Geochemical evidence supporting T. C. Chamberlin's theory of glaciation

M. E. Raymo*
Department of Geology, Melbourne University, Parkville, Victoria 3052, Australia

ABSTRACT

In 1899, T. C. Chamberlin proposed that the CO_2 content of the atmosphere decreased during times of enhanced continental erosion, ultimately resulting in glacial epochs. He ascribed the increase in the rate of chemical weathering (relative to the rate of supply of CO_2 from Earth's interior) to increased orogenic activity and globally higher average elevations, which promoted rapid chemical erosion of silicates. The oceanic record of strontium isotopes, preserved in marine sediment, supports his suggestion that glacial climates during the Phanerozoic are in part linked to increases in the rate of global chemical erosion relative to outgassing from Earth's interior. Further, the close correspondence of the major tectonic episodes of the Late Ordovician and Early Silurian, the Devonian, the Carboniferous and Permian, and the late Cenozoic to times of increased continental erosion and glaciation suggests that Chamberlin's hypothesis of the cause of glacial periods should be revived.

INTRODUCTION

Throughout its history, Earth's climate has fluctuated between glacial and nonglacial states. Evidence for glaciation has been found in Precambrian and Paleozoic rocks on all continents. In the Cenozoic, Antarctica has been glaciated for at least the past 35 m.y. (Harwood et al., 1989; Miller and Fairbanks, 1983), and at present, the Northern Hemisphere rests in a short intermission before the next episode of glaciation again extends into the mid-latitudes. Yet, even though we live at a time with glacial climates at both poles and the best possible geologic record to work with, geologists and climatologists still are uncertain as to the cause or causes of glaciation, either in the late Cenozoic or in earlier eras. Herein I propose that uplift and erosion of major mountain ranges and plateaus may be a key factor controlling atmospheric CO_2 levels and global climate.

The association of glaciations with times of orogenic uplift has been noted before (e.g., Chamberlin, 1899; LeConte, 1899; Ramsey, 1924; Hamilton, 1968; Powell and Veevers, 1987). Of these, the works of T. C. Chamberlin are particularly notable almost a century later. He proposed that enhanced rates of chemical erosion associated with major mountain-building episodes would result in a downdraw of atmosphere CO_2 levels, which would then lead to global cooling. This link between uplift and erosion of major mountain ranges and the chemical composition of the atmosphere has only recently been reconsidered as a viable mechanism to explain the onset of glacial climates (Raymo et al., 1988).

Most climate theories focus on changing arrangements of oceans and continents as major factors controlling ice-sheet growth; the presence of land masses at polar latitudes is often considered an important prerequisite to, if not a cause of, continental glaciations (Crowell and Frakes, 1970; Donn and Shaw, 1977; Barron, 1981). Studies of Paleozoic glaciations in particular focus on the apparent association between glacial deposits and polar continental positions indicated by "apparent polar wander paths" (Crowell, 1983; Caputo and Crowell, 1985; Crowley et al., 1987). However, an examination of Mesozoic and Cenozoic paleogeography indicates that while over most of the past 100 m.y. Antarctica and the northern continents have remained at approximately the same latitudes (Smith and Bryden, 1977), evidence for significant glaciation is found only for the past 35 m.y. (Harwood et al., 1989; Miller and Fairbanks, 1983). Factors other than just polar positioning would seem to be implicated.

Local changes in geography have also been proposed as critical factors controlling global climate evolution. For the late Tertiary glacial epoch, such changes include epeirogenic uplift in regions where ice sheets nucleate, such as the northeastern Canadian margin (Flint, 1943), or the formation of oceanic gateways and sills, such as the Drake Passage (Kennett, 1977) and Panamanian isthmus (Keigwin, 1982). However, in the case of Flint's hypothesis there appears to be little solid evidence of late Cenozoic uplift of the Baffin-Labrador region. Similarly, the formation of the Panamanian isthmus appears to predate major Northern Hemisphere glaciation at 2.4 Ma, and in Antarctica, initial buildup of the continental ice sheet started before, and continued long after, the opening of the Drake Passage. In addition, general circulation model simulations suggest that enhanced glaciation of polar regions would not necessarily result from such geographic changes and, in fact, glaciation might be less likely (Oglesby, 1989; Crowley et al., 1989). Thus, while local tectonic changes may exert an important influence on ocean circulation and heat transport at certain times, it is unclear whether they can explain the long-term cooling trend observed for the Tertiary. It appears that factors in addition to continent-ocean configurations must play a role in triggering glacial climates (Crowell, 1983; Barron, 1985).

One such factor is changes in atmospheric composition. Several studies (Berner et al., 1983; Arthur et al., 1985; Barron and Washington, 1985; Schneider et al., 1985) have proposed that elevated atmospheric CO_2 levels are needed to explain the warm climate of the mid-Cretaceous (100 Ma). Increased carbon dioxide levels in the atmosphere are ascribed to two primary causes: (1) more rapid sea-floor spreading and volcanic outgassing of CO_2 and (2) a decrease in the amount of global chemical weathering (which removes CO_2) related to elevated sea levels and, hence, a decrease in the land area available to erosion. These ideas have been quantified in geochemical weathering models (e.g., Berner et al., 1983; Lasaga et al., 1985) which predict severalfold higher CO_2 levels for the mid-Cretaceous. These models predict a decline in atmospheric CO_2 and global temperatures toward the present (due primarily to decreases in global sea-floor-spreading rates); however, the timing of the predicted CO_2/temperature decline differs significantly from that observed using oxygen-isotope paleotemperature data (Douglas and Woodruff, 1981). The models predict the largest coolings between 100 and 50 Ma (pre-Eocene), whereas oxygen isotopic data suggest that global climatic cooling occurred primarily between 50 Ma and the present (post-Eocene).

UPLIFT AND CLIMATE

Three related hypotheses, which focus both on paleogeographic and atmospheric CO_2 changes, have recently been suggested to explain onset of glacial climates in the Northern Hemi-

*Present address: Department of Geology and Geophysics, University of California, Berkeley, California 94720.

GEOLOGY, v. 19, p. 344–347, April 1991

sphere during the late Cenozoic. In the first, Ruddiman et al. (1986) and Ruddiman and Raymo (1988) proposed that post-Eocene uplift of the Himalayan–Tibetan Plateau region and the plateaus and mountains of western North America has had a direct effect on upper atmospheric circulation patterns, including the trajectory of the jet stream. The large southward meanders in the modern jet stream, over North America and Europe, enhance the penetration of polar air masses southward over the areas of major Northern Hemisphere ice accumulation. General circulation model experiments in which the elevations of these land masses are reduced show significantly less cooling over the major land masses of North America and Eurasia (Ruddiman and Kutzbach, 1989).

Second, the circulation model experiments predict that late Cenozoic uplift would also result in aridification at middle and subtropical latitudes (Ruddiman and Kutzbach, 1989), due primarily to rain-shadow effects and a strengthening of the Tropical Easterly Jet. Increased dust fluxes as well as paleobotanical variations provide convincing evidence for regional changes in precipitation (including aridification of the Sahara) which match the inferred timing of uplift (Ruddiman and Kutzbach, 1989; Ruddiman et al., 1989). Further, Ruddiman and Kutzbach (1989) pointed out that increased atmospheric dust concentrations would also enhance climatic cooling.

Third, Raymo et al. (1988) have proposed that accelerated uplift of the Himalayas, Tibetan Plateau, and Andes Mountains during the late Neogene would have resulted in a significant increase in the rate of global chemical erosion and, hence, a decrease in atmospheric CO_2 levels. The Amazon, Ganges-Brahmuputra, and Yangtze rivers alone account for the under 20% of the total dissolved load reaching the ocean today (Berner and Berner, 1987). In the Amazon drainage basin, more than 70% of the solutes are derived from the Andean highlands (Stallard, 1980). The large amount of chemical weathering occurring in these mountainous regions can be ascribed directly to the influence of rapid mechanical breakdown of rocks, which exposes more surface area to weathering; the relative abundance in these regions of uplifted sedimentary sequences, which are easily eroded; and the high concentration of rainfall on the slopes of these mountain ranges (Gibbs, 1967). The importance of these three factors, mechanical weathering (relief), bedrock type, and rainfall, was also emphasized by Drever (1988). Ocean geochemical records, in particular strontium-isotope records, suggest that a 50% increase in global erosional fluxes has occurred since the Miocene (Raymo et al., 1988; Hodell et al., 1989, 1990; Capo and DePaolo, 1990), a change we ascribed primarily to uplift and erosion of the Himalayan and Andean ranges. The resultant lowering of average atmospheric CO_2 values over this same time period would have contributed to the late Cenozoic global cooling.

In any CO_2 model it is important to note that at some point CO_2 levels are lowered sufficiently that the resulting colder climates inhibit chemical weathering and, hence, further decreases in atmospheric CO_2 levels. At this equilibrium point, weathering rates have decreased enough to balance CO_2 input from Earth's interior, although the climate is now cooler and the CO_2 level in the atmosphere is lower. If air temperature was a perfectly efficient negative feedback, then the time needed for balance to be regained via a reduction in weathering rates would be approximately equivalent to the residence time in the ocean of the major weathering cations that control ocean alkalinity, on the order of millions of years (Broecker and Peng, 1982). However, ambient air temperature seems to be a second-order control on weathering rates, as evidenced by the fact that much chemical weathering is associated with areas of high elevation, which are, by their very nature, colder than low-lying regions. It may be more likely that the duration of colder climates is controlled by the active uplift and erosional lifetime of a mountain range, on the order of tens of millions of years, rather than by negative feedback associated with temperature control of the global weathering reaction rate.

PHANEROZOIC STRONTIUM ISOTOPE RECORD

As shown in several studies (Raymo et al., 1988; Hodell et al., 1989; Capo and DePaolo, 1990), the oceanic record of $^{87}Sr/^{86}Sr$ preserved in marine biogenic sediments is consistent with an approximately 50% increase in the global average weathering rate since the Miocene (despite declining global temperatures). By using the marine $^{87}Sr/^{86}Sr$ record of the past 500 m.y. (Fig. 1; Koepnick et al., 1988), we can further evaluate the relation among chemical erosion rates, climate, and orogeny. The seawater $^{87}Sr/^{86}Sr$ ratio, recorded by marine carbonates, reflects primarily a balance between input of high-$^{87}Sr/^{86}Sr$ material weathered from continents (average runoff value = 0.7119; Palmer and Edmond, 1989) and low-$^{87}Sr/^{86}Sr$ material introduced by hydrothermal activity (average value = 0.7035; Palmer and Edmond, 1989). (Note, however, that the isotopic composition of the river strontium flux is not invariant but is dependent on the proportion of granitic rocks relative to igneous and carbonate rocks being weathered on land [e.g., Palmer and Elderfield, 1985]. Substantial changes in the river $^{87}Sr/^{86}Sr$ ratio would require that the types of rocks exposed at Earth's surface vary significantly through time. Given the present-day heterogeneity of crustal rocks, it seems unlikely that this factor would be a first-order control on seawater $^{87}Sr/^{86}Sr$ values through time.) A third strontium input to the ocean, from redissolution of marine carbonates (average value = 0.7084; Palmer and Edmond, 1989), serves to buffer the isotopic value of the oceanic strontium reservoir. To a first approximation, times of rising $^{87}Sr/^{86}Sr$ ratios in Figure 1 indicate increased rates of continental chemical erosion *relative* to rates of sea-floor spreading (e.g., Brass, 1976; Burke et al., 1982).

Because sea-floor spreading and continental erosion are also thought to be the primary pathways for input and output of carbon dioxide to the atmosphere on geologic time scales (e.g., Berner et al., 1983), the $^{87}Sr/^{86}Sr$ curve can also be loosely viewed as a proxy for atmospheric CO_2 levels. More positive $^{87}Sr/^{86}Sr$ values (enhanced continental erosion) would be associated with decreased carbon

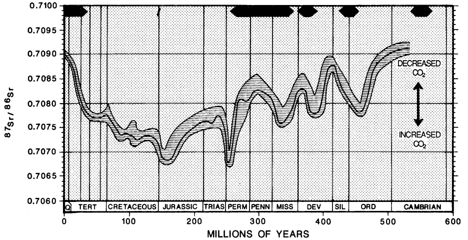

Figure 1. Estimated $^{87}Sr/^{86}Sr$ seawater ratio (middle solid line) vs. age for Phanerozoic (from Koepnick et al., 1988). Horizontal-ruled band incorporates 93% of original $^{87}Sr/^{86}Sr$ data. Black bars indicate times of inferred glaciation (taken from Crowell, 1983). Both proxies are plotted to time scale of Harland et al. (1982).

dioxide levels, whereas more negative $^{87}Sr/^{86}Sr$ values (enhanced sea-floor spreading and hydrothermal activity) would be associated with increased carbon dioxide levels. Indeed, for the past 150 m.y., variations in the carbon-isotope fractionation between marine carbonate and primary marine organic matter, interpreted by Popp et al. (1989) as a function of atmospheric CO_2 levels, look remarkably similar to the strontium-isotope curve. The carbon-isotope data also suggest that a major decrease in atmospheric CO_2 levels has occurred since the Eocene. However, the carbon system is subject to numerous additional feedbacks and influences (including the relative burial rates of carbon in oxidized vs. reduced states and the effect of climate on plant productivity); these make an exact correlation between strontium-isotope values and CO_2 levels over the past 500 m.y. unlikely.

Given the above caveats, I suggest that increasing (more positive) $^{87}Sr/^{86}Sr$ ratios reflect an increase in rates of global chemical weathering and in river-dissolved fluxes that would result in lowered atmospheric CO_2 levels and colder global temperatures. These times are associated with major orogenic episodes of the Phanerozoic. The first-order trends in Figure 1 are consistent with such a hypothesis; the $^{87}Sr/^{86}Sr$ record indicates that continental erosion, relative to sea-floor spreading, was *most* important during the Paleozoic Era and late in the Cenozoic, consistent with evidence for times of widespread continental glaciation. Furthermore, with the exception of the sharp $^{87}Sr/^{86}Sr$ rise at the Permian/Triassic boundary, second-order features in Figure 1 appear to be generally consistent with the hypothesis. Intervals during the Phanerozoic characterized by glacial climates (as summarized by Crowell, 1983) are indicated by black bars along the top of Figure 1. Given the dating uncertainties in records of Paleozoic glaciation and the potential for seawater strontium values to be affected by variations in hydrothermal activity or river $\delta^{87}Sr$ values, there appears to be a good correlation between times of rising $^{87}Sr/^{86}Sr$ values and periods for which evidence is found for glaciation. The apparent lag of peak $^{87}Sr/^{86}Sr$ values after glaciations is expected, given that the most rapid continental erosion is occurring when $^{87}Sr/^{86}Sr$ ratios are rising fastest.

Major orogenic episodes, associated with the assembly of Pangea in the Paleozoic Era and the Alpine-Himalayan and Andean orogenies in the late Cenozoic, started at the same time as upswings in oceanic $^{87}Sr/^{86}Sr$ values. The Paleozoic orogenies include the Taconic and Caledonian orogenies of the Late Ordovician and Silurian; the Acadian orogeny of the Middle Devonian; and the Alleghenian, Hercynian, and Ural orogenies of the Carboniferous and Early Permian (Van der Voo, 1982, 1983). The association of these major mountain-building episodes with times of increasing $^{87}Sr/^{86}Sr$ values suggests that the rate of global orogeny, rather than the rate of sea-floor spreading and sea level, may be an important factor controlling rates of global erosion, atmospheric CO_2 levels, and, ultimately, the timing of Phanerozoic glaciations.

DISCUSSION

Two obvious objections to this hypothesis could be made. First, there are some increases in seawater $^{87}Sr/^{86}Sr$ that are not associated with glaciation, the two clear examples being in the Early Triassic and Late Jurassic/Early Cretaceous. However, widespread glaciation may occur only when atmospheric CO_2 levels fall below some critical threshold, this threshold being dependent on the *relative* rates of removal and supply of CO_2. During the Mesozoic, the lower than average values of seawater $^{87}Sr/^{86}Sr$ indicate that rates of sea-floor spreading (and hence CO_2 outgassing) were high relative to those of the Paleozoic and Cenozoic eras, in agreement with independent estimates of spreading rates based on eustatic sea-level changes (Vail et al., 1977). By the same token, not every orogeny would necessarily be accompanied by glaciation, although it is apparent that the major orogenic episodes associated with the ~400 Ma Wilson Cycle of continental fragmentation and assembly are.

Second, one might argue that continental ice sheets would result in higher erosion rates and hence higher values of oceanic $^{87}Sr/^{86}Sr$ (Armstrong, 1971; Hodell et al., 1989). However, the majority of dissolved weathering components entering the world's oceans today originate in low- to middle-latitude mountainous regions in Asia and South America (Berner and Berner, 1987). Very little chemical weathering takes place in polar regions (Hay and Southam, 1977). In addition, recent calculations by Hodell et al. (1990) suggest that glacial erosion by the Laurentide ice sheet probably accounts for less than 25% of the ocean $^{87}Sr/^{86}Sr$ increase since 2.5 Ma.

Molnar and England (1990) argued that high rates of denudation observed in some mountainous regions are, in large part, driven by the erosional effects of mountain glaciers and, hence, that increased chemical erosion would be a result of climate cooling, not a cause. Mountain glaciers undoubtedly contribute to the break-up and continual exposure of new minerals; however, the presence of mountain glaciers at low to middle latitudes demands previously high elevations; high elevations suggest uplift and erosion. I agree with Molnar and England (1990, p. 34) when they state that glacial erosion can be viewed as a positive climate feedback. Such a process would have enhanced, for example, the post-Eocene climate cooling associated with the tectonically driven uplift and erosion of the Himalayas and Tibetan Plateau.

No single mechanism can account for the full spectrum of climate variations during Phanerozoic time. For example, excessive burial of organic matter during the Carboniferous may have lowered atmospheric CO_2 levels enough to allow glaciation to extend well into the Permian, a time when the $^{87}Sr/^{86}Sr$ ratio was falling (Callender, 1939). Similarly, broad plateaus, similar to Tibet today, formed in the Carboniferous Hercynian belt of Europe (Zeigler, 1990) and could have influenced global climate via mechanisms suggested by Ruddiman and Raymo (1988) and Ruddiman and Kutzbach (1989). More generally, changes in continental geometry, mantle CO_2 outgassing, or even solar output could influence global climate. I propose that variations in atmospheric CO_2 controlled by episodic uplift and erosion of major mountain ranges should be reconsidered as an important (if not the most important) influence on global temperatures both in the late Cenozoic (Raymo et al., 1988) and during the Paleozoic. Strontium-isotope data provide evidence of a link between times of major orogenies, enhanced rates of continental weathering, and times of glaciation. The temporal correlation between the Alpine-Himalayan and Andean orogenies and the late Tertiary deterioration of global climate is firm; however, more detailed tectonic and glacial histories for the Mesozoic and Paleozoic eras are needed. Only then will we be able to evaluate fully the influence of orogeny, specifically uplift and erosion of major mountain ranges and plateaus, on ocean and atmosphere chemistry and global climate.

REFERENCES CITED

Armstrong, R.L., 1971, Glacial erosion and the variable isotopic composition of strontium in sea water: Nature, v. 230, p. 132–133.

Arthur, M.A., Dean, W.E., and Schlanger, S.O., 1985, Variations in the global carbon cycle during the Cretaceous related to climate, volcanism, and changes in atmospheric CO_2, *in* Sundquist, E.T., and Broecker, W.S., eds., The carbon cycle and atmospheric CO_2: Natural variations Archean to present: Washington, D.C., American Geophysical Union, p. 504–530.

Barron, E.J., 1985, Explanations of the Tertiary global cooling trend: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 50, p. 45–61.

—— 1981, Paleogeography as a climatic forcing factor: Geologische Rundschau, v. 70, p. 737–747.

Barron, E.J., and Washington, W.M., 1985, Warm Cretaceous climates: High atmospheric CO_2 as a plausible mechanism, *in* Sundquist, E.T., and Broecker, W.S., eds., The carbon cycle and atmospheric CO_2: Natural variations Archean to present: Washington, D.C., American Geophysical Union, p. 546–553.

Berner, E.K., and Berner, R.A., 1987, The global water cycle: Englewood Cliffs, New Jersey, Prentice-Hall, 397 p.

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.

Brass, G.W., 1976, The variation of marine $^{87}Sr/^{86}Sr$ ratio during Phanerozoic time: Interpretation

using a flux model: Geochimica et Cosmochimica Acta, v. 40, p. 721–730.
Broecker, W.S., and Peng, T.-H., 1982, Tracers in the sea: Palisades, New York, Eldigio Press, 690 p.
Burke, W.H., Denison, R.E., Hetherington, E.A., Koepnick, R.B., Nelson, H.F., and Otto, J.B., 1982, Variation of seawater $^{87}Sr/^{86}Sr$ throughout Phanerozoic time: Geology, v. 10, p. 516–519.
Callender, G.S., 1939, The composition of the atmosphere through the ages: Meteorological Magazine, v. 74, p. 33–39.
Capo, R.C., and DePaolo, D.J., 1990, Seawater strontium isotopic variations from 2.5 million years ago to the present: Science, v. 249, p. 51–55.
Caputo, M.V., and Crowell, J.C., 1985, Migration of glacial centers across Gondwana during Paleozoic Era: Geological Society of America Bulletin, v. 96, p. 1020–1036.
Chamberlin, T.C., 1899, An attempt to frame a working hypothesis of the cause of glacial periods on an atmospheric basis: Journal of Geology, v. 7, p. 545–584, 667–685, 751–787.
Crowell, J.C., 1983, Ice ages recorded on Gondwanan continents: Geological Society of South Africa Transactions, v. 86, p. 237–262.
Crowell, J.C., and Frakes, L.A., 1970, Phanerozoic ice ages and the causes of ice ages: American Journal of Science, v. 268, p. 193–224.
Crowley, T.J., Mengel, J.G., and Short, D.A., 1987, Gondwanaland's seasonal cycle: Nature, v. 329, p. 803–807.
Crowley, T., Maier-Reimer, E., and Mikolajewicz, U., 1989, Effect of an open Central American isthmus on North Atlantic deep water production: Terra Abstracts, v. 1, p. 12.
Donn, W., and Shaw, D., 1977, Model of climate evolution based on continental drift and polar wandering: Geological Society of America Bulletin, v. 88, p. 390–396.
Douglas, R.G., and Woodruff, F., 1981, Deep-sea benthic foraminifera, *in* Emiliani, C., ed., The Sea, Volume 7: New York, Wiley-Interscience, p. 1233–1327.
Drever, J.I., 1988, The geochemistry of natural waters: Englewood Cliffs, New Jersey, Prentice-Hall, 437 p.
Flint, R.F., 1943, Growth of the North American ice sheet during the Wisconsin age: Geological Society of America Bulletin, v. 54, p. 325–362.
Gibbs, R.J., 1967, The geochemistry of the Amazon River system: Part 1. The factors that control the salinity and the composition and concentration of the suspended solids: Geological Society of America Bulletin, v. 78, p. 1203–1232.
Hamilton, W., 1968, Cenozoic climatic change and its cause: Meteorological Monographs, v. 8, p. 128–133.
Harland, W.B., Cox, A.V., Llewellyn, P.G., Pickton, C.A.G., Smith, A.G., and Walters, R., 1982, A geologic time scale: Cambridge, England, Cambridge University Press, 128 p.
Harwood, D.M., Webb, P.-N., and Barrett, P.J., 1989, Multiple Cenozoic glaciations of Antarctica from terrestrial and continental shelf data: Terra Abstracts, v. 1, p. 2.
Hay, W.W., and Southam, J.R., 1977, Modulation of marine sedimentation by the continental shelves, *in* Anderson, M.R., and Malahoff, A., eds., The fate of fossil fuel CO_2 in the ocean: New York, Plenum, p. 569–604.
Hodell, D.A., Mueller, P.A., McKenzie, J.A., and Mead, G.A., 1989, Strontium isotope stratigraphy and geochemistry of the late Neogene ocean (9 to 2 Ma): Earth and Planetary Science Letters, v. 92, p. 165–178.
Hodell, D.A., Mead, G.A., and Mueller, P.A., 1990, Variation in the strontium isotopic composition of seawater (8 Ma to present): Implications for chemical weathering rates and dissolved fluxes to the oceans: Chemical Geology, v. 80, p. 1–17.
Keigwin, L.D., 1982, Isotope paleoceanography of the Caribbean and east Pacific: Role of Panama uplift in late Neogene time: Science, v. 217, p. 350–353.
Kennett, J.P., 1977, Cenozoic evolution of Antarctic glaciation, the circum-Antarctic Ocean, and their impact on global paleoceanography: Journal of Geophysical Research, v. 82, p. 3843–3860.
Koepnick, R.B., Denison, R.E., and Dahl, D.A., 1988, The Cenozoic seawater $^{87}Sr/^{86}Sr$ curve: Data review and implications for correlation of marine strata: Paleoceanography, v. 3, p. 743–756.
Lasaga, A.C., Berner, R.A., and Garrels, R.M., 1985, An improved geochemical model of atmospheric CO_2 fluctuations over the past 100 million years, *in* Sundquist, E.T., and Broecker, W.S., eds., The carbon cycle and atmospheric CO_2: Natural variations Archean to present: Washington, D.C., American Geophysical Union, p. 397–411.
LeConte, J., 1899, The Ozarkian and its significance in theoretical geology: Journal of Geology, v. 7, p. 525–544.
Miller, K.G., and Fairbanks, R.G., 1983, Evidence for Oligocene–middle Miocene abyssal circulation changes in the western North Atlantic: Nature, v. 306, p. 250–253.
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.
Oglesby, R.J., 1989, A GCM study of Antarctic glaciation: Climate Dynamics, v. 3, p. 135–156.
Palmer, M.R., and Edmond, J.M., 1989, The strontium isotopic budget of the modern ocean: Earth and Planetary Science Letters, v. 92, p. 11–26.
Palmer, M.R., and Elderfield, H., 1985, Sr isotope composition of sea water over the past 75 Myr: Nature, v. 314, p. 526–528.
Popp, B.N., Takigiku, R., Hayes, J.M., Louda, J.W., and Baker, E.W., 1989, The post-Paleozoic chronology and mechanism of ^{13}C depletion in primary marine organic matter: American Journal of Science, v. 289, p. 436–454.
Powell, C.McA., and Veevers, J.J., 1987, Namurian uplift in Australia and South America triggered the main Gondwanan glaciation: Nature, v. 326, p. 177–179.
Ramsey, W., 1924, The probable solution of the climate problem in geology: Geological Magazine, v. 61, p. 152–163.
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.
Ruddiman, W.F., and Kutzbach, J.E., 1989, Forcing of late Cenozoic Northern Hemisphere climate by plateau uplift in southeast Asia and the American Southwest: Journal of Geophysical Research, v. 94, p. 409–427.
Ruddiman, W.F., and Raymo, M.E., 1988, Northern Hemisphere climate regimes during the last 3 Myr: Possible tectonic connections, *in* Shackleton, N.J., et al., eds., The past three million years: Evolution of climatic variability in the North Atlantic region: Cambridge, England, Cambridge University Press, p. 227–234.
Ruddiman, W.F., Raymo, M., and McIntyre, A., 1986, Matuyama 41,000-year cycles: North Atlantic Ocean and Northern Hemisphere ice sheets: Earth and Planetary Science Letters, v. 80, p. 117–129.
Ruddiman, W.F., Prell, W., and Raymo, M.E., 1989, History of late Cenozoic uplift on Southeast Asia and the American Southwest: Rationale for general circulation modeling experiments: Journal of Geophysical Research, v. 94, p. 379–391.
Schneider, S.H., Thompson, S.L., and Barron, E.J., 1985, Mid-Cretaceous continental surface temperatures: Are high CO_2 concentrations needed to simulate above-freezing winter conditions?, *in* Sundquist, E.T., and Broecker, W.S., eds., The carbon cycle and atmospheric CO_2: Natural variations Archean to present: Washington, D.C., American Geophysical Union, p. 554–560.
Smith, A.G., and Bryden, J.C., 1977, Mesozoic and Cenozoic paleocontinental maps: Cambridge, England, Cambridge University Press, 63 p.
Stallard, R.F., 1980, Major element geochemistry of the Amazon River system [Ph.D. thesis]: Massachusetts Institute of Technology–Woods Hole Oceanographic Institution, WHOI-80-29, 366 p.
Vail, P.R., Mitchum, R.M., and Thompson, S., III, 1977, Global cycles of relative changes of sea level, *in* Payton, C.E., ed., Seismic stratigraphy—Applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, p. 83–97.
Van der Voo, R., 1982, Pre-Mesozoic paleomagnetism and plate tectonics: Annual Reviews of Earth and Planetary Sciences, v. 10, p. 191–220.
——1983, A plate-tectonics model for the Paleozoic assembly of Pangea based on paleomagnetic data, *in* Hatcher, R.D., Jr., et al., eds., Contributions to the tectonics and geophysics of mountain chains: Geological Society of America Memoir 158, p. 19–23.
Ziegler, A.M., 1990, Phytogeographic patterns and continental configurations during the Permian Period, *in* McKerrow, W.S., and Scotese, C.R., eds., Paleozoic paleogeography and biogeography: Geological Society of London Memoir 12, p. 363–379.

ACKNOWLEDGMENTS

Supported by National Science Foundation Grant OCE88-10949 and a Melbourne University Special Initiatives grant. I thank Bill Ruddiman for comments and reviews; E. Barron, W. Broecker, N. Eyles, G. Houseman, and P. Molnar for useful discussion and reviews; R. Koepnick for a copy of his strontium isotope curve; and S. Pribble for drafting assistance.

Manuscript received June 27, 1990
Revised manuscript received October 19, 1990
Manuscript accepted November 6, 1990

Reviewers' comments

Revitalizes an interesting theory.
Eric Barron

Will provoke thought and argument. . . . A matter of taste . . . but I like it.
Wallace Broecker
