APPLICATIONS TO PALEOGEOGRAPHY

Early paleogeographic applications of fundamental paleomagnetic techniques (primarily by a handful of British scientists) led to one of the most broadly appreciated contributions of paleomagnetism to Earth science: the confirmation of continental drift theory. Here we develop the basic principles of applying paleomagnetism to paleogeography. The geocentric axial dipole hypothesis is a fundamental building block, and we first explore the evidence that this simple form is the first-order behavior of the geomagnetic field. Discussion of paleomagnetic poles and their presentations lead us into development of apparent polar wander paths. Introduction of a few key concepts in comparison of these paths between continents provides the tools for understanding applications to paleogeography. The chapter concludes with several examples that illustrate the powers and limitations of applying paleomagnetism to paleogeographic continental reconstructions.

THE GEOCENTRIC AXIAL DIPOLE HYPOTHESIS

The Geocentric Axial Dipole (GAD) hypothesis was introduced in Chapter 1, where its consistency with a magnetohydrodynamic origin of the geomagnetic field was noted. The GAD hypothesis implies that a paleomagnetic pole indicates the position of the rotation axis with respect to the continent from which the paleomagnetic data were acquired. Through the GAD hypothesis, paleomagnetic poles can be used to determine paleogeographic reconstructions by using the procedures developed below. Because of its crucial role in tectonic applications of paleomagnetism, the GAD hypothesis is further explored in this section.

During the 1950s and early 1960s, paleomagnetic evidence for continental drift was attacked by detractors who questioned the validity of the GAD hypothesis during the Paleozoic and Mesozoic. Irving (1964) discussed this “nondipole hypothesis” and concluded that it was a “hypothesis of desperation, useful at this stage only to those anxious to avoid implications of paleomagnetism.” With subsequent expansion of paleomagnetic data and development of plate tectonics, the fundamental validity of the GAD hypothesis is now quite firmly established.

The past 5 million years

In discussing Figure 1.9, we found that the geomagnetic pole does a random walk about the rotation axis. The average position of the geomagnetic pole over the past 2000 years is indistinguishable from the rotation axis. In Chapter 7, we analyzed paleomagnetic data from Holocene lavas of the western United States. Increasing numbers of VGPs were used to determine the “paleomagnetic poles” shown in Figure 7.5. Resulting poles fell within 3° of the rotation axis, and the confidence limit, A_{95}, decreased to 3.7° when 30 VGPs were averaged. It is apparent that the time-averaged Holocene paleomagnetic field in the western United States was geocentric axial dipolar within a 95% confidence limit of ~3°. We will return to further discussion of this data set below.

Opdyke and Henry (1969) determined mean paleomagnetic inclinations from 52 Pliocene–Pleistocene deep-sea cores. These mean inclinations are shown in Figure 8.2 and are found to closely match the inclinations predicted by a GAD: $\tan I = 2 \tan \lambda$ (Equation (1.15)). More detailed evaluation of the GAD hypothesis was made possible by compilation of paleomagnetic data from 4580 lavas with ages in the 0- to 5-Ma interval (Merrill and McElhinny, 1983). The first-order time-averaged geomagnetic field over the past 5 m.y. was found to be axial geocentric dipolar within confidence limits of ~3°. This data set is sufficiently large to allow resolution of second-order deviations, which are discussed below. The above analyses confirm the validity of the GAD hypothesis for the past 5 m.y. So in the geologic time interval for which the most rigorous tests are available, the GAD hypothesis is confirmed with an uncertainty of ~3°.

Older geologic intervals

The task of evaluating the GAD hypothesis for geologic time intervals older than 5 m.y. is complicated by motions of lithospheric plates, the phenomena that we're going to use paleomagnetic data to investigate. These evaluations can be divided into tests of (1) the geocentric dipolar nature of the paleomagnetic field and (2) the axial alignment of the geocentric dipole.

From the Late Jurassic to the present, marine magnetic anomalies provide determination of relative plate motions. At least during the Cenozoic, continents can be accurately reconstructed to their relative positions by using these anomalies. The dipolar nature of the time-averaged geomagnetic field can be tested by comparisons of paleomagnetic poles from the different continents as sequential reconstructions to older geologic times are performed. For example, if continents are reconstructed to their relative positions at 30 Ma, paleomagnetic poles from rocks of this age should agree if the time-averaged geomagnetic field was geocentric dipolar; failure of the poles to agree could indicate a nondipolar field. Such analyses have confirmed the geocentric dipolar nature of the geomagnetic field during the Cenozoic and Late Mesozoic to a precision of about 5° (e.g., Livermore et al., 1983, 1984).

Other tests have similarly confirmed the geocentric dipolar nature of the time-averaged paleomagnetic field during Phanerozoic time (e.g., McElhinny and Brock 1975; Evans, 1976). But how do we test whether this geocentric dipole was aligned with the Earth's rotation axis? Comparisons with independent determinations of paleolatitude are required. Although imperfect and of limited precision, *paleoclimatic indicators* are the best available independent measures of paleolatitude with which to compare paleolatitudes determined from paleomagnetism.

Latitudinal zones of climate exist fundamentally because the flux of solar energy strongly depends on latitude. The present mean annual temperature is 25°C at the equator but is only –25°C at the poles. Numerous biologic and geologic phenomena are controlled by climatic zones: Organic reefs (corals), evaporite deposits, and red sediments are predominantly found in equatorial regions or in temperate arid zones symmetric about the equator; and glacial phenomena are found in or surrounding polar regions.

Paleoclimatic spectra are histograms of the latitudinal distribution of these paleoclimatic indicators. Comparison of paleoclimatic spectra in present latitude with spectra in paleolatitude determined from paleomagnetism is the basic method for evaluating the axial alignment of the geocentric dipole for remote geologic times. Irving (1964) presented a thorough discussion of paleoclimatic and paleomagnetic data. The fundamental verification of the GAD hypothesis by favorable comparison with paleoclimatic indicators has not significantly changed since the synthesis by Briden and Irving (1964). The following examples are adapted from their analysis.

In Figure 10.1a, the present latitudinal distribution of modern organic reefs is shown. The observed distribution is symmetric about the equator, and almost all occurrences are within 30° of the equator. But the present latitudinal distribution of <u>fossil</u> organic reefs (Figure 10.1b) shows many fossil reefs at latitudes >30°N, and the distribution is very asymmetric about the equator. It is highly unlikely that this distribution resulted from a drastically different pattern of climatic zones at the time these fossil reefs formed. Furthermore, the distribution of fossil reefs in paleolatitude determined from paleomagnetism (Figure 10.1c) exhibits the anticipated symmetry about the paleoequator. This analysis indicates that the distribution of fossil reef deposits is consistent with the GAD hypothesis.

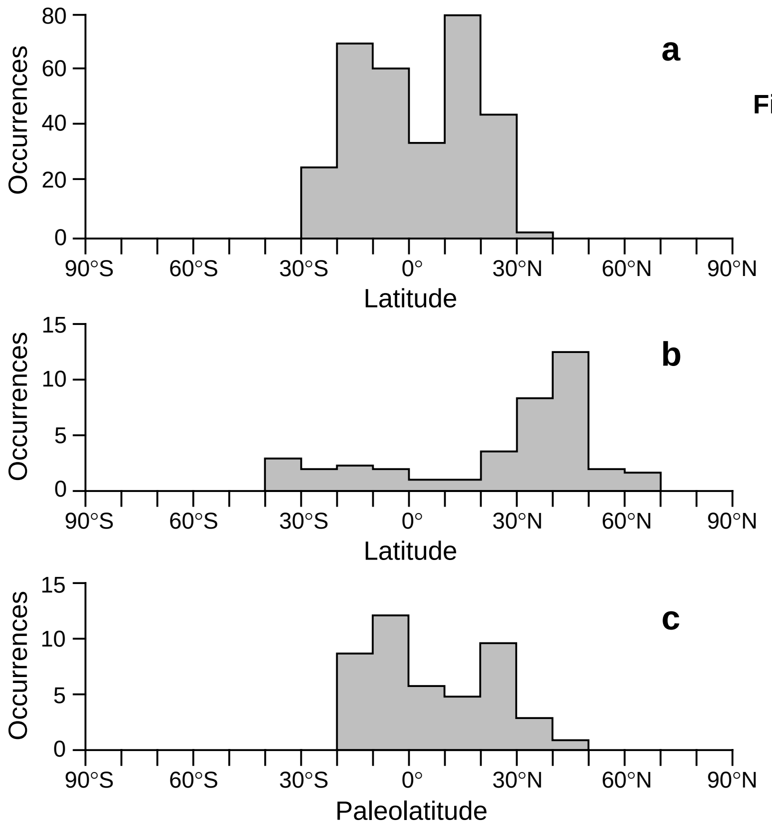

Figure 10.1 Latitudinal distribution of modern and fossil organic reefs. (**a**) Histogram of modern organic reefs within 10° bands of latitude; note the rough symmetry of modern organic reefs about the equator. (**b**) Histogram of present latitudinal distribution of ancient organic reefs; note that the majority of ancient organic reefs have present latitudes higher than 30°N. (**c**) Histogram of fossil organic reefs in paleolatitude determined from paleomagnetism; paleolatitudes of the majority of fossil organic reefs are within 30° of the paleoequator. Redrawn from McElhinny (1973) and Briden and Irving (1964).

Other examinations (e.g., Briden, 1968, 1970; Drewry et al., 1974) have led to the same basic conclusion: Paleomagnetic determinations of paleolatitude are consistent with a variety of paleoclimatic indicators, and the first-order geocentric axial dipolar nature of the time-averaged paleomagnetic field is confirmed. However, the precision of these comparisons is limited and difficult to quantify. Nevertheless, it is reasonable to conclude that the GAD hypothesis is valid at least to ~10° precision and perhaps to ~5° precision.

Second-order deviations

Acquisition of massive paleomagnetic data sets from rocks with ages <5 Ma has allowed resolution of small deviations of the time-averaged paleomagnetic field from that of a geocentric axial dipole. Wilson and Ade-Hall (1970) noted a tendency for paleomagnetic poles from Pliocene and younger lavas to be located a few degrees on the opposite side of the rotation axis from the observing locality (sites of paleomagnetic collection). This “far-sided effect” has since been thoroughly investigated (e.g., Coupland and Van der Voo, 1980; Merrill and McElhinny, 1983; Schneider and Kent, 1990).

Although complicated in detail, the basic result is that small nondipole components of the time-averaged paleomagnetic field are evident. Over the past few million years, paleomagnetic poles are far-sided by ~3°. An example of this far-sided effect is given in Figure 10.2, in which the paleomagnetic pole determined from the entire set of 77 Holocene lavas from the western United States is shown. The pole falls 2.5° on the opposite side of the geographic pole from the collecting location, and the geographic pole is just outside the 95% confidence limit. So while the first-order time-averaged paleomagnetic field confirms the GAD hypothesis to a precision of perhaps ~5°, second-order deviations amounting to ~3° are resolvable during the past few m.y.

Paleomagnetic poles and paleogeographic maps

As discussed in Chapter 7, the usual method of summarizing results of a paleomagnetic study is to determine and display the paleomagnetic pole position computed from the set of site-mean VGPs. If a number of

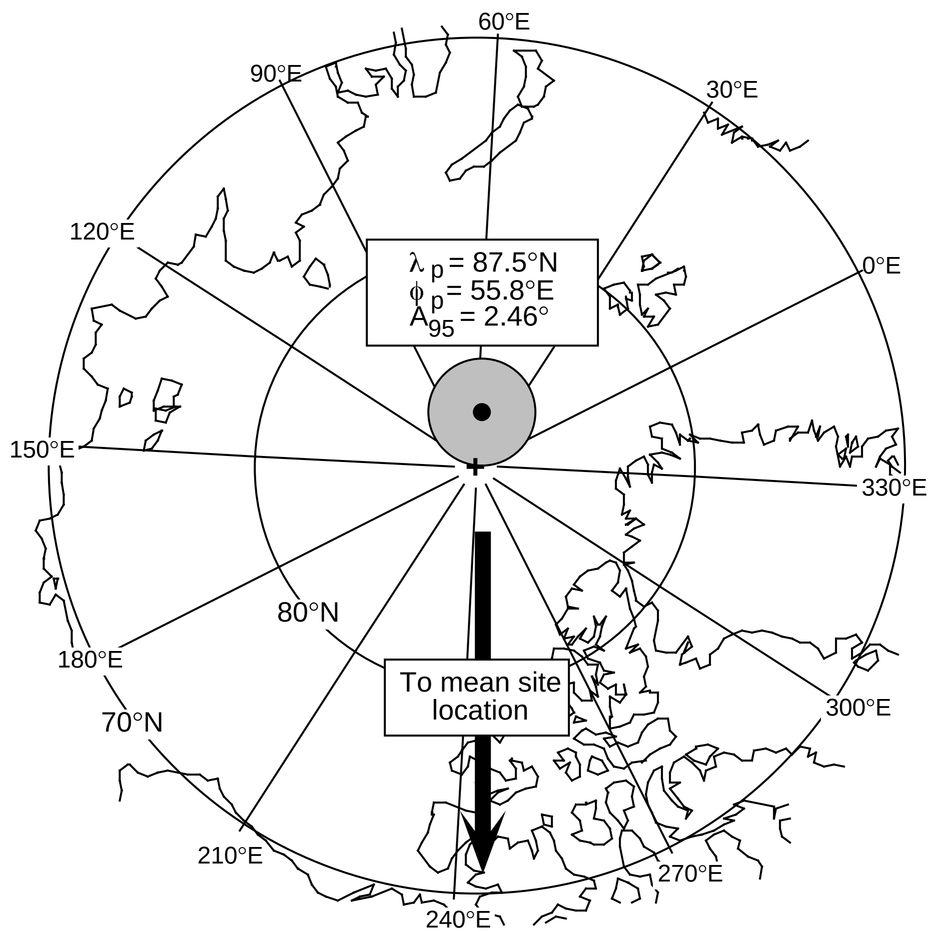

Figure 10.2 Paleomagnetic pole from Holocene lavas of the western United States. The entire data set of 77 VGPs from Holocene lavas was averaged; the paleomagnetic pole is located on the opposite side of the geographic pole from the collecting sites in the western United States; note that the geographic north pole is just outside the 95% confidence limit about the paleomagnetic pole; latitude circles are shown in 10° increments and longitude lines in 30° increments. Modified from Champion (1980).

"reliable" paleomagnetic poles have been determined from rocks of similar age from different areas of a continental interior (basic reliability criteria are discussed in Chapter 7), these poles should ideally be tightly clustered. In practice, even a collection of reliable paleomagnetic poles will have some scatter, owing to imperfect sampling of geomagnetic secular variation, uncertainties in structural correction, or other unknown effects.

In Figure 10.3, four paleomagnetic poles determined from mid-Cretaceous rocks of North America are illustrated. Each of these poles would be judged reasonably reliable by most paleomagnetists. Perhaps the most questionable is from the Niobrara Formation, which is a marine sedimentary formation with attendant uncertainty about possible shallowing of paleomagnetic inclination (Chapter 8). These four mid-Cretaceous poles are reasonably well grouped and represent a typical situation for a geologic time interval during which the paleomagnetic pole is regarded as "well determined."

For a geologic time interval during which paleomagnetic poles from a continent are reasonably clustered without systematic motion of the pole, it is common to compute a mean pole. The individual paleomagnetic poles are treated as unit vectors, and a mean is computed by using Fisher statistics. The resulting mean mid-Cretaceous paleomagnetic pole for North America is shown in Figure 10.3.

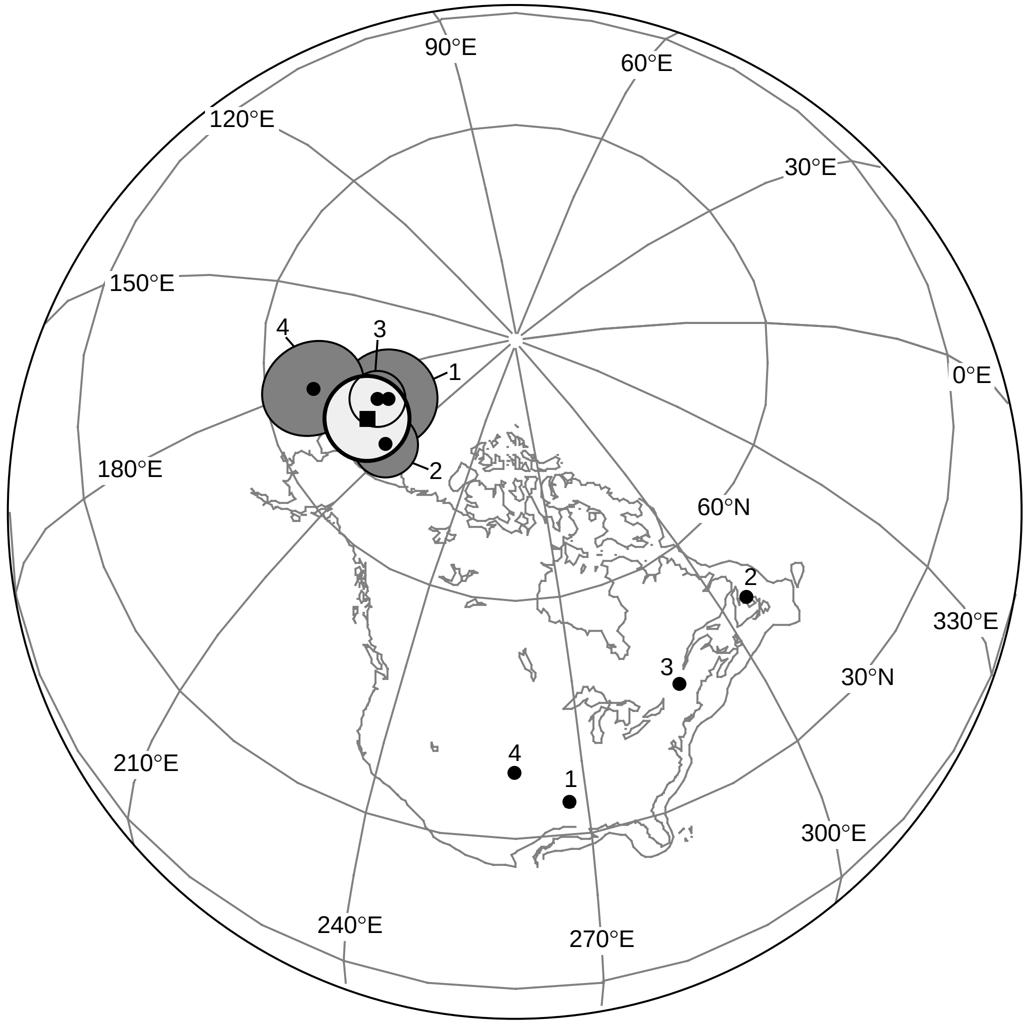

Figure 10.3 Comparison of four mid-Cretaceous paleomagnetic poles for North America. Sampling locations are shown by solid circles; corresponding paleomagnetic poles determined from each sampling location are shown with numbers labeling the stippled 95% confidence limits; 1 = alkalic intrusions, Arkansas (Globerman and Irving, 1988); 2 = lamprophyric dikes, Newfoundland (Prasad, 1981; Lapointe, 1979); 3 = alkalic intrusions, Quebec (Foster and Symons, 1979); 4 = Niobrara Formation, Kansas (Shive and Frerichs, 1974); the mean of these four poles is shown by the solid square with the surrounding lightly stippled 95% confidence region. Modified from Globerman and Irving (1988) with permission from the American Geophysical Union.

The mid-Cretaceous paleomagnetic pole for North America is located in northern Alaska. This pole is illustrated in Figure 10.4a in the usual fashion of plotting the paleomagnetic pole and continent of observation on a projection of the present geographic grid. Through the geocentric axial dipole hypothesis, we know that the mean paleomagnetic pole approximates the paleoposition of the rotation axis with respect to the continent from which the paleomagnetic pole was determined. We can produce a mid-Cretaceous paleogeographic map for North America by rotating the mid-Cretaceous paleomagnetic pole (and North America, to which that pole is rigidly attached) so that the paleomagnetic pole is positioned on the axis of the geographic grid. The resulting mid-Cretaceous *paleogeographic map* for North America is shown in Figure 10.4b. This map shows the distribution of paleolatitudes across North America and the azimuthal orientation of the continent with respect to paleomeridians. Because the time-averaged geomagnetic field is symmetric about the rotation axis, absolute values of paleolongitudes are arbitrary.

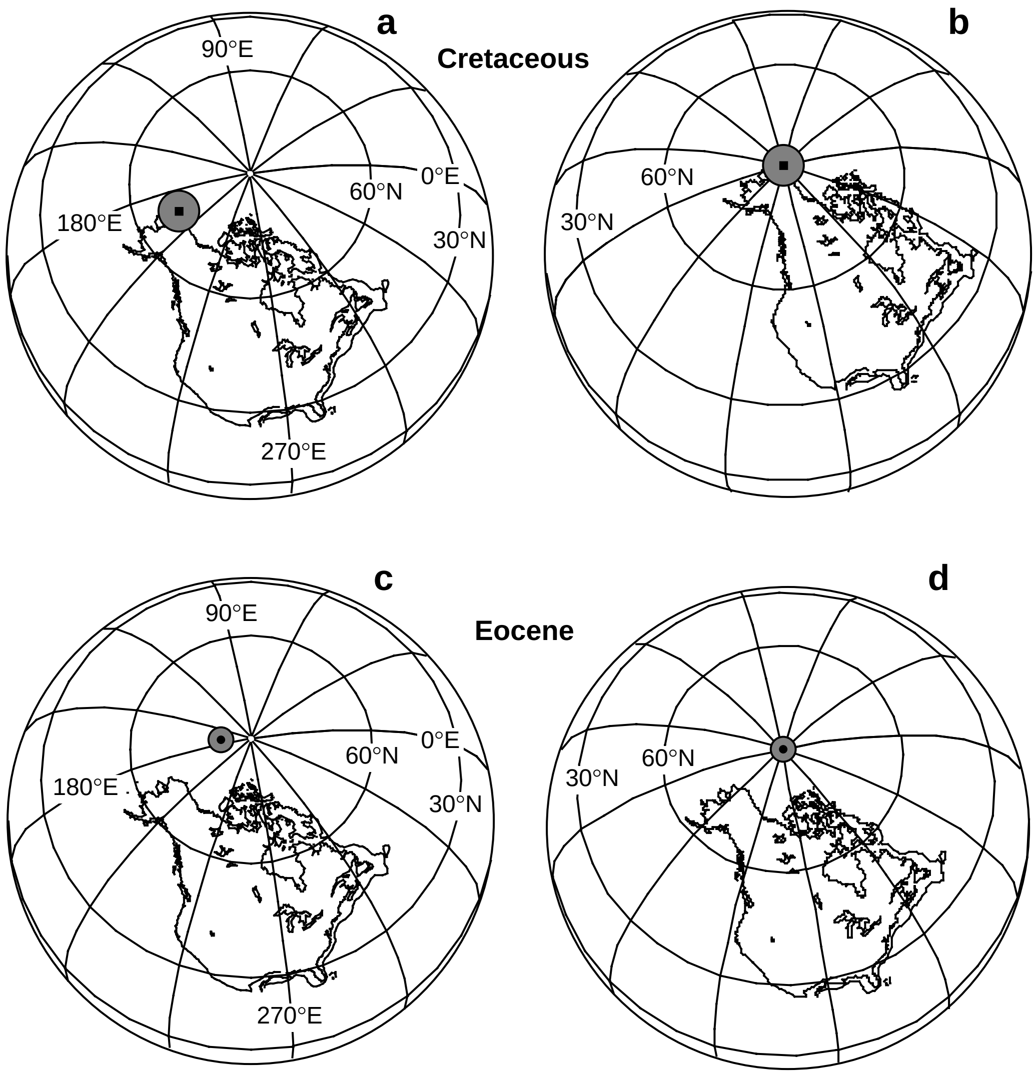

Figure 10.4 North American mid-Cretaceous and Eocene paleomagnetic poles and resulting paleogeographies. (**a**) Mid-Cretaceous paleomagnetic pole plotted on the present geographic grid; (**b**) mid-Cretaceous paleogeographic position of North America resulting from rotating the mid-Cretaceous paleomagnetic pole (and North America) so that the paleomagnetic pole coincides with the axis of the grid; (**c**) Eocene paleomagnetic pole of Diehl et al. (1983) plotted on the present geographic grid; (**d**) Eocene paleogeographic position of North America.

From the mid-Cretaceous paleogeographic map of Figure 10.4b, we see that locations in western North America were at higher northerly latitudes in the mid-Cretaceous than at present; locations in northeastern North America were at lower mid-Cretaceous latitudes than at present. And during the mid-Cretaceous, North America was clockwise rotated in comparison to its present azimuthal orientation.

The Eocene paleomagnetic pole for North America is shown in Figure 10.4c; the resulting Eocene paleogeographic map is shown in Figure 10.4d. By comparing the paleogeographic maps of Figures 10.4b and 10.4d, you can infer the motion of North America with respect to the rotation axis between mid-Cretaceous and Eocene times. The minimum motion involved counterclockwise rotation of North America about a pivot point located off the southeast coast of North America. Try to visualize how this motion accounts for the changing paleogeography. A basic feeling for continental motions indicated by paleomagnetic poles of that continent will prove immediately useful.

APPARENT POLAR WANDER PATHS

From the above presentation, we understand that sets of paleogeographic maps could be used to summarize paleomagnetic results from a particular continent. But this approach requires construction of a paleogeographic map for every geologic time increment and is cumbersome for large bodies of paleomagnetic data. A more effective approach is to develop an *apparent polar wander (APW) path* for the continent. This technique was introduced by Creer et al. (1954) and has become the standard method of presenting paleomagnetic data covering significant geologic time intervals.

Fundamentally, an APW path is a plot of the sequential positions of paleomagnetic poles from a particular continent, usually shown on the present geographic grid. We have plotted individual North American paleomagnetic poles in Chapter 7 (Figures 7.6 and 7.7) and in this chapter. To develop an APW path, a set of paleomagnetic poles of varying geologic age are presented in a single diagram. As we shall see, paleomagnetic poles for the Neogene are located near the present geographic pole, even for continents that are carried on fast-moving lithospheric plates. For older geologic times, paleomagnetic poles generally fall on a circuitous path leading away from the geographic pole.

Through the geocentric axial dipole hypothesis, an APW path represents the apparent motion of the rotation axis with respect to the continent of observation. Hence the name “apparent polar wander” path. When APW paths were first developed, it was thought that apparent polar wander was largely due to rotation of the whole Earth with respect to the rotation axis (which is fixed with respect to the stars). This whole-Earth rotation is known as *true polar wander*. We now understand that the major portion of apparent polar wander is due to lithospheric plate motions carrying continents over the Earth’s surface (e.g., continental drift).

Constructing APW paths

For continents that are currently in the northern hemisphere, it is convenient to plot the APW path as the sequence of paleomagnetic poles that track away from the north geographic pole. For southern hemisphere continents, the APW path is constructed as a sequence of paleomagnetic poles tracking away from the south geographic pole. Geomagnetic polarity reversals introduce a potential ambiguity in construction of an APW path. But this ambiguity is more apparent than real because the rate of geomagnetic reversals is rapid in comparison to plate motions.

VGPs determined from Cenozoic rocks of normal polarity will be close to the north geographic pole. But VGPs from reversed-polarity rocks will be close to the south geographic pole. For example, the North American Eocene paleomagnetic pole is located less than 10° from the present north geographic pole (Figure 10.4c). This is the position of the Eocene *north paleomagnetic pole*, and normal-polarity Eocene rocks will yield VGPs in this vicinity. Reversed-polarity Eocene rocks will yield VGPs near the south geographic pole. As discussed in Chapter 7, the usual convention (for northern hemisphere continents) is to determine the north paleomagnetic pole by averaging normal-polarity VGPs with the antipodes of reversed-polarity VGPs. For southern hemisphere continents, the convention is to determine the south paleomagnetic pole by averaging reversed-polarity VGPs with the antipodes of normal-polarity VGPs. When abundant paleomagnetic poles are available, the APW path can be unambiguously tracked going away from the present geographic pole. This is now the case for the major continents during Proterozoic and Phanerozoic times.

Methods of analyzing paleomagnetic data to construct APW paths have changed as more data have become available. When few paleomagnetic results were available, average poles were determined for each geologic time period. For example, when only four paleomagnetic poles were available from Jurassic rocks of North America, those poles were averaged to yield the Jurassic pole of the North American APW path (Irving and Park, 1972). As more paleomagnetic poles were determined, more details of APW could be determined by averaging poles within time intervals shorter than geologic time periods. A series of APW paths were produced by using versions of the *sliding-time-window* technique (Van Alstine and deBoer, 1978;

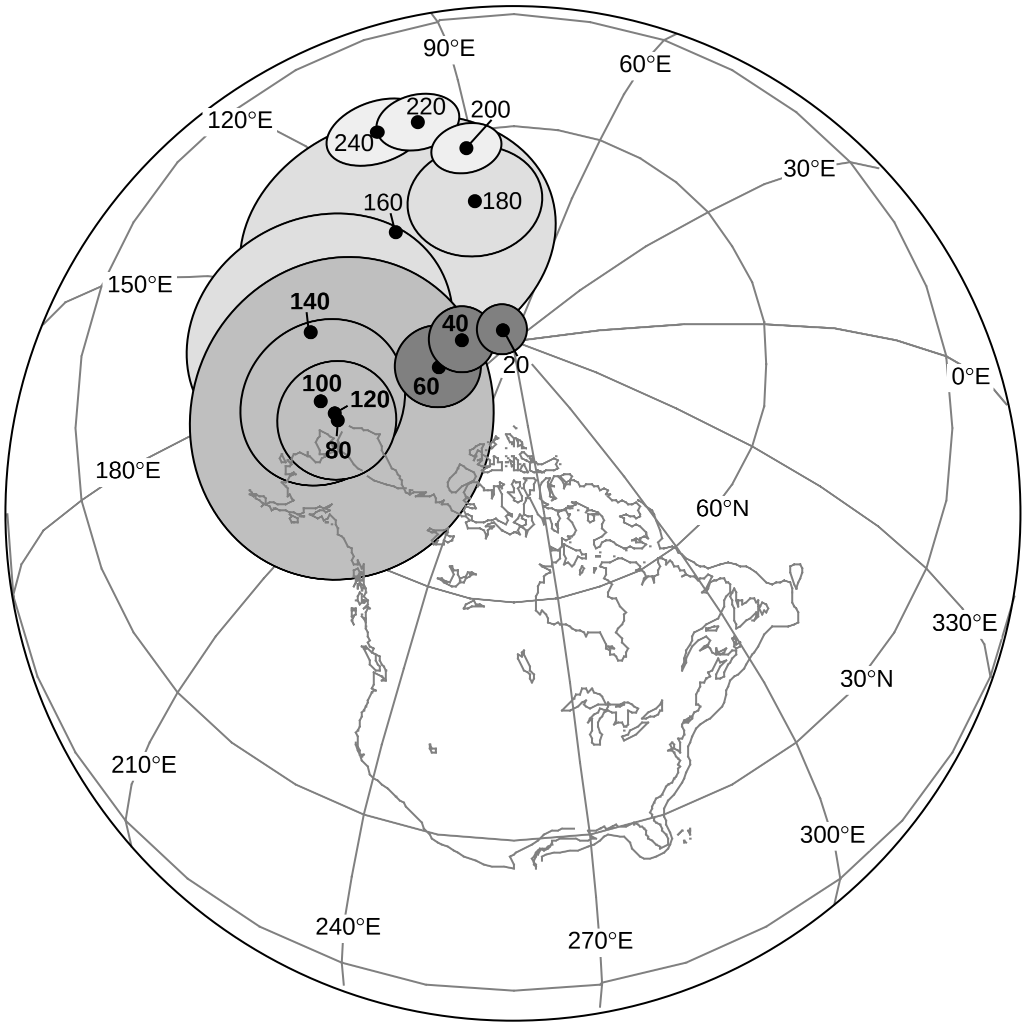

Figure 10.5 North American Mesozoic and Cenozoic apparent polar wander path of Irving and Irving (1982) using the sliding-time-window technique. Ages of mean paleomagnetic poles are labeled in Ma; the time window duration is 30 m.y.; 95% confidence limits are shown surrounding each mean pole.

Irving, 1979b; Harrison and Lindh, 1982; Irving and Irving, 1982). The Mesozoic and Cenozoic portion of the Irving and Irving (1982) North American APW path is shown in Figure 10.5.

The basic sliding-time-window technique is to (1) assign an absolute age to available paleomagnetic poles from a continent, (2) choose a duration (e.g., 30 m.y.) for the time window, and (3) average all paleomagnetic poles with ages falling within the time window centered on a particular absolute age. For example, the time window duration used to construct the APW path of Figure 10.5 was 30 m.y., so the average paleomagnetic pole for 200 Ma was determined from poles assigned absolute ages between 185 and 215 Ma. The sliding-time-window technique is effective in averaging out random noise and allowing the basic pattern of APW to be determined. But if systematic errors are present (e.g., unremoved present-field components of NRM), these errors are reinforced. Also, the sliding-time-window technique limits the detail with which the APW pattern can be determined; meaningful details of APW such as sharp corners in the APW path might not be recognizable in paths constructed by this technique.

Another approach is to construct the APW path from what are interpreted as the "most reliable" paleomagnetic poles, without applying time averaging. The paleomagnetic poles that are judged most reliable are generally those determined most recently by using more rigorous demagnetization analyses and larger data sets than were previously available. A Mesozoic and Cenozoic APW path for North America constructed in this fashion is shown in Figure 10.6. More rapid variations in the APW path, such as the sharp corner (or cu*sp*) in the Late Triassic–Early Jurassic interval, are resolved by this technique. The drawback is that the interpreted pattern of APW is strongly dependent on the accuracy of individual paleomagnetic poles. If some of these poles are inaccurate because of reasons not yet understood, the interpreted pattern of APW is obviously compromised.

Development of APW paths is a topic of active paleomagnetic research. As paleomagnetic techniques become more advanced and more rock units are investigated, older paleomagnetic poles are reevaluated and sometimes discarded. For example, Prévot and McWilliams (1989) have recently questioned the accuracy of the paleomagnetic poles determined from the Newark Trend intrusives (poles NT1 and NT2 of Figure 10.6), and the paleomagnetic pole from the Moenave Formation (pole MO of Figure 10.6) is a recent addition to the set of Mesozoic North American paleomagnetic poles.

The precision of APW paths varies from continent to continent because of differences in the quantity and quality of paleomagnetic data; the Phanerozoic APW path is much better determined for North America than for South America. For a particular continent, the precision of the APW path also depends on geologic age. Comparison of the APW paths of Figures 10.5 and 10.6 indicates that these paths are similar during the Triassic, Cretaceous, and Cenozoic but are different during the Jurassic. The primary reason for this difference is that, until recently, few North American Jurassic paleomagnetic poles were available. To complicate matters, the Jurassic appears to be a geologic time interval of rapid North American apparent polar wander. In evaluating tectonic interpretations that depend on APW paths, you must keep in mind that APW paths are well known for some geologic time intervals and poorly known for other intervals.

Paleomagnetic Euler poles

Some paleomagnetic researchers view apparent polar wander paths as a series of arcuate tracks separated by sharp corners called “cusps” (Gordon et al., 1984). The series of tracks and cusps for the Mesozoic APW path of North America is shown schematically at the top of Figure 10.6. Each track of APW is considered to result from the continent riding on a lithospheric plate that rotated about a fixed *Euler pole* for an extended interval of geologic time (say, 50 m.y.). Different tracks represent rotations about different Euler poles, and cusps represent times of reorganization of the lithospheric plate boundaries and resulting driving forces (Cox and Hart, 1986).

The basics of the *paleomagnetic Euler pole model* (PEP model) are presented in Figure 10.7, in which we consider a planet with only two lithospheric plates. Plate F is fixed, but Plate M is rotating counterclockwise about an Euler pole that is fixed with respect to the underlying mantle and the rotation axis. Transform faults separating the plates are on small circles (latitude circles) centered on the Euler pole. If a hotspot (fixed to the mantle) exists under Plate M, a seamount chain results, with seamounts on a small circle centered on the Euler pole. Paleomagnetic poles determined from young rocks on Plate M are located near the rotation axis. For older rocks, the paleomagnetic poles are located on an APW path, which also describes a small circle about the Euler pole. These paleomagnetic poles are points that were previously at the rotation axis and have subsequently been displaced by rotation of Plate M about the Euler pole.

In PEP analysis, an arcuate track of APW is used to determine the position of an Euler pole (paleomagnetic Euler pole) about which the continent rotated to produce that track of APW. The resulting paleomagnetic Euler pole is used to infer the motion and plate boundary configuration of former lithospheric plates that carried the continent. PEP analysis applied to continental APW paths is relatively new and somewhat controversial. Further refinement of APW paths is required to provide thorough evaluation of this model. The interested reader is referred to Gordon et al. (1984), May and Butler (1986), and Witte and Kent (1990) for further (pro and con) discussion of PEP analysis.

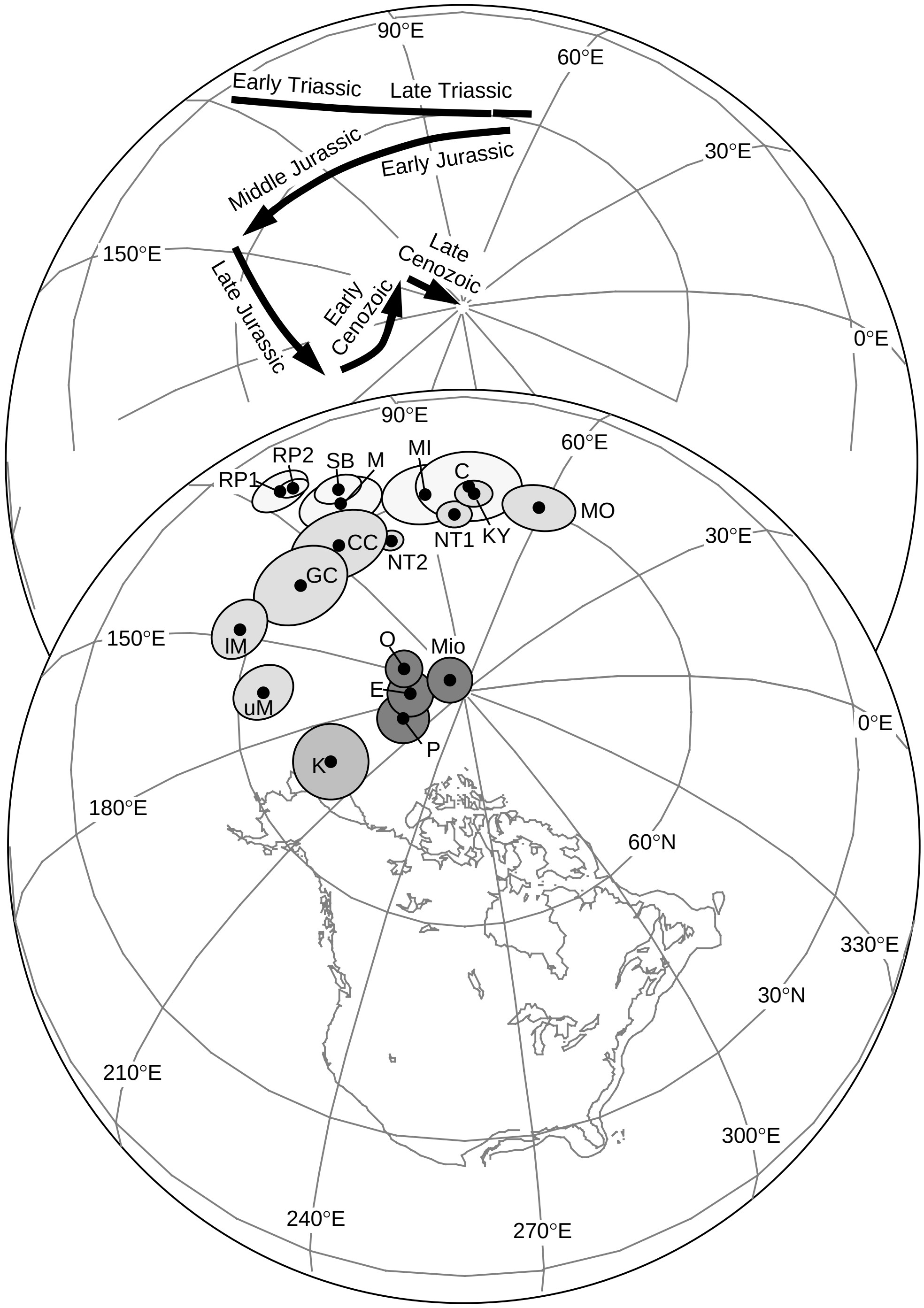

Figure 10.6 North American Mesozoic and Cenozoic apparent polar wander path based on compilation of the most reliable paleomagnetic poles. Stippled regions surrounding each pole are the 95% confidence limits; Triassic poles have the lightest stippling of confidence limits, while Jurassic, Cretaceous, and Cenozoic poles have progressively heavier stippling of confidence limits; Mio = Miocene (Hagstrum et al., 1987); O = Oligocene (Diehl et al., 1988); E = Eocene and P = Paleocene (Diehl et al., 1983); K = mid-Cretaceous (Globerman and Irving, 1988); uM and lM = upper and lower Morrison Fm, respectively; GC = Glance Conglomerate; CC = Corral Canyon; NT2 and NT1 = Newark trend group 2 and group 1 intrusives; KY = Kayenta Fm; MO = Moenave Fm; C = Chinle Fm; MI = Manicoagan impact structure; M = Moenkopi Fm; SB = State Bridge Fm; RP1 and RP2 = Red Peak Fm; for references to Jurassic and Triassic poles, see Ekstrand and Butler (1989); arc and cusp interpretation of the APW pattern is shown in the upper diagram.

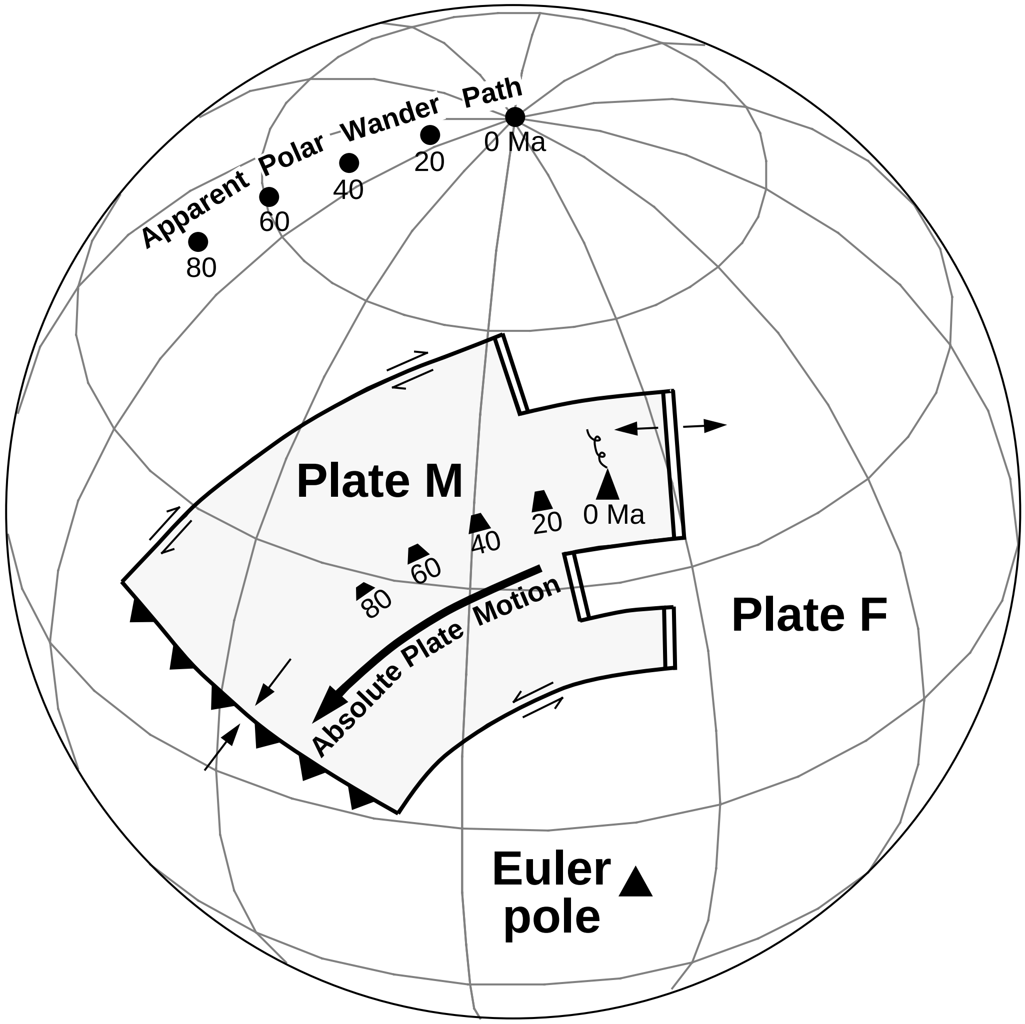

Figure 10.7 Paleomagnetic Euler pole model of apparent polar wander paths. The geographic grid is shown centered on the present rotation axis; Plate F is fixed, while Plate M is rotating about an Euler pole that is fixed in position (with respect to Plate F and the underlying mantle); the direction of absolute motion of Plate M is shown by the bold arrow; directions of relative plate motion along plate boundaries are shown by small arrows; ridge boundaries are shown by double lines; transform fault boundaries are shown by single lines; the convergent plate boundary is shown by the thrust fault symbol with teeth on the overriding plate; a hotspot under the active seamount labeled 0 Ma is fixed to the mantle and produces a seamount chain (hotspot track) with ages indicated; the recent paleomagnetic pole for Plate M is located at the rotation axis, while older paleomagnetic poles fall on the APW path with ages of poles indicated; the APW path, transform faults, and hotspot track all lie on circles of latitude (small circles) centered on the Euler pole. Modified from Gordon et al. (1984) with permission from the American Geophysical Union.

PALEOGEOGRAPHIC RECONSTRUCTIONS OF THE CONTINENTS

The basic confirmation of Wegener's continental drift theory by paleomagnetic research in the late 1950s and early 1960s is clearly a major contribution of paleomagnetism to Earth science (Irving, 1988). This early success of paleomagnetism in paleogeographic reconstruction of the continents is sometimes mistaken to indicate that fundamental Mesozoic and Paleozoic paleogeography is well established and of little current interest. Nothing could be further from the truth. Global paleogeography is an active and exciting (if sometimes mind-boggling) Earth science discipline.

Paleomagnetism is properly viewed as one of several tools in paleogeographic research. Paleoclimatology, paleobiogeography and especially geology are important contributors. In paleogeography, we are faced with the formidable challenge of mapping the Earth in time by fitting available evidence together into a coherent picture. The status of current knowledge was elegantly summarized by Scotese and McKerrow (1990) in a discussion of currently available Paleozoic paleogeographic maps. They stated that "the maps we present here are similar in their precision to the maps of Asia and the New World produced by 16th Century explorers. In the 500 years since the voyages of these early discoverers, we have mapped the Earth 'in space.' We are now embarking on a voyage to map the Earth 'in time.'"

In this section, we first introduce basic principles of applying paleomagnetism to paleogeographic reconstructions. Then the example of North America–Europe reconstruction is used to illustrate a comparatively well-understood example. We then proceed to the reconstruction of Pangea with discussions of alternative reconstructions and timing of formation and dispersal of the supercontinent. To show the rapid evolution of paleogeographic research and the important implications thereof, this section is concluded with an introduction to the current debate about the Paleozoic drift history of Gondwana.

Some general principles

Matching of APW paths of continents is the fundamental paleomagnetic method of proposing and testing past relative positions. For example, any viable paleogeographic reconstruction of Africa and North America for the Permian must result in agreement of the Permian paleomagnetic poles from Africa and North America; these poles must coincide within the uncertainties involved in their determination. This principle is simply a corollary of the GAD hypothesis. A paleomagnetic pole provides the past position of the rotation axis with respect to the continent of observation. There can be only one rotation axis at any particular geologic time. So if two continents are placed in their proper relative positions for a particular geologic time, their paleomagnetic poles for that time must coincide. Furthermore, if these continents had a fixed relative position for a significant interval of geologic time, their paleomagnetic poles during that entire time interval (APW paths) must coincide.

Figure 10.8 presents a hypothetical example to illustrate how matching of APW paths can be used in paleogeographic reconstruction. As detailed in the figure caption, if two continents drift together with respect to the rotation axis prior to undergoing separate drift histories, the portions of their APW paths recording the common drift history can be matched to produce a paleogeographic reconstruction. In this hypothetical example, paleomagnetic poles of perfect accuracy are recorded by rocks of the two continents at set increments of geologic time. With these idealized conditions, any latitudinal motion of the continents during their common drift history results in APW paths that can be matched to yield a unique paleogeographic reconstruction. Such a reconstruction would be ambiguous only if the common drift of the two continents were purely longitudinal, with no resulting common path of APW.

The obvious complication in practice is that APW paths of continents are determined with at best limited precision; the Paleozoic APW paths of some continents are in fact known in only a rudimentary fashion. So from APW paths that are vastly more complex and uncertain than those of Figure 10.8, we must propose and test paleogeographic reconstructions. Inferences drawn from comparisons of continental APW paths also must be balanced against available paleobiogeographic, geologic, and paleoclimatic data.

Knowledge of APW paths in general deteriorates with age, as does the clarity of other forms of paleogeographic data. For Cretaceous and Cenozoic time, a vast array of marine geological and geophysical data are available for reconstruction of ocean basins. These data allow detailed reconstruction of many ocean basins during this time interval. But for geologic times older than Cretaceous, few pieces of former oceanic lithospheric plates are preserved, and this source of paleogeographic information is very limited. Morel and Irving (1978) thus recognized three categories of paleogeographic maps: "Those for the early Jurassic onwards which have reasonably sound basis; those for the Carboniferous, Permian, and Triassic that are less reliable; and those for earlier times with errors of uncertain magnitude."

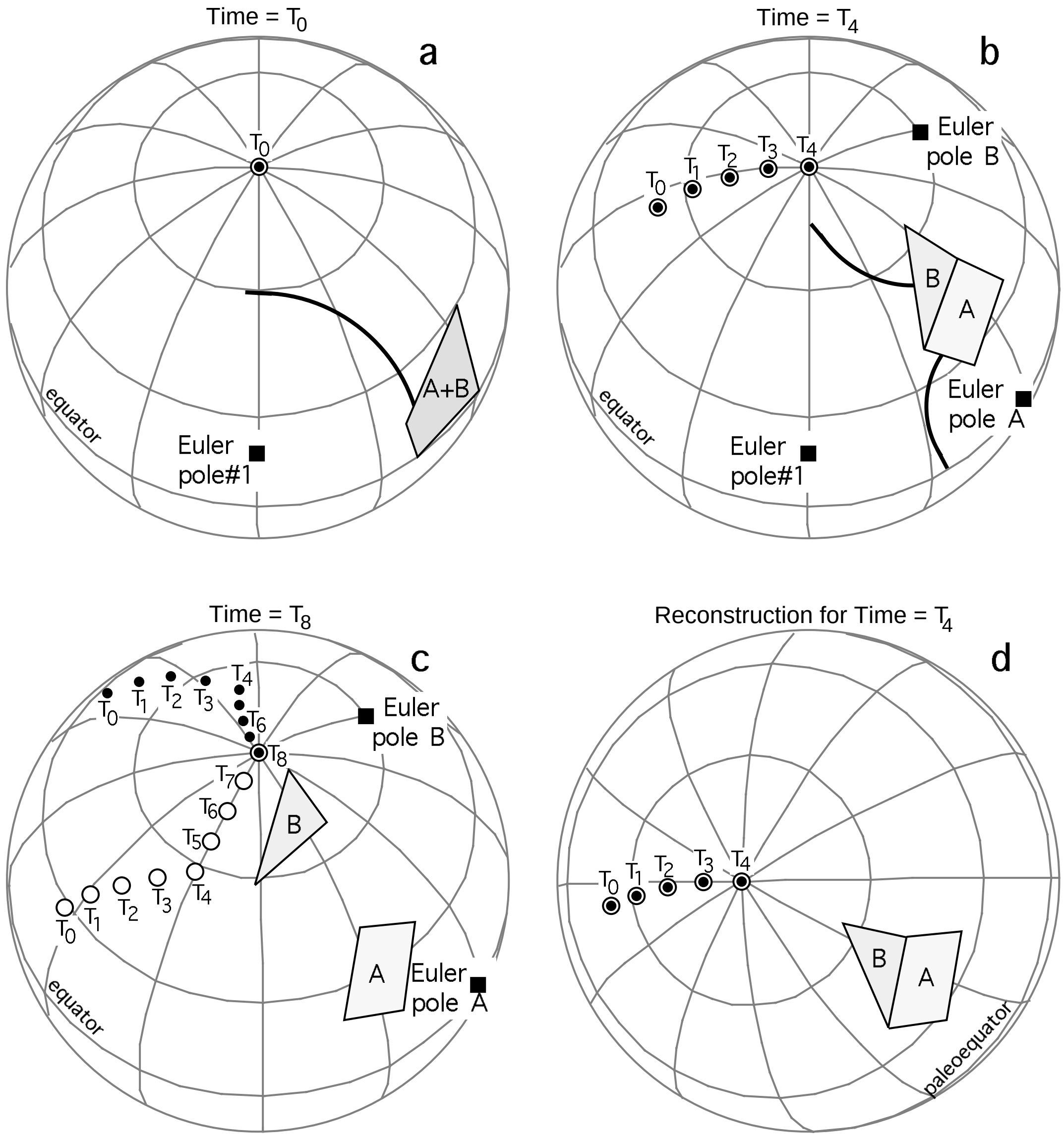

Figure 10.8 Paleogeographic reconstruction from apparent polar wander paths. (**a**) Continents A and B were joined together at geologic time T_0; the paleomagnetic pole for rocks of age T_0 on continents A and B records the position of the rotation axis; during the time interval from T_0 to T_4, the continents rotate about Euler pole #1 at a rate of 10° per time unit (e.g., T_1 to T_0 = one time unit). (**b**) The APW paths for continents A and B have recorded the past positions of the rotation axis during the interval T_0 to T_4; these APW paths are rotated along with continents A and B during subsequent rotations; at geologic time T_4, continents A and B rift apart; continent A begins to rotate about Euler pole A (rate = 10°/time unit), and continent B begins to rotate about Euler pole B (rate = 8°/time unit). (**c**) At geologic time T_8 (present), continent A has the APW path indicated by the open circles while continent B has the APW path indicated by the solid circles; the form of the APW paths during the T_0 through T_4 interval and the geometric relationships between the APW paths and the continents to which they belong are the same as at time T_4. (**d**) Paleogeographic reconstruction for time T_4; continent A was fixed in position, and continent B was rotated until the APW paths of continents A and B overlapped during the T_0 to T_4 interval; the axis of the geographic grid was then placed on paleomagnetic pole T_4 to produce paleolatitude lines for time T_4; the absolute values of the longitude lines are indeterminate; note that the relative placements and paleolatitudes of continents A and B are the same in (**b**) and (**d**). Modified from Graham et al. (1964) with permission from the American Geophysical Union.

Europe–North America reconstruction

Comparison of APW paths for North America and Europe provided the initial paleomagnetic confirmation of continental drift (Irving, 1956; Runcorn, 1956); paleomagnetic poles from Paleozoic and Mesozoic rocks of Europe were systematically displaced eastward from poles determined from rocks of North America. Over the past 30 years, there has been a vast increase in the quantity and quality of paleomagnetic data from North America, Greenland, and Europe. Besides securely confirming the necessity of continental drift between these continents, the data now permit detailed tests of alternative paleogeographic reconstructions prior to Cretaceous and younger opening of the North Atlantic. Van der Voo (1990) has provided a detailed analysis of this problem, and the results are summarized in Figure 10.9.

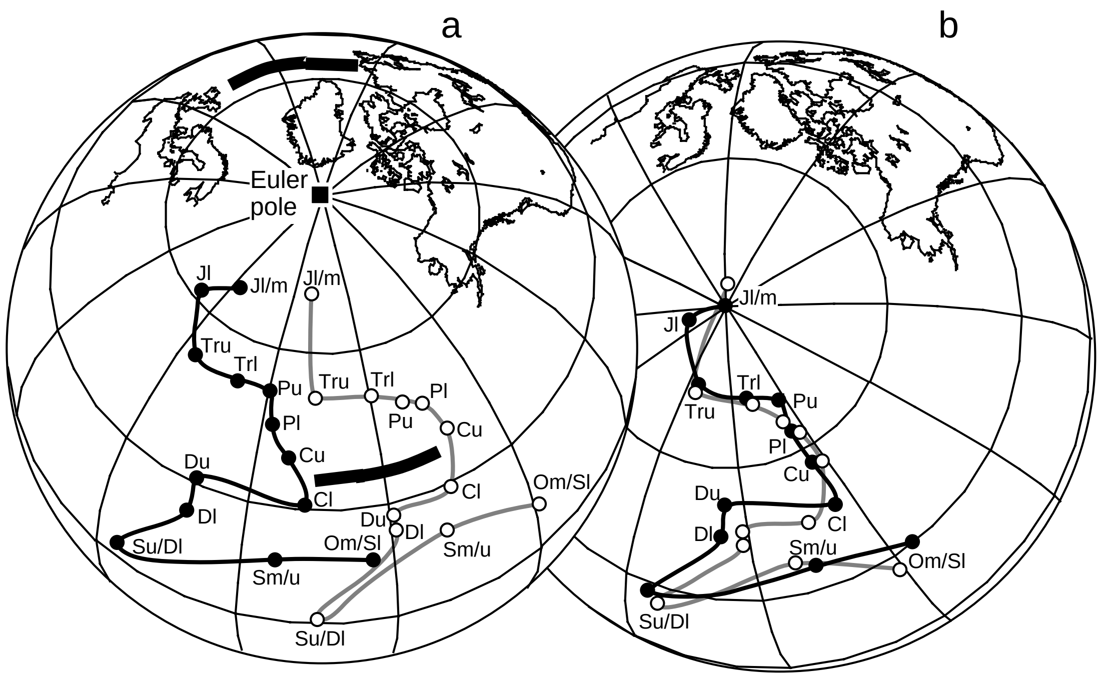

Figure 10.9 (**a**) Paleozoic and Mesozoic APW paths of North America and Europe. North American poles are shown by solid circles; European poles are shown by open circles; the Euler pole of Bullard et al. (1965) for reconstruction of the North Atlantic prior to Cretaceous and Cenozoic opening is shown by the solid square; the Euler pole location is 88.5°N, 27.7°E; in (**b**), Europe is rotated 38° clockwise about the Euler pole toward a fixed North America (upper bold arrow); during this rotation, the European APW path also rotates clockwise about the Euler pole (lower bold arrow). (**b**) Middle Jurassic paleogeographic reconstruction of North America and Europe; O = Ordovician; S = Silurian; D = Devonian; C = Carboniferous; P = Permian; Tr = Triassic; J = Jurassic; l = lower; m = middle; u = upper. Modified from Van der Voo (1990) with permission from the American Geophysical Union.

Van der Voo (1990) compiled and evaluated Phanerozoic paleomagnetic results from Europe and North America (including Greenland). Using paleomagnetic data from appropriate parts of Europe and avoiding poles obtained from major orogenic zones, Van der Voo compiled paleomagnetic poles that can reasonably allow construction of APW paths for the continental interiors. Only results based on testing of paleomagnetic stability through demagnetization experiments were considered. Van der Voo used a checklist of reliability criteria to assign a “quality index” to each paleomagnetic pole. This quality index considered availability and results of fold or conglomerate tests, the reversals test, and other paleomagnetic stability indicators. For Middle Ordovician through Early Jurassic, 111 North American and 110 European paleomagnetic poles satisfied reasonable quality control.

From the selected paleomagnetic poles, mean poles for time intervals of ~25-m.y. duration were determined, and APW paths for Europe and North America were drawn by connecting these mean poles (Figure 10.9a). These APW paths were then used to test Euler pole rotations that had been proposed in alternative paleogeographic reconstructions of North America and Europe. Each Euler pole rotation was applied to the European APW path, and the resulting fit with the North American APW path was examined. The rotation that minimized the misfit between the two APW paths is that proposed by Bullard et al. (1965). The resulting Middle Jurassic paleogeographic reconstruction is shown in Figure 10.9b, in which the agreement of the European and North American APW paths is indeed quite striking.

Two principles of paleomagnetic applications to paleogeography are nicely illustrated by this example:

1. Note that the motion of North America and Europe during opening of the North Atlantic was almost purely longitudinal. A purely longitudinal motion of a continent results in no APW during that geologic time interval. Nevertheless, relative longitudinal motion between two continents can be detected if those continents experienced significant latitudinal motion prior to separation.
2. The fidelity of paleogeographic reconstructions from paleomagnetism depends on the length and clarity of the APW paths that must be matched. The extended Paleozoic through Early Mesozoic drift history of La*urasia* (North America, Greenland, Europe, and parts of Asia) resulted in long, sinuous APW paths for North America and Europe. So the common drift history of these two continents has provided APW paths that allow accurate tests of paleogeographic reconstructions. For continents with drift histories providing short common segments of APW, tests of paleogeography from paleomagnetism will be much less effective.

Pangea reconstructions

The supercontinent *Pangea* is generally considered to have existed from the Carboniferous through the Triassic. Subsequent Late Mesozoic–Cenozoic Earth history is dominated by lithospheric plate motions resulting from the dispersal of Pangea. The elements of Pangea are the northern supercontinent *Laurasia* and the southern supercontinent *Gondwana*, which are joined by closing the Atlantic Ocean (Figure 10.10).

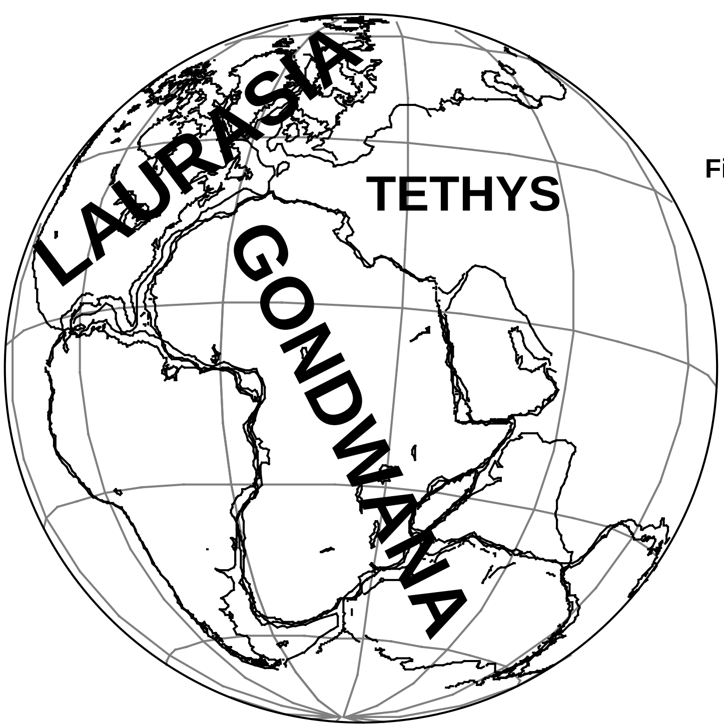

Figure 10.10 Late Triassic reconstruction of Pangea. Northern continents (North America, Greenland, Europe, and parts of present-day Asia) are grouped into the supercontinent Laurasia; southern continents (South America, Africa with Arabia and Madagascar, India, East Antarctica, and Australia) are grouped into supercontinent Gondwana; northeast Gondwana and southeast Laurasia are separated by the Tethys Ocean.

Laurasia and Gondwana are separated on their eastern sides by the intervening Tethys Ocean. The observation that this puzzle of continents could be reconstructed by closing the Atlantic and Indian Oceans was the basis of Wegener's (1924) postulation of continental drift. DuToit (1937) then developed a variety of geological arguments for the existence and configuration of Gondwana. Determining the time and space assembly of Gondwana and Laurasia to form Pangea is perhaps the major challenge of Phanerozoic paleogeography. Only the major features of the Pangean puzzle can be presented here, and even these basic features must be painted with a rather broad brush. Nevertheless, this summary will provide some appreciation for the fundamentals of Phanerozoic paleogeography and the role of paleomagnetism in that discipline.

The continents making up Gondwana were probably assembled by Middle Cambrian time (Piper, 1987). Paleomagnetic tests of alternative reconstructions of Gondwana have been discussed by Irving and Irving (1982). The reconstruction shown in Figure 10.10 is that of DuToit (1937), which was quantified by Smith and Hallam (1970). The major differences between alternative reconstructions are the relative placements of West Gondwana (South America and Africa) and East Gondwana (Antarctica, Australia, and India).

A perceived problem with DuToit's Gondwana was the resulting overlap of the Antarctic Peninsula with the Falkland Plateau (southeastern portion of the South American continental crust). To avoid this problem, several alternative reconstructions were proposed in which East Gondwana was displaced southward so that the Antarctic Peninsula was placed on the western side of southern South America. Irving and Irving (1982) showed that the paleomagnetic data from the Gondwana continents are in better agreement with the DuToit reconstruction than with the alternative fits. The "Antarctic Peninsula problem" is now understood to be more apparent than real; the present Antarctic Peninsula was constructed in part from continental fragments that were assembled after the initial breakup of Gondwana.

By comparison with the simple existence of Gondwana as a supercontinent from essentially the beginning of the Paleozoic, the assembly of Laurasia is complex and much less well understood. At the beginning of the Phanerozoic, there were four major Precambrian "cratonic nuclei": Gondwana, Laurentia, Baltica, and Siberia (Ziegler et al., 1979). Laurentia is North America and Greenland along with the northern portion of the British Isles. Baltica is the interior portion of northeastern Europe. The Siberia cratonic nucleus is the region of the present-day Central Siberian Plateau.

Baltica and Laurentia were joined together by mid-Paleozoic time. In turn, Siberia joined Baltica before the end of the Permian, thus amalgamating the major elements of Laurasia. The fundamental assembly of Pangea occurred during the Carboniferous. Beyond this simplest possible presentation of major events, detailed descriptions of continental distributions, motions, collisions, and resulting orogenies are quite complex and beyond the scope of this treatment. A major source for state-of-the-art Paleozoic paleogeography is McKerrow and Scotese (1990). Kent and May (1987) provide an incisive summary of recent paleomagnetic data; particularly noteworthy are data indicating that major crustal blocks of China were not in place adjacent to Siberia until after the Permian.

While it is generally agreed that Pangea was assembled in the Carboniferous, the exact configuration of the constituent continents is less clear (see the discussion by Kent and May, 1987). The configuration proposed by Wegener (1924) is called *Pangea A* and is generally thought to apply for the Early Jurassic, prior to breakup of the supercontinent. However, the configuration of Pangea for earlier times is a matter of debate.

Van der Voo and French (1974) proposed that Permian and Early Triassic paleomagnetic poles for Gondwana and Laurasia are best grouped by rotating Gondwana ~20° clockwise from the Pangea A fit to produce *Pangea A2*. (The reconstruction in Figure 10.10 is a compromise configuration intermediate between Pangea A and Pangea A2.) In the Pangea A2 fit, northwestern South America is fit tightly into the Gulf of Mexico.

A larger (~35°) clockwise rotation of Gondwana with respect to Laurasia was proposed by Irving (1977) and Morel and Irving (1981). This *Pangea B* reconstruction placed northwestern South America adjacent to eastern North America. Morel and Irving proposed that Pangea B existed during the latest Carboniferous through Early Permian. Then during Late Permian and Triassic, counterclockwise rotation of Gondwana led to the Pangea A configuration. However, the Pangea B configuration has not been favored in more recent analyses of the paleomagnetic data (Livermore et al., 1986; Ballard et al., 1986) and is considered at odds with geological and paleobiogeographic data (Hallam, 1983). The most likely scenario is an initial Carboniferous and Permian Pangea A2 configuration that evolves to the Pangea A configuration by Late Triassic (Livermore et al., 1986).

It is evident that more paleomagnetic data and other forms of paleogeographic data are required for a clearer picture of the evolution of Laurasia and Pangea. From this discussion, you should take two general observations:

1. Paleozoic and Mesozoic paleogeography is a vital and active earth science discipline that depends heavily on paleomagnetic observations. Current research will no doubt lead to exciting new realizations about the assembly and evolution of the continents.

2. While many details are different from those presented by the early champions of continental drift, Wegener and DuToit had extraordinary insight into fundamental paleogeography.

Paleozoic drift of Gondwana

The existence of Gondwana as a supercontinent from the Early Paleozoic through the Early Mesozoic is substantiated by a variety of geologic, paleontologic, and paleomagnetic data. But the drift history, latitudinal positions, and possible collisions of Gondwana with the northern continents are matters of widely differing interpretations and much interest. We conclude our examination of global paleogeography with an introduction to the current debate concerning the mid-Paleozoic drift history of Gondwana.

Figure 10.11a shows two alternative interpretations of the APW path for Gondwana from the Ordovician to the Carboniferous. An Ordovician paleomagnetic pole position in the present-day Sahara Desert region of northwest Africa has been known for some time (McElhinny, 1973). The implied location of northern Africa at the south pole in the Ordovician is confirmed by Late Ordovician glaciation of northern Africa (Caputo and Crowell, 1985). Carboniferous and Permian paleomagnetic poles for Gondwana are located in or near southern Africa, consistent with widespread Late Paleozoic glaciation of southern Gondwana. A major difficulty in constructing a Paleozoic APW path for Gondwana occurs for the mid-Paleozoic. Where is the Silurian paleomagnetic pole for Gondwana?

Until recently, the only Silurian paleomagnetic poles from the Gondwana continents were determined from rocks of the Tasman foldbelt in southeast Australia. These poles fall near southwest South America. But McElhinny and Embleton (1974) suggested that southeast Australia did not accrete to Australia until the Late Paleozoic. So it is unclear whether mid-Paleozoic poles from southeast Australia should be used to construct the Gondwana APW path. This ambiguity led to discussions of alternative mid-Paleozoic Gondwana APW paths (Schmidt and Morris, 1977; Morel and Irving, 1978). The conservative view was to interpolate between the Ordovician pole in northern Africa and the Carboniferous pole in southern Africa, thus producing an APW path that simply tracks across Africa during the Paleozoic. This option is the dashed line of Figure 10.11a. The alternative view was to argue that the Silurian poles from southeast Australia do pertain to Gondwana. In this option, there is a large loop of APW from northwest Africa in the Ordovician to southwest South America in the Silurian and then back to Africa. This path is shown by the solid line in Figure 10.11a.

Recently, Hargraves et al. (1987) have obtained paleomagnetic data from Silurian intrusive rocks of cratonic Africa (Niger). The resulting paleomagnetic pole is located in southern South America. Hurley and Van der Voo (1987) determined a Late Devonian paleomagnetic pole from rocks in cratonic western Australia. This Late Devonian pole falls in central Africa. These two mid-Paleozoic poles lend considerable support to the interpretation that the Paleozoic APW path for Gondwana includes a large mid-Paleozoic loop. This APW path for Gondwana must still be considered controversial because it is based on only a few paleomagnetic studies. However the possible implications are major.

Van der Voo (1988) has explored the paleogeographic and tectonic implications of the mid-Paleozoic loop in the Gondwana APW path. The major features are shown in the reconstructions of Figure 10.11.

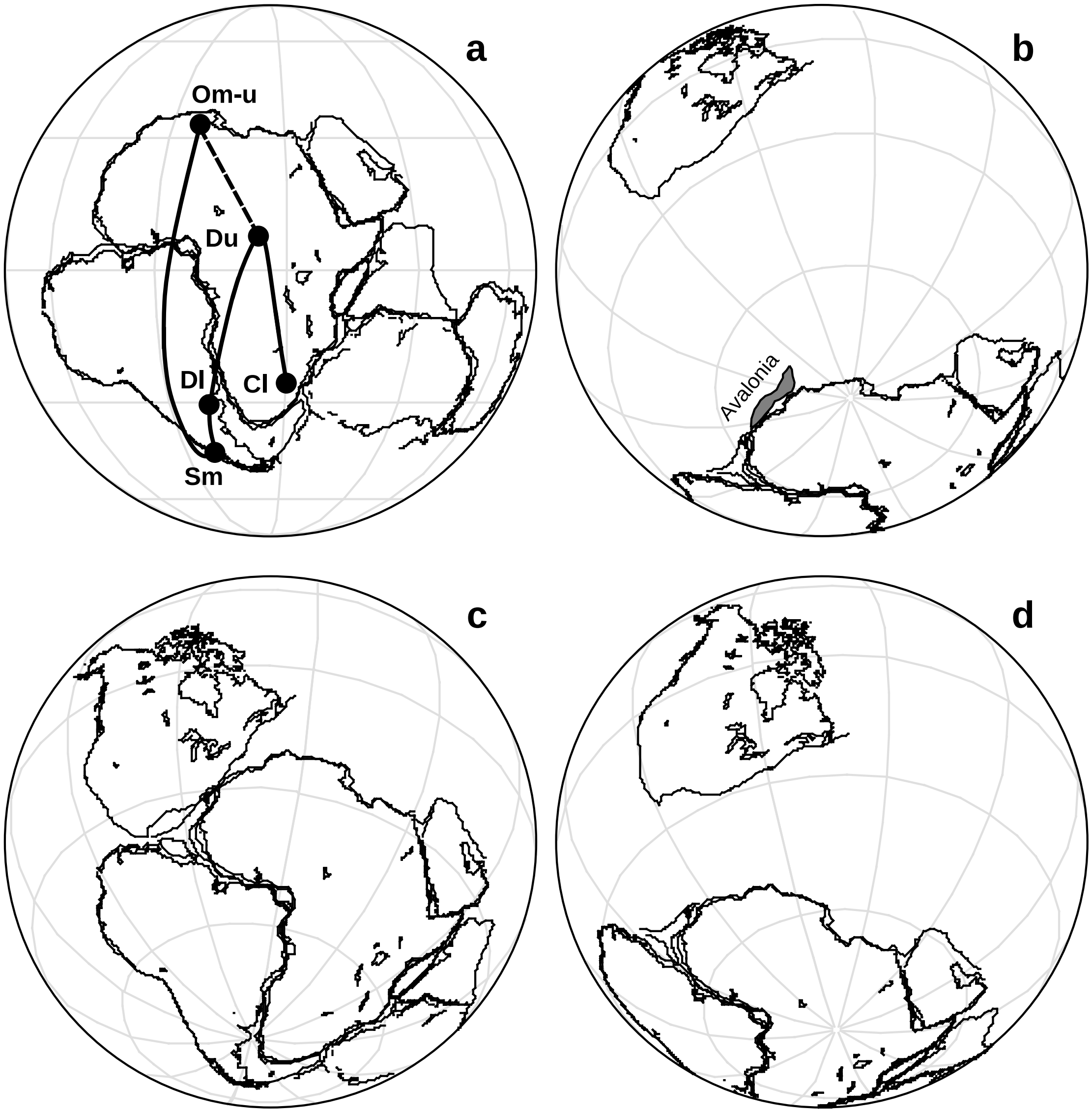

Figure 10.11 Paleozoic APW paths and paleogeographies for Gondwana. (**a**) The APW path shown by the bold curve contains a loop in the Silurian through Early Devonian; "traditional" interpolation of the Silurian through Early Devonian portion of the APW path is shown by the dashed line; the paleomagnetic south poles are plotted on the present geographic grid fixed to Africa; labels on paleomagnetic poles are as in Figure 10.9. (**b**) Ordovician paleogeography of Gondwana and North America; the Avalon terrane is adjacent to northwest Africa; the paleogeographic grid is centered on the Gondwana paleomagnetic pole. (**c**) Early Devonian paleogeography of Gondwana and North America; northern Africa has moved rapidly north into subtropical to equatorial paleolatitudes during latest Ordovician–Early Silurian; the Africa–North America collision causes the Acadian orogeny and transfers the Avalon terrane to North America; the paleogeographic grid is centered on the Early Devonian paleomagnetic pole for Gondwana. (**d**) Late Devonian paleogeography of Gondwana and North America; during the Devonian, a medium-width ocean opens between North America and northern Gondwana; the paleogeographic grid is centered on the Late Devonian paleomagnetic pole for Gondwana. Modified from Van der Voo (1988) with permission from the Geological Society of America.

Throughout the Early Paleozoic, North America is in equatorial paleolatitudes. In the Ordovician, northwest Africa is situated at the south pole with Gondwana and North America separated by a wide ocean. Several terranes that later become parts of the northern continents are thought to have been adjacent to northern Gondwana during the Early Paleozoic. These terranes include the Avalon terrane (now part of the Appalachians) and the Armorica terrane (portions of southern Europe). The position of the Avalon terrane adjacent to northwest Africa in the Ordovician is shown schematically in Figure 10.11b.

The loop in the Paleozoic APW path of Gondwana implies that Gondwana moved rapidly northward during latest Ordovician-Early Silurian time. The resulting Early Devonian paleogeography of Gondwana and North America is shown in Figure 10.11c. This northward motion of Gondwana allows the possibility that northwest Africa was adjacent to eastern North America in the Early Devonian. Thus the Africa-North America collision might have caused the Caledonian-Acadian orogeny and transferred the Avalon and Armorica terranes to North America. During the Devonian, a medium-width ocean opened between North America and northern Gondwana with the resulting Late Devonian paleogeography shown in Figure 10.11d. This new ocean closed during the Carboniferous with the collision of Gondwana and Laurasia, producing the Hercynian-Alleghanian orogenies and forming Pangea.

Scotese and Barrett (1990) have argued against portions of the motion history of Gondwana implied by the mid-Paleozoic loop in the APW path. They agree that the Gondwana paleomagnetic pole moves to southern South America in the Silurian, but they do not accept a central Africa position for the Late Devonian pole. Instead, they favor a progression of the Gondwana APW path from southern South America in the Silurian to southern Africa in the Early Carboniferous. The Scotese and Barrett (1990) interpretation accepts the rapid northward motion of Gondwana during the latest Ordovician–Early Silurian but does not accept the subsequent southward Devonian motion outlined above. The implications of these alternative drift histories for Gondwana are of great importance to Paleozoic paleogeography and tectonics. It will be interesting to see what new data, arguments, and interpretations are offered in the coming years.

REFERENCES

M. Ballard, R. Van der Voo, and I. W. Haelbich, Remagnetizations in Late Permian and Early Triassic rocks from southern Africa and their implications for Pangea reconstructions, *Earth Planet. Sci. Lett.*, v. 79, 412–418, 1986.

J. C. Briden, Paleoclimatic evidence of a geocentric axial dipole field, In: *The History of the Earth's Crust*, ed. R. A. Phinney, Princeton University Press, Princeton, N. J., pp. 178–194, 1968.

J. C. Briden, Palaeolatitude distribution of precipitated sediments, In: *Palaeogeophysics*, ed. S. K. Runcorn, Academic Press, New York, pp. 437–444, 1970.

J. C. Briden and E. Irving, Palaeoclimatic spectra of sedimentary palaeoclimatic indicators, In: *Problems in Palaeoclimatology*, ed. A. E. M. Nairn, Interscience, New York, pp. 199–250, 1964.

E. C. Bullard, J. E. Everett, and A. G. Smith, A symposium on continental drift. IV. The fit of the continents around the Atlantic, *Phil. Trans. Roy. Soc. London*, v. A258, 41–51, 1965.

M. V. Caputo and J. C. Crowell, Migration of glacial centers across Gondwana during the Phanerozoic Era, *Geol. Soc. Amer. Bull.*, v. 96, 1020–1036, 1985.

D. E. Champion, Holocene geomagnetic secular variation in the western United States: Implications for the global geomagnetic field, *U.S. Geol. Surv. Open File Rep. 80-824*, p. 314, 1980.

D. H. Coupland and R. Van der Voo, Long-term nondipole components in the geomagnetic field during the last 130 m.y., *J. Geophys Res.*, v. 85, 3529–3548, 1980.

A. Cox, Frequency of geomagnetic reversals and the symmetry of the nondipole field, *Rev. Geophys.*, v. 13, 35–51, 1975.

A. V. Cox and R. B. Hart, *Plate Tectonics: How It Works*, Blackwell Scientific Publications, Palo Alto, Calif., 392 pp., 1986.

K. M. Creer, E. Irving, and S. K. Runcorn, The direction of the geomagnetic field in remote epochs in Great Britain, *J. Geomagn. Geoelectr.*, v. 6, 163–168, 1954.

J. F. Diehl, M. E. Beck, Jr., S. Beske-Diehl, D. Jacobson, and B. C. Hearn, Paleomagnetism of the Late Cretaceous–Early Tertiary north-central Montana alkalic province, *J. Geophys. Res.*, v. 88, 10,593–10,609, 1983.

J. Diehl, K. M. McClannahan, and T. J. Bornhorst, Paleomagnetic results from the Mogollon–Datil volcanic field, southwestern New Mexico, and a refined mid-Tertiary reference pole for North America, *J. Geophys. Res.*, v. 93, 4869–4879, 1988.

G. E. Drewry, A. T. S. Ramsay, and A. G. Smith, Climatically controlled sediments, the geomagnetic field, and trade wind belts in Phanerozoic time, *J. Geol.*, v. 82, 531–553, 1974.

A. L. DuToit, *Our Wandering Continents*, Oliver and Boyd, Edinburgh, 336 pp., 1937.

E. J. Ekstrand and R. F. Butler, Paleomagnetism of the Moenave Formation: Implications for the Mesozoic North American apparent polar wander path, *Geology*, v. 17, 245–248, 1989.

M. E. Evans, Test of the dipolar nature of the geomagnetic field throughout Phanerozoic time, *Nature*, v. 262, 676, 1976.

J. Foster and D. T. A. Symons, Defining a paleomagnetic polarity pattern in the Monteregian intrusives, *Can. J. Earth Sci.*, v. 16, 1716–1725, 1979.

B. R. Globerman and E. Irving, Mid-Cretaceous paleomagnetic reference field for North America: Restudy of 100 Ma intrusive rocks from Arkansas, *J. Geophys Res.*, v. 93, 11,721–11,733, 1988.

R. G. Gordon, A. Cox, and S. O'Hare, Paleomagnetic Euler poles and the apparent polar wander and absolute motion of North America since the Carboniferous, *Tectonics*, v. 3, 499–537, 1984.

K. W. T. Graham, C. E. Helsley, and A. L. Hales, Determination of the relative positions of continents from paleomagnetic data, *J. Geophys Res.*, v. 69, 3895–3900, 1964.

J. T. Hagstrum, M. G. Sawlan, B. P. Hausback, J. G. Smith, and C. S. Grommé, Miocene paleomagnetism and tectonic setting of the Baja California Peninsula, Mexico, *J. Geophys. Res.*, v. 92, 2627–2639, 1987.

A. Hallam, Supposed Permo–Triassic megashear between Laurasia and Gondwana, *Nature*, v. 301, 499–502, 1983.

R. B. Hargraves, E. M. Dawson, and F. B. Van Houten, Palaeomagnetism and age of mid-Palaeozoic ring complexes in Niger, West Africa, and tectonic implications, *Geophys. J. Roy. Astron. Soc.*, v. 90, 705–729, 1987.

C. G. A. Harrison and T. Lindh, A polar wandering curve for North America during the Mesozoic and Cenozoic, *J. Geophys. Res.*, v. 87, 1903–1920, 1982.

N. F. Hurley and R. Van der Voo, Paleomagnetism of Upper Devonian reefal limestones, Canning Basin, western Australia, *Geol. Soc. Am. Bull.*, v. 98, 138–146, 1987.

E. Irving, Palaeomagnetic and palaeoclimatological aspects of polar wandering, *Geofis. Pura Appl.*, v. 33, 23–41, 1956.

E. Irving, *Paleomagnetism and Its Applications to Geological and Geophysical Problems*, John Wiley, New York, 399 pp., 1964.

E. Irving, Drift of the major continental blocks since the Devonian, *Nature*, v. 270, 304–309, 1977.

E. Irving, Pole positions and continental drift since the Devonian, In: *The Earth: Its Origin, Structure and Evolution*, ed. M. W. McElhinny, Academic Press, London, pp. 567–593, 1979a.

E. Irving, Paleopoles and paleolatitudes of North America and speculations about displaced terrains, *Can. J. Earth Sci.*, v. 16, 669–694, 1979b.

E. Irving, The paleomagnetic confirmation of continental drift, *Eos Trans. AGU*, v. 69, 994–1014, 1988.

E. Irving and G. A. Irving, Apparent polar wander paths Carboniferous through Cenozoic and the assembly of Gondwana, *Geophys. Surv.*, v. 5, 141–188, 1982.

E. Irving and J. K. Park, Hairpins and superintervals, *Can. J. Earth Sci.*, v. 9, 1318–1324, 1972.

D. V. Kent and S. R. May, Polar wander and paleomagnetic reference pole controversies, *Rev. Geophys.*, v. 25, 961–970, 1987.

P. L. Lapointe, Paleomagnetism of the Notre Dame lamprophyre dikes, Newfoundland, and the opening of the North Atlantic Ocean, *Can. J. Earth Sci.*, v. 16, 1823–1831, 1979.

R. A. Livermore, F. J. Vine, and A. G. Smith, Plate motions and the geomagnetic field. I. Quaternary and late Tertiary, *Geophys. J. Roy. Astron. Soc.*, v. 73, 153–171, 1983.

R. A. Livermore, F. J. Vine, and A. G. Smith, Plate motions and the geomagnetic field. II. Jurassic to Tertiary, *Geophys. J. Roy. Astron.* Soc., v. 79, 939–962, 1984.

R. A. Livermore, A. G. Smith, and F. J. Vine, Late Paleozoic to early Mesozoic evolution of Pangea, *Nature*, v. 322, 162–165, 1986.

S. R. May and R. F. Butler, North American Jurassic Apparent polar wander: Implications for plate motions, paleogeography and Cordilleran tectonics, *J. Geophys. Res.*, v. 91, 11,519–11,544, 1986.

M. W. McElhinny, *Palaeomagnetism and Plate Tectonics*, Cambridge University Press, London, 358 pp., 1973.

M. W. McElhinny and B. J. J. Embleton, Australian palaeomagnetism and the Phanerozoic plate tectonics of eastern Gondwana, *Tectonophys.*, v. 22, 1–29, 1974.

M. W. McElhinny and A. Brock, A new palaeomagnetic result from east Africa and estimates of the Mesozoic palaeoradius, *Earth Planet. Sci. Lett.*, v. 27, 321–328, 1975.

M. W. McElhinny and R. T. Merrill, Geomagnetic secular variation over the past 5 m.y., *Rev. Geophys.*, v. 13, 687–708, 1975.

W. S. McKerrow and C. R. Scotese, eds., *Palaeozoic Palaeogeography and Biogeography*, Geol. Soc. London Mem. No. 12, 1990.

R. T. Merrill and M. W. McElhinny, Anomalies in the time-averaged paleomagnetic field and their implications for the lower mantle, *Rev. Geophys.*, v. 15, 309–323, 1977.

R. T. Merrill and M. W. McElhinny, *The Earth's Magnetic Field: Its History, Origin and Planetary Perspective*, Academic Press, San Diego, 401 pp., 1983.

P. Morel and E. Irving, Tentative paleocontinental maps for the early Phanerozoic and Proterozoic, *J. Geol.*, v. 86, 535–561, 1978.

P. Morel and E. Irving, Paleomagnetism and the evolution of Pangea, *J. Geophys Res.*, v. 86, 1858–1872, 1981.

N. D. Opdyke and K. W. Henry, A test of the dipole hypothesis, *Earth Planet. Sci. Lett.*, v. 6, 139–151, 1969.

J. D. A. Piper, *Palaeomagnetism and the Continental Crust*, John Wiley, New York, 434 pp., 1987.

J. N. Prasad, Paleomagnetism of the Mesozoic lamprophyric dikes in north-central Newfoundland, M.S. thesis, 119 pp., Mem. Univ. of Newfoundland, St. John's, 1981.

M. Prévot and M. McWilliams, Paleomagnetic correlation of Newark Supergroup volcanics, *Geology*, v. 17, 1007–1010, 1989.

S. K. Runcorn, Paleomagnetic comparisons between Europe and North America, *Proc. Geol. Assoc. Canada*, v. 8, 77–85, 1956.

P. W. Schmidt and W. A. Morris, An alternative view of the Gondwana Paleozoic apparent polar wander path, *Can. J. Earth Sci.*, v. 14, 2674–2678, 1977.

D. A. Schneider and D. V. Kent, The time-averaged paleomagnetic field, *Rev. Geophys.*, v. 28, 71–96, 1990.

C. R. Scotese and S. F. Barrett, Godwana's movement over the south pole during the Palaeozoic: Evidence from lithological indicators of climate, In: *Palaeozoic Palaeogeography and Biogeography*, ed. W. S. McKerrow and C. R. Scotese, Geol. Soc. London Mem. No. 12, pp. 75–85, 1990.

C. R. Scotese and W. S. McKerrow, Revised world maps and introduction, In: *Palaeozoic Palaeogeography and Biogeography*, ed. W. S. McKerrow and C. R. Scotese, Geol. Soc. London Mem. No. 12, pp. 1–21, 1990.

P. N. Shive and W. E. Frerichs, Paleomagnetism of the Niobrara Formation in Wyoming, Colorado, and Kansas, *J. Geophys Res.*, v. 79, 3001–3007, 1974.

A. G. Smith and A. Hallam, The fit of the southern continents, *Nature*, v. 225, 139–149, 1970.

D. R. Van Alstine and J. deBoer, A new technique for constructing apparent polar wander paths and revised Phanerozoic path for North America, *Geology*, v. 6, 137–139, 1978.

R. Van der Voo, Paleozoic paleogeography of North America, Gondwana, and intervening displaced terranes: Comparisons of paleomagnetism with paleoclimatology and biogeographical patterns, *Geol. Soc. Am. Bull.*, v. 100, 311–324, 1988.

R. Van der Voo, Phanerozoic paleomagnetic poles from Europe and North America and comparisons with continental reconstructions, *Rev. Geophys.*, v. 28, 167–206, 1990.

R. Van der Voo and R. B. French, Apparent polar wandering for the Atlantic-bordering continents: Late Carboniferous to Eocene, *Earth Sci. Rev.*, v. 10, 99–119, 1974.

A. Wegener, *The Origin of Continents and Oceans* (English translation by J. G. A. Skerl), Methuen, London, 212 pp., 1924.

R. L. Wilson, Permanent aspects of the Earth's non-dipole magnetic field over upper Tertiary times, *Geophys. J. Roy. Astron. Soc.*, v. 19, 417–437, 1970.

R. L. Wilson, Dipole offset—The time-average palaeomagnetic field over the past 25 million years, *Geophys. J. Roy. Astron. Soc.*, v. 22, 491–504, 1971.

R. L. Wilson and J. M. Ade-Hall, Paleomagnetic indications of a permanent aspect of the non-dipole field, In: *Paleogeophysics*, ed. S. K. Runcorn, Academic Press, San Diego, pp. 307–312, 1970.

W. K. Witte and D. V. Kent, The paleomagnetism of red beds and basalts of the Hettangian extrusive zone, Newark Basin, New Jersey, *J. Geophys Res.*, v. 95, 17,533–17,545, 1990.

A. M. Ziegler, C. R. Scotese, W. S. McKerrow, M. E. Johnson, and R. K. Bambach, Paleozoic paleogeography, *Ann. Rev. Earth Planet. Sci.*, v. 7, 473–502, 1979.