19, p. 1–40.

Hallam, A., 1992, Phanerozoic sea-level changes: New York, Columbia University Press, 266 p.

Hamilton, W. B., 1988, Plate tectonics and island arcs: Geological Society of America Bulletin, v. 100, p. 1503–1527.

Karunakaran, C., and Rao, A. R., 1976, Status of exploration for hydrocarbons in the Himalayan region—Contributions to stratigraphy and structure: New Delhi, India, Oil and Natural Gas Commission, Himalayan Geology Seminar, v. 3, p. 49–69.

Kerrick, D., and Caldeira, K., 1993, Paleoatmospheric consequences of CO_2 released during early Cenozoic regional metamorphism in the Tethyan orogen: Chemical Geology, v. 108, p. 201–230.

Meissner, C. R., Hussain, M., Rashid, M. A., and Sethi, U. B., 1975, Geology of the Parachinar quadrangle, Pakistan: U.S. Geological Survey Professional Paper 716, p. 1–24.

Meyers, P. A., and Dickens, G. R., 1992, Accumulations of organic matter in sediments of the Indian Ocean: American Geophysical Union Monograph 70, p. 295–309.

Molnar, P., and England, P., 1990, Late Cenozoic uplift of mountain ranges and global climate change: Chicken or egg?: Nature, v. 346, p. 29–34.

Pegram, W. J., 1992, The record of sea water $^{187}Os/^{186}Os$ variation through the Cenozoic: Earth and Planetary Science Letters, v. 113, p. 569–576.

Raymo, M., 1994, The Himalayas, organic carbon burial, and climate in the Miocene: Paleoceanography, v. 9, no. 3, p. 399–404.

Rea, D. K., 1993, Geologic records in deep sea muds: GSA Today, v. 3, p. 208–210.

Selverstone, J., and Gutzler, D. S., 1993, Post–125 Ma carbon storage associated with continent-continent collision: Geology, v. 21, p. 885–888.

Seuss, E., Kulm, L. D., and Killingley, J. S., 1987, Coastal upwelling and a history of organic-rich mudstone deposition off Peru, *in* Brooks, J., and Fleet, A. J., eds., Marine petroleum source rocks: Geological Society of London Special Publication 26, p. 181–197.

Shackleton, N. J., 1987, The carbon isotope record of the Cenozoic: History of organic carbon burial and of oxygen in the ocean and atmosphere, *in* Brooks, J., and Fleet, A. J., eds., Marine petroleum source rocks: Geological Society of London Special Publication 26, p. 423–434.

Sinha, A. K., and Upadhyay, R., 1990, Subduction accretion and subduction kneading: A possible mechanism for the incorporation of sedimentary sequences within the Ophiolite mélange belt in the Western Ladakh Himalaya, India: Journal of Himalayan Geology, v. 1, p. 259–264.

Sloan, L. C., Walker, J. C. G., Moore, T. C. J., Rea, D. K., and Zachos, J. C., 1992, Possible methane-induced polar warming in the early Eocene: Nature, v. 357, p. 320–322.

Summerfield, M. A., and Hulton, N. J., 1994, Natural controls of fluvial denudation rates in major world drainage basins: Journal of Geophysical Research, v. 99, no. B7, p. 13,871–13,883.

Thurow, J., Brumsack, H. J., Littke, R., Meyers, P., and Rullkotter, J., 1992, The Cenomanian/Turonian boundary event in the Indian Ocean: American Geophysical Union Monograph 70, p. 253–274.

Tissot, B. P., and Welte, D. H., 1978, Petroleum formation and occurrence: A new approach to oil and gas exploration: Berlin, Springer-Verlag, 538 p.

Wolfe, J. A., and Poore, R. Z., 1982, Tertiary marine and nonmarine climatic trends, *in* Climate in Earth history: Washington, D.C., National Academy Press, p. 154–158.

Zachos, J. C., Rea, D. V., Seto, K., Nomura, R., and Niitsuma, N., 1992, Paleogene and early Neogene deep water paleoceanography of the Indian Ocean as determined from benthic foraminifer stable carbon and oxygen isotope records: American Geophysical Union Monograph 70, p. 351–386.

Manuscript received September 26, 1994
Revised manuscript received February 1, 1995
Manuscript accepted February 8, 1995