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3

Mobility of Pangea: Implications for Late Paleozoic and Early Mesozoic Paleoclimate

Dennis V. Kent and Giovanni Muttoni

Several recent analyses of paleomagnetic data support the concept of Pangea, an assemblage of most of the world's continents that was mobile in terms of large-scale internal deformation and with respect to paleolatitude. The main feature of internal deformation involved the transformation from a Pangea B–type configuration in the late Paleozoic, with northwestern South America adjacent to eastern North America, to a more traditional Pangea A–type configuration in the early Mesozoic, with northwestern Africa adjacent to eastern North America. Pangea B thus seems to coincide in time with extensive low-latitude coal deposition and high southern-latitude Gondwana glaciations, whereas Pangea A coincides with generally drier conditions over the continents and no polar ice sheets. Although the configuration of Pangea may have been more stable as an A-type configuration in the Early and Middle Jurassic prior to breakup, the paleomagnetic evidence suggests that there was appreciable latitudinal change of the assembly. Such changing tectonic boundary conditions emphasize the practical importance of age registry of paleoclimate data in making valid comparisons with model results. A simple zonal climate model coupled with the geocentric axial dipole hypothesis for establishing paleolatitudes in precisely controlled paleogeographic reconstructions can explain many of the climate patterns in both the late Paleozoic and the early Mesozoic, but it cannot explain the presence or absence of continental ice sheets.

* * *

The supercontinent of Pangea included most of the continents over the late Paleozoic and the early Mesozoic (∼300 Ma to ∼175 Ma). Over its existence, Pangea experienced a wide range of global climate conditions, from extensive Gondwana glaciations in the Permo-Carboniferous to generally drier continental climates and the absence of evidence for high-latitude ice sheets in the Triassic and Jurassic (Frakes 1979). If there was indeed little change in continental positions from the late Paleozoic to the early Mesozoic, as is often supposed, then the role of paleogeography in explaining the large contrast of climates across these intervals is not very obvious (Hallam 1985).

However, some recent analyses of paleomagnetic data support the concept of a more mobile Pangea, in which the relative arrangement of the main continental elements and the paleolatitudinal setting changed appreciably with time. The concept of a mobile Pangea expands opportunities for testing the sensitivity of tectonic boundary conditions in climate simulations; however, the changing tectonic boundary conditions also emphasize the importance of precise age correlation of paleoclimate data in making valid paleogeographic reconstructions. This chapter highlights some recent developments in our understanding of the evolution of Pangea in the late Paleozoic and early Mesozoic and calls attention to their possible paleoclimate implications.

PALEOMAGNETIC DATA

Paleomagnetism provides one of the best recorders of past locations of the geographic axis and therefore can place critical constraints independent of paleoclimatology on the latitudinal distribution of landmasses. Descriptions of the methodology and assumptions of the subject are discussed extensively elsewhere (for a recent general treatment, see Butler 1992, and for a modern and comprehensive analysis of tectonic applications, see, especially, Van der Voo 1993). Some comments are offered here to remind the reader of the scope and limitations of paleomagnetic data when such data are used for paleocontinental reconstructions.

A central assumption of paleomagnetism is that the Earth's magnetic field, when averaged over some thousands of years, will be approximated closely by that of a geocentric axial dipole (GAD). Thus an observed mean inclination, I, can be related to geographic latitude, L, according to the dipole formula ($\tan I = 2 \tan L$). Paleomagnetic observations for the past few million years, where accumulated plate motions are small or can be taken into account, indicate that the GAD model is an accurate representation of the paleofield to within a few degrees (e.g., Opdyke and Henry 1969; Schneider and Kent 1990b). The detailed configuration of the paleofield is known less precisely for earlier eras (e.g., Livermore, Vine, and Smith 1984; Schneider and Kent 1990a), and evidence for the general validity of the GAD hypothesis comes to rely mainly on the degree of congruence with the inferred latitudinal dependence of various climate indicators (e.g., Blackett 1961; Briden and Irving 1964). It is therefore useful to maintain a distinction between estimates of latitude obtained from paleomagnetic data and those obtained from paleoclimate data so that the nature of any discrepancies (e.g., those possibly arising from more complicated magnetic fields, regionally nonzonal climate, or simply poor or undiagnostic data) can be better understood.

According to the GAD hypothesis, paleomagnetic directions of similar age from any locality on a rigid tectonic plate should give the same paleomagnetic pole and hence the location of that plate with respect to the geographic axis. In practice, there will be some scatter in such determinations, and the resulting uncertainty in the mean pole position is usually expressed by the radius of the circle of 95% confidence (A95), according to Fisher statistics (Fisher 1953). The uncertainty in paleopole determinations, where A95 is typically a few degrees and higher, is thought to be caused mainly by experimental and observational errors rather than by complexities in the paleofield (for a caveat on Paleozoic and Precambrian data, see Kent and Smethurst 1998).

A temporal sequence of paleopoles or an apparent polar wander (APW) path is a convenient way to represent the motion of a tectonic plate with respect to the rotation axis. Van der Voo (1993) has introduced a set of seven minimum reliability criteria for evaluating published paleopoles. A low overall quality factor is grounds for rejection, but relatively few results satisfy all the threshold criteria for reliability. Van der Voo (1993) suggested that only those results that pass three or more reliability criteria should be retained as the most suitable candidates for documenting polar wander. Acceptable paleopoles from specific rock units are typically averaged over intervals, usually something such as a geologic epoch or 10 to 30 million years depending on the availability of data, in order to enhance the coherence of the APW path. Paleomagnetic data are not uniform in quality or abundance, so there is considerable variability in the definition and reliability of APW paths for different plates or time intervals. Paleocontinental reconstructions accordingly are not uniformly constrained and may change as better data become available.

Relative motions between tectonic plates or their continental proxies are detected by systematic differences in their respective APW paths. It is also possible that the whole Earth rotated with respect to the rotation axis (e.g., Goldreich and Toomre 1969), a phenomenon referred to as true polar wander (TPW). For the late Mesozoic and Cenozoic, where plate motions are constrained by evidence from the seafloor and by a hot-spot reference frame more or less fixed to the solid Earth, the amount of any TPW has been estimated to have been much smaller than plate motions in accounting for polar wander (e.g., Courtillot and Besse 1987; Gordon 1987). Some researchers have suggested episodes of larger TPW for some earlier intervals, such as the Permo-Triassic (Marcano, Van der Voo, and Mac Niocaill 1999), but TPW will remain a moot issue for paleoclimatology provided that the GAD hypothesis remains valid; that is, the dynamo in the fluid outer core always responds to the geographic or rotation axis so that the dipole field tends to remain aligned along it.

There have been occasional suggestions, although they are not well posed as a testable hypothesis, that the paleomagnetic and geographic axes were significantly decoupled for long intervals. For example, Donn (1982, 1989) attempted to explain apparently large disagreements between paleomagnetic data and other paleolatitudinal indicators for the Triassic to Eocene with what might be referred to as paleomagnetic polar wander. Some discrepancies between paleomagnetic and paleoclimatic estimates of paleolatitude have been resolved with better paleomagnetic data—for example, in the Devonian of North America (Heckel and Witzke 1979; Miller and Kent 1988; Stearns, Van der Voo, and Abrahamsen 1989)—or have been taken as an indication of a significant climate problem, as in the case of high-latitude warmth in the Cretaceous and Eocene (Barron, Thompson, and Schneider 1981; Barron 1987). But the underlying nature of other discrepancies is debated still—for example, the evidence for low-latitude glaciation in the late Precambrian (Crowley and Baum 1993; Meert and Van der Voo 1994; Schmidt and Williams 1995; Sohl, Christie-Blick, and Kent 1999). Here we assume the validity of the GAD hypothesis as a basis for determining paleolatitudes in assessing paleoclimate implications.

Finally, it should be noted that the axial symmetry of the dipole model of the field means that a paleomagnetic pole can used to determine the position of a tectonic plate only with respect to lines of paleolatitude, leaving paleolongitude indeterminate. For the late Mesozoic and younger time, marine magnetic anomalies and other signatures of seafloor spreading provide a precise measure of relative paleolongitudes for most tectonic plates. For the early Mesozoic and earlier time, the matching of geological or biogeographic features or provinces, in conjunction with minimum motion arguments, must be relied on to provide some constraints on the relative longitudinal distribution of tectonic plates.

PANGEAN CONFIGURATIONS IN THE PERMIAN, TRIASSIC, AND JURASSIC

Although a variety of data have demonstrated decisively the existence of Pangea in the late Paleozoic and early Mesozoic, uncertainty remains on its precise configuration. For example, the positions of the various tectonic blocks in eastern Asia may not have become assembled with the rest of Laurasia until sometime in the Jurassic (Enkin et al. 1992). However, a first-order problem considered here is the position of the southern continental assembly of Gondwana with respect to the northern continental assembly of Laurasia. Two general models have been proposed: (1) a supercontinent that maintained a more or less static Pangea A–type configuration over the late Paleozoic and early Mesozoic; and, largely on the basis of paleomagnetic results, (2) a supercontinent that experienced appreciable internal deformation and evolved from a Pangea B–type to a Pangea A–type configuration over this interval.

The Pangea A–type model is the traditional Wegenerian configuration, whose salient feature for this discussion is the placement of northwestern Africa adjacent to eastern North America. A widely used version (Pangea A-1) is Bullard, Everett, and Smith's (1965) reconstruction, which is based on a computerized best fit of the present circum-Atlantic continental margins. Pangea A-1 should thus approximate the relative position of the major continents just prior to the opening of the Atlantic Ocean sometime in the Jurassic.

It has long been recognized, however, that Permian and Triassic paleomagnetic poles from Gondwana (mainly from Africa and South America) with respect to Laurasia (mainly from North America and Europe) do not agree well with the Bullard fit for Pangea, so various alternative reconstructions have been offered to explain the systematic discordance between the respective APW paths. Van der Voo and French (1974) proposed a modification of Pangea A-1 that requires a further approximately 20° clockwise rotation of Gondwana with respect to Laurasia. This adjustment (Pangea A-2) brings the northwestern margin of South America much closer to the Gulf Coast margin of North America but does not fully account for the differences in Permian poles.

To bring Permian paleomagnetic poles into even better mutual agreement, Gondwana has to be rotated clockwise as well as northward. However, this rotation results in an unacceptable overlap with Laurasia unless Gondwana is also shifted appreciably eastward, taking advantage of the longitude indeterminacy of the pa-leomagnetic method. The Pangea B reconstruction proposed by Irving (1977) and by Morel and Irving (1981) is the best-known model of this type (see also Smith, Hurley, and Briden 1980; Livermore, Smith, and Vine 1986). An important distinguishing feature of Pangea B is that northwestern South America is placed against eastern North America, whereas northwestern Africa is positioned south of Europe. This would require approximately 3,500 km of subsequent right-lateral relative motion between Gondwana and the northern continents because the Atlantic Ocean opened from a Pangea A–type configuration. The reality of Pangea B thus has been much debated on the basis of geologic and paleomagnetic data (e.g., Hallam 1983; Van der Voo, Peinado, and Scotese 1984; Smith and Livermore 1991; see summary in Van der Voo 1993).

The Permo-Triassic APW path of Gondwana generally is poorly documented, which contributes to the uncertainty in Pangea configurations. To augment the definition of APW in this interval, Muttoni, Kent, and Channell (1996) included paleomagnetic data from the southern Alps in Italy as a proxy for Gondwana and generated a new tectonic model for the evolution of Pangea from the Early Permian to the Early Jurassic by integrating these data with the recently published APW paths representative of Gondwana and Laurasia (Van der Voo 1993). According to this model, the reconstruction that satisfies Early Permian paleopoles is virtually the same as Morel and Irving's (1981) Pangea B (figure 3.1). This conclusion is not strongly dependent on the paleomagnetic data from the southern Alps.

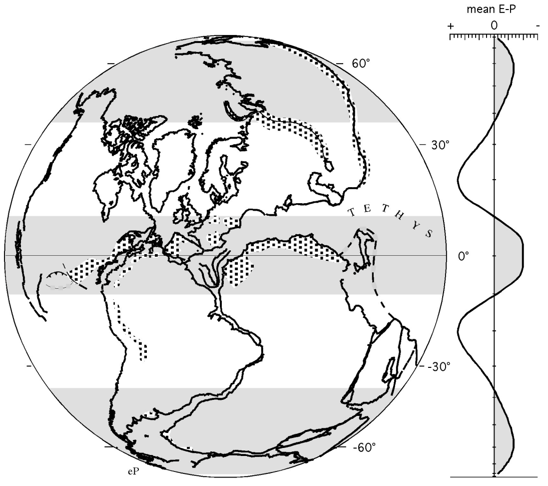

FIGURE 3.1 Early Permian (~275 Ma) paleocontinental reconstruction that resembles Pangea B. The Gondwana and Laurasia continents were assembled by using reconstruction parameters from Lottes and Rowley (1990) and from Bullard, Everett, and Smith (1965), respectively, and were oriented with respect to the paleolatitudinal grid according to mean paleopoles summarized by Muttoni, Kent, and Channell (1996), with Gondwana translated longitudinally to avoid overlap with Laurasia. The distribution of the Alleghanian–Hercynian–Variscan orogenic belt (*gray*) is from Morel and Irving (1981); tectonic lines are from Arthaud and Matte (1977). Tethyan tectonics are highly diagrammatic. Shown for reference is the mean zonal variation in evaporation minus precipitation (E – P) for the modern land plus ocean surface (Crowley and North 1991), which has been further averaged over the Southern and Northern Hemispheres. (From Muttoni, Kent, and Channell 1996).

For the Late Permian–Early Triassic and into the Middle–Late Triassic, the Gondwana-proxy data from the southern Alps allow a reconstruction resembling a Pangea A-2 model (figure 3.2). According to Muttoni, Kent, and Channell's (1996) analysis, the major transformation from a Pangea B–type to a Pangea A–type configuration thus occurred effectively by the end of the Permian. This timing allows the large strike-slip motion associated with the transformation to be connected with the final stages of the Variscan orogeny (Arthaud and Matte 1977). The transition from Pangea B to Pangea A was suggested previously by Irving (1977), by Morel and Irving (1981), and more recently by Torcq et al. (1997) to have occurred during the Triassic. We believe that the Triassic is more likely associated with the tectonically more modest shift from Pangea A-2 to Pangea A-1. Unconformity-bound tectonostratigraphic units preserved in the early Mesozoic rift basins along the central Atlantic margins (Olsen 1997) may reflect such regional transtensional tectonic activity.

Early to Middle Jurassic paleopoles representative of Laurasia and Gondwana are reasonably concordant

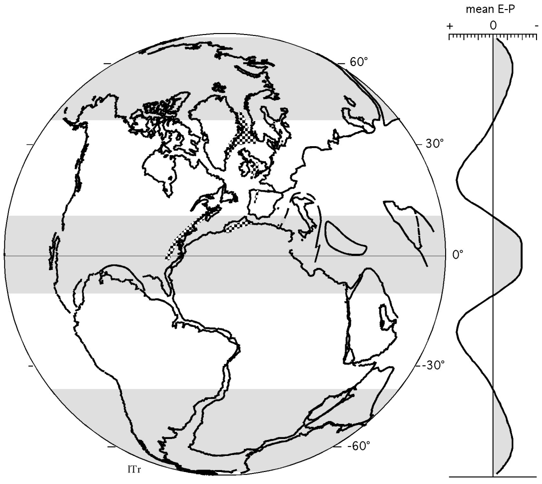

FIGURE 3.2 Middle–Late Triassic (~225 Ma) paleocontinental reconstruction that resembles Pangea A-2. Notes and abbreviations are as given in figure 3.1. (From Muttoni, Kent, and Channell 1996).

with a Pangea A-1 fit (Van der Voo 1993; Muttoni, Kent, and Channell 1996) from which the Atlantic Ocean began opening at approximately 175 Ma, or during the middle Middle Jurassic (Klitgord and Schouten 1986) (figure 3.3). As indicative of the amount of APW over the Jurassic as a whole, there is approximately 30° of great-circle distance separating Early Jurassic and Early Cretaceous poles for North America, the continent with the most abundant and reliable paleopoles for this interval (Van der Voo 1993). However, because of possible remagnetizations and local tectonic rotations, it is uncertain whether the Jurassic APW track for North America follows more or less along the 60th parallel (e.g., May and Butler 1986) or reaches high present-day latitudes of approximately 75° or more in the Middle Jurassic (e.g., Van Fossen and Kent 1990; for reviews and further analysis, see also Hagstrum 1993 and Van der Voo 1992, 1993). Courtillot, Besse, and Theveniaut (1994) constructed synthetic APW paths by transferring data from other Atlantic-bordering continents according to various reconstruction parameters. They concluded that high-latitude APW for North America was the option most compatible with the global paleopole database, as Van der Voo (1993) also found. The high-latitude APW model for North America results in a paleogeographic position of Pangea in the Middle Jurassic, as shown in figure 3.3.

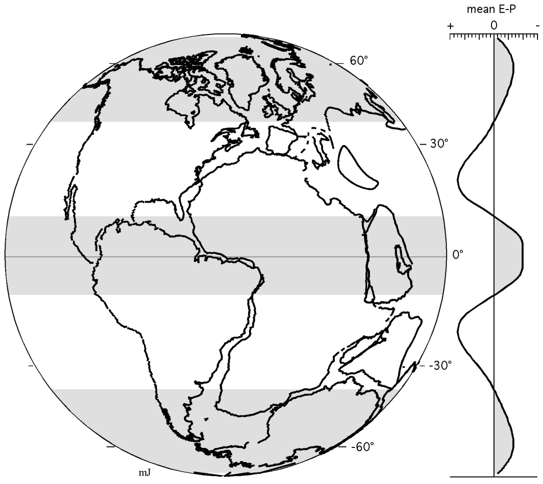

FIGURE 3.3 Middle Jurassic (~175 Ma) paleocontinental reconstruction that resembles Pangea A-1 (for just prior to the opening of the Atlantic Ocean), with a high-latitude option for Jurassic APW. Notes and abbreviations are as given in figure 3.1. The position of Gondwana versus Laurasia (i.e., Africa versus North America) is from Bullard, Everett, and Smith (1965). The Pangea assembly was oriented with respect to the paleolatitude grid by using the approximately 175 Ma Newark B paleopole of Witte and Kent (1991), which agrees with the synthetic APW path for North America of Courtillot, Besse, and Theveniaut (1994).

PANGEAN CLIMATES

Pangea A–type reconstructions have been used in climate simulations of the late Paleozoic and the early Mesozoic (Crowley, Hyde, and Short 1989; Kutzbach and Gallimore 1989; Chandler, Rind, and Ruedy 1992; Klein 1994). However, rather than a single configuration over the Permian and Triassic, an internally mobile Pangea suggested by Irving (1977) is supported in manner, if not in exact timing, by several more recent analyses of paleomagnetic data (Muttoni, Kent, and Channell 1996; Torq et al. 1997; but see dissent in Van der Voo 1993). If corroborated by further work to exclude artifacts from remagnetizations, inclination error, and even nondipole fields, the internal mobility of Pangea provides an additional source of paleogeographic variability that might be relevant to changes in global climate. In general, the Pangea B configuration seems to coincide temporally with extensive low-latitude coal deposits and high southern-latitude Gondwana glaciations in the late Paleozoic. In contrast, a Pangea A paleogeography seems to have ushered in the apparently drier continentality of the early Mesozoic when there were no polar ice sheets.

Analogous to the geocentric axial dipole model, which constitutes a powerful testable model for paleomagnetism, a zonal climate model is a useful null hypothesis for understanding the distribution of climate proxies. The zonal-mean annual averages of evaporation (E) and precipitation (P) and especially of their relative variations (E-P rate) (Crowley and North 1991:fig. 2.3) are important elements of climate and hydrology, just as inclination is an important observable element of the geomagnetic field. The measured E-P values in modern-day climate show excess of precipitation over evaporation at middle and high latitudes as well as in the equatorial zone between 10° north and 10° south, whereas a deficit of precipitation is found in the subtropical regions between approximately 10 and 35° latitude. These latitudinal bands of relative aridity and humidity are superposed on the Pangea reconstructions (figures 3.1–3.3). It should be noted that this zonal configuration of relative humidity and aridity need not have been the same in the past. For example, many analyses have suggested that there was a desertlike equatorial belt in the Triassic (e.g., Ziegler et al. 1993; Wilson et al. 1994), which, if true, would constitute a first-order discrepancy with the modern atmospheric circulation pattern. Climate proxies should also represent the characteristic state over several million years to minimize aliasing from Milankovitch climate cyclicity (Olsen and Kent 1996).

The difference between Pangea B and Pangea A is mainly in the relative paleolongitudes of Laurasia versus Gondwana; hence the latitudinal distribution of land areas is not very different in the two alternative reconstructions. However, Pangea as a whole gradually shifted northward over the Permian and Triassic and into the Jurassic so that, for example, European sites of near-equatorial coal deposition in the late Paleozoic (figure 3.1) had migrated into the arid belt by the early Mesozoic (figure 3.2). Although Late Triassic paleoclimate indicators from eastern North America are often regarded as the result of local orographic effects (e.g., Manspeizer 1982; Hay and Wold 1998), they are actually very consistent, when correlated precisely using magnetic polarity stratigraphy, with a latitudinal variation in the balance of evaporation to precipitation not that different from today's mean zonal regime. In contrast to many previous analyses for the early Mesozoic, the existence of an equatorial humid belt is clearly shown in the Late Triassic by the progression from coal-bearing deposits near the paleoequator in eastern North America (e.g., Dan River basin, North Carolina and Virginia [Kent and Olsen 1997]) to eolian deposits at around 10° paleolatitude (e.g., Fundy basin, Nova Scotia [Kent and Olsen 2000]), as well as by evidence of a major through-going Chinle–Dockum paleoriver system that flowed generally northward from Texas in the U.S. Southwest (Riggs et al. 1996). By the time Pangea breakup was under way in the Middle Jurassic, eastern North America had drifted farther north into the arid belt (figure 3.3), which is consistent with the presence of extensive evaporites of likely Jurassic age under the North American east coast margin (Poppe and Poag 1993) and of major eolian deposits such as the Navajo Sandstone in the U.S. Southwest.

A zonal climatic model applied to a mobile Pangea configuration therefore can account for the comings and goings of a variety of climatic conditions. Furthermore, some major paleogeographic differences between Pangea B and Pangea A may have important, nonzonal paleoclimate implications. Pangea B is characterized by a narrow Tethys Sea, open ocean to the south of North America, and an orogenic belt (Alleghanian–Hercynian–Variscan) along the equatorial zone (figure 3.1). Otto-Bliesner (1993) suggested that significant topography along the equator can enhance humidity in the tropical zone and hence the formation of coals. In contrast, the Pangea A–type reconstruction has a wide Tethys Sea, mostly landmass to the south of North America, and the eventual development of rift basins with a more meridional trend along the central Atlantic margins (figures 3.2 and 3.3).

An important issue is the ability to separate actual nonzonal features of climate from artifacts of poor spatiotemporal resolution or from errors in continental reconstructions. Even with very slow latitudinal drift, which characterized North America in the Late Triassic (~0.3°/million years [Kent and Witte 1993]), the customary mapping of paleoclimate data in time slices of 10 to 15 million years (e.g., the Carnian or Norian–Rhaetian [Hay et al. 1982; Wilson et al. 1994]) is likely to obscure evidence for narrow climate zones with steep latitudinal gradients, such as the tropical humid belt. Distortion of climate patterns is exacerbated for faster latitudinal drift (e.g., 1° per million years in the Jurassic [Van Fossen and Kent 1990]),

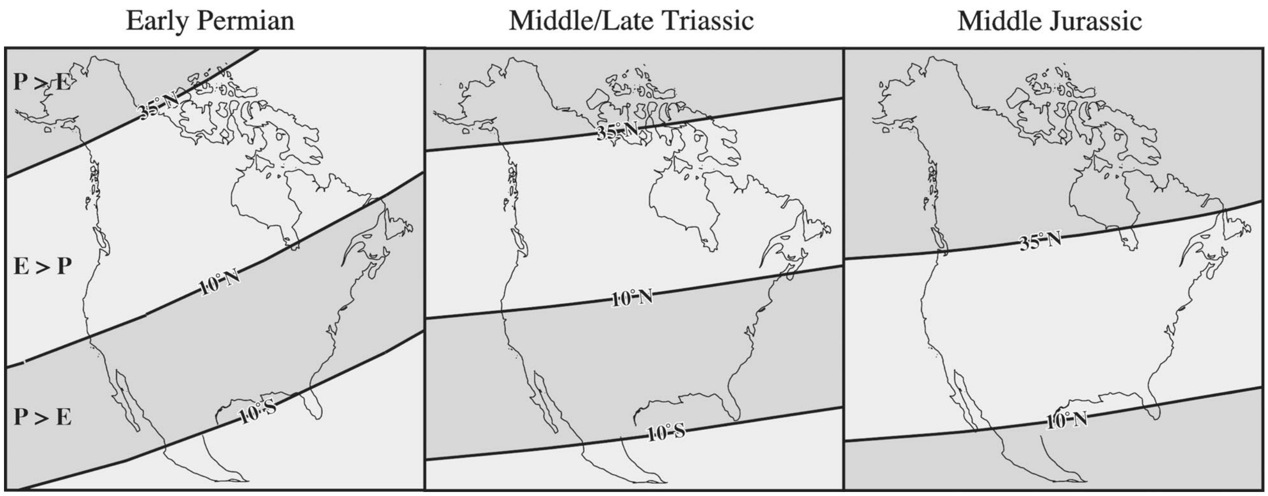

FIGURE 3.4 Map of present-day North America with inferred zonal bands of arid (E > P) and humid (P > E) climate for the Early Permian, Middle–Late Triassic, and Middle Jurassic. Paleopoles used to construct paleolatitudes for North America are 46°N 124°E for Early Permian (~275 Ma), 51°N 96°E for Middle–Late Triassic (~225 Ma) (both poles from Muttoni, Kent, and Channell 1996:table 3), and 74°N 96°E for Middle Jurassic (~175 Ma) (Witte and Kent 1991).

where there is also the greater likelihood of poor age registry and systematic offsets between the paleoclimate indicators and the paleomagnetic observations that are inevitably needed for the paleolatitudinal framework. Artifacts of such loose cataloging provide a testable alternative explanation to nonzonal effects for what are sometimes interpreted as contradictory geographic arrays of climate indicators (e.g., Chandler, Rind, and Ruedy 1992; Hay and Wold 1998).

Conclusions

The mobility of Pangea has important but largely underestimated implications for understanding the significance of late Paleozoic and early Mesozoic paleoclimate indicators. Pangea paleogeographic reconstructions from the Early Permian to the Middle Jurassic (Muttoni, Kent, and Channell 1996; this study) have been compared with modern-day climatic indicators such as the relative rate of evaporation and precipitation under the null hypothesis of a zonal climate model. Climatic variations from arid (E > P) to humid (P > E) conditions across large portions of the Pangea-forming continents can be accounted for by internal or total Pangea mobility or by both. A large portion of North America, for example, was characterized in the Early Permian by humid (P > E) conditions, which correspond on modern-day Earth to the savanna–rain forest equatorial belt, whereas by the Middle Jurassic the same areas fell within the arid belt (E > P), which currently characterizes tropical deserts such as the Sahara (figure 3.4). Reliable paleomagnetic-derived paleogeographic reconstructions under the hypothesis of a zonal climate model therefore can explain a wide variety of climatic conditions over late Paleozoic and early Mesozoic Pangea. At the present level of analysis, it is not even obvious that the widths of the humid and arid belts in the late Paleozoic and early Mesozoic were markedly different from those of today's world, despite the major differences in paleogeography.

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