Vol. 4, No. 3 March 1994

GSA TODAY

A Publication of the Geological Society of America

INSIDE

Metamorphic CO_2 Degassing and Early Cenozoic Paleoclimate

*Derrill M. Kerrick, Ken Caldeira**
Earth Systems Science Center and Department of Geosciences, Pennsylvania State University, University Park, PA 16802

ABSTRACT

Due in part to enhanced atmospheric CO_2 content, the Eocene was the warmest period in the Cenozoic. Global carbon cycle modeling suggests that metamorphic CO_2 fluxes to the atmosphere of $\geq 10^{18}$ mol/m.y. would have markedly affected the Eocene paleoclimate. The Himalayan orogen, which formed during the closing of the Tethys and consequent Late Cretaceous–Early Tertiary collision of the Indian and Asian plates, is one of the world's largest early Cenozoic metamorphic belts. On the basis of estimates for the duration of prograde metamorphism, volumetric proportions and bulk compositions of CO_2-source rocks, and the total volume of crust undergoing metamorphism, we estimate that between 10^{18} and 10^{19} mol/m.y. of CO_2 were generated at depth by metamorphic degassing in the Himalayan orogen alone. Furthermore, considerable CO_2 may have been generated from early Cenozoic metamorphism in the Mediterranean Tethys and circum-Pacific orogenic belts. If a significant fraction of this CO_2 escaped to Earth's surface, perhaps through focused fluid flow along shear zones such as the Main Central thrust in the Himalaya orogen, there would have been detectable paleoclimatic consequences. India-Asia collision may have contributed to Eocene warming, in addition to proposed post-Eocene cooling.

INTRODUCTION

Freeman and Hays (1992) estimated late Eocene atmospheric CO_2 contents to be about twice the modern value, based on analysis of the carbon isotopic composition of porphyrins from ancient phytoplankton. Using a similar method on bulk organic carbon, M. A. Arthur et al. (1991, personal commun.) reported preliminary Eocene atmospheric CO_2 estimates that are about six times the modern value. This CO_2 would have contributed to greenhouse warming in the Eocene (Fig. 1). CO_2 released to the atmosphere from orogenic metamorphism would have contributed to this enhanced atmospheric content. In this paper, we focus on CO_2 released during Himalayan collisional orogenesis and attempt to quantify the paleoatmospheric consequences of this CO_2 degassing.

There remains considerable uncertainty regarding the sources and fluxes of CO_2 from Earth degassing (Touret, 1992; Varekamp et al., 1992). In contrast to emissions from volcanoes and mid-ocean ridges (e.g., Gerlach, 1991), the past and present fluxes from other sources have received little attention.

HIMALAYAN METAMORPHIC CO_2 PRODUCTION

The following provides an analysis of factors affecting CO_2 production during Himalayan metamorphism. Quantification of the amount of metamorphic CO_2 produced at depth requires data on the timing and duration of prograde (increasing temperature) metamorphism, bulk compositions and volumetric proportions of CO_2 source rocks, and the total volume of the Himalayan orogen that underwent early Cenozoic metamorphism.

Timing and Duration of Metamorphism

The Himalayan orogen (Fig. 2) formed during Late Cretaceous–early Tertiary time from the closure of the Neo-Tethys and subsequent collision of the Indian and Asian plates (Searle, 1991). Two major phases of metamorphism affected the Himalayan orogen: postcollisional Barrovian-type regional metamorphism that affected a huge volume of rock within the orogen (Fig. 2B), followed in the Oligocene-Miocene by a less extensive, lower pressure regional metamorphism (Sorkhabi and Stump, 1993). The pervasive Barrovian metamorphism may have been the most significant CO_2-producing metamorphic event in the orogen.

Definitive radiometric evidence for early Cenozoic metamorphism is confined to the western part of the Himalayan orogen (i.e., west of Zanskar; Fig. 2B). Treolar et al.'s (1989) analysis implies that prograde metamorphism lasted 5–10 m.y. following collision at 50-55 Ma, and DiPietro (1991) concluded that prograde metamorphism in the Lower Swat area of northern Pakistan lasted 7–16 m.y. and culminated in the late Eocene (ca. 38 Ma). If so, prograde metamorphism would have postdated the late Paleocene warming. However, recent radiometric age determination suggests that metamorphism may have culminated by 45-50 Ma (Smith et al., 1992; Tonarini et al., 1993; Sorkhabi and Stump, 1993). If collision occurred as early as 65 Ma as suggested by Klootwijk et al. (1992) and Smith et al. (1992), prograde metamorphism would have been contemporaneous with the late Paleocene warming. In spite of the lack of definitive geochronologic data, several workers (Hodges and Silverberg, 1988; Hodges et al., 1988; Treloar et al., 1989; Searle et al., 1992) have alluded to the possibility that the Oligocene-Miocene metamorphic event overprinted an earlier Barrovian metamorphism that affected the entire Himalayan orogen.

Geochronologic studies (Treloar et al., 1989; DiPietro, 1991) suggest that prograde metamorphism lasted 5–15 m.y. Coupling this evidence with the duration of prograde metamorphism from the thermal modeling of England et al. (1992) for this orogen, we suggest that the duration of prograde metamorphism may have been as short as 10 m.y.

Bulk-rock Composition and Reaction Progress

Metamorphic CO_2 is produced by the breakdown (decarbonation) of carbonate minerals. We consider two primary metamorphic CO_2 source rock lithologies: carbonates and pelites.

As shown in numerous studies (e.g., Searle, 1991; DiPietro, 1991) all of the primary carbonate lithologies are common within the Himalayan orogen. However, the lack of available petrologic data for the Himalaya metacarbonate rocks precludes determining an average reaction progress for carbonate rocks in the Himalayan orogen. Thus, we computed CO_2 loss for a model carbonate-rock reaction progress

Paleoclimate *continued on p. 62*

Challenger mission photo showing the Karakoram and Himalaya Mountain ranges. Photo from the U.S. Department of the Interior, U.S. Geological Survey EROS Data Center.

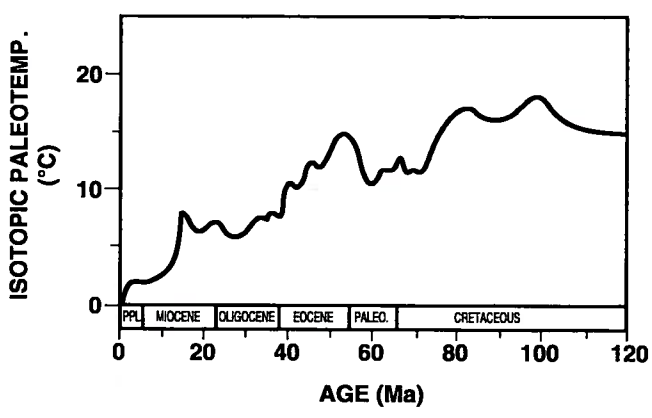

Figure 1. Deep-ocean paleotemperatures derived from benthic foraminiferal oxygen isotopes (from Douglas and Woodruff, 1981). These data indicate the temperature of ocean deep water (a sensitive indicator of global climate change).

* Present address: Physics/G Division, Lawrence Livermore National Laboratory, Livermore, CA 94550.

Each month, *GSA Today* features a short science article on fast-breaking items or current topics of general interest to the 17,000 members of GSA. What do you think of these articles? Do you have an idea for an article that you would like to see published in *GSA Today*? If so, please contact Eldridge Moores, Science Editor, *GSA Today*, (916) 752-0352, fax 916-752-0951.

Paleoclimate *continued from p. 57*

from the average orogenic carbonate rock bulk composition of Ronov et al. (1990). For this bulk composition, we assume that all MgO (4.10 wt%) and Al_2O_3 (3.44 wt%) are assigned to tremolite and zoisite, respectively, in the greenschist facies, whereas these components are assigned to diopside and grossular, respectively, in the amphibolite facies. Model reactions to form these phases are

5 dolomite + 8 quartz + H_2O = tremolite + 3 calcite + $7CO_2$,

3 anorthite + calcite + H_2O = 2 zoisite + CO_2

for the greenschist facies, and

dolomite + 2 quartz = diopside + $2CO_2$

anorthite + 2 calcite + quartz = grossular + $2CO_2$

for the amphibolite facies. Coupling these reactions with the average orogenic carbonate bulk rock composition given by Ronov et al. (1990), approximately 7% (by weight) of CO_2 would be lost in forming a (fictive) low-grade (greenschist facies) tremolite-zoisite assemblage, whereas ~12 wt% CO_2 would be evolved in metamorphism to a (fictive) diopside-grossular assemblage in the amphibolite facies. We stress that these reactions are utilized for mass balance calculations, and are not intended to represent the actual reactions that formed calc-silicate assemblages in metacarbonate rocks. Nevertheless, the calc-silicates formed by the above reactions are typical of those in metacarbonate rocks of the greenschist facies and amphibolite facies. Our approach is similar to that of Symmes and Ferry (1991), who quantified the reaction progress of pelitic schists using an average bulk composition of shale.

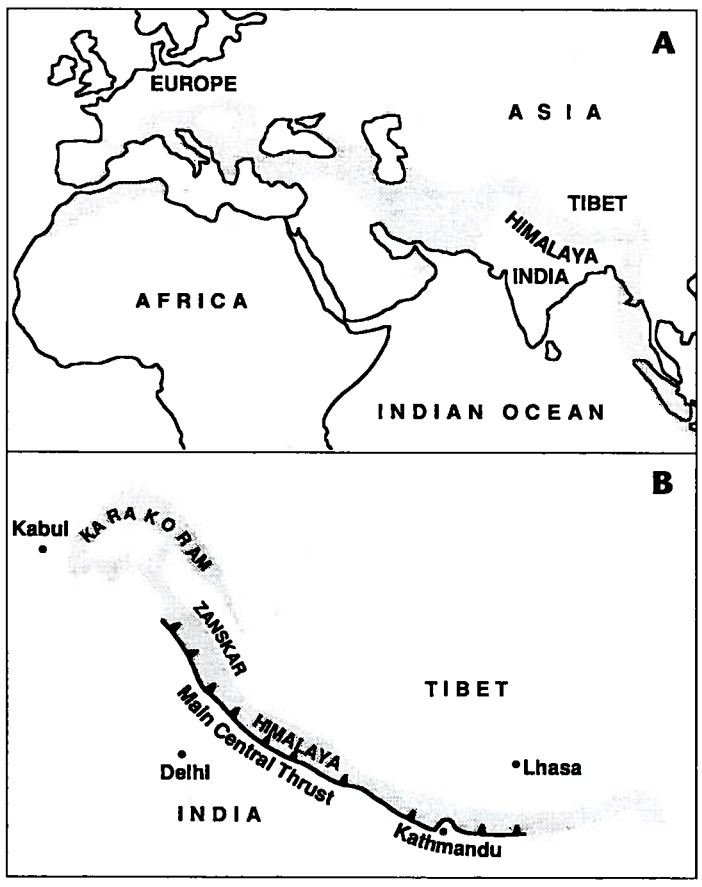

Figure. 2. A: The Tethyan Mesozoic-Cenozoic orogenic belt (shaded); modified from Spencer (1974). B: The Himalayan orogen, showing Searle's (1991) depiction of the 2500-km-long area affected by Barrovian regional metamorphism (shaded).

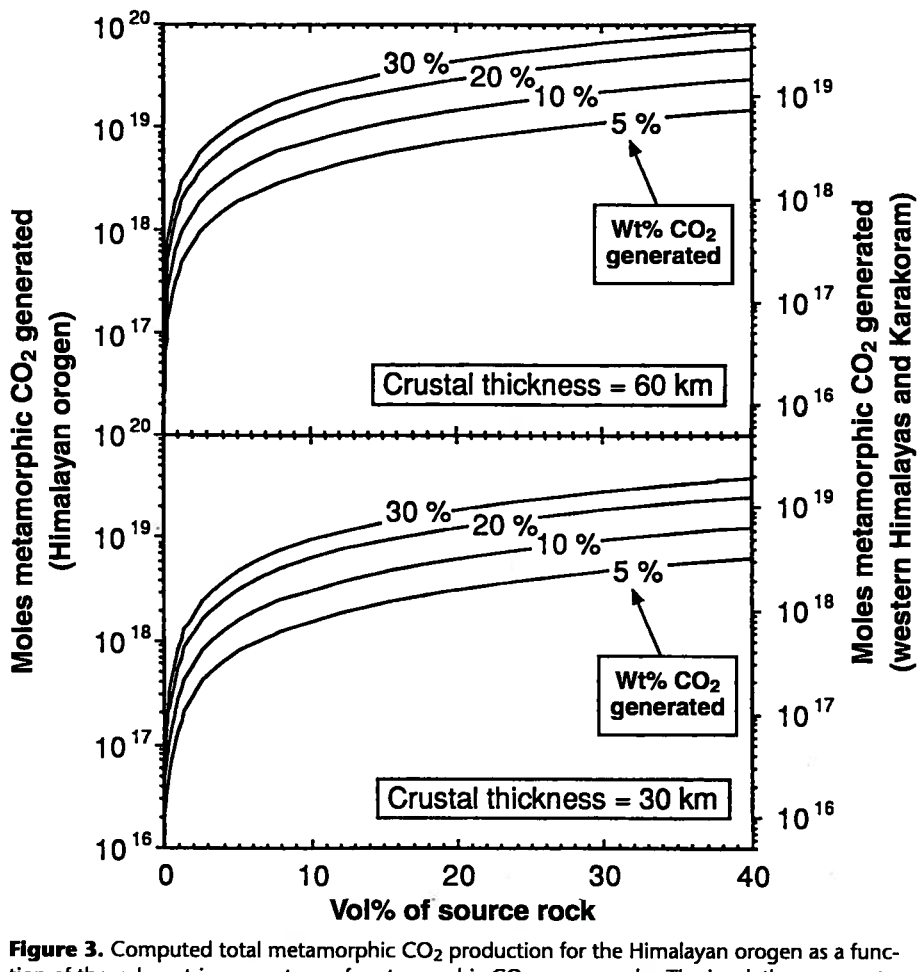

Figure 3. Computed total metamorphic CO_2 production for the Himalayan orogen as a function of the volumetric percentage of metamorphic CO_2 source rocks. The isopleths represent selected values of the weight % CO_2 produced by metamorphic decarbonation. The ordinate on the right represents the northwestern part of the Himalayan orogen; the ordinate on the left refers to the entire Himalayan orogen (see text for discussion).

On average, pelitic sediments (shales) have ~5 wt% CO_2 (Symmes and Ferry, 1991). Following Ferry (1983), we assume that this CO_2 is largely released upon metamorphism in the lower greenschist facies.

Volumetric Proportions of CO_2 Source Rocks

The literature provides surprisingly little quantitative information on the volumetric proportions of metamorphic CO_2 source rocks within the area affected by the Eocene metamorphism. Thus, we used volumetric estimates of metacarbonate and metapelitic rocks that were obtained through communication with several experts in Himalaya geology (see Acknowledgments). Based on their estimates, we suggest that the western half of the Himalaya orogen (i.e., Zanskar and west) contains ~20–30 vol% metacarbonate, and 5%–10% metapelites, whereas the central and eastern parts of the orogen contain approximately 10%–20% metacarbonates and 20%–30% metapelites.

Total Volume of the Himalayan Metamorphic Belt

Computation of the total CO_2 released requires an estimate of the total volume of the orogen that underwent postcollisional metamorphism. This volume was derived from the area of exposed metamorphic rock (Fig. 2B) and the assumption that metamorphism extended to a depth of 60 km (Searle, 1991).

Computed Metamorphic CO_2 Production

Our computed metamorphic CO_2 production from the Himalayan orogen is given in Figure 3. If, as discussed above, we assume that the western half of the orogen contains 20–30 vol% metacarbonate rocks, and that metacarbonates release 10–15 wt%, this lithology would have yielded $>10^{19}$ mol of CO_2. Assuming pelitic rocks constitute 5–10 vol% of the western half of the orogen, and that pelites release ~5 wt% during metamorphism, pelites would have contributed ~10^{18} moles.

On the basis of the volumetric estimates of metacarbonate and metapelitic rocks in the central and eastern part of the orogen, we estimate that ~10^{19} mol of CO_2 were produced. Assuming that prograde metamorphism lasted 10 m.y. in this part of the orogen, we estimate that approximately 10^{18} mol of CO_2 were released over a 1 m.y. period. Combining this with the estimated CO_2 production from the western part of the orogen, we conclude that for the entire Himalayan orogen a total CO_2 of well above 10^{18} mol/m.y. could have been produced at depth. This CO_2 far exceeds the present atmospheric CO_2 reservoir (~6×10^{16} mol) and is larger than the present combined ocean-atmosphere inorganic carbon reservoir (~3×10^{18} mol).

Our computations assumed that CO_2 was linearly released during a 10 m.y. period of prograde metamorphism. However, for impure carbonate rocks (Ferry, 1983; Labotka et al., 1988), CO_2 release is not a linear function of metamorphic grade; rather, much of the CO_2 is lost at the lowest metamorphic grades. Accordingly, there would be a significant loss of CO_2 during the early, low-grade (greenschist facies) period of prograde metamorphism. Consequently, the time period for release of substantial metamorphic CO_2 in the Himalayan orogen would be compressed in comparison with the model of linear release of CO_2 with metamorphic grade. Considering a linear heating rate over a 10 m.y. period with the assumption that much of the CO_2 is released during progradation through lower greenschist facies metamorphic conditions (~350–450 °C), the bulk of CO_2 release during the Himalayan metamorphism could have occurred over a few million years. This would yield CO_2 production rates that are two to four times larger than the values computed with a model of linear production of CO_2 over a 10 m.y. period.

CO_2 Transport to the Surface

On the basis of the above calculations, we conclude that the amount and production rate of metamorphic CO_2 generated during the Eocene Himalayan metamorphism could have significantly perturbed the atmospheric CO_2 concentration. However, this conclusion hinges on adequate flux of the CO_2 to Earth's surface.

Thompson and Connolly (1992) concluded that significant advective flux of metamorphic fluids occurs by focused fluid flow along lithological contacts, faults, and shear zones. There appears to be a correlation between fluid motion in fault zones and earthquake activity (Sibson, 1992); thus, focused expulsion of metamorphic CO_2 would be aided by seismic activity in orogens. Transient seismicity should yield enhanced, short-term expulsion of volatiles, thereby having a potentially important short-term climatic effect. The very large fluid/rock ratios of ~10^4 for mineralized fractures (Thompson and Connolly, 1992) attest to the efficacy of fluid flow along fractures in metamorphic rocks. Expulsion of advecting volatiles is favored by hydrofracturing resulting from the thermal expansion of volatiles that occurs during advection to shallow depths (Norris and Henley, 1976). As speculated by Oliver (1986), expulsion of significant amounts of metamorphic volatiles from major shear zones may account for the near-surface concentration of natural gas and anthracite coal deposits. The lowest grade rocks, which are considered to have been a major source for metamorphic CO_2 (as discussed above) are in the shallower parts of the Himalayan orogen (see Searle, 1991, Fig. 14.1). In addition to comparatively short distances of transport of volatiles to Earth's surface, shallow depths would facilitate brittle deformation (fracturing and faulting) that would provide channelways for escape of volatiles to the surface (Thompson and Connolly, 1992).

Support for the discharge of significant quantities of metamorphic CO_2 to the atmosphere is provided by Barnes et al. (1978, 1984), who carried out a comprehensive study of the correlation between the present-day global distribution of major zones of seismicity and CO_2 discharged from hot springs. Using ^{13}C stable isotope data of gases, coupled with the spatial correlation between areas of CO_2 discharge, zones of seismicity, and areas with high heat flow, they concluded that CO_2 discharged from seismically active regions of Europe and Asia and from the circum-Pacific belt is largely derived from contemporary metamorphism of carbonates.

Numerous studies suggest that significant focused fluid flux occurred along the extensive (>2000 km long) Main Central thrust (Fig. 2B). Copeland et al. (1991) concluded that a large flux of hydrothermal fluid occurred along

continued on p. 63

the thrust during a 1 m.y. period in the Pliocene and that "CO_2 may make up a significant fraction" of the fluid. A significant flux of metamorphic CO_2 in the Main Central thrust zone is supported by the fluid inclusion studies of Pêcher (1979) and Craw (1990). As noted by Craw (1990), hot springs near the thrust zone attest to contemporary focused flow of hydrothermal fluids, and the CO_2-rich compositions of the effluents (Grimaud et al., 1985; Absar et al., 1991) support the hypothesis that the Main Central thrust and/or similar shear zones could have provided a conduit for the escape to Earth's surface of significant quantities of metamorphic CO_2 generated during the Eocene Himalayan metamorphism.

CO_2 FROM EARLY CENOZOIC METAMORPHISM IN OTHER OROGENIC BELTS

To derive a global flux of atmospheric CO_2 produced from early Cenozoic metamorphism, we must consider the integrated flux from all orogens undergoing simultaneous regional metamorphism.

In addition to the Himalaya sector, the Mediterranean Tethys (Fig. 4) contains a large area of rocks that underwent early Cenozoic regional metamorphism (Papanikolaou, 1984; Okrusch and Bröcker, 1990). Marble and calc-silicate rocks are abundant in the Hellenides and Cyclades of Greece and the Menderez massif in western Turkey (Fig. 4); however, the proportion and bulk compositions of CO_2 source rocks cannot be estimated with certainty (M. J. Bickle and A. I. Okay, personal commun.). Provisionally assuming that the proportions of carbonate lithologies in the Mediterranean Tethys are the same as in the Himalayas, the Mediterranean Tethys would produce ~10^{18} mol of CO_2/m.y.

Within the circum-Pacific orogenic belt, Eocene metamorphism has been documented for New Caledonia (Brothers and Yokoyama, 1982), the Hidaka Belt of Japan (Osani et al., 1992), and the Cordilleran belt of western North America (Greenwood et al., 1991). The Eocene metamorphic belt in western North America may considerably exceed the size of the Eocene Himalayan metamorphic belt (L. S. Hollister, personal commun.). We are pursuing further study of present and past metamorphic CO_2 evolution in the circum-Pacific orogen.

In light of the integrated metamorphic flux from the Tethys and circum-Pacific orogens, the early Cenozoic global production of metamorphic CO_2 could have been 10^{18}–10^{19} mol/m.y. If a significant portion of the metamorphic CO_2 produced at depth escaped to Earth's surface, the flux could have been $\geq 10^{18}$ mol/m.y., thereby significantly affecting the Eocene paleoatmosphere (see discussion below).

FYFE'S ANALYSIS

In a brief but illuminating analysis of the significance of metamorphic decarbonation as a source of atmospheric CO_2, Fyfe (1986) concluded that "a significant perturbation of global CO_2 could result from a Himalayan [orogenic] event," and that "major continental collisions and minor overthrust events associated with transform faults can lead to massive [CO_2] degassing." However, Fyfe's analysis involved the metamorphism of an idealized 1-km-thick carbonate slab of uniform composition, and included no attempt to model explicitly the impact of the degassed CO_2 on atmospheric CO_2 content or climate. Fyfe computed a total CO_2 production from the Himalayan metamorphism of 10^{18} mol. However, using Fyfe's assumptions and correcting for an apparent error in his computation, we obtain instead a total CO_2 production of 4.5×10^{19} mol. In addition to the Himalayan orogenic belt, Fyfe's (1986) computations assumed that metamorphism encompassed the Tibetan plateau. In contrast, our estimate of the total volume of crust undergoing metamorphism was based only on the exposed area of metamorphic rocks within the Himalayan orogen (Fig. 2B). The India-Asia collision may have resulted in the transfer of large volumes of crust below the Tibetan plateau (Le Pichon et al., 1992). Le Pichon et al. (1992) estimated that ~5×10^7 km^3 of crust could have been involved in this underthrusting. No conclusions can be reached regarding the possible role of the sub-Tibetan crust in the Himalayan metamorphism. However, it is notable that Le Pichon et al.'s (1992) estimate of the volume of crust that was underthrust beneath the Tibetan plateau considerably exceeds our estimate of 1.2×10^7 km^3 for the volume of crust subjected to Himalayan metamorphism. If some of the sub-Tibetan crust were involved in the postcollisional metamorphism, this could have contributed to additional release of metamorphic volatiles, such that our estimates of CO_2 production based on the exposed area of Barrovian metamorphism (Fig. 2B) would provide a minimum estimate of metamorphic CO_2 production.

EFFECT OF METAMORPHIC CO_2 DEGASSING ON EARLY CENOZOIC PALEOCLIMATE

To estimate the impact of CO_2 releases over periods of 105 yr and longer, we must consider the effect of CO_2 consumption by silicate weathering and subsequent carbonate sedimentation (Walker et al., 1981). Silicate weathering can be schematically represented (Berner et al., 1983) by

$$CaSiO_3 + 2CO_2 + H_2O \rightarrow Ca^{2+} + 2HCO_3^- + SiO_2, \quad (1)$$

and carbonate sedimentation in marine environments can be represented by

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 + CO_2 + H_2O. \quad (2)$$

Thus, the net silicate-weathering–carbonate sedimentation reaction may be written

$$CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2, \quad (3)$$

whereby atmospheric CO_2 is eventually sequestered in carbonate sediments.

To estimate the change in atmospheric CO_2 content due to a specified global flux of metamorphic CO_2, we need to know the amount and timing of CO_2 emission and the rate at which this CO_2 is sequestered by silicate weathering and subsequent carbonate accumulation. Volk (1987) pointed out that on time scales >10^6 yr, the impact of enhanced CO_2 degassing on atmospheric CO_2 content can be calculated without explicitly resolving ocean carbon reservoirs. Calculating by the method described by Volk (1987), a rough estimate of the long-term atmospheric CO_2 increase from early Cenozoic metamorphism in orogenic belts can be made using Berner's (1990) silicate-weathering rate formulation and his estimate of today's background metamorphic plus mantle CO_2 flux (~6.7×10^{12} mol/yr). By this means, we estimate that a metamorphic CO_2 flux of ~2×10^{18} mol/m.y. could have doubled the atmospheric CO_2 content (yielding ~1.5 to 5 °C warming), and ~10^{18} mol/m.y. could have increased atmospheric CO_2 concentration by 40% (~0.75 to 2.5 °C warming). Enhanced CO_2 degassing associated with possible seafloor generation rate increases could have contributed additional CO_2 to the atmosphere.

EARLY CENOZOIC CLIMATE AND ATMOSPHERIC CO_2

Several lines of evidence indicate that the early Eocene (50–55 Ma) was the warmest period in the Cenozoic (Crowley and North, 1991). A warming trend began in the late Paleocene and culminated in the early Eocene (Shackleton and Kennett, 1975; Savin, 1977; Miller et al., 1987). Evidence of tropical flora indicates that tropical climates extended to ~45°N paleolatitude (Wolfe, 1980; Hubbard and Boulter, 1983), and early Eocene alligator fossils have been found on Ellesmere Island (Dawson et al., 1976) at a paleolatitude of ~78°N (McKenna, 1980). Laterite soil horizons, interpreted as indicative of warm climates with seasonal rainfall, developed to ~45° latitude in both hemispheres (Frakes, 1979); however, these horizons may not be diagnostic of tropical climates (Taylor et al., 1992). Tropical planktonic nannofloral assemblages extended to ~55°N in the North Atlantic, farther north than in any other period in the Cenozoic (Haq et al., 1977). Oxygen isotopes from planktonic foraminifera have been used to infer a greatly reduced equator-to-pole temperature gradient (Shackleton and Boersma, 1981); however, some of this signal may be the result of diagenetic alteration (Schrag et al., 1992). Oxygen isotopes from benthic foraminifera indicate that ocean bottom water was warmer during the early Eocene than at any other time during the Cenozoic (Fig. 1).

Two major processes may have contributed to the Eocene warmth: (1) enhanced ocean heat transport and (2) elevated atmospheric CO_2 content. Ocean equator-to-pole heat transport may have been greater in the Eocene (Rind and Chandler, 1991). This increased heat transport may have been sufficient to prevent the formation of extensive sea ice. Because sea water has a lower albedo than sea ice, this would result in enhanced absorption of solar radiation and, thus, global

Paleoclimate *continued on p. 64*

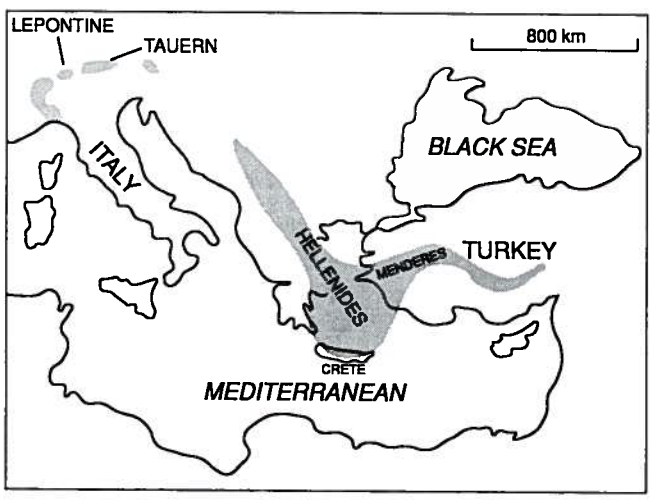

Figure 4. Map of the Mediterranean Tethys showing the area affected by Eocene regional metamorphism (shaded). Note that an extensive area of the Greek Archipelago (north of Crete) has been affected by this metamorphism. (From Ricou et al., 1986, Fig. 1.)

Paleoclimate *continued from p. 63*

warming. Several studies (Freeman and Hayes, 1992; Arthur et al., 1991; Berner et al., 1983) have indicated enhanced atmospheric CO_2 content during the Eocene.

Eocene warming may have resulted from enhanced fluxes of CO_2 to the atmosphere associated with enhanced rates of mid-ocean ridge spreading (Berner et al., 1983). Enhanced CO_2 fluxes to the atmosphere would result in elevated atmospheric CO_2 concentrations, thereby leading to greenhouse warming. Berner et al. (1983) proposed that metamorphic CO_2 degassing is roughly proportional to seafloor generation-subduction rates, and most subsequent long-term carbon cycle models have incorporated this proposal. Studies of seafloor generation-subduction rates have shown little (Engebretson et al., 1992) or no (Kominz, 1984) increase in the Eocene. As India collided with Asia, the Indian plate slowed (Klootwijk et al., 1992); thus, maximum plate velocities preceded regional metamorphism in the Himalayan orogenic belt. Consequently, Eocene metamorphic CO_2 fluxes to the atmosphere may not have been directly proportional to seafloor generation rates. This proportionality has also been challenged by data and calculations indicating that the flux of carbonate transported to metamorphic environments in subduction zones increased through the Cenozoic (Caldeira, 1992). Regardless of whether seafloor generation rates were higher in the Eocene, there is ample reason to believe that widespread Eocene regional metamorphism produced a CO_2 flux to the atmosphere that was in excess of that estimated from seafloor generation rates alone. Earth generally remained warm throughout the Eocene (Crowley and North, 1991). Even if prograde metamorphism postdated late Paleocene warming, enhanced degassing of metamorphic CO_2 could have nevertheless contributed to sustaining Eocene warmth. Furthermore, CO_2 degassing from regional metamorphism in the central and eastern Himalayas during the Miocene (Treloar et al., 1989; Searle, 1991; Sorkhabi and Stump, 1993) may have contributed to global warming during that epoch (Fig. 1). Thus, even with the uncertainty in the geologic data, it is clear that metamorphic CO_2 released from the Himalayan and other Tethyan or circum-Pacific metamorphic belts may have played an important, and heretofore neglected, role in Cenozoic climate evolution.

PRIMARY UNCERTAINTIES

The accuracy of our computed CO_2 production from the Himalayan orogen, and consequent paleoclimatic implications, are contingent upon several variables (e.g., timing of collision, duration of metamorphism, and the volumetric proportions and compositions of the CO_2 source rocks). Unfortunately, there is considerable uncertainty in quantification of these variables. However, even if our calculated production is excessive by a factor of two, metamorphic CO_2 released from the Himalayan and other Tethyan or circum-Pacific metamorphic belts may have played an important, and heretofore neglected, role in Eocene climate evolution.

DISCUSSION AND CONCLUSIONS

Barron (1987 and personal commun.) estimated Eocene global warming to be in the range of 1–4 °C, with the preferred value of 2 °C. Our analysis indicates that a 2 °C warming could be produced by an enhanced metamorphic flux of ~2×10^{18} mol/m.y., which is half the CO_2 generated at depth computed for the Himalayan orogen alone. Earth generally remained warm throughout the Eocene (Crowley and North, 1991). Even if prograde metamorphism postdated late Paleocene warming, enhanced degassing of metamorphic CO_2 could have nevertheless contributed to sustaining Eocene warmth. Furthermore, CO_2 degassing from regional metamorphism in the central and eastern Himalayas during the Miocene (Treloar et al., 1989; Searle, 1991; Sorkhabi and Stump, 1993) may have contributed to global warming during that epoch (Fig. 1). Thus, even with the uncertainty in the geologic data, it is clear that metamorphic CO_2 released from the Himalayan and other Tethyan or circum-Pacific metamorphic belts may have played an important, and heretofore neglected, role in Cenozoic climate evolution.

In their provocative (Caldeira, 1992; Caldeira et al., 1993) studies, Raymo and coworkers (Raymo et al., 1988; Raymo and Ruddiman, 1992) proposed that the Himalayan orogenesis could have provided an important sink for atmospheric CO_2 by enhancing the weatherability of silicate rock, thereby producing a middle to late Cenozoic cooling trend. Metamorphic degassing of CO_2 from carbonate rocks during Eocene collisional orogenesis would have preceded the uplift-induced cooling proposed by Raymo et al. (1988); thus, Himalayan orogenesis may have been largely responsible for both the warm Eocene and subsequent global cooling.

Our provisional computations suggest that elevated early Cenozoic paleoatmospheric CO_2 levels could have resulted from CO_2 released during regional metamorphism that affected extensive segments of the Tethys orogenic belt. Total world-wide CO_2 produced at depth may have been 10^{18}–10^{19} mol/m.y. Our calculations of atmospheric CO_2 consumption by silicate weathering show that metamorphic CO_2 releases of ~10^{18} mol/m.y. could readily account for the Eocene warming. If a significant fraction of metamorphic CO_2 escaped to Earth's surface, there would have been significant paleoclimatic consequences.

ACKNOWLEDGMENTS

This research was supported by National Science Foundation grant EAR-9304939. We thank C. P. Chamberlain, J. A. DiPietro, N. B. W. Harris, K. P. Hodges, M. S. Hubbard, P. E. LeFort, D. Schelling, M. P. Searle, and P. J. Treloar for their input regarding metamorphism, and for providing provisional estimates of metamorphic CO_2 source rocks, in the Himalayan orogen; A. K. Okay for valuable insight on metamorphism in the Mediterranean Tethys; E. J. Barron and L. R. Kump for their encouragement and support; and Café Gourmet, Ltd., for their support and interest in this project.

REFERENCES CITED

Absar, A., Prakash, G., and Aggarwal, R. K., 1991, A preliminary conceptual model of Nubra Valley geothermal system, Ladakh, J&K, India: Geological Society of India, v. 37, p. 533–545.

Arthur, M. A., Hinga, K. R., Pilson, M. E. Q., Whitaker, D., and Allard, D., 1991, Estimates of pCO_2 for the last 120 Myr based on the $\partial^{13}C$ of marine phytoplanktic organic matter [abs.]: Eos (Transactions, American Geophysical Union), v. 24, p. 166.

Barnes, I., Irwin, W. P., and White, D. E., 1978, Global distribution of carbon dioxide discharges, and major zones of seismicity: U.S. Geological Survey Open-File Report, Water-Resources Investigation 78–39, 12 p.

Barnes, I., Irwin, W. P. and White, D. E., 1984, Global distribution of carbon dioxide discharges and major zones of seismicity: U.S. Geological Survey Map I-1528, 10 p. text.

Barron, E. J., 1987, Eocene equator-to-pole surface ocean temperatures: A significant climate problem?: Paleoceanography, v. 2, p. 729–739.

Berner, R. A., 1990, A model for atmospheric CO_2 over Phanerozoic time: American Journal of Science, v. 291, p. 339–376.

Berner, R. A., Lasaga, A. C., and Garrels, R. M., 1983, The carbonate-silicate geochemical cycle and its effect on atmospheric carbon dioxide over the past 100 million years: American Journal of Science, v. 283, p. 641–683.

Brothers, R. N., and Yokoyama, K., 1982, Comparison of the high-pressure schist belts of New Caledonia and Sanbagawa, Japan: Contributions to Mineralogy and Petrology, v. 79, p. 219–229.

Caldeira, K., 1992, Enhanced Cenozoic chemical weathering and the subduction of pelagic carbonate: Nature, v. 357, p. 578–581.

Caldeira, K., Arthur, M. A., Berner, R. A., and Lasaga, A. C., 1993, Cenozoic cooling: Nature, v. 361, p. 123.

Copeland, P., Harrison, T. M., Hodges, K. V., Maruejol, P., LeFort, P., and Pêcher, A., 1991, An Early Pliocene thermal disturbance of the Main Central Thrust, Central Nepal: Implications for Himalayan tectonics: Journal of Geophysical Research, v. 96, p. 8475–8500.

Craw, D., 1990, Fluid evolution during uplift of the Annapurna Himalaya, central Nepal: Lithos, v. 24, p. 137–150.

Crowley, T. J., and North, G. R., 1991, Paleoclimatology: New York, Oxford University Press, 339 p.

Dawson, M. R., West, R. M., Langston, W., and Hutchinson, H., 1976, Paleogene terrestrial vertebrates; northernmost occurrence, Ellesemere Island, Canada: Science, v. 192, p. 781–782.

DiPietro, J. A., 1991, Metamorphic pressure-temperature conditions of Indian plate rocks south of the Main Mantle thrust, Lower Swat, Pakistan: Tectonics, v. 10, p. 742–757.

Douglas, R., and Woodruff, F., 1981, Deep-sea benthic foraminifera, *in* Emiliani, C., ed., The sea, Volume 7: New York, Wiley-Interscience, p. 1233–1328.

Engebretson, D. C., Kelley, K. P., Cashman, H. J., and Richards, M. A., 1992, 180 million years of subduction: GSA Today, v. 2, p. 93–95, 100.

England, P., LeFort, P., Molnar, P., and Pêcher, A., 1992, Heat sources for Tertiary metamorphism and anatexis in the Annapurna-Manaslu region, Central Nepal: Journal of Geophysical Research, v. 97, p. 2107–2128.

Ferry, J. M., 1983, Mineral reactions and element migration during metamorphism of calcareous sediments from the Vassalboro Formation, south-central Maine: American Mineralogist, v. 68, p. 334–354.

Frakes, L. A., 1979, Climates throughout geologic time: Amsterdam, Elsevier, 310 p.

Freeman, K. H., and Hayes, J. M., 1992, Fractionation of carbon isotopes by phytoplankton and estimates of ancient CO_2 levels: Global Biogeochemical Cycles, v. 6, p. 185–198.

Fyfe, W. S., 1986, Fluids in deep continental crust, *in* Barazangi, M., and Brown, L., eds., Reflection seismology: The continental crust: American Geophysical Union Geodynamics Series, v. 14, p. 33–39.

Gerlach, T. M., 1991, Present-day CO_2 emissions from volcanoes: Eos (Transactions, American Geophysical Union), v. 72, p. 249, 254–255.

Greenwood, H. J., Woodsworth, G. J., Read, P. B., Ghent, E. D., and Evenchick, C. A., 1991, Metamorphism, *in* Gabrielse, H., and Yorath, C. J., eds., Geology of the Cordilleran orogen in Canada: Geological Survey of Canada, Geology of Canada, v. 4, (Geological Society of America Geology of North America, v. G-2), p. 535–570.

Grimaud, D., Huang, S., Michard, G., and Zheng, K., 1985, Chemical study of geothermal waters of central Tibet (China): Geothermics, v. 14, p. 35–48.

Haq, B. U., Premoli-Silva, I., and Lohmann, G. P., 1977, Calcareous plankton paleobiogeographic evidence for major climatic fluctuations in the early Cenozoic Atlantic Ocean: Journal of Geophysical Research, v. 8, p. 427–431.

Hodges, K. V., and Silverberg, D. S., 1988, Thermal evolution of the greater Himalaya, Garhwal, India: Tectonics, v. 7, p. 583–600.

Hodges, K. V., Hubbard, M. S., and Silverberg, D. S., 1988, Metamorphic constraints on the thermal evolution of the central Himalayan orogen: Royal Society of London Philosophical Transactions, ser. A, v. 326, p. 257–280.

Hubbard, R. N. L. B., and Boulter, M. C., 1983, Reconstruction of Paleogene climate from palynological evidence: Nature, v. 301, p. 147–150.

Klootwijk, C. T., Gee, J. S., Peirce, J. W., Smith, G. M., and McFadden, P. L., 1992, An early India-Asia contact: Paleomagnetic constraints from Ninetyeast Ridge, ODP leg 121: Geology, v. 20, p. 395–398.

Kominz, M. A., 1984, Oceanic ridge volumes and sea-level change—An error analysis, *in* Schlee, J. S., ed., Interregional unconformities and hydrocarbon accumulation: American Association of Petroleum Geologists Memoir 36, p. 109–127.

Labotka, T. C., Nabelek, P. I., Papike, J. J., Hover-Granath, V. C., and Laul, J. C., 1988, Effects of contact metamorphism on the chemistry of calcareous rocks in the Big Horse limestone member, Notch Peak, Utah: American Mineralogist, v. 73, p. 1095–1110.

Paleoclimate *continued on p. 65*

WASHINGTON REPORT

Bruce F. Molnia

Washington Report provides the GSA membership with a window on the activities of the federal agencies, Congress and the legislative process, and international interactions that could impact the geoscience community. In future issues, Washington Report will present summaries of agency and interagency programs, track legislation, and present insights into Washington, D.C., geopolitics as they pertain to the geosciences.

NSTC and PCAST—Yes; FCCSET—No More!

Science and technology are essential tools for achieving this Administration's goals: for strengthening the economy, creating high-quality jobs, protecting the environment, improving our health care and education systems, and maintaining our national security. This country must sustain world leadership in science, mathematics, and engineering if we are to meet the challenges of today ... and of tomorrow.

—President Bill Clinton, November 23, 1993

By executive order, as part of the continuing effort to reinvent government, President Bill Clinton established a new cabinet-level council to oversee and coordinate science, technology, and space policy for the entire federal government. The National Science and Technology Council (NSTC), created in late November 1993, supersedes the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET), which was discussed in several 1993 Washington Reports. Also being superseded are the National Space Council and the National Critical Materials Council.

The executive order states that the principal functions of the Council are: "(1) to coordinate the science and technology policy-making process; (2) to ensure science and technology policy decisions and programs are consistent with the President's stated goals; (3) to help integrate the President's science and technology policy agenda across the federal government; (4) to ensure science and technology are considered in development and implementation of Federal policies and programs; and (5) to further international cooperation in science and technology."

The President stated that the "principal purposes of the NSTC will be to establish clear national goals for Federal science and technology investments and to ensure that science, space, and technology policies and programs are developed and implemented to effectively contribute to those national goals." The President further stated that "Our most important measure of success will be the ability to make a difference in the lives of the American people. We must use this new council to harness science and technology to improve our quality of life and the long-term economic strength."

The executive order defines the membership of the NSTC. Specifically identified as members are the President, who will serve as the chair; the Vice-President; the Assistants to the President for Science and Technology, Domestic Policy, and Economic Policy; the Secretaries of Commerce, Defense, Energy, Health and Human Services, Interior, and State; the Administrators of the Environmental Protection Agency and the National Aeronautics and Space Administration; the Directors of the National Science Foundation and the Office of Management and Budget; and the National Security Advisor.

The President stated that completing an across-the-board review of federal spending, focused on research and development, will be one of the most critical tasks that he expects the NSTC to begin. Specifically identified as disciplines within which the NSTC will prepare coordinated research and development are "budget recommendations for accomplishing national objectives in areas ranging from information technologies to health research, from improving transportation to strengthening fundamental research and international science and technology programs."

A "fact sheet" accompanying the President's executive order identifies nine specific research and development coordinating committees that will be established to "prepare coordinated R&D strategies and budget recommendations for accomplishing national goals." These are the committees for health, safety, and food research and development (R&D); fundamental science and engineering research; information and communication R&D; environment and natural resources research; civilian industrial technology R&D; education and training R&D; transportation R&D; national security R&D; and international science, engineering, and technology R&D. As needed, ad hoc working groups will be established to "review and coordinate specific policies and initiatives." Among the existing committees being replaced is the Committee on Earth and Environmental Sciences, which administers the Subcommittee on Global Change Research (SGCR), the home of the U.S. Global Change Research Program (USGCRP). What place the USGCRP will have in the new NSTC is as yet not clear.

Additionally, by executive order, the President established the President's Committee of Advisors on Science and Technology (PCAST). The PCAST will serve as a nongovernmental oversight group for the President and for the NSTC. The PCAST will consist of "16 members, one of whom shall be the Assistant to the President for Science and Technology," and "15 of whom shall be distinguished individuals from the non-Federal sector appointed by the President" including representatives from industry, academia, research institutions, nongovernmental organizations, and state and local government. John H. Gibbons, Assistant to the President for Science and Technology, was named by President Clinton as co-chair of the PCAST. An as yet unnamed private-sector representative will be the other co-chair.

In his executive order, President Clinton stated that the "PCAST will advise the President on science and technology issues and assist the NSTC in securing private sector involvement in its activities." PCAST members will serve without any compensation for their work on the PCAST, other than travel expenses and per diem.

Legislation to establish the NSTC is now moving through both houses of Congress. ■

Paleoclimate *continued from p. 64*

Le Pichon, X., Fournier, M., and Laurent, J., 1992, Kinematics, topography, shortening, and extrusion in the India-Eurasia collision: Tectonics, v. 11, p. 1085–1098.

McKenna, M. C., 1980, Eocene paleolatitude, climate, and mammals of Ellesmere Island: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 30, p. 349–362.

Miller, K. G., Fairbanks, R. G., and Mountain, G. S., 1987, Tertiary oxygen isotope synthesis, sea level history, and continental margin erosion: Paleoceanography, v. 2, p. 1–19.

Norris, R. J., and Henley, R. W., 1976, Dewatering of a metamorphic pile: Geology, v. 4, p. 333–336.

Okrusch, M., and Bröcker, M., 1990, Eclogites associated with high-grade blueschists in the Cyclades archipelago, Greece: A review: European Journal of Mineralogy, v. 2, p. 451–478.

Oliver, J., 1986, Fluids expelled tectonically from orogenic belts: Their role in hydrocarbon migration and other geologic phenomena: Geology, v. 14, p. 99–102.

Osani, Y., Owada, M., and Kawasaki, T., 1992, Tertiary deep crustal ultrametamorphism in the Hidaka metamorphic belt, northern Japan: Journal of Metamorphic Geology, v. 10, p. 401–414.

Papanikolaou, D. J., 1984, The three metamorphic belts of the Hellenides: A review and a kinematic interpretation, *in* Dixon, J. E., and Robertson, A. H. F., eds., The geological evolution of the eastern Mediterranean: Geological Society of London Special Publication 17, p. 551–561.

Pêcher, A., 1979, Les inclusions fluides des quartz d'exsudation de la zone du M.C.T. Himalayen au Nepal central: Données sur la phase fluide dans une grande zone de cisaillement crystal: Bulletin Mineralogique, v. 102, p. 537–554.

Raymo, M. E., and Ruddiman, W. F., 1992, Tectonic forcing of the late Cenozoic climate: Nature, v. 359, p. 117–122.

Raymo, M. E., Ruddiman, W. F., and Froelich, P. N., 1988, Influence of late Cenozoic mountain building on ocean geochemical cycles: Geology, v. 16, p. 649–653.

Ricou, L. E., Dercourt, J., Geyssant, J., Grandjacquet, C., Lepvrier, C., and Biju-Duval, B., 1986, Geological constraints on the alpine evolution of the Mediterranean Tethys: Tectonophysics, v. 123, p. 83–122.

Rind, D., and Chandler, M., 1991, Increased ocean heat transports and warmer climate: Journal of Geophysical Research, v. 96, p. 7437–7461.

Ronov, A. B., Yaroshevsky, A. A., and Migdisow, A. A., 1990, Chemical structure of the Earth's crust and major element geochemical balance: Moscow, Nauka, 182 p.

Savin, S. M., 1977, The history of Earth's surface temperature during the past 100 million years: Annual Review of Earth and Planetary Sciences, v. 5, p. 319–355.

Schrag, D. P., DePaolo, D. J., and Richter, F. M., 1992, Oxygen isotope exchange in a two-layer model of the oceanic crust: Earth and Planetary Science Letters, v. 111, p. 305–317.

Searle, M. P., 1991, Geology and tectonics of the Karakoram Mountains: New York, John Wiley & Sons, 358 p.

Searle, M. P., Waters, D. J., Rex, D. C., and Wilson, R. N., 1992, Pressure, temperature and time constraints on Himalayan metamorphism from eastern Kashmir and western Zanskar: Geological Society of London Journal, v. 149, p. 753–773.

Shackleton, N. J., and Boersma, A., 1981, The climate of the Eocene ocean: Geological Society of London Journal, v. 138, p. 153–157.

Shackleton, N. J., and Kennett, J. P., 1975, Paleotemperature history of the Cenozoic and the initiation of Antarctic glaciation, *in* Initial reports of the Deep-Sea Drilling Project, Volume 29: Washington, D.C., U.S. Government Printing Office, p. 743–755.

Sibson, R. H., 1992, Fault-valve behavior and the hydrostatic-lithostatic fluid pressure interface: Earth-Science Reviews, v. 32, p. 141–144.

Smith, H. A., Chamberlain, C. P., and Zeitler, P. K., 1992, Possible early Paleocene initiation of Himalayan orogeny suggested by Eocene anatexis within the Indian plate, NW Himalaya, Pakistan: Geological Society of America Abstracts with Programs, v. 24, no. 7, p. A281.

Sorkhabi, R. B., and Stump, E., 1993, Rise of the Himalaya: A geochronologic approach: GSA Today, v. 3, p. 85, 88–91.

Spencer, A. M., editor, 1974, Mesozoic-Cenozoic orogenic belts: Geological Society of London Special Publication 4, 809 p.

Symmes, G. H., and Ferry, J. M., 1991, Evidence from mineral assemblages for infiltration of pelitic schists by aqueous fluids during metamorphism: Contributions to Mineralogy and Petrology, v. 108, p. 419–438.

Taylor, G., Eggleton, R. A., Holzhauer, C. C., Maconachie, L. A., Gordon, M., Brown, M.C., and McQueen, K. G., 1992, Cool climate lateritic and bauxitic weathering: Journal of Geology, v. 100, p. 669–677.

Thompson, A. B., and Connolly, J. A. D., 1992, Migration of metamorphic fluid: Some aspects of mass and heat transfer: Earth-Science Reviews, v. 32, p. 107–121.

Tonarini, S., Villa, I. M., Oberli, F., Meier, M., Spencer, D. A., Pognante, U., and Ramsay, J. G., 1993, Eocene age of eclogite metamorphism in Pakistan Himalaya: Implications for India-Eurasia collision: Terra Nova, v. 5, p. 13-20.

Touret, J. L. R., 1992, CO_2 transfer between the upper mantle and the atmosphere: Temporary storage in the lower continental crust: Terra Nova, v. 4, p. 87–98.

Treloar, P. J., and eight others, 1989, K-Ar and Ar-Ar geochronology of the Himalayan collision in NW Pakistan: Constraints on the timing of suturing, deformation, metamorphism and uplift: Tectonics, v. 8, p. 881–909.

Varekamp, J. C., Kreulen, R., Poorter, R. P. E., and VanBergen, M. J., 1992, Carbon sources in arc volcanism, with implications for the carbon cycle: Terra Nova, v. 4, p. 363–373.

Volk, T., 1987, Feedbacks between weathering and atmospheric CO_2 over the last 100 million years: American Journal of Science, v. 287, p. 763-779.

Walker, J. C. G., Hays, P. B., and Kasting, J. F., 1981, A negative feedback mechanism for the long-term stabilization of the Earth's surface temperature: Journal of Geophysical Research, v. 86, p. 9776–9782.

Wolfe, J. A., 1980, Tertiary climates and floristic relationships at high latitudes in the Northern Hemisphere: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 30, p. 313–323.

Manuscript received June 15, 1993; revision received August 17, 1993; accepted August 25, 1993 ■