Climate of the Supercontinent Pangea[1]

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ABSTRACT

Numerous climate models predict that the geography of the supercontinent Pangea was conducive to the establishment of a "megamonsoonal" circulation. In general, geologic evidence supports the hypothesis of a megamonsoon that reached maximum strength in the Triassic. Pangea in the Late Carboniferous had widespread peat formation in what is now central and eastern North America and Europe and relatively dry conditions on the Colorado Plateau. The equatorial region of the continent became drier through the end of the Carboniferous. By the Permian, the equatorial region of Pangea was dry, and indicators of aridity and rainfall seasonality became more widespread. Wind directions from Colorado Plateau eolian sandstones are consistent with an increasing influence of monsoonal circulation at this time. In the Triassic, climate in the Colorado Plateau region became relatively wet, though still seasonal, and the few eolian sandstones indicate a major shift in wind direction at that time. In addition, sedimentation in Australia, which was in relatively high latitudes, took on a much drier and more seasonal character. These two events support the hypothesis that the Pangean monsoon was at maximum strength during the Triassic. In the Early Jurassic, the Colorado Plateau region became arid again, but climate apparently became wetter in eastern Laurussia and Gondwana. Finally, drying occurred in Gondwana and southern Laurasia, indicative of the breakdown of the Pangean monsoon.

Introduction

The supercontinent Pangea represented an exceptional phase in earth's paleogeographic history, a maximum of continental aggregation (Valentine and Moores 1970) that began in the Carboniferous with the collision of Laurussia and Gondwana and culminated in the Triassic with the addition of Kazakhstan, Siberia, and parts of China and southeastern Asia (Smith and Briden 1977; Smith et al. 1973; McElhinny et al. 1981; Klimetz 1983; Ziegler et al. 1983). In the Triassic, exposed land extended from about 85°N to 90°S (Ziegler et al. 1983). Although epeiric seaways were present, sea level was relatively low through much of what might be called the "peak" Pangean interval—Permian and Triassic—and the area of exposed land was great (Vail et al. 1977). More importantly, most of this exposed land area was in a contiguous mass.

First, it is expected that the continent would have had an extraordinary effect on global climate. It cut across, and therefore would have disrupted, nearly every part of the zonal circulation. In addition, the great size of the exposed land, the presence of large portions in low mid-latitudes, and the presence of a warm seaway, Tethys, to act as a source of moisture would have maximized summer heating.

In the past decade, increasing attention has been paid to the geography and climate of the supercontinent. Much of this work has concentrated on specific parts of the Pangean interval, which comprises the Late Carboniferous through Middle Jurassic Periods. The purpose of this paper is to consolidate some of this work into a progress report on Pangean climatic studies. During the next several years, such efforts as "Project Pangea," the newest project under the Global Sedimentary Geology Program, will significantly increase our understanding of Pangea.

This paper is organized in four sections. First, given is a brief history of Pangean paleogeographic evolution. This is not intended to be an exhaustive review of various paleogeographic models, but simply to provide the basis for the discussion on climate. Second, a review is presented of work prior to 1982. Beginning in that year, the dynamical underpinnings for the evolution of Pangean climate were treated with global climate models. Prior to 1982, only one paper limited to the Permian attempted to apply climate models to the understanding of

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Pangean climate (Nairn and Smithwick 1976). Nevertheless, this early work already outlined the cardinal feature of Pangean paleoclimate what Kutzbach and Gallimore (1989) were to call the "megamonsoon." Third, I discuss monsoonal circulation, drawing on current understanding of the dynamics of the Asian monsoon and showing why such a system probably occurred with a Pangean geography. Fourth, is a summary of current modeling results, and finally, with the climatologic framework in place, the geological evidence for the evolution of Pangean climate. Because most studies of Pangean paleoclimate have concentrated on specific intervals, this section is arranged chronologically.

Paleogeographic Evolution of Pangea

Published reconstructions of the major continental plates during the Pangean interval have been relatively stable since at least the late 1970s (e.g., Zonenshayn and Gorodnitskiy 1977; Scotese et al. 1979; Smith et al. 1981; and subsequent publications). The major differences have been in the placement of the blocks that make up China and southern Eurasia. Eastern Tethys was interpreted as having been completely open throughout the Pangean interval (Scotese et al. 1979), but more recently as having been blocked by a continuous line of large islands and shallow continental shelves (Scotese and Golonka 1992). Interpretations of the placement of these blocks probably would not affect the gross features of atmospheric circulation over the continent but certainly would have an effect on predictions of the oceanography.

Apart from the placement of the small circum-Tethyan plates, the major proposed change in Pangean geographic reconstructions is in the orientation of the continent during the Early Jurassic. Until recently, nearly all reconstructions showed the western coastline as parallel to longitude along most of its length. This orientation places most of the Eurasian part of the continent into low and mid-latitudes. Recent paleomagnetic data of Bazard and Butler (1991), however, rotates the North American part of the continent a few degrees counterclockwise. If northern Pangea were still a single, coherent continental plate at that time, Bazard and Butler's (1991) rotation would result in a major displacement of the eastern portions of the continent to the north. This would most strongly affect interpretations of the climate of the eastern Eurasian part of Pangea (discussed in Jurassic climates). However, the coherence of northern Pangea at that time is now being questioned (Nie Shangyou, pers. comm.), so climatic conclusions herein are preliminary until the paleogeography is better known.

In general, Pangea came into being during the Carboniferous with the collision of Gondwana and Laurussia. By the Permian, the continent was largely assembled, except for the numerous small fragments that would eventually constitute most of Asia (McElhinny et al. 1981; Nie et al. 1990). Most of the continental area in the Late Carboniferous (306 Ma) and Late Permian (255 Ma, Scotese and Golonka 1992; table 1) was south of the equator, about 58% and 61%, respectively. These figures are similar to Parrish's (1985).

During the Triassic and Early Jurassic, Pangea was nearly symmetrical about the equator (Parrish 1985; table 1). By the Early Jurassic (195 Ma, Scotese and Golonka 1992), about 56% of the land was in the Northern Hemisphere. In addition, epeiric seaways formed as sea level rose during the Jurassic, dividing the areas of exposed land, especially in the Northern Hemisphere. By the Late Jurassic, Pangea was breaking up, first in the Central Atlantic and then by the separation of Laurasia and Gondwana.

The large area of exposed land, its symmetry about the equator, and the relative positions of the exposed land and Tethys created the paleogeographic conditions favorable to formation of the megamonsoon described by Dubiel et al. (1991) and Kutzbach and Gallimore (1989). These conditions were optimal in the Triassic.

Early Work on Pangean Climate

In a landmark work linking the then-new concept of polar wandering/continental drift and paleoclimate, Briden and Irving (1964) compared the modern and paleolatitudinal distributions of climati-

Table 1. Percentages of Total Exposed Land Area in the Northern and Southern Hemispheres During the Pangean Interval

Time (Ma)	Northern Hemisphere	Southern Hemisphere
Late Carboniferous (277)	32	68
Late Permian (255)	38	62
Early Triassic (237)	45	55
Late Triassic (216)	45	55
Early Jurassic (195)	56	44

Note. Measurements were made with a planimeter from Mollweide equal-area projections of paleogeography by Scotese and Golonka (1992). The dates refer to the dates of the reconstructions given by them, and the paleogeography represents an average for at least the corresponding geologic age, if not epoch.

cally significant rocks. Although they used the paleoclimatic data as a test of continental reconstructions based on paleomagnetic data, their results gave some hint of the patterns that were to become clearer as continental reconstructions became more independent and reliable. Briden and Irving (1964) started with the assumption that the distributions of climatically controlled sediments were similar in the past to their distributions today, that is, that the general zonal pattern characteristic of much of modern circulation and climate over most of the earth's surface would have existed throughout earth history. With this assumption, the distributions of most rock types, and particularly carbonates, made more sense when plotted against paleolatitude than against present latitude. Modern reef carbonates, for example, occur between 30° north and south. Plotted against present latitude, ancient reef carbonates ranged between 40°S and 70°N, peaking at about 50°N latitude; plotted against paleolatitude, they ranged between 20°S and 50°N, peaking at 10°S and 30°N.

Unlike carbonates, evaporites and eolian sandstones did not fit the paleolatitudinal reconstructions (Briden and Irving 1964). Modern evaporites and sand seas tend to occur in the "dry belts" centered on 30° north and south (Borchert and Muir 1964; McKee 1979). Plotted against modern latitudes, their ancient counterparts showed a similar distribution. Plotted on the continental reconstructions, however, evaporites and eolian sandstones clustered near the equator (Briden and Irving 1964; see also Parrish et al. 1982; Ziegler et al. 1979). A breakdown of the plots by time into four intervals—lower and upper Paleozoic, Mesozoic, and Cenozoic—revealed that Mesozoic and Cenozoic deposits plotted where expected when restored to their paleolatitudes but that Paleozoic deposits, particularly those of the upper Paleozoic, did not (Briden and Irving 1964). Parrish et al. (1982) showed further that the upper Paleozoic pattern extended into the lower Mesozoic. Although Briden and Irving (1964) were using the paleoclimatic data as a test of the paleomagnetic data, they did not change their reconstructions for the late Paleozoic based on the discrepancy between the two data sets. They recognized, instead, that the anomaly might have been due to some different climatic process.

The distribution of Permian marine faunas presented similar problems for Stehli (1970). Plotted on modern base maps, Permian tropical faunas formed a regular latitudinal diversity gradient, similar to that observed in modern marine faunas. Plotted against paleolatitude (as understood at the time), however, the faunal diversity appeared to be completely random, and the faunas thus appeared to offer evidence against continental drift.

Robinson (1973) was the first to describe explicitly the climate of Pangea as monsoonal. She based this description on the global distribution of red beds, evaporites, and coals in Triassic rocks. She confirmed Briden and Irving's (1964) finding that these paleoclimatically significant rocks were not distributed in simple latitudinal zones and also found that the rocks formed an odd geographic mixture. Although this mixture was at least partly an artifact of plotting data for the entire period on one map, Robinson (1973) suggested that the climate was strongly seasonal, and used the term "monsoon" to describe it.

The concept of a Pangean monsoon has appeared elsewhere in different forms. Daugherty (1941), for example, described the flora and environment of the Triassic red bed Chinle Formation of the Colorado Plateau as "savannah." Much of the earth's present savannah occurs within the region influenced by the Asian monsoon (Espenshade and Morrison 1978; Rumney 1968) and always in areas of strongly seasonal rainfall.

One of the most interesting outgrowths of the fascination with the Pangean interval has been the debate on the climatic significance of red beds (e.g., Van Houten 1964). The Permo-Triassic especially has long been regarded among geologists as an unusual time in earth history because red beds and evaporites were exceptionally widespread (Schwarzbach 1963; Volkheimer 1967, 1969; Waugh 1973; Turner 1980; Glennie 1987; Enos 1993; and many others). Evaporites accumulated faster, over a greater area, in the Triassic than at any other time (Gordon 1975). As paleoclimatically significant data have gradually accumulated and put into the context of plate tectonics, the strangeness of the Pangean interval has only been emphasized.

Red beds have been attributed to environments ranging from desert to marine (Ziegler and McKerrow 1975), and eventually Van Houten (1982) was moved to point out that not all red beds are alike. The present consensus is that the reddening of alluvial and fluvial deposits (as opposed to sabkha or marine deposits; Van Houten 1982) occurs with alternating wet and dry climates. Iron is leached from easily weathered iron-bearing minerals during the wet cycle. Hematite, which is relatively stable, is then precipitated during the dry cycle (Walker 1967, 1976; Bown and Kraus 1981). In red beds ranging from desert sandstones (Walker 1967; Van Houten 1982) through red paleosols (Bown

1979; Bown and Kraus 1981; Kraus and Bown 1986) to even bauxites, the reddening is dependent upon seasonality of rainfall (Bárdossy and Aleva 1990). Thus red beds are formed along a climatic gradient, with seasonal rainfall in a mostly dry environment at one extreme and seasonal rainfall in a mostly wet environment at the other. Calibration may show that red beds can be useful as paleoclimatic indicators (Gyllenhaal 1991 and Bárdossy and Aleva 1990).

Monsoonal Circulation and the Pangean Megamonsoon

The Asian monsoon is a complex system that has been the object of intense study for hundreds, if not thousands, of years (G. Kutzbach 1987; Warren 1987); the following discussion of modern monsoons is thus highly simplified. Recent work has shown that hypotheses about relatively subtle features of ancient monsoonal circulation can be tested in the Quaternary and Holocene records (Rossignol-Strick 1985; J. E. Kutzbach 1987; Davis 1988). However, the pre-Quaternary record is much more poorly resolved, and most current efforts are directed toward testing the general hypothesis of monsoonal circulation during the Pangean interval. If the hypothesis is supported, a future task will be to attempt predictions of the subtler features of the Pangean monsoon.

General Monsoonal Circulation and the Asian Monsoon. The word "monsoon" is derived from the Arabic word for season (Webster 1987). Reference is made, therefore, to the winter monsoon as well as the summer (alternatively, Southwest) monsoon, particularly in Asia. The meridional circulations in the Asian summer and winter monsoons are illustrated diagrammatically in figure 1. The summer monsoonal circulation in Asia is controlled by four factors: (1) the sensible heating of the land surface of Asia; (2) the thermal cross-equatorial contrast between the Indian Ocean and Asia; (3) the supply of moist air from the Indian Ocean and release of latent heat over the continent; and (4) the effect of the Tibetan Plateau as a high-altitude heat source.

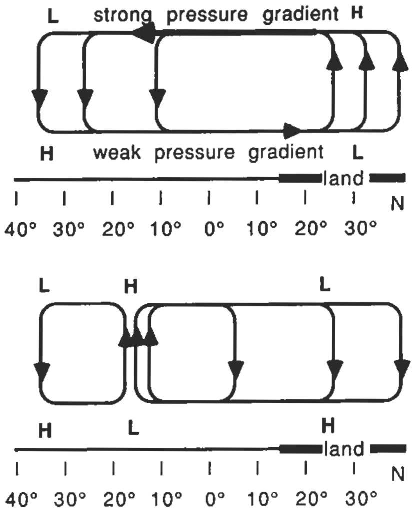

Figure 1. Schematic diagrams of meridional circulation in the Asian summer (top) and winter (bottom) monsoons (adapted from Webster 1987). H = high pressure, L = low pressure.

(1) Sensible heating. Initiation of the summer monsoonal circulation occurs when Asia begins to warm up in the spring (Ramage 1966); this is called sensible heating. This warming occurs because the net radiative flux changes from strongly negative (more heat radiated to space than absorbed at the surface) to weakly negative or positive (Webster 1987). With the warming, the surface air rises and southward return flow toward the cold hemisphere commences in the middle and upper troposphere. Monsoonal circulation is possible with simply a cross-equatorial difference in sensible heating (Young 1987, figure 2G) although it would be relatively weak and shallow (that is, occupying only the lower few kilometers of the atmosphere, Webster 1987). Sensible heat is about one-tenth the magnitude of latent heat (Webster 1981) released when precipitation forms. The so-called heat low centered over northwest India and Pakistan, which remains arid through the summer monsoon, is maintained and intensified by high-level subsidence of air warmed by the release of latent heat over southwestern and northeastern India (Ramage 1971; Das 1986, figure 3) and blocks the northward penetration of moist air in that region (Krishnamurti and Ramanathan 1982). Although surface pressures are low (e.g., Riehl 1978, his figure 10.4), net radiation over the region indicates strong cooling (Winston and Krueger 1977) from the surface.

(2) Cross-equatorial contrast. This effect is best developed in the modern summer Asian monsoon. Circulation in the southern Indian Ocean is strongly affected by the circulation in the northern hemisphere (Ramage 1971; Webster et al. 1977). The subtropical high-pressure cell (called the Mascarene High in many papers) has an annual cycle unlike any other. Typically, a subtropical high-pressure cell is centered over the eastern half of the ocean basin it occupies, and its intensity is greatest during the summer, the season of maximum thermal contrast between ocean and adjacent continents. The southern Indian Ocean high, however,

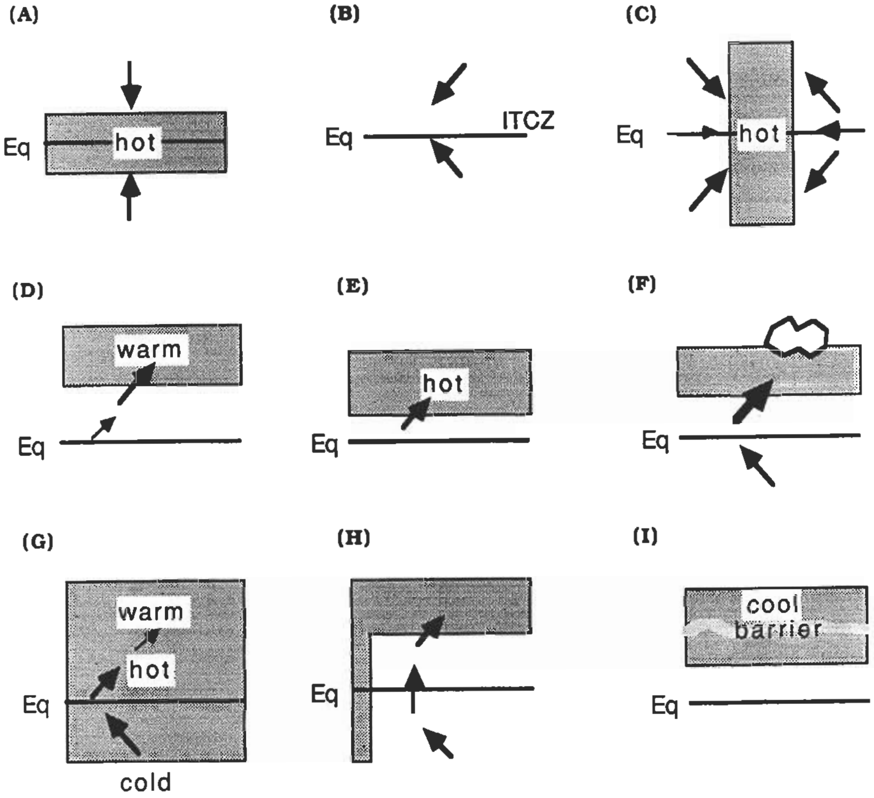

Figure 2. Idealized geographic conditions of monsoon circulation (adapted from Young 1987). *A:* Latitude-parallel equatorial continent, no monsoonal circulation. *B:* Equatorial ocean, northern summer (cf. central Pacific); ITCZ = Intertropical Convergence Zone. *C:* Latitude-normal equatorial continent (cf. Pangea); note reversal of western equatorial flow. *D:* High-latitude continent, weak monsoon resulting from sensible heat contrast (cf. Pangea). *E:* Low-latitude continent, stronger monsoonal circulation resulting from sensible heat (cf. Pangea). *F:* Low-latitude continent with mountains, very strong monsoonal circulation resulting from sensible heating and latent heat release (cf. southern Asia, Tibetan Plateau). *G:* Wholly terrestrial Earth (cf. Mars), monsoonal circulation. *H:* Equatorial barrier to easterly flow (cf. Africa). *I:* Latitudinal barrier between warm and cool parts of continents (cf. Tibetan Plateau).

occupies the expected position only during January–March. During the height of the Asian summer monsoon, the cell is shifted to the west; it is also at its strongest, despite the season (southern winter; see, for example, Knox 1987, his figure 13.1). Clearly the intensity and position of the southern Indian Ocean subtropical high-pressure cell, at least during the northern summer, are controlled in large part by the climate in the north (Webster et al. 1977). This illustrates the importance of a cross-equatorial pressure contrast in disrupting zonal circulation and enhancing the effect of the monsoon. Some workers, e.g. Young (1987), consider the cross-equatorial flow a fundamental component of monsoonal circulation. An equatorial barrier (Africa in the Asian monsoon, the central portion of the continent in the Pangean monsoon) enhances cross-equatorial flow (figure 2H).

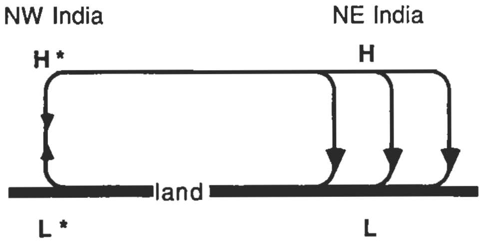

Figure 3. East-west circulation in the Asian summer monsoon (Das 1986). The winter monsoon counterpart to this circulation is between Asia and the eastern Pacific (sink) and the region of New Guinea (source). Heavy line at the bottom symbolizes the land surface.

A consequence of the cross-equatorial flow is that equatorial East Africa is much drier than would be expected in a zonal climate. Equatorial South America and the eastern East Indies have annual rainfall patterns more typical of zonal climate. In a zonal climate, the equatorial easterlies carry warm, very moist air over the land, which is released as abundant rainfall. Equatorial East Africa, by contrast, receives relatively little rainfall, and most of that occurs in the spring and fall. This is because the equatorial easterlies are diverted by the monsoon, northward in the summer and southward (but less strongly) in the winter; most of the rainfall occurs during the transition from winter to summer circulation and back. The highest rainfall in Africa is in the western equatorial regions. This also is attributed to the summer monsoon over Asia. The thermal low over the Sahara, which is especially strong in the summer, is intense enough to reverse equatorial flow (Das 1986).

(3) Latent heating. Moist processes are very important to the strength of the Asian monsoon, particularly the summer monsoon (Webster 1981). In a dry climate system, the heating of the air at the ground surface—sensible heating—forces the air

to rise, creating a relatively weak inflow of air at ground level. The strength and duration of the circulation depends entirely on continued heating at the ground surface. In a moist system, however, the convection is self-propagating. Once the air starts to rise and precipitation forms, the energy of the system is increased further by the release of latent heat.

The source of moisture for the Asian monsoon is the Indian Ocean. Air flowing into the monsoon at the surface originates in the high-pressure cell over the southern Indian Ocean. As that air is drawn northward, it is heated and picks up additional moisture.

(4) High-altitude heat source. The Tibetan Plateau enhances the summer monsoonal circulation by functioning as a heat source high in the atmosphere. The ground surface of the plateau lies on average about 5 km above sea level and almost 4 km above the average elevation of the surrounding lowlands. Heating of the ground surface increases the altitude of warm isotherms, so that the temperature at 6000 m on the plateau is much warmer than the temperature of air at the same altitude over the lowlands. The effect on circulation is to intensify the low pressure that forms with heating of the land surface in general.

Although the cross-equatorial thermal contrast is the primary cause of the monsoon (Young 1987; Murakami 1987*a*; Webster 1987), the Tibetan Plateau is important to the strength of the monsoon, as has been discussed at length in the literature (Flohn 1968; Hahn and Manabe 1975; Das 1986; Murakami 1987*b*). For example, Hahn and Manabe (1975) modeled the Asian monsoonal system with and without mountains (M and NM cases, respectively). The major differences they noted in the results of the simulations were the following:

(a) The center of the low-pressure cell over Asia is far to the northeast in the NM case, over northeastern China. Even though the low pressure was as intense as the observed and simulated M low pressure, the important effect was to decrease the pressure gradient over southern Asia.

(b) Partly because of the smaller pressure gradient, latent heat release and, therefore rainfall, did not penetrate far into the continental interior in the NM simulation. Summer and winter rainfall would have been confined to the coastal regions and desert-like conditions for the interior, as in Australia today (Webster 1981) and was predicted for Pangea by Parrish et al. (1982). The distribution of latent and sensible heating in Asia is similar for the two models except in the vicinity of the Tibetan Plateau. The overall effect is that Asia is dominated by sensible heating in the NM simulation and by latent heating in the M simulation, but it should be noted that the modeled circulation patterns were similar everywhere but over the plateau itself (Hahn and Manabe 1975, figure 4.5).

(c) The Somali jet, a concentration of northward moving streamlines parallel to the Somalian coast, is predicted by the M but not the NM simulation. A possible effect is that precipitation in the adjacent region of Africa would be higher in the absence of the Tibetan Plateau, whereas in the present system, precipitation in eastern equatorial Africa is low and limited to spring and fall. However, the differences between the M and NM simulations in precipitation and the position of the ITCZ in that region are small.

The Tibetan Plateau, besides contributing to the deep penetration of heat into the atmosphere, also isolates southern Asia from the interior. The thermal significance of the plateau in winter is apparently not great (Murakami 1987*b*), but the plateau is effective as a mechanical barrier to air flow. Although the emphasis has been on the pooling of cold air north of the plateau and the role of the plateau in cold surges and cyclogenesis (Murakami 1987*b*, and references therein), the barrier effect of the plateau may also work in the other direction, isolating the interior of the continent from the ameliorating influences of the Indian Ocean. The pooling of cool air north of the plateau must also play some minor role in facilitating the heating of southern Asia in the summer.

General Monsoonal Circulation and the Pangean Monsoon. The controls on Asian monsoonal circulation—sensible heating, cross-equatorial contrast; latent heating, and, possibly, high-altitude heat effects—can be applied to Pangea. Because of the great size of the continental area in mid-latitudes, a strong monsoonal circulation would be expected for Pangea. The continent was large, but more importantly, divided by the equator, with the two halves flanking Tethys (Hansen, in Parrish 1982; Parrish and Curtis 1982; Parrish et al. 1979). The shape of Pangea enhanced the seasonally alternating circulation that would have occurred in both hemispheres by maximizing the pressure contrast. The pressure contrast would have caused air to flow across the equator in opposite directions during the year.

In the Pangean monsoon, differential heating between Tethys and the summer hemisphere would have been similar to that occurring during the summer Asian monsoon. The interhemispheric thermal contrast would have been much greater, however, because both hemispheres were land

(Crowley et al. 1989). The pressure contrast over Pangea might be compared with the seasonal pressure contrast over Asia today. The pressure contrast between winter and summer over Asia is more than 36 mb (Espenshade and Morrison 1978). Model results for Pangea, for example those of Kutzbach and Gallimore (1989), show a pressure contrast of about 25 mb.

The interhemispheric thermal contrast alone might have been enough to drive a monsoonal circulation over Pangea, as on Mars (figure 2*G*; Haberle 1986; Young 1987). In addition, the expanse of warm, equatorial ocean that the air would have had to cross (Tethys) is comparable to the width of the Indian Ocean crossed by the modern air mass, so the latent energy in the two systems might be expected to have been comparable.

By comparison with the collision of India and Laurasia, Pangea may have had mountains equivalent to the Tibetan Plateau where Gondwana and Laurussia collided. These mountains may have had an effect on the development of Pangean climate in the Carboniferous (Rowley et al. 1985). In addition, Hay et al. (1982) proposed that these mountains were as high as 4 km, not as high as the Tibetan Plateau, but comparable to the Colorado Plateau, which today generates a weak monsoonal circulation. A mountain chain that probably resembled the Andes lay along the northern margin of Tethys, formed during northward movement and subduction of the paleo-Tethyan plate (the present Tien Shan and Nan Shan mountain ranges; Sengör 1979; Klimetz 1983). These mountains might have enhanced the release of latent heat much as the Western Ghats in southwestern India do now (Ramage 1966). In addition, the mechanical effects of the Tibetan Plateau during the winter monsoon might have been duplicated by the mountain barrier along the northern margin of Tethys.

Despite the aspects of Pangean paleogeography favorable to monsoonal circulation, the absence of regions equivalent to the Tibetan Plateau cannot be dismissed out of hand in considerations of Pangean circulation. Two possible models, full monsoonal and modified monsoonal, can be constructed for meridional circulation during the Pangean interval (bearing in mind that significant zonal motions are obscured in these diagrams). The full monsoonal circulation (figure 4*A*) is equivalent to the circulation during the Asian summer monsoon. The modified monsoonal circulation (figure 4*B*) is analogous to the situation that obtains in the Arabian Sea during the Asian summer monsoon. Air warmed by the release of latent heat over the Western Ghats in southwestern India subsides over the heat low centered in Pakistan, intensifying the aridity in that region (Ramage 1966; Das 1986). The mountains along the northern margin of Pangea might have created similar conditions, restricting rainfall to the coastal regions (as predicted by Parrish and Curtis 1982).

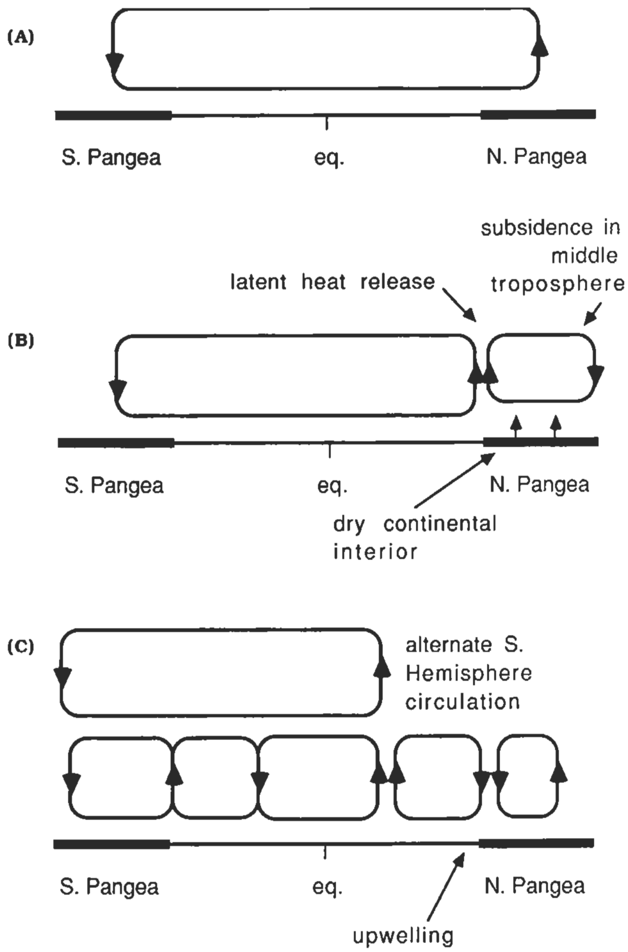

Figure 4. Simplified alternative scenarios for meridional circulation over Pangea and Tethys, northern summer. Significant zonal circulations are obscured in these diagrams. *A:* Full monsoonal circulation similar to the present Asian summer monsoon. *B:* Modified monsoonal circulation with latent heat release confined to coastal mountain ranges. *C:* "Normal" summer zonal circulation as favored, for example, by Hay et al. (1982). Heavy lines symbolize the land surfaces and the intervening thin line symbolizes the surface of Tethys.

Models of Pangean Climate. Based on the basic principles of atmospheric, including monsoonal, circulation outlined in the previous sections, the beginnings of a theoretical basis for the hypothesis of Pangean monsoonal circulation were established using conceptual climate models of: the general hypothesis (Parrish et al. 1982; Parrish et al. 1986), the development of the monsoon (Nairn and Smithwick 1976; Rowley et al. 1985; Parrish

1993*a*), the monsoonal maximum (Parrish and Peterson 1988), and the breakdown of the monsoon (Parrish 1993*b*). Subsequently, the so-called "Fujita-Ziegler" model, a parametric, semi-quantitative model (Gyllenhaal et al. 1991), was applied to Permian paleogeography by Patzkowsky et al. (1991). Finally, several different numerical models have been applied to Pangean paleoclimates that support the interpretation of a monsoon-dominated circulation system (Crowley et al. 1989; Kutzbach and Gallimore 1989; Chandler et al. 1992; Valdes and Sellwood 1992). The Pangean interval is the only time period other than the Cretaceous for which global climate has received treatment by seven completely different models and approaches (two conceptual models, a parametric model, and four different numerical models), so comparing the models is especially interesting.

What all model predictions have in common is strong seasonality. Nairn and Smithwick (1976), Parrish (1982), Patzkowsky et al. (1991), and Crowley et al. (1989) all treated the Permian. The principal difference between the conceptual model predictions of Nairn and Smithwick (1976) and Parrish (1982) were in the intensity of the seasonality, which was less in Nairn and Smithwick's (1976) predictions. Crowley et al.'s (1989) models explicitly predicted temperature, and they obtained a cold-month mean temperature of −30°C and a warm-month mean temperature of +25°C for southern Pangea. The temperatures reported by Crowley et al. (1989) were similar to those obtained by Kutzbach and Gallimore (1989), using a global circulation model for a schematic Pangea approximating Triassic paleogeography, and Chandler et al. (1992) using a realistic Early Jurassic paleogeography. The Late Jurassic models of Valdes and Sellwood (1992) show less extreme seasonality, not surprising given that Pangea had by that time split in two. The winds predicted by Kutzbach and Gallimore (1989) were qualitatively comparable to those predicted from the conceptual circulation models (Parrish 1982; Parrish and Curtis 1982). Patterns of barometric pressure and, indirectly, evapotranspiration, obtained using the Fujita-Ziegler model (Patzkowsky et al. 1991) were similar to those predicted by Parrish (1982) and Kutzbach and Gallimore (1989).

Implications and Predicted Effects of Monsoon Climate. If Pangea had a strong monsoonal circulation, the expected effects on the distribution of climatically significant rocks are as follows:

(1) Evidence of seasonality will commonly be strong and rocks containing such evidence will be widespread. Seasonality may be expressed as sedimentary cycles, biological cycles (e.g., growth rings in trees and shells, Dubiel et al. 1991), or in certain types of paleosols. Seasonal cycles have been observed in rocks of all ages, but for each age, deposits showing seasonal cycles are relatively uncommon. This suggests one of two things, either (a) most sedimentary systems are relatively insensitive to seasonality or (b) seasonality is commonly or in most places not strong enough to overcome the other controls on sedimentation to impose cyclicity. A strong, full monsoonal system would have created a strong seasonal cycle over much of Pangea, and it might be expected that (a) sedimentary systems that might not otherwise have reflected seasonality would have had a seasonal cycle imposed on them, or (b) the wide distribution of strong seasonality would have created more opportunities for seasonality to be expressed, or both.

(2) The equatorial region, particularly along the eastern continental margin, will be dry relative to the high-latitude regions of Pangea or to the continental equatorial region at most other times in earth history. At its greatest intensity, the monsoon might have been strong enough to reverse equatorial flow, and in that event the western equatorial region of Pangea will be relatively humid.

(3) Climatic belts will not be zonal. Although some asymmetry exists on even the smallest continents, particularly if the isolatitudinal coastal regions are compared (Parrish and Ziegler 1980), the proposed monsoonal circulation over Pangea would have completely disrupted zonality. Instead, the equatorial region would be expected to have been dry, particularly in the east, and rainfall would have been concentrated in belts paralleling the northern and southern coasts of Tethys and along the western high mid-latitude coasts (i.e., in a position equivalent to southern British Columbia). Terrestrial organisms, especially plants, should reflect the loss of zonality.

(4) The conditions described above should reach a maximum in the Triassic. The hypothesis of Pangean monsoonal circulation is dependent on the size of Pangea and the cross-equatorial contrast between its northern and southern halves, and that contrast would be expected to be maximal when the contrasting continental areas are about equal in size. Thus, the strongest period of monsoonal circulation is expected to have been in the later part of the Triassic, when the land area was divided in half by the equator (table 1; Parrish 1985; Parrish et al. 1986).

The major distinction between the full and modified monsoonal models (figure 4) would be the penetration of moisture into the continental interior. In the modified monsoon model, rainfall would be most abundant in the coastal regions, whereas in the full monsoon model, seasonal rainfall would be expected some distance into the continental interior, perhaps 600–1200 km, the approximate distance from the heads of the Bengal Gulf and Arabian Sea, respectively, to the Himalayan mountain front.

The prediction that the monsoon would have reached its maximum development in the Triassic implies that the climate system would have undergone some evolutionary changes. As the monsoon developed, equatorial Pangea would have become progressively drier. Drying would have started in the west and extend eastward. The western equatorial regions of Pangea would have become arid first as the continent consolidated and sea level fell because those areas would have been downwind of the equatorial easterlies carrying moisture from Tethys. As the longitudinal extent of the exposed land at the equator increased, the downwind regions would have become drier. As the monsoon developed and increasingly disrupted zonal circulation, aridity would have progressed eastward as the equatorial easterlies were diverted north or south into the summer hemisphere. As the monsoon strengthened, however, the summer lows could become strong enough to draw moisture from the west, as occurs in Africa today. A gradient from wet in the west to dry in the east would mark the monsoon maximum. In addition, the climate of Pangea should have evolved with increasing aridity in the low- and mid-latitude continental interiors and with poleward expansion of relative aridity and strong seasonality of rainfall.

It should be noted, however, that aridity can be brought about by increases in temperature, and within limits, a warming trend can make the climate, as recorded in the geologic record, drier, independent of changes in the precipitation regime. Climatic indicators of relative humidity such as paleosols and plants are controlled by the balance between precipitation and evaporation (which is principally dependent on temperature), not by precipitation alone. Higher temperatures increase evapotranspiration, and the net water balance is recorded in the geologic record.

Geological Evidence of the Pangean Megamonsoon

Throughout the following discussion, reference is made to coals as wet-climate indicators but, in fact, caution must be exercised in interpreting climate from the presence of coal. Peat formation is only secondarily related to rainfall (Gyllenhaal 1991), and is mostly due to high groundwater tables (McCabe 1984; Ziegler et al. 1987; McCabe and Parrish 1992). However, the refinement of coals as climatic indicators has not progressed far, and a reevaluation of all Pangean coals for their paleoclimatic significance is not feasible at this time. In most cases mentioned below, changes in the distribution of coal are paralleled by changes in other climatic indicators, thus strengthening the interpretations.

Development of the Monsoon—Late Carboniferous and Permian.

The greatest extent of continental glaciation in the Carboniferous began toward the end of the Westphalian Age (Late Carboniferous; Veevers and Powell 1987). At the end of the Carboniferous, peat formation on Pangea itself began to shift from low latitudes to high latitudes (Ziegler et al. 1979, 1981; Parrish et al. 1982), although peat formation continued in the microcontinents that now constitute China. This shift may mark the beginning of large-scale poleward transport of moisture (Manabe and Wetherald 1980; Brass et al. 1982; Parrish et al. 1982; Parrish 1993*a*). Major supporting evidence for the monsoon hypothesis and, indeed, the evidence that prompted Robinson (1973) to suggest monsoonal circulation in the first place, is the widespread aridity in Pangea.

In central North America, the trend from wet in the Early Carboniferous to dry in the Early Permian was not monotonic (Phillips et al. 1985). Rowley et al. (1985) suggested that the development of the monsoon was retarded by the highlands that resulted from the collision of Gondwana and Laurasia and that lay along the equator. If these highlands were Himalaya-scale, they would have had the same effect as the Tibetan Plateau, intensifying latent heat release. However, in the Carboniferous, the mountains would have intensified the normal equatorial low pressure. The strong effect of these highlands might have countered the effects of the increasing size of Pangea and symmetry of the continent about the equator, and the alternating wet and dry periods leading into the Permian might reflect a system poised between two climatic states, zonal, with the strongest low pressure on the equator, and monsoonal, with the strongest low in low mid-latitudes in the summer hemisphere. Eventually, as Pangea grew and moved north, this effect might have subsided. At the same time, global climate was warming (Dickins 1977, 1979, 1983, 1985; Berner 1990) and this would have resulted in not only increasing aridity but also poleward expansion of the relatively arid regions because, globally, the evapotranspiration rate would have increased.

Recent numerical climate modeling results (Kutzbach et al. 1993) show that the topographic effect suggested by Rowley et al. (1985) may indeed have operated. These models further suggest that the rainfall resulting from the topography may have been seasonal on either side of the mountains. A test of these models would include seeking evidence for seasonality within the coal-bearing sequences in the adjacent lowlands, a climatic pattern already suggested by Cecil (1990).

Increases in aridity during the Permian are suggested by changes from sedimentary indicators of relatively humid climate, such as coals, to indicators of dry climate, such as eolian sandstones and evaporites, especially in the equatorial regions (e.g., Gordon 1975; Ziegler 1982; Witzke 1990). Redbeds also became more widely distributed during the Permian and into the Triassic (Waugh 1973).

Eolian sandstones of the Colorado Plateau generally show north-northeasterly or northeasterly flow during the Permian (Parrish and Peterson 1988). Had the circulation associated with the monsoon flow predominated, flow would have been northwesterly (Parrish and Peterson 1988). However, the Queantoweap Sandstone, Nevada and Utah (Early Permian) does show northwesterly flow (Parrish and Peterson 1988; Peterson 1988, figure 10). This suggests that the monsoon continued to vary in strength before reaching its maximum in the Triassic.

As the South Pole became marine in the Early Permian, significant glaciation ceased (Veevers and Powell 1987). At the same time, extensive evaporites and eolian sandstones were being deposited across the Northern Hemisphere (Nairn and Smithwick 1976; Glennie 1972, 1983; Ziegler 1982; Witzke 1990), and red beds and evaporites were deposited across Gondwana (Rocha-Campos 1973; Nairn and Smithwick 1976; Ziegler 1982). Plants typical of desert and summer-wet (i.e., monsoonal) climates were widespread in low latitudes in the Permian (Kremp 1980; Ziegler 1990).

Peat swamps formed on low-latitude islands and in high northern and southern latitudes on Pangea (Rocha-Campos 1973; Nairn and Smithwick 1976; Veevers and Powell 1987; Enos 1993). For the most part, the coal deposits in southeastern Gondwana (Australia and India) occur stratigraphically above the glacigenic deposits, which are widespread in the earlier part of the Early Permian (Rocha-Campos 1973; Veevers and Powell 1987). Faunas dominated by the cold-water bivalve, *Eurydesma* (Dickins 1978, 1985) occur in southern Gondwana (Dickins 1985; Veevers and Powell 1987).

Evaporites and, particularly, red beds spanned a slightly greater latitudinal range in the Late Permian than in the Early Permian (Assereto et al. 1973; Rocha-Campos 1973; Sokolova et al. 1973; Waugh 1973; Nairn and Smithwick 1976; Witzke 1990; Ziegler 1982; Enos 1993). Coals were less widespread in both Asia and southern Gondwana (Nairn and Smithwick 1976; Veevers and Powell 1987; Enos 1993). Only in Australia did peat formation apparently retain its original extent (Brakel and Totterdell 1990; J. T. Parrish, M. T. Bradshaw et al., unpub. data). Monsoonal floras were less widespread, and desert floras more widespread than in the Early Permian (Kremp 1980; Ziegler 1990). The overall trend in the Permian, then, appears to have been toward increasing aridity, either through an absolute reduction of rainfall, an increase in evapotranspiration, or an increase in seasonality of rainfall. The simplest explanation is that evapotranspiration increased owing to global warming following the disappearance of large-scale glaciation, and that the resulting drying was enhanced by increasing seasonality as the Pangean monsoon strengthened.

The Monsoon Maximum—Triassic

As Pangea moved north and the land area was distributed more evenly on either side of the equator (Parrish 1985), seasonality would have become stronger and the equatorial region and mid-latitude continental interiors drier until the Triassic. In the Triassic, the monsoonal circulation is predicted to have been at maximum strength because the exposed land area was large and divided in half by the equator (Parrish 1982; Parrish and Curtis 1982; Parrish and Peterson 1988). The monsoon might have been strong enough to draw moisture along the equator from the west.

The Triassic is the time of greatest evaporite formation worldwide (Gordon 1975), but on the Colorado Plateau, in westernmost equatorial Pangea, the Triassic was the wettest part of the Pangean interval, shifting from evaporite and eolian deposition in the Late Carboniferous and Permian, to fluvial red bed deposition in the Triassic, and back to eolian deposition in the Jurassic (e.g., Peterson 1988). The few eolian sandstones deposited on the Colorado Plateau during the Late Triassic and earliest Jurassic show a 90° change in wind direction to westerly or northwesterly from the predominantly northerly or northeasterly winds of most of the rest of the Pangean interval (Peterson 1988). Parrish and Peterson (1988) suggested that the proposed Pangean monsoonal circulation became strong enough at this time to influence circulation on the western side of Pangea and draw moisture along the equator from the west. The Triassic Chinle Formation is a fluvial system with lakes, although it does contain some evidence of aridity (Dubiel et al. 1991).

In studies of the fluvial deposits in the Chinle Formation, Blakey and Gubitosa (1983, 1984) and DeLuca and Eriksson (1989) agree that climate had been warm and seasonal with respect to rainfall. DeLuca and Eriksson's (1989) study showed that perennial and ephemeral streams coexisted in the Chinle, precisely the pattern observed in regions with abundant, but highly seasonal, rainfall. Blakey and Gubitosa (1984) proposed that the surrounding highlands were humid in order to supply the perennial streams with water. Rainfall in the source area need not be constant to maintain perennial streams, so long as total annual precipitation is high. A wet source region is not inconsistent with the monsoon hypothesis because mountains usually are wetter and total annual rainfall in a monsoon system, though extremely seasonal, is also very high compared with other climatic regimes (Dubiel et al. 1991).

Recent, interdisciplinary studies of the depositional systems and paleobiological communities in the Chinle basin have provided evidence for a monsoonal paleoclimate (Dubiel et al. 1991), but an interesting aspect of Chinle deposition is the controversy over interpretations of the flora. The first full description of the major elements of the fossil flora of the Chinle was published by Daugherty (1941). Subsequently, voluminous and detailed work by Ash (1967–1989) revealed the full extent and diversity of the flora, which includes pterophytes, sphenophytes, cycadophytes, and coniferophytes. In addition to the major groups, some taxa of uncertain affinity also have been described. Daugherty (1941) and Ash (1975, 1977, 1987, 1989) believed that Chinle flora grew in a warm climate with abundant rainfall. However, Daugherty (1941) also noted that growth rings preserved in the permineralized logs were evidence of some sort of seasonality in the climate (see also Dubiel et al. 1991), and that the Chinle flora compared well to modern savannahs. By contrast, Ash (1967, 1972*a*, 1978; Ash and Creber 1990) favors warm to hot temperatures and everwet (see also Ziegler 1990) conditions based principally on comparisons with the habitats of nearest living relatives, general leaf physiognomy, the presence of large trees, thin organic-rich swamp deposits, and cuticles (Ash 1967, 1978). At the other extreme to Ash's views, Gottesfeld (1972) regarded the climate of the Chinle as predominantly arid. Gottesfeld's (1972) interpretation is supported by evidence of at least periodic drying, and depended partly on the interpretation of red beds as indicators of arid conditions.

The invertebrate, vertebrate, and ichnofaunas of the Chinle Formation are diverse (Robinson 1915; Camp 1930; Colbert 1952; Breed 1972; Tasch 1978; Dubiel 1987; Dubiel et al. 1987; Murray 1987; Miller and Ash 1988; Hasiotis and Mitchell 1989; Parrish 1989; Kietske 1989; Good 1989). Among the invertebrates, only the molluscs have been studied in detail (Good 1989; Dubiel et al. 1991). Dubiel et al. (1991) interpreted growth banding in the shells of these molluscs to reflect seasonal variations in growth rate. The vertebrate fauna consists of both aquatic and terrestrial forms. Parrish (1989) used the taphonomy of vertebrate fossils and the presence of lungfish burrows and teeth in the Chinle to support hypotheses that these animals lived and died in an environment characterized by seasonal rainfall. Dubiel et al. (1987, 1991) and Parrish (1989) suggested that the deep (>2 m) lungfish and crayfish burrows may indicate a high range and repeated cycles of water table fluctuation owing to highly seasonal precipitation. At present, lungfish live in monsoonal environments, and the trace fossil *Scoyenia* also commonly occurs in shallow lake deposits subject to periodic drying (Ekdale et al. 1984).

Although the Chinle represents a climatic anomaly on the Colorado Plateau during the Pangean interval, the Triassic record is not complete. The only other Triassic unit is the Middle Triassic Moenkopi Formation, which Stewart et al. (1972) described as a "typical red bed unit," comprising alluvial fan, floodplain, sabkha, and marine facies (Stewart et al. 1972; Baldwin 1973). The sabkha facies of the Moenkopi contains abundant primary gypsum, and salt crystal casts and mudcracks are common throughout the unit, especially in the lower part (Baldwin 1973).

The wetter conditions suggested by Triassic red beds and associated rocks are consistent with a reversal of equatorial flow into the strong monsoon system created by Pangea (Parrish and Peterson 1988), and are unlikely to be the result of global cooling. No independent evidence exists for global cooling at this time, and the region was in low latitudes throughout the late Paleozoic and early Mesozoic. Indeed, Berner (1990) modeled substantially higher CO_2 levels for the Triassic relative to the Permian (about 4 × present CO_2 versus 1.5–2 × present CO_2, respectively). In addition, global temperature change is poorly expressed in low latitudes, implying that any temperature change was likely to have been too small to account for the dramatic change in style of sedimentation. The strong seasonality associated with monsoonal circulation may explain the contradictory climatic interpretations of units such as the Chinle Formation (Dubiel et al. 1991).

Wetter climates also occurred farther east in western Europe (Simms and Ruffell 1990; Simms and Ruffell 1989). Simms and Ruffell (1989, 1990) attributed this change to rifting, but it might also be evidence for increased strength of the monsoon, or a combination. In discussing the wide distribution of evaporite deposits in the Pangean interval, Gordon (1975, p. 681) offered the explanation that Pangea ". . . provided an unusually wide expanse of tropical and subtropical land with a minimum of marine influence." Hay et al. (1982) noted that neither the zonal model of the distribution of climatic belts nor the Köppen and Wegener (1924, cited in Frakes 1979) modified zonal model could explain sedimentation in the proto-Atlantic rift. Hay et al. (1982) suggested, in contrast to the monsoon model (although not necessarily in conflict with it), that aridity in the equatorial region resulted partly from a rainshadow effect of the rift system highlands. The northern and eastern end of the rift system lay, in their reconstruction, at about 20°N, and was drier throughout the interval studied (Late Triassic-Early Jurassic). Farther to the west and south, ephemeral lakes and playas, reminiscent of the East African rift lakes, formed the principal deposits. This general paleogeographic distribution was maintained throughout the interval, although the evaporites became more widespread, attributed by Hay et al. (1982) to northward drift of the continent. It should be noted, however, that in their reconstruction (Hay et al. 1982, their figures 5 and 6), the whole of northern Africa lies along the equator to the east of the rift system. In normal zonal circulation, it is unlikely that the equatorial easterlies could retain enough moisture across that continental expanse to create the wet conditions described for the windward sides of the highlands (Hay et al. 1982 apparently assumed no heating of the air over northern Africa [p. 26] prior to its arrival at the rift system). In a monsoonal circulation, however, the effects of topography, as pointed out by Hay et al. (1982), are profound, as seen in the contribution of the Tibetan Plateau to the Asian monsoon. The increase of wetter-climate indicators on both sides of the rift suggest that rather than acting as a rainshadow, the rift highlands reinforced the monsoon.

The Triassic is poorly preserved worldwide and is best studied in North America. The geology in other parts of the world is consistent with a monsoonal climate. Redbeds, with local occurrences of evaporites and eolian sandstones, are widespread in South America in the Triassic (Volkheimer 1967, 1969; Rocha-Campos 1973; Parrish and Peterson 1988), and occur in Triassic continental rocks in China (Enos 1993), and South Africa. Although the Triassic record is especially sparse in Australia, Triassic rocks there are commonly red beds with fluvial deposits similar to those of the Chinle. The presence of such deposits in Australia, where they replaced Permian deposits indicative of much wetter climates, notably the widespread Permian coals, is further evidence of the strength of the monsoon in the Triassic (J. T. Parrish, M. T. Bradshaw, and others, unpub. data).

The Breakdown of the Pangean Monsoon—Jurassic

The Colorado Plateau region became arid again by the Jurassic, as indicated by widespread deposition of eolian sandstones and sabkha deposits (Blakey et al. 1988). Earliest Jurassic eolian sandstones of the Colorado Plateau recorded northwesterly winds, consistent with the predicted summer monsoonal circulation (Parrish and Peterson 1988) and with the pattern indicated by the few Triassic eolian sandstones. Later in the Early Jurassic, however, the sandstones recorded a divergence of northerly winds to the southeast and southwest. This could represent either a geographic boundary between the summer monsoonal circulation to the east and the "normal" summer subtropical high-pressure cell to the west or an alternation of monsoonal and "normal" circulation. Either case is consistent with weakening summer monsoonal circulation during the Early Jurassic (Parrish and Peterson 1988). Data from Middle Jurassic eolian sandstones show no consistent wind field on the Colorado Plateau, and by the Late Jurassic, the zonal westerlies are well expressed in the eolian sandstones. The disorganized vectors in the Middle Jurassic sandstones might have recorded a transitional climatic state, from monsoonal to zonal (Parrish and Peterson 1988), either because the winds were relatively weak and variable or because monsoonal and zonal circulation alternated rapidly. Further study of the Middle Jurassic eolian sandstones might make it possible to distinguish between these two possibilities.

The shift from monsoonal to zonal circulation does not appear to have had a major impact on climate in the Colorado Plateau region, which continued to be relatively dry (Parrish 1993*b*). Evaporitic lakes are represented by the Todilto Limestone and Pony Express Limestone Members of the Wanakah Formation (Middle Jurassic; Condon and Peterson 1986) and the Brushy Basin Member of the Morrison Formation (Upper Jurassic; Lake T'oo'dichi', Turner-Peterson and Fishman 1986; Turner and Fishman 1991; see also Bell 1986). However, fossil wood of Jurassic age is common in the Morrison Formation in Utah (C. E. Turner pers. comm.; J. T. Parrish, unpub. data), indicating that the water table was high enough to permit tree growth, and in some respects, the Morrison resembles the Chinle Formation. Given the predicted evolution of the Pangean megamonsoon, evidence for seasonality in the Morrison should be less than in the Chinle; a comparison between the Morrison and Chinle Formations could throw light on the problem of interpreting seasonality rainfall from the geologic record.

Laurasia was relatively dry during the Late Triassic, but on the evidence of the onset of widespread coal deposition in eastern Laurasia, appears to have become wetter during the Early Jurassic, in contrast to the pattern observed on the Colorado Plateau. Hallam's (1984) data indicate that the Early Jurassic pattern in Laurasia persisted into the Middle Jurassic. A possible explanation implied by Parrish et al. (1982) is that evaporation was reduced because of cooler temperatures brought about by the more northerly position of Laurasia in the Early Jurassic. If global temperature was dropping as well, the shift could be explained simply by changing the precipitation-evaporation balance with a change in temperature and no changes in the northward transport of moisture by the monsoon. Berner's (1990) CO_2 curve would suggest that global temperature was more likely to have warmed at this time. However, evidence exists for cooling, at least in the higher latitudes. Cooling during the Early Jurassic is suggested by the appearance of the Boreal Realm ammonite fauna in the Northern Hemisphere (Taylor et al. 1984), which is commonly interpreted to represent cooler water, and of glendonites in high latitudes (Kemper 1987). In addition, peat formation was widespread in midlatitudes in Gondwana (Volkheimer 1967).

Rising sea level during the Early Jurassic, coupled with favorable basin settings in eastern Laurasia, may explain the onset of widespread peat formation there, and peat formation was in lower latitudes there than in Gondwana. The problem of interpreting Early Jurassic climates is further complicated by uncertainty regarding the position and coherence of Pangea at that time, as discussed at the beginning of this paper. Cooling could be regional owing to the northward movement of northeastern Pangea as the continent rotated counterclockwise (Bazard and Butler 1991). However, this would not explain the distribution of coals in Gondwana (whether or not Pangea was coherent or fragmented) nor would it explain the southward movement of the Boreal Realm faunas. Clearly, a number of lines of research must be pursued regarding Early Jurassic climates before these problems can be sorted out.

A dramatic shift in climate at the Middle-Late Jurassic boundary in southern Laurasia is indicated by changes in the distributions of not only coals, but also evaporites, red beds, and laterites (Vakhrameyev and Doludenko 1977; Parrish et al. 1982; Vakhrameyev 1982; Hallam 1984). By the Late Jurassic, coal deposition in eastern Laurasia was replaced by evaporite deposition between 20° and 40° north, consistent with zonal circulation and the breakdown of the northern monsoon (Parrish et al. 1982; Parrish 1988). The rifting of Laurasia from Gondwana removed the principal forcing factor of the monsoon, the Pangean geography. Once the monsoon broke down, the mechanism of moisture transport to those latitudes would have ceased to exist. The maximum southward extension of Boreal Realm ammonites at the end of the Middle Jurassic (Taylor et al. 1984) suggests that the drying could not be the result of global warming, although the coolest polar temperatures in the north may actually have been earlier in the Middle Jurassic, as evidenced by the presence of glacial-marine sediments, diamictes ("pebbly argillites"), and glendonites (Brandt 1986; see discussion in Parrish 1993*b*).

The shift to drier climate in southern Laurasia is also reflected in changes in the distribution of *Classopollis*, the pollen of the conifer family Cheirolepidiaceae, which is interpreted to have been drought-tolerant (Alvin et al. 1978; Alvin et al. 1981; Doyle and Parrish 1984). This shift has been documented with high resolution and appears to have taken place during late Bathonian-Callovian time (Vakhrameyev 1982).

Although not as well resolved, climatic changes in the Southern Hemisphere appear to have roughly paralleled those of the Northern Hemisphere. This indicates that although Gondwana is likely to have had its own monsoonal circulation, that circulation was probably much weaker than the Pangean monsoon. In the Early Jurassic, abundant fossil floras and widespread peat deposition occurred, and humid conditions continued into the Middle Jurassic (Volkheimer 1967). In the Late Jurassic, arid conditions were established in mid-latitudes, resulting in extensive eolian sand deposition (Volkheimer 1967). Monsoonal circulation would be expected to continue at a somewhat reduced strength in Gondwana, which was comparable in size to modern Eurasia (Parrish and Curtis 1982; Valdes and Sellwood 1992).

Summary

The starting point for climate on Pangea is Late Carboniferous, which began with widespread peat formation (e.g., Raymond et al. 1989) in what is now central and eastern North America and Europe, and relatively dry conditions on the Colorado Plateau. As the period drew to a close, the equatorial regions became drier, although this progression was uneven. By the Permian, however, the equatorial region of mainland Pangea was dry, and during the Permian, indicators of aridity and seasonality of rainfall became more widespread. This change was most likely driven by an increase in evapotranspiration owing to global warming following the disappearance of large-scale glaciation, and an enhancement of the resultant drying by increasing seasonality as the Pangean monsoon strengthened. Wind directions derived from Colorado Plateau eolian sandstones are consistent with an increasing influence of monsoonal circulation.

In the Triassic, two changes occurred that support the hypothesis that the monsoonal circulation attained its maximum strength in the Triassic. First, climate in the Colorado Plateau region became relatively wet, though still seasonal, in the Late Triassic, in contrast to the climate before and after. The few eolian sandstones indicate a major shift in wind direction at that time. Second, much of the sedimentation in Australia, which was in relatively high latitudes, took on a much drier and more seasonal character than before or after. As indicated in figures 1 and 4, monsoonal circulation generally involves only the low-latitude portions of the Earth's surface. If the changes in Australia are attributable to the monsoon, the strength of the Pangean megamonsoon was great indeed.

In the Early Jurassic, the Colorado Plateau region again became arid and the eolian sandstones record zonal as well as monsoonal circulation. In eastern Laurussia, however, and in Gondwana, climate apparently became wetter, owing either to global cooling or, in the case of Laurussia, rotation of that portion of the continent into higher latitudes. Finally, drying occurred in Gondwana and southern Laurasia, and is interpreted as indicative of the breakdown of the Pangean monsoon.

Details of the climatic developments outlined in this paper will inevitably change as more is learned about Pangean geology and climatology. For example, any new research into the climatic significance of red beds will have a profound effect on our understanding of this time. However, at least two major problems remain in the study of Pangean climates that could change substantially some of the conclusions in this paper. One is the problem of the timing of the monsoon maximum in the Triassic. Triassic rocks are relatively scarce and poorly studied, particularly from a global perspective. The other problem lies in uncertainties about the geography of Pangea during the Jurassic, that is, its orientation and integrity.

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