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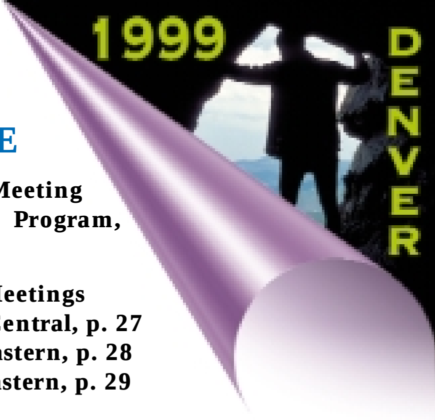

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Does climatic change drive mammalian evolution?

Donald R. Prothero, *Department of Geology, Occidental College, Los Angeles, CA 90041, prothero@oxy.edu*

ABSTRACT

Neo-Darwinian evolutionary theory argues that species and faunas are exquisitely adapted to their environment and should respond when their habitat changes. To test this hypothesis, the mammalian response to four of the largest climatic events of the Cenozoic (as documented by the marine record, oxygen isotopes, land plants, and other climatically sensitive organisms) are examined. These events occurred during the global cooling at the end of the middle Eocene (37 Ma), the cooling and drying event in the earliest Oligocene (33 Ma), the spread of C4 grasslands in the late Miocene (7 Ma), and the rapid climatic fluctuations of the Pliocene-Pleistocene (2.5 Ma to present). In each case, there is relatively little short-term response of the mammalian fauna. Typically, there is greater turnover millions of years before and after the time of climatic change than during the climatic event itself. This pattern suggests that the climatic control on mammalian evolution is much more complex than previously supposed, or that intrinsic biotic controls may be more important than extrinsic environmental controls.

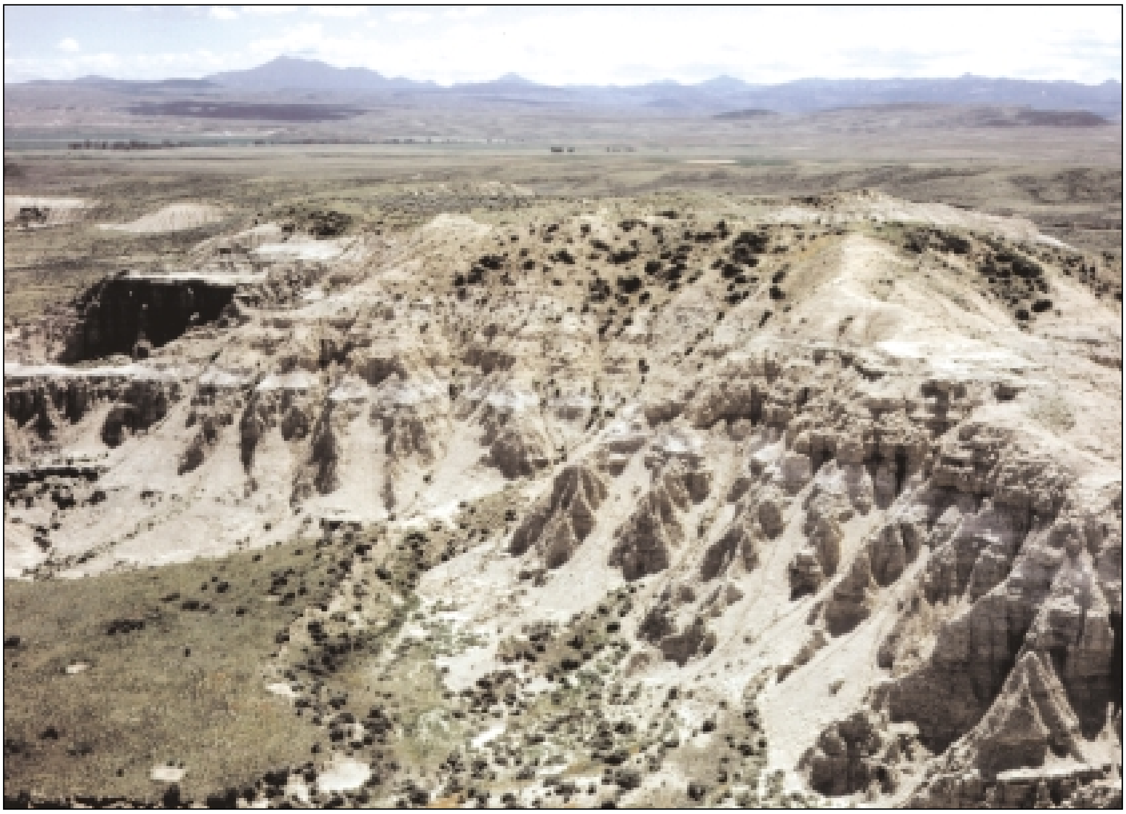

Figure 1. Looking south at exposures of the Eocene-Oligocene White River Group south of Douglas, Wyoming (Laramie Range in the background). The prominent white ash layer in the middle of the cliff (5a tuff of Evanoff et al., 1992) has been ^{40}Ar/^{39}Ar dated at 33.9 ± 0.13 Ma (Prothero and Swisher, 1992). Extinction of the brontotheres and most other faunal events at the end of the Chadronian occurred just before and after deposition of this ash. Yet the climatic change (as shown by the sedimentology and land snails—Evanoff et al., 1992) is reflected much higher in this same section.

INTRODUCTION

One of the central tenets of neo-Darwinian evolutionary theory is the idea that organisms are highly responsive to changes in their environment caused by climate, and readily adapt to environmental selection pressures. Evolutionary biologists have documented many elegant (but small-scale and short-term) examples of organisms responding to environmental selection (Weiner, 1994). One explicitly testable hypothesis related to this idea was Vrba's (1985, 1993) "turnover pulse" hypothesis, which suggests that most evolutionary turnover events are correlated with episodes of major climatic change. The turnover pulse idea has appeared in many recent books that purport to explain human evolution as a response to climatic change and instability (Stanley, 1996; Potts, 1996; Boaz, 1997).

However, a growing body of data conflicts with the notion that all organisms are highly sensitive to climatic changes, and respond by adaptation to environmental selection pressures. One of the surprising outcomes of the punctuated equilibrium model of Eldredge and Gould (1972) has been recognition of the prevalence of stasis among species through millions of years and many episodes of climatic change (Eldredge, 1995, p. 64). This is not to say that most organisms are insensitive to climate. For some groups of organisms, such as microplankton or land plants, the response to environmental change is well established. However,

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IN THIS ISSUE

In Memoriam

Thomas F. Bates
State College,
Pennsylvania
June 19, 1999

William F. Jenks
Newburyport,
Massachusetts
March 18, 1999

Sheldon Judson
Princeton, New Jersey
May 28, 1999

Charles J. Orth
Los Alamos, New Mexico
October 6, 1994

John D. Ridge
Charlottesville, Virginia

Richard C. Thompson
San Francisco, California
June 27, 1999

Robert T. White
Lafayette, Louisiana
July 2, 1999

Please contact the GSA Foundation for information on contributing to the Memorial Fund.

Did You Remember To Vote?

The GSA ballots to elect officers for 2000 and councilors for the term 2000–2002 are due September 13, 1999.

Don't forget to vote!

Please note, for the ballot you received, this updated information on Council: Position 3 Nominee Mary P. Anderson. PROF. EXP.: **PROF. HYDROGEOLOGY, UNIV. WISCONSIN–MADISON, 97-.**

Climatic Change *continued from p. 1*

the environmental sensitivity of other organisms (especially marine invertebrates and terrestrial vertebrates) is less obvious.

In recent years, the potential to document and evaluate such patterns with excellent, detailed fossil records of certain organisms has greatly improved. The development of high-resolution chronostratigraphy with integrated biostratigraphy, magnetostratigraphy, and ^{40}Ar/^{39}Ar dating has allowed paleontologists to directly date and correlate patterns of faunal response in both the marine and terrestrial realms at a very fine scale. It is now possible to test aspects of the "turnover pulse" hypothesis with a much better data base than was available only a decade ago.

We now can ask whether turnover pulses are typical of the history of mammals. Broad, long-term changes in mammalian faunas (spanning tens of millions of years) apparently correlate with the well-documented climatic changes of the Cenozoic (Webb, 1977; Webb and Opdyke, 1995; Janis, 1989, 1993), but do mammalian faunas respond to rapid, short-term climatic changes, as predicted by the turnover pulse model? Alroy (1995, 1997, 1998) showed that there was a very poor correlation between the turnover patterns of North American Cenozoic mammals and accepted proxies of climatic change, such as the global oxygen isotope record. Hill (1995) and Behrensmeyer et al. (1997) argued that the turnover pulses reported by Vrba (1985) for African Pliocene-Pleistocene mammals are not substantiated by the much larger database of Pliocene mammals from the Tugen Hills and Turkana Basin of Kenya. Thus, even the original data set that led to the turnover pulse hypothesis is under question.

Dialogue

Good communication is stimulating as black coffee, and just as hard to sleep after.

—*Anne Morrow Lindbergh*

Sara Foland, Executive Director/CEO

As new chief executive officer of GSA, I'm thrilled to have this opportunity each month to talk to the Society's members and friends. As good as it is, however, *GSA Today* is a one-way medium. By itself, it can't give us the open, immediate and interactive communication we need as a scientific society on the verge of a new millennium.

There's Lots to Talk About

GSA's Strategic Plan, approved by Council in 1998, set the stage for sweeping change, while preserving and building on our 111-year heritage. The inspiring vision on which the plan is based reads, "GSA will be a broad unifying scientific society: fostering the human quest for understanding Earth, planets, and life; catalyzing new scientific ways of thinking about natural systems; and applying geoscience knowledge and insight to human needs and aspirations and stewardship of the Earth."

It's my job to lead the headquarters staff in implementing the Strategic Plan on your behalf. But we have a mutual responsibility to discuss and debate the issues that arise from our individual interpretations of the vision. In that spirit, here's a brief overview of what you can expect to see in the months ahead.

GSA's main focus will continue to be the science on which the Society was founded. We'll pursue our mission of advancing the geosciences and the professional growth of our members through our traditional disciplines and Divisions. At the same time, we'll aggressively pursue integrated science that crosses disciplines within our field and with allied sciences.

In the coming months, you'll also see GSA's intrinsic values take their place alongside the science. We'll explore the concept of stewardship and our role as stewards of earth science knowledge and of Earth itself. We'll strive to de-politicize this term, exploring its meaning for both the environmentalists and natural resource professionals among us. If GSA is to grow into its vision of a broad, unifying scientific society, unification must begin here at home. As a Society, we intend to model for others the kind of discourse that makes this possible.

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Photo taken at Dinosaur Ridge near Morrison, Colorado.

We'll better articulate the role of service at GSA—service to our members, to the geoscience education community, and to society as a whole. We intend to encourage and support geoscientists in offering their services in whatever ways are most rewarding and meaningful to them.

You'll also be hearing about the "globalization" of GSA. This may seem like a departure from how we've thought of ourselves in the past, but in fact, it's an acknowledgement of trends already well underway.

Ways to Get in Touch and Stay in Touch

I'm looking forward to lively exchange of ideas on these and other subjects. You can call me at my office here at headquarters (303-447-2020, ext. 139) or send e-mail to ceo@geosociety.org. You can post questions to me on the GSA Web site, www.geosociety.org, by going to "How to Contact Us" and clicking on "Ask Sara Foland."

We're also considering a series of interactive chat room sessions on topics of interest. Watch for details on the Web site and here in *GSA Today*.

I hope to meet as many of you as possible at next month's Annual Meeting in Denver. Watch for notices in *Down to Earth*, the daily meeting newsletter, about locations where you can stop by and say hello. We'll be joined, at various times, by GSA President Gail Ashley, Vice President Mary Lou Zoback, and 1999 Annual Program Committee Chair Sharon Mosher.

I'm excited about working with you all as we move this venerable organization forward. We are GSA. Let's stay in touch. ■

TESTING THE HYPOTHESIS

What is the mammalian response to the major climatic events of the past 50 m.y.? The highly detailed climatic history now available for much of the Cenozoic allows us to pinpoint certain episodes of major environmental change (as recognized in marine faunas, oxygen isotopes, land plants, and other climatically sensitive organisms). With improved dating and correlation, we can examine any mammalian response to each of these global climatic events. If the turnover pulse hypothesis is generally valid for Cenozoic mammals, then there should be similar responses to the other great climatic crises of the Cenozoic. Four major climatic events stand out (see below).This study excludes turnover events such as those at the Paleocene-Eocene boundary, or the Grande Coupure in the European Oligocene, because those episodes include significant immigrational turnover, which complicates the picture of in situ change.

Test 1—Middle Eocene Event

The first major step in the climate change of the Cretaceous through middle Eocene "greenhouse world" was the profound cooling event at the end of the middle Eocene, dated at 37.0 Ma (Berggren and Prothero, 1992; Berggren et al., 1995) (Fig. 1). Oxygen isotope records from benthic foraminifera show that the oceans cooled by about 4–5 °C at this time (Miller et al., 1987). Boersma et al. (1987) argued that there was a major cooling of oceanic bottom waters, which became decoupled from surface waters. In response to this rapid cooling and oceanographic change, there was a major extinction in the warm-water foraminifera (Boersma et al., 1987), a major extinction of many long-lived tropical nannoplankton (Aubry, 1992), and extinctions in the bivalves (84% of species) and gastropods (89% of species) in the Gulf Coastal Plain (Hansen, 1987, 1992). By any standard, the end of the middle Eocene was a dramatic cooling and extinction event, especially in the marine realm.

The terrestrial paleoclimatic record of the middle–late Eocene transition is rather limited, but there are some important clues. Land plants from Alaska to the Gulf Coast indicate a reduction of mean annual temperature of about 14–16 °C (Wolfe, 1978, 1994). Late Duchesnean paleosols from the Big Badlands of South Dakota indicate dense tropical forests with more than 1 m of annual rainfall, while those of the overlying upper Eocene Chadron Formation received between 500 and 1000 mm and were less densely forested (Retallack, 1983).

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How did land mammals respond to these climatic changes? The middle–late Eocene boundary at 37.0 Ma is now correlated with the boundary between the Duchesnean and Chadronian North American land mammal "ages" (Prothero, 1995; Prothero and Emry, 1996). Most mammalian faunas can be correlated to this interval through a combination of magnetic stratigraphy and ^{40}Ar/^{39}Ar dates. In west Texas, the Duchesnean-Chadronian transition can be directly calibrated between ^{40}Ar/^{39}Ar dates of 36.7 ± 0.07 and 37.8 ± 0.15 Ma, and by correlation with other faunas, the overall pattern in North America can be determined.

All recent studies of this interval conclude that there was very little change in mammalian faunas between the Duchesnean and Chadronian. Large-scale compilations of species and generic diversity and turnover (Stucky, 1990, 1992; Alroy, 1998) show no significant diversity changes or unusual turnover rates between the late Duchesnean and early Chadronian; there was a stable equilibrium value of between 72 and 84 genera throughout this 5 m.y. (40–35 Ma) interval (Fig. 2). Turnover rates are about average for the late Paleogene. In fact, Emry (1981) and Wilson (1984, 1986) argued that the Duchesnean could be considered a "subage" of the Chadronian, because the differences were so slight. A much greater faunal change (Fig. 2) occurred between the early Duchesnean and the late Duchesnean (Wilson, 1986; Lucas, 1992). This turnover occurred at 39 Ma, 2 m.y. before the climatic change in the oceanic realm (Prothero and Emry, 1996).

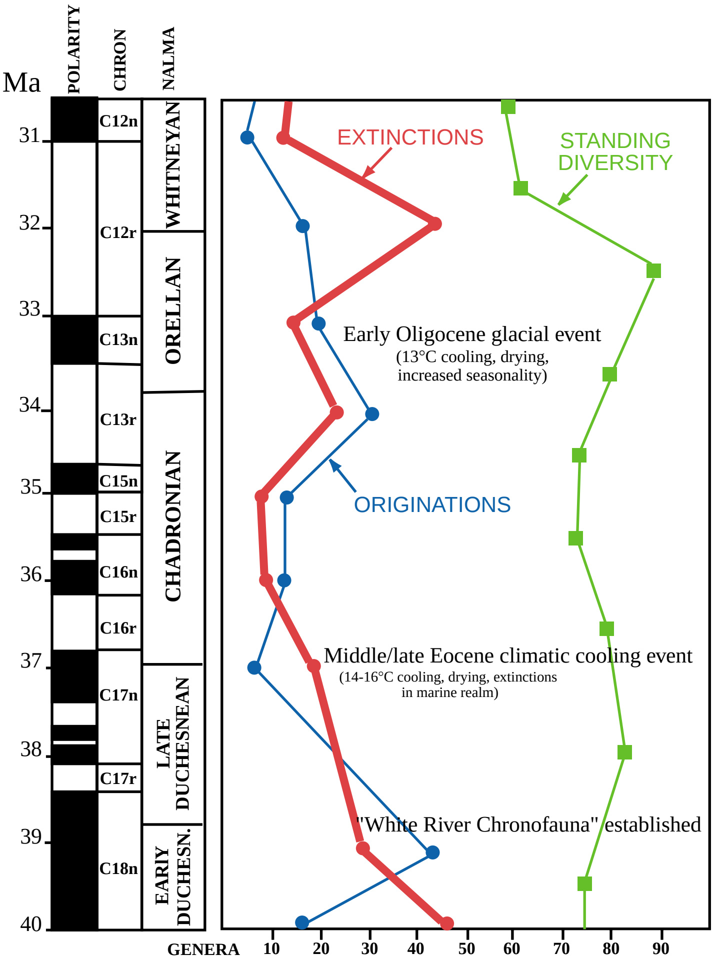

Figure 2. Mammalian diversity and turnover through the late middle Eocene (Duchesnean), late Eocene (Chadronian), and early Oligocene (Orellan and Whitneyan). Diversity data modified from Stucky (1992) for the Duchesnean, and Prothero and Heaton (1996) for the Chadronian through Whitneyan. Total generic diversity (green squares) shown in the middle of 1 m.y. increments; originations (blue circles) shown at the beginning of each 1 m.y. interval, and extinctions (red circles) at the end of each 1 m.y. interval. NALMA = North American land mammal "ages." Time scale after Berggren et al. (1995) and Prothero and Emry (1996).

Test 2—Early Oligocene Event

On the basis of the oxygen isotope curve (Miller et al., 1987) or the land floras (Wolfe, 1978, 1994), the most significant climatic event in the Cenozoic was the global refrigeration that occurred in the earliest Oligocene (about 33.2 Ma). This event was marked by the first significant Antarctic glaciers, and about 5–6 °C of global cooling (Miller et al., 1987; Miller, 1992). The cooling was as drastic as that at the end of the middle Eocene, and extinctions in the marine realm were almost as severe. There were major extinctions in the calcareous nannoplankton (Aubry, 1992), diatoms (Baldauf, 1992), and benthic foraminifera (Gaskell, 1991). Gulf Coast molluscs were decimated again; 97% of gastropod species and 89% of bivalve species disappeared after their late Eocene recovery (Hansen, 1987, 1992). Echinoids dropped 50% in species diversity at this time (McKinney et al., 1992). Planktonic foraminifera underwent a minor extinction; most surviving early Oligocene species were small, low in diversity, and cold adapted (Boersma et al., 1987).

Numerous climatic indicators show that the earliest Oligocene was a time of rapid (less than a few thousand years) change in terrestrial habitats. Land plants from the Gulf Coast to Alaska indicate a decrease of 13 °C in mean annual temperature, a great increase in seasonality (mean annual range of temperatures increased dramatically from about 5 °C to almost 25 °C), and much drier climates (Wolfe, 1978, 1994). Floras indicate that most of North America changed from paratropical forests (like those of tropical Central America) to broad-leaved deciduous forests (like those of New England) in a very short period of time. Paleosols from the Big Badlands of South Dakota show that late Eocene forests, which received more than 1 m of rainfall, were replaced in the early Oligocene by open scrublands with less than 500 mm of annual precipitation (Retallack, 1983, 1992). In Douglas, Wyoming (Fig. 1), flood-plain deposits were replaced by eolian deposits, indicating even greater trends toward aridity (Evanoff et al., 1992). Late Chadronian land snails are large forms adapted to wet, subtropical habitats (like those of modern central Mexico). In the early Orellan they were replaced by smaller taxa with restricted apertures, typical of drier climates, like those of modern Baja California (Evanoff et al., 1992). Late Chadronian reptiles and amphibians were predominantly aquatic taxa, such as crocodilians, pond turtles, and salamanders, but only dry land tortoises are common in the Orellan (Hutchison, 1982, 1992).

How did land mammals respond to this dramatic change in their environment? As Prothero and Heaton (1996) have shown, there was almost no response (Fig. 2). The earliest Oligocene climatic event (middle early Orellan, Chron C13n) was almost ignored by land mammals. Of 70 species known from the earliest Orellan, 62 persisted unchanged into the late Orellan. Most of the modest faunal responses during the Chadronian-Orellan transition had already taken place more than 250 k.y. before the climatic crash of the early Orellan. But even these changes were unimpressive: A few archaic groups from the Chadronian, such as the brontotheres, oromerycid artiodactyls, and cylindrodont rodents disappeared, and the oreodont *Miniochoerus* underwent slight dwarfing, but most mammalian lineages showed no changes worth documenting. Compared to the 177 species now documented for this interval, this is a remarkably mild response to what all the other evidence indicates was a major climatic and floral change. This lack of change cannot be dismissed as an artifact of sampling or preservation, because the White River Group in eastern Wyoming is densely fossiliferous through all of the relevant interval (Prothero and Heaton, 1996; Evanoff et al., 1992).

Test 3—Late Miocene Carbon Isotopes and Grasslands

One of the classic cases of evolutionary response to climate is the well-known story of how some herbivorous mammals acquired high-crowned teeth for eating gritty grasses in the Miocene. This is most often noted in the evolution of horses, but it also occurred in camels, bovids, pronghorns, rhinoceroses, and other groups. Scientists have long pointed to this as a clear example of an evolutionary response to a climatic and vegetational change. There is a major problem with this scenario: the timing is all wrong. Hypsodont horses, camels, rhinos, and bovids all first developed their high-crowned teeth in the middle Miocene (about 15–16 Ma), but geochemical evidence of extensive C4 grasslands (the grasses that now dominate most temperate and tropical latitudes) did not become widespread until the late Miocene (8-7 Ma), at least 7 m.y. later (Quade et al., 1989; Cerling, 1992; Cerling et al., 1997). Retallack (1997) has argued that there must have been an expansion of C3 grasslands in the middle Miocene, but if this is so, we have no modern analogues for such a vegetation (Wang et al., 1994).

Regardless of how one tries to explain this mismatch between teeth and vegetation, the C4 carbon isotope signal, which marks the great expansion of tropical and temperate grasslands and savannas at 8–7 Ma, produces another climatic-evolutionary enigma (Cerling et al., 1997). The carbon isotopic records of several areas (in North America, South America, East Africa, Pakistan) indicate a dramatic and abrupt global isotopic event at 7 Ma. C4 grasslands must have rapidly taken over huge areas in lower and middle latitudes at this time (Fig. 3).

Such a dramatic vegetational change should have led to drastic changes in the mammalian faunas that ate the grasses, especially in their abundance, extinction, and diversification. Yet, a detailed examination of the mammalian record does not support this. In North America, the 7 Ma isotope event falls at the early-late Hemphillian boundary (Woodburne and Swisher, 1995). The change in carbon isotope values at this time was dramatic (Cerling et al., 1997). Before 7 Ma, the values range between –7‰ and –14‰ (all C3 plants), but after 7 Ma, there are numerous values above –7‰ and some as high as +5‰ (mostly C4 plants). At the end of the early Hemphillian, there was some extinction in the horses, browsing camels, and pronghorns (Webb, 1983; Webb et al., 1995), for a total of 9 genera of large ungulates, and 27 genera overall (Stucky, 1990). But only 33 new genera (Stucky, 1990) appeared as the grasslands expanded in the late Hemphillian, and there was no great increase in grazing taxa. No new grazing ungulate genera were added, and the percentage of grazing taxa actually declines from 87% in the late Clarendonian-early Hemphillian to 80% in the late Hemphillian Coffee Ranch Quarry, Texas (Webb, 1983). Janis et al. (1999) found no increases in grazing ungulate taxa in this interval.

In addition, much greater turnover (45 new early Hemphillian genera, 36 Clarendonian genera extinct) marked the beginning of the Hemphillian (9.0 Ma), which was 2 million years before the C4 grasslands appeared. The most significant turnover event (37 new genera, 63 genera extinct) of the entire Miocene occurred 2.5 million years later, at the end of the Hemphillian (4.5 Ma), when most of the savanna fauna of North America (especially among the horses, camels, pronghorns, protoceratids, dromomerycids, rhinoceroses, gomphotheres, and mylagaulids) disappeared (Webb, 1983).

In Asia, isotopic data (Cerling et al., 1997) show an abrupt and dramatic increase in grasslands at 7 Ma (Fig. 3). Before 7 Ma, the δ^{13} C values are between –5 and –14 ‰, but after 7 Ma, the values range from 0 to +5‰. Barry (1995) showed the detailed history of faunal change (mostly bovids and rodents) in the well-studied Siwalik deposits of Pakistan. There was a major turnover event between 9.0 and 8.5 Ma, but none at 7 Ma (Fig. 3). In fact, turnover rates (both first and last occurrences) declined dramatically after 8.0 Ma (Barry, 1995). Cerling et al. (1997) suggested that there were some faunal replacement events between 8 and 7 Ma, but this change in dominance is not reflected in the overall taxonomic turnover. In addition, there are many pulses of turnover throughout the Miocene of Pakistan that do not seem to be correlated with any known climatic event. Researchers have argued that these data are evidence of climatically driven turnover, but much of the turnover has no apparent climatic explanation (Barry et al., 1985). Even if higher-resolution studies should show more turnover at 7 Ma, the salient fact remains that turnover was higher before and after the C4 event.

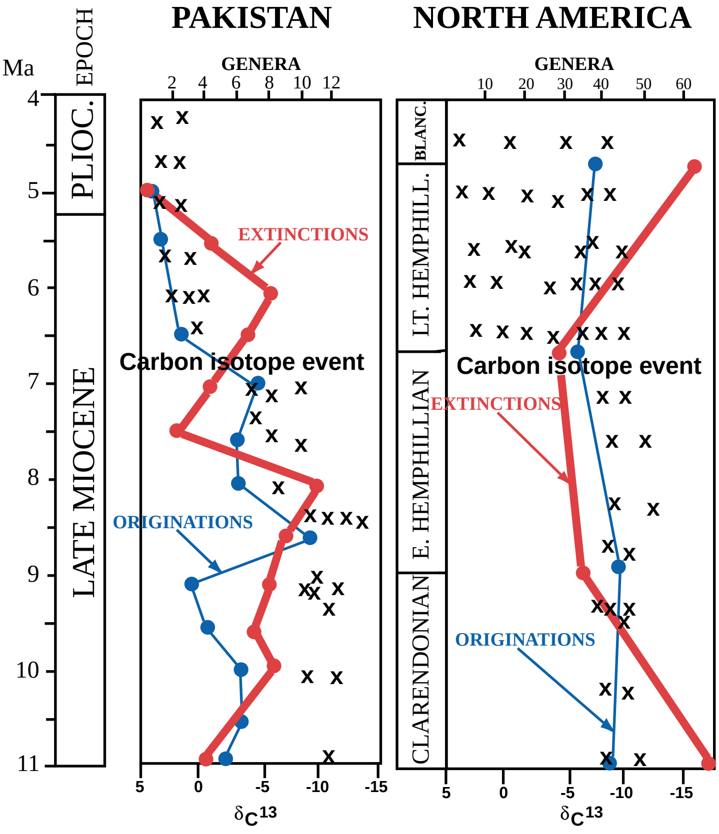

Figure 3. Comparison between carbon isotope values and changes in late Miocene mammalian diversity in Pakistan and North America. Symbols for origination and extinction curves as in Figure 2. Carbon isotopic values (X's) modified from Cerling et al. (1997, Fig. 2). Mammalian diversity statistics for North America after Stucky (1990), and for Pakistan after Barry (1995). Time scale after Woodburne and Swisher (1995) and Barry (1995).

In western Europe, the pattern is similar. Köhler et al. (1998) showed that there were two major faunal turnover events in the Neogene mammals of Spain, one at 10-9 Ma, and the other at 6.5 Ma, but none at 7.0-7.5 Ma. This is consistent with the episodes of maximum turnover in Pakistan. Köhler et al. (1998) suggested that the synchronous turnover across Western Eurasia uncorrelated with the C4 grasslands (which developed in Pakistan but not in Spain) supports a model of protracted faunal change that is caused by more complex forcing factors than a single climatic change.

Isotopic studies from East Africa (Cerling et al., 1997) document a significant carbon isotope event between 9 and 7 Ma. Yet Hill (1987, 1995) argued that the faunas of East Africa show little evidence of grassland dominance until Pliocene-Pleistocene time. Leakey et al. (1996) also found little faunal change in the 9–7 Ma interval. South America also shows the 7 Ma carbon isotope event (MacFadden et al., 1994, 1996; Cerling et al., 1997; Latorre et al.,

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1997), yet there was no obvious response in turnover or hypsodonty of South American mammals (MacFadden et al., 1994, 1996).

Test 4—Pleistocene Climatic Changes

The most rapid climatic fluctuations of the entire Cenozoic have occurred in the past 2 m.y.a, when climate has been controlled by 120 ka glacial-interglacial cycles. In the classic neo-Darwinian model that postulates species adapting to each climatic change, we would expect that such climatic variability would trigger much adaptation and speciation in Pleistocene mammals. Yet Barnosky (1987, 1994) and Barnosky et al. (1996) have shown that the response is much more complicated than this. Most Pleistocene mammals persist through many climatic cycles. They usually respond to climate change not by evolving new adaptations and producing new species, but simply by migrating north or south as climatic belts shift in latitude. Relatively few evolutionary changes (other than size changes) can be directly attributed to climatic change. The same evolutionary stability has been documented in Pleistocene reptiles and amphibians (Holman, 1995).

CONCLUSIONS

Paleontologists and evolutionary biologists have long sought to explain the excellent fossil record of land mammals, with its many dramatic faunal changes, and examples of adaptations (such as high-crowned teeth or long limbs) in terms of the Cenozoic changes in vegetation and climate. As our understanding of the fossil record of mammals improves, and the dating of the relevant deposits reaches higher levels of resolution and precision, it is possible to test hypotheses of climatic causes for evolutionary changes in much greater detail. In each of these four examples of independently established climatic change (as documented by the marine record, terrestrial isotopes, and terrestrial soils, plants, and climatically sensitive organisms), there are very few instances of direct response of the mammalian fauna to a specific, temporally limited climatic stimulus. Instead, the striking feature of each of these abrupt climatic changes is the *lack* of response of land mammals, even though in each example, it is clear that land plants and other elements of the terrestrial biota are responding. Clearly, the response of mammalian faunas to climatic stimuli is much more complicated than we have previously suspected. As previous studies of species and faunal stasis have shown, many organisms are much more stable in face of environmental change than classic neo-Darwinian models have previously supposed.

In past studies of excellent faunal records through long periods of time, scientists tried to explain each pulse of turnover by a specific external environmental event. Yet as the quality of the dating and of external records of climate improves, the emerging picture is not one of each pulse of turnover having a direct climatic cause. Instead, we are finding that many faunal events occur with no obvious extrinsic trigger, and many other climatic changes seem to cause no mammalian faunal change. On the longer-term scale, this is similar to the conclusions reached by Alroy (1995, 1997, 1998), who found that few of the major global climatic events (as represented by changes in marine oxygen isotopes) were correlated with peaks of mammalian turnover in North America, and vice versa. This noncorrelation seems to reveal an inherent bias toward focusing on possible instances of climatic causation of faunal change, and ignoring all the other unexplained turnover events. Instead, an objective (and statistically valid; Alroy, 1998) view of the mammalian faunal record in the Cenozoic leads to the conclusion that few turnover events can be directly tied to specific climatic changes.

This suggests that scientists should be more skeptical and more rigorous when they wish to suggest a cause-and-effect relationship between short-term climatic and faunal change. Such relationships may exist, but scientists must establish correlation on a very highly resolved chronostratigraphic basis before these hypotheses can be evaluated. To date, when such detailed correlations have been established between global climatic signals and terrestrial faunal change, the response has been contrary to expectations.

ACKNOWLEDGMENTS

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Tributes Honor Halbouty for 90th Birthday

Internationally known geologist and engineer Michel T. Halbouty is accustomed to accolades—he has received many in his long career. Two events in June were especially meaningful to him, however, as he marked his 90th birthday: a symposium on natural resources and hazards, sponsored by the U.S. Geological Survey, the National Academy of Sciences–-National Research Council, and the Circum-Pacific Council, and a tribute sponsored by the American Association of Petroleum Geologists, Texas A&M's College of Geosciences, and the Houston Geological Society. Halbouty spoke at both events.

Michel Halbouty joined the Geological Society of America in 1958, and it was just a year later that he discovered a gas field in the Kenai Peninsula, Alaska. He was the first independent driller to initiate wildcat wells in Alaska.

Halbouty has received numerous awards and honors, including the GSA Distinguished Service Award (1993). He has lectured all over the world, has served on many government energy-related committees and commissions, and has written or edited hundreds of scientific publications. A fellow of GSA, he was instrumental in the formation of the GSA Foundation and served as a trustee on its first board.

In his response to the tribute in Houston, Halbouty said, "I consider my profession and the science it represents as one of the most vital to the welfare of the world's people.... To me geology is more than a science. It is a vital element—the basic entity which formed my outlook and philosophy of life.... Geology has no rival in the spectrum of science. The story of this earth, the evolution and destruction of continents, the recording of all life since the beginning of time has attracted countless men and women to its realm and continuously records the captivating events of the planet upon which we all live.... When I leave this earth, I trust my contributions to the science will leave it better than the day I became its student."

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