Continental Drift (Palaeomagnetism)

Definition

Paleomagnetism is the study of the Earth's ancient magnetic field through the record of remanent magnetism preserved in rocks. The directions of remanent magnetization are used to deduce the position of the Earth's magnetic pole relative to the study location at the time when this magnetization was acquired. By studying magnetizations of varying age from a single lithospheric plate, one can construct a path of apparent polar wandering (APWP) that tracks the motion of that plate relative to the geographic pole. A well-defined APWP can serve as a geochronological tool, i.e., for dating magnetizations of unknown age through a comparison of their directions with those expected from the reference APWP. Paleomagnetism can be used to date any geologic event that engenders the acquisition of remanent magnetization, including formation of igneous and sedimentary rocks, deposition of ore minerals, episodes of deformation, and other remagnetization processes.

Introduction

The development and broad acceptance of the theory of plate tectonics in the 1960s (e.g., McKenzie and Parker 1967) was the culmination of decades of scrutiny and intense debate among the Earth science community that ultimately witnessed the establishment of a mobilistic paradigm for the Earth's surface, which had first been introduced by Wegener (1912) in the form of "continental drift." Paleomagnetism was a key to this revolution, as it provided unambiguous evidence both for the "drift" of continents (Runcorn 1956) and for seafloor spreading (Hess 1962). The latter was validated by the observation of marine magnetic anomalies, which revealed symmetric, age-dependent stripes of remanent magnetization carried by seafloor that was created at mid-ocean ridges during periods of opposite geomagnetic polarity (Vine and Matthews 1963). While the concept of seafloor spreading provided a qualitative explanation for the mechanism of continental drift, identifications of marine magnetic anomalies allowed quantitative estimates of displacements between continents through geologic time, paving the way for the development of the modern theory of plate tectonics.

The geomagnetic field averaged over a sufficiently long time interval (tens to hundreds of thousands of years) is closely approximated by the field of a geocentric dipole aligned parallel to the Earth's rotation axis (McElhinny and McFadden 2000; Merrill et al. 1996). The dipolar geometry of the time-averaged field allows paleomagnetists to estimate positions of geographic poles relative to the studied locations by analyzing directions of remanent magnetization, provided that these magnetizations were acquired over a time interval that was sufficiently long to average out short-term deviations of the geomagnetic field from that of a geocentric axial dipole (paleosecular variation). The poles obtained through measurements of magnetic remanence are commonly referred to as "paleomagnetic poles." Due to the motion of lithospheric plates relative to the Earth's spin axis, the position of the paleomagnetic pole in the reference frame of a specific plate varies with age. To an observer on the plate who is not aware of plate motion, it would appear that the spin axis slowly changes its orientation through time, so that the geographic pole moves along a unique path that we refer to as the "apparent polar wander path" (APWP). The motion reflected by APWPs may be due to the "drift" of individual plates, the rotation of the entire planet relative to the spin axis (true polar wander, TPW), or a combination of these two processes.

Creer et al. (1954) were the first to publish an APWP for "Europe" based on paleomagnetic poles from Britain. The paleomagnetic poles (plotted as south poles in Fig. 1a) differed markedly from the present-day pole and left Creer et al. (1954) with two possible explanations: either the pole itself had moved (TPW) or Britain/Europe (Fig. 1b) had moved relative to the pole ("continental drift"). Initially, they interpreted their results as "a slow change in the axis of rotation of the earth with respect to its surface," in other words, TPW. However, two years later, Runcorn (1956) published an APWP for North America and crucially observed that it was separated from the APWP of Europe by ~30° longitude, thus demonstrating that the continents must have moved relative to each other. Specifically, Runcorn (1956) attributed the separation of the APWPs to the "drift" between North America and Europe corresponding to the opening of the Atlantic Ocean. This interpretation was later corroborated by the analysis of marine magnetic anomalies (Vine and Matthews 1963).

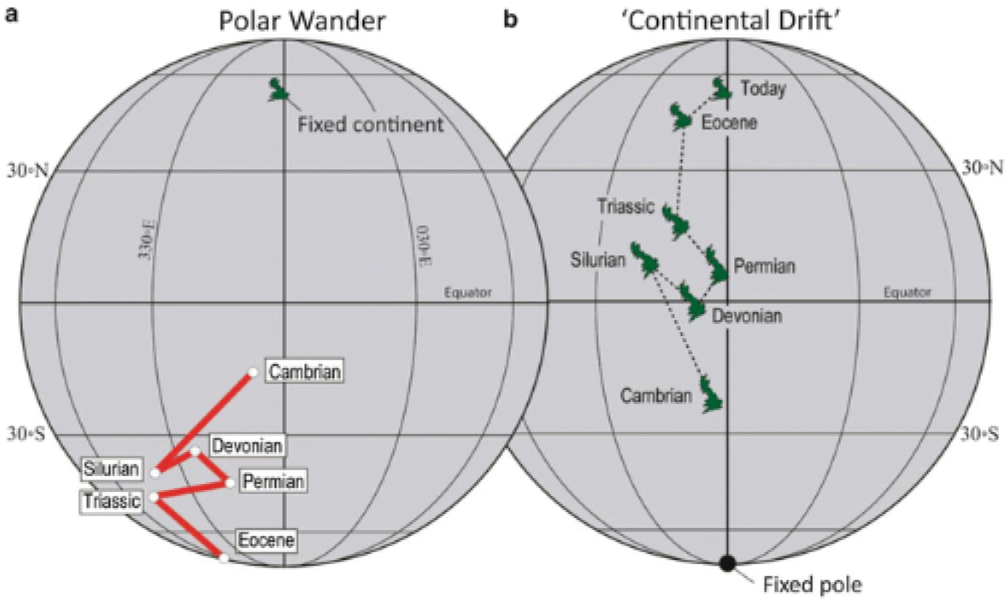

Fig. 1 (a)
The first Phanerozoic polar wander path for "Europe" (Creer et al. 1954) based on six paleomagnetic poles from Britain. These poles - here shown as south poles - differ from the present-day South Pole, and this was originally interpreted as a change in the Earth's rotation axis through time, i.e., true polar wander (TPW). In this plot, the continent (British Isles) stays fixed, but the polar axis is left to wander and following a path that is dubbed apparent polar wander path (APWP). "Apparent" means that the wandering may not be real and that it could be the result of "continental drift" as in (b). (b) The location of the British Isles at different times (longitude is arbitrary) according to the poles in (a), and here assuming a moving continent with a fixed polar axis. This was originally coined "continental drift." Note that Scotland and England were actually separated by the Iapetus Ocean before the Silurian (Fig. 2a). This was not known in 1954 and thus the British Isles cannot be plotted as a coherent unit in the Cambrian

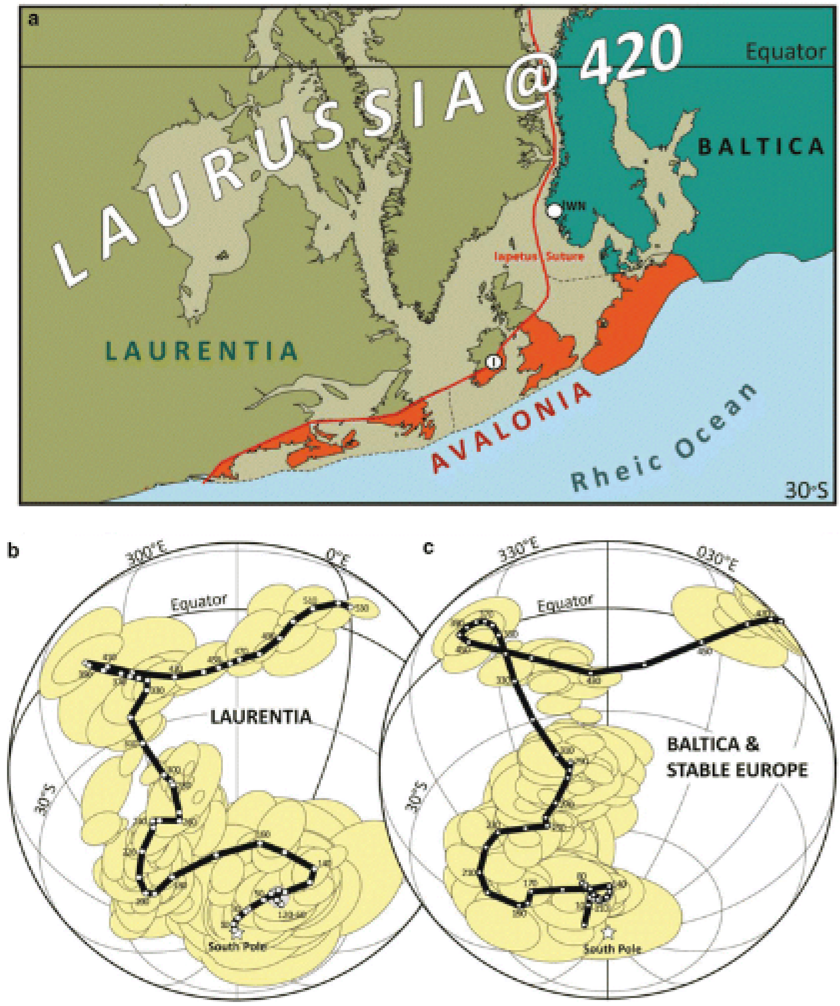

Fig. 2 (a)

Reconstruction of Laurussia at 420 Ma. Avalonia collided with Baltica at ~450 Ma and later Baltica/Avalonia collided with Laurentia (including North America, Greenland, Scotland, and Northern Ireland) at 430 Ma along the Iapetus Suture. The locations of paleomagnetically dated fault rocks in Western Norway (WN) and mineral deposits in Ireland (I) are shown as open white circles. The Irish mineral deposits are located near the Iapetus Suture and about 50 km north of the Variscan Front in Fig. 3b. (b) APWP for Laurentia. Moderately smoothed spherical spline path shown in 10 Ma intervals from the Early Cambrian (530 Ma) to the present. (c) APWP for Baltica/Stable Europe from Early Ordovician to the present. Input poles for both Laurentia and Baltica/Europe are shown with 95 % confidence ovals (yellow shading) and detrital sedimentary input poles have been corrected for potential I-errors (after Torsvik et al. 2012)

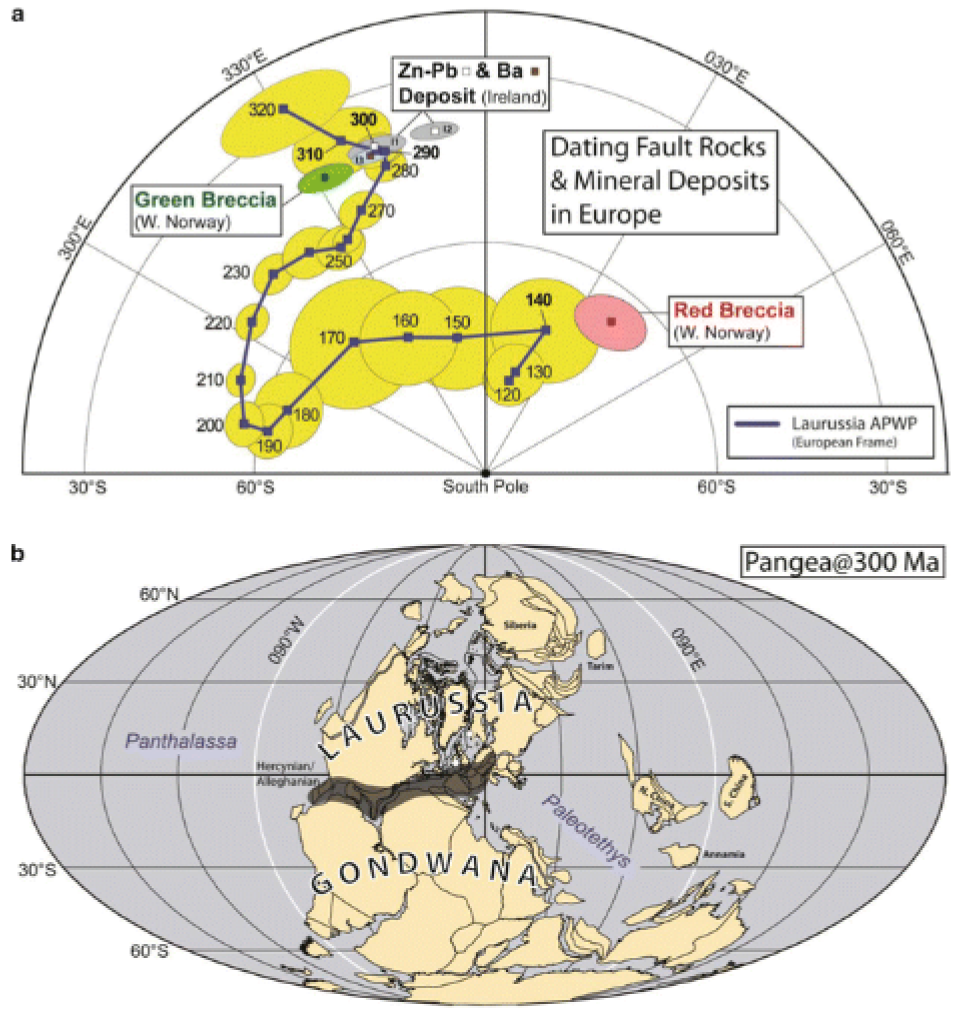

Fig. 3 (a)
Laurussian (Baltica/Stable Europe and Laurentia rotated to European coordinates) running mean path shown with A $_{95}$ circles (yellow shading). The APWP is corrected for potential inclination shallowing in detrital sedimentary rocks (Torsvik et al. 2012). The APWP is shown in 10-Myr intervals from the Late Carboniferous (320 Ma) to the Cretaceous (120 Ma), and each mean pole is based on a sliding time window of 20 Myr. The APWP is compared with paleomagnetic poles derived from two generations of fault rocks in Western Norway (Torsvik et al. 1992) and Zn-Pb and Ba deposits in Ireland (Pannalal et al. 2008a, b; Symons et al. 2007). These poles are shown with 95 % confidence ovals (dp/dm). (b) The Zn-Pb/Ba and the green breccia poles in (a) dates to around 310-290 Ma; they can potentially be linked to the waning stages of Hercynian orogenic activity

It is now well established that tectonic plates (which may include both continental and oceanic lithosphere) are constantly moving relative to each other, although at times they may coalesce or fragment, and their boundaries are otherwise frequently modified. APWPs from the individual continents attest to their often independent history of motion but also reveal an incessant, but commonly subordinate component of TPW. After more than a half-century of paleomagnetic research, the APWPs of most continents can be traced back to the dawn of the Phanerozoic, although they are generally much better defined for younger time. Consequently, when and where these APWPs are well constrained, it is now possible to invert the traditional workflow of paleomagnetic studies and use the APWP as a geochronological tool for dating magnetizations of unknown age.

Constructions of Reference APWPs

APWPs constructed as paths of apparent motion for the northern or southern geographic pole conveniently summarize paleomagnetic data for continents, terranes, and other tectonic blocks. In order to define an APWP, paleomagnetic poles of various ages are plotted on a stereonet and then fitted with a model path of polar motion, either with the use of spherical splines or by applying a running mean technique. With the spherical spline method (Jupp and Kent 1987), a spline curve constrained to lie on the surface of the sphere is fitted to the paleomagnetic poles providing a regression model that smoothly approximates the positions of the poles at their respective ages (Fig. 2b-c). The paleomagnetic poles that serve as the input data for the regression are assigned statistical weights that are inversely proportional to the precision of the poles (A_{95}) or the paleomagnetic quality factor Q (Van der Voo 1990). In Fig. 2b-c, the input poles were weighted by the value of 7/Q, which causes the spline path to pass closer to high-quality poles (7 is the highest possible value of Q factor).

In the running mean method, the position on the APWP corresponding to a specific age is calculated as a Fisherian mean (Fisher 1953) of paleomagnetic poles whose ages fall within a selected time window (e.g., 20 Ma) centered on that age. For example, the 160 Ma pole in Fig. 3a averages all Laurussian paleomagnetic poles within the 150-170 Ma age window. In practice, the mean poles are commonly calculated at age increments equal to half the width of the averaging window (e.g., 10 Ma increments for the 20 Ma window in Fig. 3a). An advantage of the running mean technique is that the pole uncertainty, commonly expressed as a circle of 95 % confidence (A_{95}), can be estimated for each mean pole through Fisherian statistics (Figs. 3-5). Both the spline method and the running mean technique effectively average out random biases of individual paleomagnetic poles and allow the basic pattern of APW to be determined.

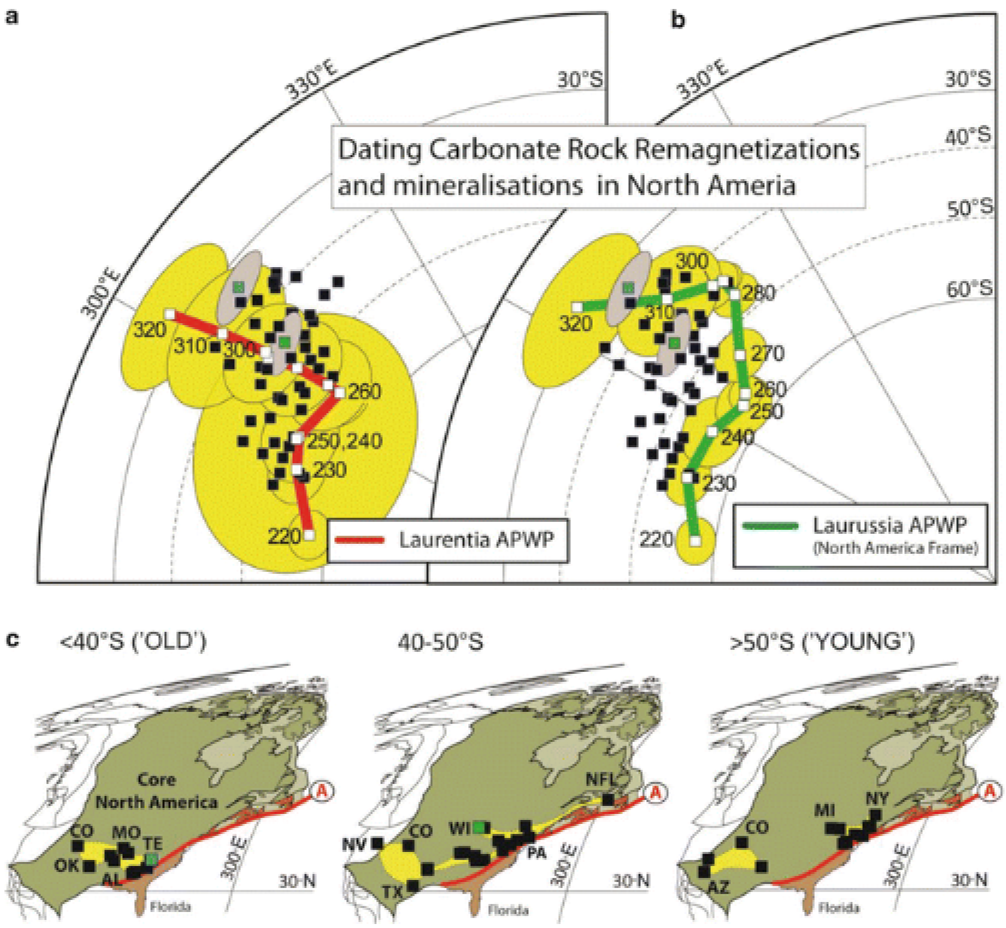

Fig. 4 (a)

Laurentia running mean path with A_{95} circles (yellow shading) from the Late Carboniferous (320 Ma) to the Triassic (220 Ma) shown together with remagnetized carbonate rock poles from North America (Van der Voo and Torsvik 2012) and two Zn-Pb mineralization poles (blue squared is the pole from Eastern Tennessee, Symons and Stratakos 2002; green squared is the pole from Wisconsin, Pannalal et al. 2004). Remagnetized carbonate poles (black squares) are shown without 95 % confidence ovals for clarity. (b) Similar to (a) but the North American poles are compared with the Laurussia APWP (North American frame). (c) Geographic locations of sampling sites poles in (a-b) but plotted for sites with pole latitude <40°S (presumed oldest remagnetizations, i.e., Late Carboniferous when compared with the Laurentia APWP), 40-50°S (Permian), and >50°S (Late Permian-Triassic). Yellow shading denotes regions of remagnetization and mineralization. TE Tennessee, WI Wisconsin, OK Oklahoma, MO Missouri, AL Alabama, AZ Arizona, PA Pennsylvania, MI Michigan, NY New York

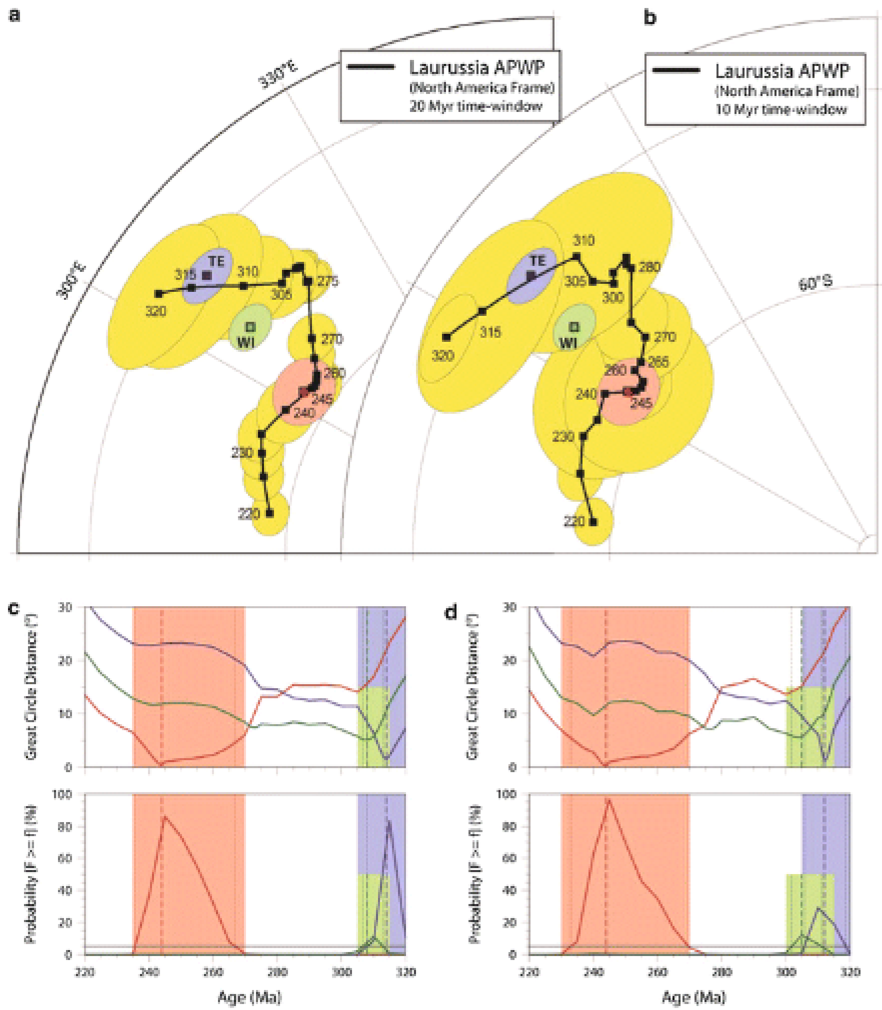

Fig. 5 (a, b)

Laurussia running mean path with A $_{95}$ circles (yellow shading) from the Late Carboniferous (320 Ma) to the Triassic (220 Ma) shown together with a paleomagnetic pole from intrusions in southern Illinois (red square with the pink A $_{95}$ circle) from Domeier et al. (2011) and Zn-Pb mineralization poles from Tennessee (TE) and Wisconsin (WI) (black and green square with light blue and light green A $_{95}$ circles; same as in Fig. 4, but the dp/dm ovals were recalculated into A $_{95}$ circles using the formulations of Cox (1970)). The running mean path is shown in two versions: (a) time window = 20 Myr and (b) time window = 10 Myr. (c, d) Great circle distance and the probability of the McFadden and Lowes (1981) test for the comparisons of the poles with the APWPs ((c) 20-Myr window, (d) 10-Myr window). Red curves correspond to the pole from the southern Illinois intrusions, blue curves to the Tennessee Zn-Pb mineralization pole, and green curves to the Wisconsin Zn-Pb mineralization pole. Thick dashed vertical lines show the best estimates of ages; thin dashed lines indicate their nominal 95 % confidence limits. Shaded bands show the conservative confidence intervals (pink shading for the southern Illinois pole, light blue shading for the Tennessee pole, and light green shading for the Wisconsin pole)

APWPs have changed dramatically over the course of the past six decades, in part due to a much greater pool of paleomagnetic data. For example, in contrast to the initial compilation of merely five Phanerozoic poles from Britain (Fig. 1a), the most recent Phanerozoic APWP for Europe (Fig. 2c) is based on several hundred paleomagnetic poles. APWP refinements have also been made through the implementation of more sophisticated analytical methods and better instrumentation. Important recent developments include novel techniques to identify and correct for the inclination shallowing errors in data from clastic sedimentary rocks, which are now recognized to be commonly biased (Torsvik et al. 2012). An improved understanding of paleogeography has also driven notable changes in how we group paleomagnetic data. For example, the "European" path in Fig. 2c is constructed only with paleomagnetic poles from Baltica before 430 Myr, but after this time we also include poles from Scotland (originally a part of Laurentia, Fig. 2a), Avalonia (which was a separate terrane in the Ordovician), and progressively younger poles from Europe derived from rocks formed after their accretion to Laurussia. The Laurentian path in Fig. 2b is constructed from North American and Greenland poles; the latter have been rotated to North America after adjusting for the Cenozoic opening of the Labrador Sea and Baffin Bay.

The relative positions between North America, Greenland, and Baltica/Europe are known reasonably well after the Silurian, and paleomagnetic poles from these continents can be combined into a Laurussian APW path (Figs. 3 and 4b, Torsvik et al. 2012). In the following section, we will use this APWP as a reference path to illustrate the essentials of the paleomagnetic dating technique with examples of age estimates from fault rocks in Western Norway, Zn-Pb deposits in Ireland, intrusions in southern Illinois (USA), and remagnetized carbonate rocks and mineral deposits in North America.

Examples of Paleomagnetic Age Determinations

Example 1: Fault Rocks in Western Norway

After the Silurian Caledonide collision of Baltica and Laurentia (Fig. 2a), post-orogenic collapse and extensional shearing was accommodated along the Nordfjord-Sogn Detachment (NSD) in Western Norway (e.g., Andersen et al. 1991). The NSD and Devonian mylonites are cut by younger brittle faults, most spectacularly exposed in outcrops on the island of Atløy (Torsvik et al. 1992; Eide et al. 1997) where a nearly flat-lying fault-breccia zone comprises a green network breccia crosscut by a red breccia. The magnetic mineralogy of the green breccia is dominated by magnetite, and magnetization components yielded a mean pole position that was originally assigned a Late Permian age (250-260 Ma) by Torsvik et al. (1992). The green breccia pole plots slightly off the APWP for Laurussia, but is within the 95 % confidence circle of the 310 Ma reference pole (Fig. 3a). Considering that the acquisition of fault-related remanence in the green breccia has likely occurred over a time interval that does not fully average the secular variation of the geomagnetic field (Torsvik et al. 1992), the uncertainty of the pole location may be substantially larger than that implied by its nominal 95 % confidence region (shown by a green ellipse in Fig. 3a). Hence, the post-Devonian fault rejuvenation along the NSD can only be loosely constrained to Late Carboniferous (310 Ma) to Early Permian (280 Ma) time. The red breccia pole overlaps with the 140 Ma mean pole for Laurussia (Fig. 3a), suggesting Early Cretaceous fault movements corresponding to the formation of the red breccia along the NSD.

Brittle fault rocks are notoriously difficult to date with conventional isotopic methods and $^{40}Ar/^{39}Ar$ whole-rock spectra from the breccias defined several age groups that were interpreted to correspond to separate thermal episodes (Eide et al. 1997). However, the oldest whole-rock ages from the green breccia, 296.2 ± 2.6 Myr (8 steps, 47 % of total $^{39}Ar_k$ gas) and 296.4 ± 2.8 Myr (4 steps, 58.4 % of total $^{39}Ar_k$ gas), are in agreement with the age suggested by paleomagnetic data (280-310 Ma). The youngest $^{40}Ar/^{39}Ar$ ages range from 96 ± 3 Ma to 163 ± 4 Myr and may reflect argon loss related to low-temperature hematite precipitation during the formation of the red breccia at ~140 Ma (Fig. 3a).

Example 2: Zn-Pb Deposits in Ireland

The Lisheen Zn-Pb deposit in Ireland is one of the major Lower Carboniferous carbonate-hosted base metal deposits, but the timing of ore mineralization and its genesis have been debated due to the lack of absolute ages. Paleomagnetic results from twelve Zn-Pb mineralized sites and eight host-rock sites (Pannalal et al. 2008a) yield a combined pole that is indistinguishable from the 300 and 290 Ma mean poles for Laurussia (pole I1 in Fig. 3a). A paleomagnetic pole (Symons et al. 2007) from the nearby Magcobar Ba deposit (pole I3 in Fig. 3a) is virtually identical to the Lisheen pole and a pole from the Galmoy Zn-Pb deposit plots slightly off the 300-290 Ma poles (pole I2 in Fig. 3a). These poles postdate peak Variscan folding and deformation (Fig. 3b), and Pannalal et al. (2008b) argued for an epigenetic model in which mineralization occurred during cooling from the Variscan thermal episode. These Irish Zn-Pb and Ba deposits were previously paleomagnetically dated through a comparison with an APWP published in Torsvik et al. (1996) that suggested a 269-290 Ma range for the age of mineralization. We now favor an Early Permian age of approximately 295 Ma based on our updated APWP (Fig. 3a).

Example 3: Remagnetization and Mineralization of Carbonate Rocks in North America

A well-documented remagnetization event is known to have widely affected Paleozoic carbonate rocks in North America. The cause of this far-reaching event remains enigmatic, but the age of the remagnetization can be deduced by a

comparison against reference APWPs. This was most recently done by Van der Voo and Torsvik (2012), who also illustrated how the reference APWP for Laurentia had evolved over the past three decades. Figure 4a shows a comparison of the remagnetization poles listed by Van der Voo and Torsvik (2012, Table 1) with the most recent APWP for Laurentia (Torsvik et al. 2012) that suggests that the remagnetization events date from the Late Carboniferous (310 Ma) to the Early Triassic (230 Ma). This range of ages is also manifested when the poles are compared with the Laurussian APWP (Fig. 4b), but the majority of the remagnetization poles plot slightly west of the main Laurussian path. This occurs because the Permian poles from Europe differ slightly from those of North America, and the inclusion of the European poles pulls the combined Laurussian APWP eastward. The reasons for this discrepancy are unclear. Because the North American and European poles of both older and younger age are in good agreement, it is unlikely that the discrepancy originates from erroneous relative fits between Laurentia and Baltica/Stable Europe. Nonetheless, this example demonstrates the importance of considering the differences among reference paths, as well as their limitations.
Remagnetization sites are located mostly within 1,000 km of the Alleghanian/Quachitan Sutures, but remagnetization has also been observed in sites as far as 3,000 km away (Fig. 4c), highlighting the broad scale of this protracted, continent-wide event. Spatial trends in the timing of remagnetization are not entirely clear (Fig. 4c), but as pointed out in earlier compilations, the southern states of Alabama, Georgia, and Tennessee near the Appalachian Suture appear to be affected earlier than those of the Central Appalachians (Miller and Kent 1988; Van der Voo and Torsvik 2012). Late Carboniferous (~310-300 Ma) remagnetization and Zn-Pb mineralization events were confined to an area from Alabama, Georgia, and Tennessee to Colorado. By contrast, Permian remagnetizations are much more widespread - from Newfoundland to Nevada - whereas Late Permian to Early Triassic remagnetizations are confined to the Central Appalachians (e.g., New York and Michigan) and the southwestern parts of North America (e.g., Colorado and Arizona). The cause of this pattern of remagnetization and its relation to the emplacement of Mississippi Valley-type deposits (e.g., Zn-Pb deposits) is still mystifying, but a commonly preferred hypothesis invokes tectonically expelled fluids driven from the Alleghanian orogenic belt (Oliver 1986).

Example 4: Intrusions in Southern Illinois (USA)

In the south end of the Illinois Basin, near the Illinois-Kentucky border (USA), a series of dikes, sills, and diatreme breccia bodies are observed to invade Devonian-Carboniferous sedimentary rocks on and around a structural dome (Hicks Dome) that is inferred to be cogenetic with the intrusive rocks. Due to extensive surface weathering and alteration, the intrusive rocks have proven difficult to classify and interpret. Consequently, many outstanding questions remain regarding their relationship to each other and to the greater tectonic framework of the region. Initial attempts to isotopically date the intrusive episode(s) ended in ambiguity, leading Reynolds et al. (1997) to employ paleomagnetism to date the rocks. From an intrusive breccia and a lamprophyric sill, Reynolds et al. (1997) isolated a remanent magnetization carried predominantly by high-temperature-oxidized titanomagnetite, as witnessed by microscopic observations of magnetite-ilmenite intergrowths that suggest a primary igneous origin of the mineral. Matching the resulting paleomagnetic pole with the APWP of Laurentia, Reynolds et al. (1997) concluded that the magnetization was acquired in late Paleozoic-early Mesozoic time during the emplacement of the intrusions. A comparison of the results of a recent paleomagnetic study that revisited these intrusive rocks (Domeier et al. 2011) with the updated APWP for Laurussia indeed reveals a close correspondence between the paleomagnetic pole and the 240-260 Ma mean poles of the APWP (Fig. 5a).

Uncertainties of Paleomagnetic Age Estimates

In the examples of the previous section, we restricted our discussion to qualitative age assignments through a visual comparison of paleomagnetic poles derived from magnetizations of unknown age with a reference APWP. In most cases, however, it is desirable to obtain a formal age estimate and specify its uncertainty. In this section, we will present a simple statistical approach that can be used to estimate the "best-fitting" age and its confidence interval.
The accuracy of ages estimated from paleomagnetic data depends on several factors, and certain conditions must be satisfied for paleomagnetic age estimates to be meaningful. It is critical that the magnetizations used to calculate a pole of unknown age have sampled a sufficiently long time interval to average out paleosecular variation (e.g., at least tens to hundreds of thousands of years) and that tectonic tilts or rotations postdating the acquisition of magnetization have been structurally corrected. When either of these two conditions is not met, the calculated pole may be significantly biased, resulting in an erroneous age estimate. In cases when it is suspected that the paleosecular variation has not been

averaged out (as, e.g., in the fault breccias from Western Norway discussed in the previous section) or that there may have been unaccounted structural tilts, the most conservative approach is to conclude that whereas the pole provides some indication for a particular age, the age cannot be constrained with certainty.

Although the reference APWP can vary depending on the construction method, the differences between the spline-fitted and running mean paths that are defined using a large number of high-quality paleomagnetic poles are usually not significant (e.g., Torsvik et al. 2012). It is most common to construct running mean APWPs at 10-Myr intervals with a sliding time window of 20 Myr (e.g., Figs. 3 and 4). Irrespective of whether the reference APWP is a spline or a running mean path, the best estimate of the unknown age of the pole is the age corresponding to a position on the APWP, for which the great circle distance (GCD) between the pole and APWP is minimal. Because the reference APWPs are usually tabulated at rather large age increments (10 Ma in most cases), we recommend resampling the reference APWP at smaller steps (e.g., 1 Ma) by interpolation between the consecutive poles assuming a constant rate of polar motion, calculating GCDs between the pole and APWP at these increments, and defining the age corresponding to the minimum GCD value.

The confidence region for the estimated age can be defined by testing whether the dated pole is statistically distinct from the reference APWP at a specified level of significance (e.g., 5 % to constrain a 95 % confidence interval). In spline models, the uncertainty of the APWP is not known, and it is not possible to rigorously define the confidence region. If the spline curve intersects the 95 % confidence circle (A_{95}) of the pole, the range of ages corresponding to the APWP segment within the circle may serve as a "minimal" confidence region. Without incorporating the uncertainty of the APWP, it clearly underestimates the interval of acceptable ages.

In the running mean APWPs, the uncertainty of a mean pole (A_{95}) depends on the directional dispersion (Fisher precision parameter K) and the number (N) of the individual poles within the averaging window that have been used to define the mean. The directional dispersion reflects both the random deviations of the individual poles from the "true" mean and the differences of their ages from the mean pole age. If the ages of individual poles are evenly distributed within the averaging window (which is normally the case), the mean age is expected to be nearly identical to the median age of the window. Hence, in our simplified approach, we will not consider the age uncertainties of the mean poles separately and will treat each pole of a running mean APWP as an "unbiased estimate" of the pole corresponding exactly to the nominal age (median age of the averaging window).

The range of acceptable ages can be defined by comparing the pole of unknown age and the reference poles from the APWP and deciding whether the differences are significant at the 95 % confidence level. First-order conclusions can be made through a visual comparison of confidence regions. If the A_{95} circles of two poles do not overlap, it can be concluded that the poles are distinct at the 95 % confidence level. When one of the poles is within the A_{95} circle of the other, the difference between them is not significant. In the remaining cases, when the confidence regions overlap, but neither of the two poles is within the A_{95} of the other, the significance of the observed difference can be assessed through a formal test for a common mean (McFadden and Lowes 1981).

Suppose that the pole of unknown age was estimated from a dataset comprising N_1 individual measurements (VGPs) that yielded a resultant vector R_1 (sum of unit vectors corresponding to the individual VGPs) and the reference pole is based on averaging N_2 paleomagnetic poles, with a resultant vector R_2 . Assuming Fisherian-distributed data, the precision parameters of the underlying distributions of VGPs and poles can be estimated as

$$K_1 = \frac{N_1 - 1}{N_1 - R_1}, .25em K_2 = \frac{N_2 - 1}{N_2 - R_2} \tag{1}$$

where R_1 and R_2 are the lengths of the respective resultant vectors. In cases when the R values have not been presented in original studies (which is common for the running mean APWP compilations), they can be computed from the Fisher (1953) equation for A_{95}:

$$\cos A_{95} = 1 - \frac{N-R}{R}\left[\left(\frac{1}{0.05}\right)^{1/(N-1)} - 1\right] \quad (2)$$

The statistics f for testing the null hypothesis that the two directional datasets (VGPs and poles averaged by the running mean) can be drawn from Fisherian distributions sharing a common mean is calculated using the equation

$$f = (N_1 + N_2 - 2)\frac{\frac{K_2}{K_1}\left[(R_1+R_2)^2 - R_c^2\right]}{2\left[(N_1 - R_1) + \frac{K_2}{K_1}(N_2 - R_2)\right]\left[R_1 + \frac{K_2}{K_1}R_2\right]} \quad (3)$$

where R_c is the length of the resultant vector for the combined dataset ($R_c = R_1 + R_2$). McFadden and Lowes (1981) showed that this statistic is approximately distributed as the F distribution with 2 and $2(N_1 + N_2 - 2)$ degrees of freedom, and the probability of observing the test statistic as large as f or larger is

$$P(F \geq f) = \left(\frac{f}{N_1 + N_2 - 2} + 1\right)^{2-N_1-N_2} \quad (4)$$

The probability $P(F \geq f)$ corresponds to the significance level for retaining the null hypothesis. Hence, if it is smaller than 0.05, we can conclude that the poles are distinct at the 5 % significance level. Otherwise ($P \geq 0.05$), the poles should be considered indistinguishable at that level of significance.
Considering that the ages of the reference poles that are not distinguishable from the pole of unknown age at the 95 % confidence level should be within the confidence interval for the estimated age, and the ages of the reference poles that are distinct from the pole should be outside this interval, the confidence limits can be defined by the range of ages for which the probability values calculated using Eqs. (3) and (4) are equal or greater than 5 %. In practice, we recommend performing the McFadden and Lowes (1981) test for all poles of the reference APWP, plotting the calculated probability as a function of age, defining the age interval for which the probability curve is above the 5 % value, and using this interval as a nominal 95 % confidence region. A more conservative estimate can be obtained by using the ages of the two closest reference poles that significantly differ from the dated pole (i.e., fail the test) as the upper and lower confidence limits. The "conservative region" may in fact be preferable because of the simplifying assumptions for the treatment of pole uncertainties discussed above and the approximate nature of the test itself (see McFadden and Lowes 1981, for discussion).
To illustrate this technique, we will now derive formal age estimates and their confidence limits for some examples discussed in the previous section (examples 3 and 4). In Fig. 5a and b, we show the Laurussia APWPs calculated at 5-Myr increments with two different time windows, 20 and 10 Myr. The pole from the southern Illinois intrusions (example 4) plots directly on the APWPs, and the analysis of GCD values suggests an age of 244 Ma for both comparisons (Fig. 5c and d). The probability values for the McFadden and Lowes (1981) test (Eqs. 3 and 4) are plotted as solid red curves in Fig. 5c and d, suggesting a 236-267 Ma confidence region for the age estimated using the APWP with the 20-Myr window (Fig. 5c) and a 233-270 Ma region for the estimate obtained with the 10-Myr-window APWP (Fig. 5d). The conservative estimates are 235-270 Ma and 230-270 Ma, respectively. Using similar analysis for the Tennessee and Wisconsin Zn-Pb mineralization poles (example 3) and the 20-Myr-window APWP (Fig. 5a and c), we arrive to the age estimates of 314 Ma (308-320 Ma nominal confidence interval, 305-320 Ma conservative confidence interval) and 308 Ma (307-313 Ma nominal confidence interval, 305-315 Ma conservative confidence interval), respectively. With the use of the 10-Myr-window APWP (Fig. 5d), the estimates become 312 Ma (306-319 Ma nominal confidence interval, 305-320 Ma conservative confidence interval) for the Tennessee pole and 305 Ma (302-311 Ma nominal confidence interval, 300-315 Ma conservative confidence interval) for the Wisconsin pole.
The examples considered here illustrate the sensitivity of the estimated ages and their precision to the choice of a reference APWP. In all examples, the ages estimated using the APWPs with the 20-Myr and 10-Myr averaging windows

do not differ significantly (the differences are below the uncertainty limits). The reference poles in the 10-Myr-window APWP have larger uncertainties (A_{95}), producing slightly wider confidence intervals for the estimated ages. This result shows that that there is no real advantage in using a reference path with an averaging window shorter than 20 Myr for obtaining a better constrained age (smaller confidence region). Hence, we recommend using APWPs constructed with a 20-Myr window for most applications of paleomagnetic dating technique.

Our examples also illustrate that the precision of paleomagnetic age estimates critically depends on the rate of polar motion (spacing of reference poles along the APWP). A 40-Myr-long confidence interval for the estimated age of the southern Illinois intrusions can be tracked back to a virtual standstill between ~245 and 265 Ma in both APWPs, whereas higher rates of polar motion over the 300-320 Ma period produce much tighter confidence intervals for the Zn-Pb mineralization poles from eastern Tennessee and Wisconsin (10-15 Ma). Thus, the temporal resolution of the reference APWP imposes a fundamental limitation on the precision of ages estimated using paleomagnetic data.

Summary and Conclusions

APWPs have proven invaluable as a means to succinctly communicate plate motions, as well as a convenient tool by which to study them. Well-defined APWPs may be used as a geochronological tool, capable of revealing the unknown age of a magnetization according to the position of the paleomagnetic pole derived from it on a reference APWP. The paleomagnetic dating method can be used to deduce the age of any geologic event which produces an attendant remanent magnetization, assuming there is a well-characterized APWP corresponding to the age and area (continent/terrane) of the event. We have presented several case studies which demonstrate the application of this method to the dating of intrusive rocks, faulting, ore mineralization, and regional remagnetization. We have also discussed a simple statistical technique that can be used to derive a best-fit estimate of the unknown age and constrain its 95 % confidence interval. It is important to note that random but persistent short-term variations in the geomagnetic field (paleosecular variation), uncertainties of the reference APWP, and its temporal resolution (rate of polar motion) impose fundamental limitations on the geochronological resolution of this method. Even the most ideal paleomagnetic result would normally yield a paleomagnetic pole with an intrinsic uncertainty of $A_{95} \approx 5°$, which would roughly correspond to an age error of approximately ± 11 Ma if the host continent had a N-S drift of 5 cm/year and its APWP was perfectly defined. A slower plate speed and/or a poorly defined APWP will see an increase in the age uncertainty. Finally, a word of caution: paleomagnetic results dated by this technique cannot subsequently be used in the construction of an APWP unless their age is verified independently, as the estimated age of the magnetization is derived from the path itself.

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Continental Drift (Palaeomagnetism)

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