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Review Article

Paleomagnetism and Pangea: The road to reconciliation

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ABSTRACT

Outside the realm of paleomagnetic studies, it has been a long held tenet that Pangea amalgamated into and disseminated from essentially the same paleogeography, the conventional Pangea reconstruction of Alfred Wegener. There is widespread geologic and geophysical support for this continental configuration during the Late Triassic–Early Jurassic, but global paleomagnetic data have been repeatedly shown to be incompatible with this reconstruction for pre-Late Triassic time. This discrepancy, which has endured from the late 1950s to the present day, has developed into a fundamental enigma of late Paleozoic–early Mesozoic paleomagnetism. The problem stems from a large disparity in the apparent polar wander paths (APWPs) of Laurussia and Gondwana when the landmasses are restored to the conventional fit. If the APWPs are forced to coincide while some semblance of this fit is maintained, a substantial crustal overlap (1000+km) results between Laurussia and Gondwana. To resolve this problem, alternative Pangea reconstructions have been built to accommodate the paleomagnetic data, but these invariably require large-scale shearing between Laurussia and Gondwana to reach the conventional configuration, from which it is unanimously agreed that the Atlantic Ocean opened in the Jurassic. Evidence for a megashear between these landmasses is critically lacking. Another proposed solution invokes time-dependent non-dipole fields, but challenges the common assumption that the geomagnetic field has effectively been a geocentric axial dipole through the Phanerozoic. The remaining alternative is that the problem is a manifestation of artifacts/contamination in the paleomagnetic data. Here we review the historical development of this problem and conduct an up-to-date re-analysis. Using the most recent late Paleozoic–early Mesozoic paleomagnetic data, we examine the influence of data-quality, refined continental fits, and theoretical inclination shallowing corrections, and confirm that the paleomagnetic data can be reconciled with Pangea, without invoking alternative reconstructions or non-dipole fields.

Contents

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1. Introduction

While a vast array of geological and geophysical data support the conventional paleogeographic model of Pangea for the Jurassic, it has been known since the earliest paleomagnetic investigations of Pangea that the late Paleozoic–early Mesozoic paleomagnetic data are incompatible with this reconstruction. Paleomagnetic analysis is the only quantitative method for determining paleolatitude prior to the Cretaceous, so this prominent model–data discrepancy is a fundamental problem that undermines the conclusions drawn from innumerous studies of pre-Mesozoic tectonics. Here we review the development of this problem, which has endured for more than a half-century, and present a new analysis that enables us to reconcile the paleomagnetic data and the conventional paleogeographic model. We begin with a historical perspective, including the early recognition of the model–data discrepancy, and an account of some early paleomagnetic observations from Europe which curiously foretell the broader course of this work. Our review continues with a summary of the various solutions that have been proposed to explain the discrepancy, and their counter-arguments. From there we consider what roles data-quality, reconstruction parameters, and sedimentary inclination shallowing play in this problem, and we end with a discussion on the implications these findings have on Pangea reconstructions.

2. Historical development of Pangea and early problems

2.1. The origins of Pangea A

The origin of Pangea, as a concept, has been attributed to the 16th century geographer Abraham Ortelius, who perhaps first noted the congruency of the peri-Atlantic coasts of America, Europe, and Africa, in his 1596 *Thesaurus Geographicus* (Romm, 1994). Two and a half centuries later, Snider-Pellegrini (1858) drafted the first paleogeographic map of what would later be recognized as Pangea, and, notably, remarked on some geologic relics common to the peri-Atlantic continents. But, it wasn't until the early 20th century that Pangea was introduced to mainstream science as a defensible paleogeographic model (Wegener, 1915; 1922), presented as the vanguard of the then-contentious hypothesis of continental drift; it took another half-century of impassioned, community-wide debate before Pangea, and its precondition of tectonic mobility, was broadly adopted (Hallam, 1973). Remarkably, the geographic framework of Wegener's Pangea (he called it "*Urkontinent*") has endured as the conventional late Paleozoic–early Mesozoic paleogeographic model, with minor modification, despite the gross continental distortion in his reconstruction (Fig. 1). This paleogeography, which is also known as "Pangea A", results from simple closure of the Atlantic so that Africa lies to the south of Europe and is juxtaposed with the eastern seaboard of North America, and South America lies to the south of North America. Yet, even before plate tectonics gained general acceptance, nascent alternatives to this model were being formulated. Alexander du Toit, best-known as an early promulgator of Wegener's ideas of continental drift, treated Gondwana and Laurussia as independent, in contrast to the unified and internally rigid Pangea of Wegener (du Toit, 1937). Fundamentally, it is this challenge to the model of a single, largely static landmass that the following arguments adhere; and, invariably, the alternative reconstructions return to the general supercontinental boundaries of du Toit (Irving, 2004).

2.2. Initial paleomagnetic tests

Carey (1958) improved upon the schematic reconstruction of Wegener (1922) through a semi-quantitative "orocline analysis", which involved the closing of ocean basins through continental rotations that straightened curved mountain belts. Interestingly, one of the most prominent features introduced in Carey's treatise, a hypothetical intra-continental shear zone called the Tethyan Shear System, anticipated a series of similar structures later invoked to reconcile global paleomagnetic data; we shall return to this shortly. While some aspects of Carey's synthesis are now recognized as invalid, the resulting reconstruction was effectively identical to Wegener's, but, importantly, comparatively free of distortion (Fig. 2). For example, Carey (1958) verified the actuality of the South American–African continental margin congruence by means of movable spherical tracings on a globe, countering criticism that the fit was only apparent or an artifact of projection. Using the very few paleomagnetic data from North America and Europe available at the time (which, moreover, predated routine laboratory demagnetization and principal component analysis), Carey (1958) and Irving (1958) were able to show the first-order veracity of the reconstruction of the northern continents (Laurussia) for the late Paleozoic and early Mesozoic. With respect to the global reconstruction, however, Jeager and Irving (1957) discovered a disparity in the position of the late Paleozoic–early Mesozoic paleopoles of Laurussia and Australia, and concluded that the reconstruction was in need of revision (Fig. 2). Similarly, Carey (1958) noted a wider scatter in the Carboniferous and Permian paleopoles (from both Laurussia and Gondwana), relative to those from the Triassic and Jurassic. He interpreted this to be an indication that the reconstruction was only appropriate for the latter periods, and that additional (late Paleozoic) strain would need to be reversed in order to reach the true paleogeography of the late Paleozoic. Although preliminary, these early observations represent the inception of the conundrum that has persisted to the present day: the paleomagnetic data appear irreconcilable with the conventional

Fig. 1. Late Paleozoic assembly of Pangea ("*Urkontinent*"), according to Wegener (1922), the classic "A-type" reconstruction. Note the prominent distortion of India, among other more minor flaws.

paleogeographic model of Pangea for late Paleozoic–early Mesozoic time.

2.3. The Tethys Twist

In the early 1960s, students of the University of Utrecht, under the supervision of R.W. Van Bemmelen, began conducting routine paleomagnetic investigations during their graduate studies. From the course of this work it was discovered that Permian rocks from Alpine Europe repeatedly yielded paleomagnetic poles that were incompatible with those derived from stable (interior) Europe (Dietzel, 1960; Van der Lingen, 1960; Van Hilten, 1962; 1964; De Boer, 1963; 1965; Guicherit, 1964; and references therein). Although it was initially considered plausible that these "anomalous" results were discordant due to insufficient averaging of secular variation, an internal consistency among them became apparent as the number of studies grew, and this seemed to imply a common tectonic origin for the anomalous poles. The Permian paleomagnetic directions from Alpine Europe were consistently steeper than those determined from rocks from the stable interior; the inclinations from Alpine Europe ranged from −20° (northeastern Spain) to −30° (northern Italy), vs. the expected range of −5° to +5° extrapolated from stable Europe (Fig. 3). The smallest theoretical displacement of Alpine Europe that could explain the observed anomalous inclinations was immediately recognized as untenable, as it would require the region to occupy the same space as northern Europe during the Permian. It was also regarded as implausible that Alpine Europe had drifted northward from the southern hemisphere, as the declinations were approximately south-directed, in agreement with the concomitant Kiaman Reversed Superchron (~318–265 Ma). Drift from the Southern-Hemisphere would have been accompanied by a requisite ~180° rotation, necessitating that the original (Permian) magnetizations were acquired in a normal polarity field, in violation of the Kiaman Reversed Superchron.

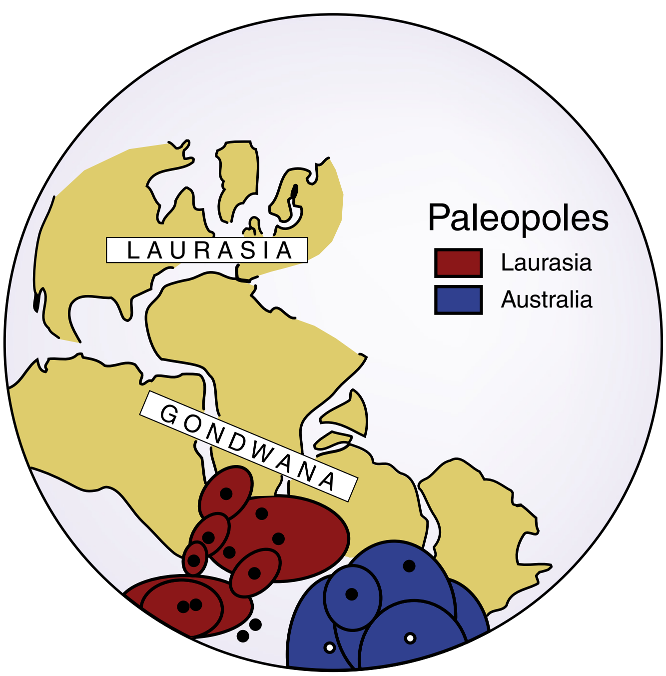


Fig. 2. Semi-quantitative Pangea reconstruction of Carey (1958), generated in part by his "orocline analysis". Distortion was minimized through the use of spherical tracings, but Carey ultimately abandoned a completely distortion-free approach to achieve a good fit. Superposed are the late Paleozoic–early Mesozoic paleomagnetic data of Jeager and Irving (1957), showing the already-then recognized disparity between data from Laurussia (Laurasia) and Gondwana (Australia).
From Irving (2004) with permission from American Geophysical Union.

Instead, De Boer (1963; 1965) and Van Hilten (1964), recognizing the longitude indeterminacy of paleomagnetic data, argued that Alpine Europe was far-traveled, originating 4500+ km to the east of its present location (near present-day Pakistan), where the −20°/−30° paleoisoclines, extrapolated from stable Europe, intersected the Tethyan mobile belt (Fig. 4). Building on the conceptual idea of a Tethyan Shear System (Carey, 1958) and the Indian Ocean "mega-undations" of Van Bemmelen (see Van Bemmelen, 1966), Van Hilten (1964) and De Boer (1965) postulated that Alpine Europe was transported 4500+ km along a dextral megashear between Laurussia and Gondwana, which ran parallel to their Tethyan margins (see also Irving, 1967). It was suggested that Alpine Europe was an extension of Gondwana, and therefore moving in concert with it, until it was "smeared off" during Alpine orogenesis. Accordingly, the megashear was determined to be active from Permian to Eocene time through a comparison of Triassic and Cenozoic paleomagnetic data from Alpine Europe with that of stable Europe (De Boer, 1965); Van Hilten (1964) called this ~200 Myr event the "Tethys Twist".

Subsequent studies of late Mesozoic and Cenozoic tectonics have demonstrably shown the postulated timing of the Tethys Twist to be indefensible. More importantly, the underlying paleomagnetic argument was refuted by later paleomagnetic work, which demonstrated that the reported Permian reference magnetization directions (from stable Europe; Fig. 3) were too shallow, due to contamination by viscous overprints (Zijderveld, 1967). Similarly, successive

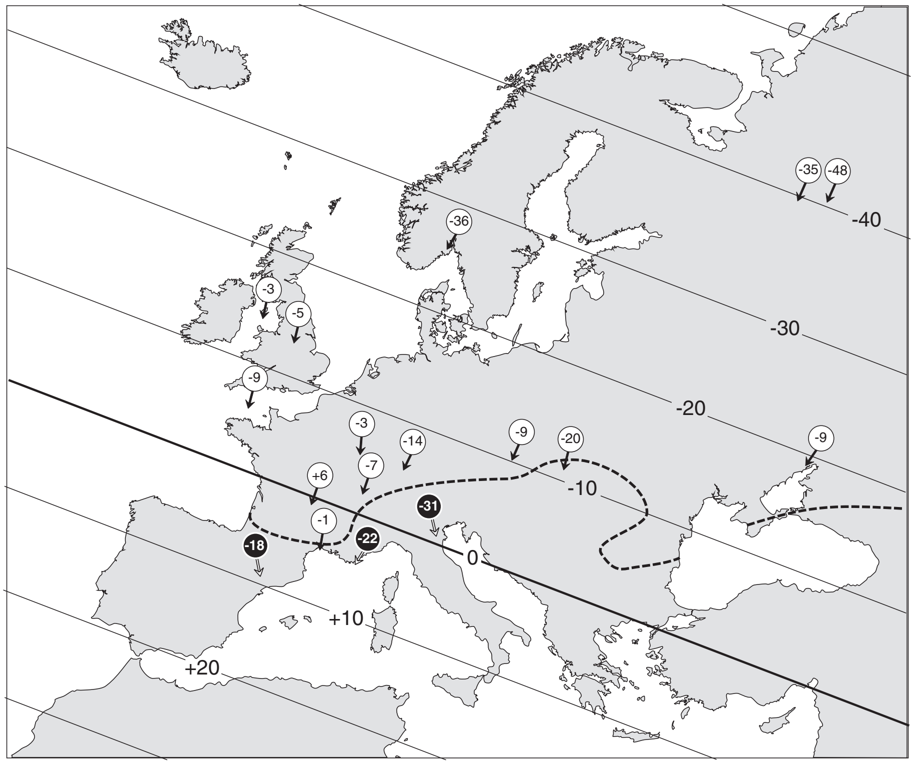


Fig. 3. Permian isocline map redrafted after Van Hilten (1964) and De Boer (1965). The circles represent locations of paleomagnetic study: the values denote the mean inclination and the arrows portray the mean declination as measured in rocks from these locations. The dashed line separates Alpine Europe (filled circles) from stable interior Europe (open circles). The Permian isoclines were determined from the stable European results, which are in stark disagreement with the neighboring inclinations from Alpine Europe. Later work showed both populations of results to be in need of improvement (see text). With permission from Elsevier.

paleomagnetic work in northern Italy demonstrated that the Permian inclinations from this region, as reported by Van Hilten (1964) and De Boer (1965), were too steep (Zijderveld et al., 1970). Using the more reliable stable European paleomagnetic results of Zijderveld (1967), Hospers and Van Andel (1969) showed that there was no longer a statistically significant difference between the inclinations measured from rocks in Alpine Europe vs. the expected inclinations extrapolated from reference directions from stable Europe. And so the Tethys Twist was refuted. Yet, it would be less than a decade before a renewed model of intra-continental dextral megashear would be proposed on the grounds of disparate paleomagnetic data between Laurussia and Gondwana.

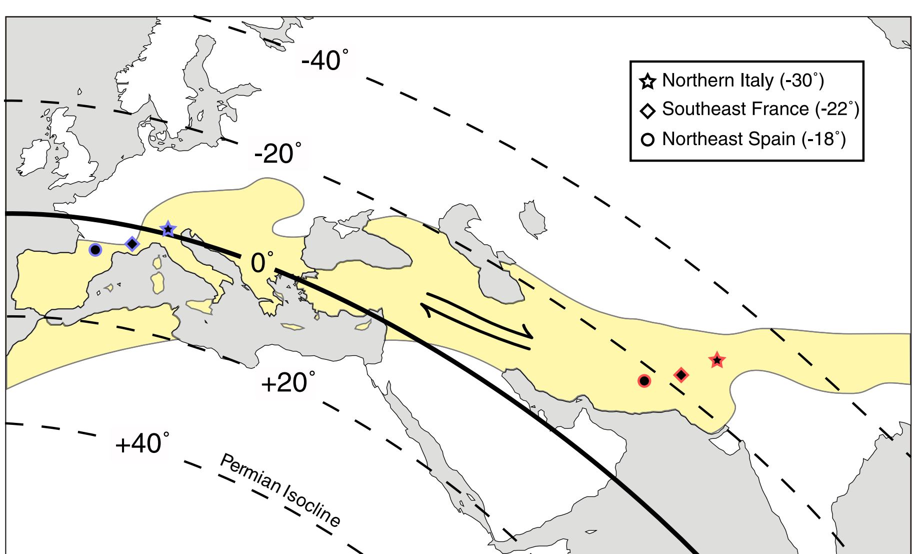


Fig. 4. Extrapolation of Permian isoclines from Fig. 3 along the "Tethyan mobile belt" (yellow zone). Van Hilten (1964) and De Boer (1965) concluded that the anomalous inclinations observed in Alpine Europe (Fig. 3), here denoted as solid shapes with blue outlines, must have been transported along a dextral megashear from where the −20° Permian isocline meets the Tethyan mobile belt (solid shapes with red outlines). The arrows illustrate the inferred dextral sense of motion between Gondwana + Alpine Europe with respect to stable Eurasia.
Redrafted from De Boer (1965) and Irving (2004) with permission from American Geophysical Union.

3. Quantitative A-type Pangea reconstructions

3.1. Pangea A-1

The first quantitative reconstruction of the Atlantic-bordering continents was produced by Bullard et al. (1965) by least-squares fitting of the 500 fathom bathymetric contours of the continental margins, performed by computer. Modifications to the modern margins, including the omission of prominent Cenozoic features, such as the Niger Delta, and the rotation of the Iberian Peninsula to close the Bay of Biscay, were minimal. The result was a landmark achievement that illustrated the remarkable congruence of the Atlantic coastlines, free of relative distortion. Smith and Hallam (1970) applied this technique to the task of reconstructing Gondwana, which allowed them to verify and refine the earlier work of du Toit (1937). Being similar in framework to the conceptual reconstruction of Pangea A (Wegener, 1922), the reconstruction built from the combined parameters of Bullard et al. (1965) and Smith and Hallam (1970) has become known as Pangea A-1 (Fig. 5A). Although numerous modifications have been proposed for the peri-Atlantic fit of the A-1 reconstruction (Dietz and Holden, 1970; Le Pichon et al., 1977, etc.), they have generally been minor and the parameters of Bullard et al. (1965) have endured as the conventional reference. An important exception is the Euler rotation used to bring Laurussia and Gondwana together (thereby closing the central Atlantic), which, as noted by Bullard et al. (1965), is the least well-constrained parameter, due to the non-unique fit of the central Atlantic continental margins. This ill-defined reconstruction parameter exerts a strong control on the separation of North and South America (present-day Gulf of Mexico), which is relatively large in the A-1 reconstruction. By reducing this continental gap through a modification of the Euler rotation, West Gondwana can be more tightly fit against southern North America; we consider the paleomagnetic and geologic consequences of this adjustment next.

3.2. Pangea A-2

Van der Voo and French (1974) tested the Pangea A-1 fit of Bullard et al. (1965) with late Paleozoic and Mesozoic paleomagnetic data from North America, Europe, and West Gondwana. Although they concluded that the fit along the North Atlantic was satisfactory, according to good agreement among the paleomagnetic poles from North America and Europe, they reported a distinct and systematic difference between the late Paleozoic poles of West Gondwana and Laurussia. Yet, the late Paleozoic APWPs defined by these distinct pole populations shared a common trend, such that they could be brought into alignment (although with skewed ages) by a single ~20° clockwise rotation applied to Gondwana, about an Euler pole situated in the southern Sahara. This rotation effectively closes the Gulf of Mexico gap in the Pangea A-1 fit, bringing northern South America into a snug fit with southern North America (Fig. 5B). This modified A-type reconstruction, which was earlier proposed by Le Pichon and Fox (1971) and Walper and Rowett (1972) on geologic grounds, is called Pangea A-2. As discussed by Van der Voo et al. (1976), this model improves the alignment of late Paleozoic orogenic belts and provides a more reasonable paleogeographic setting for the Florida peninsula, but it also complicates any scheme describing the tectonic evolution of Central America and the Caribbean, as it eliminates the space for northern Mexico and its neighboring continental blocks

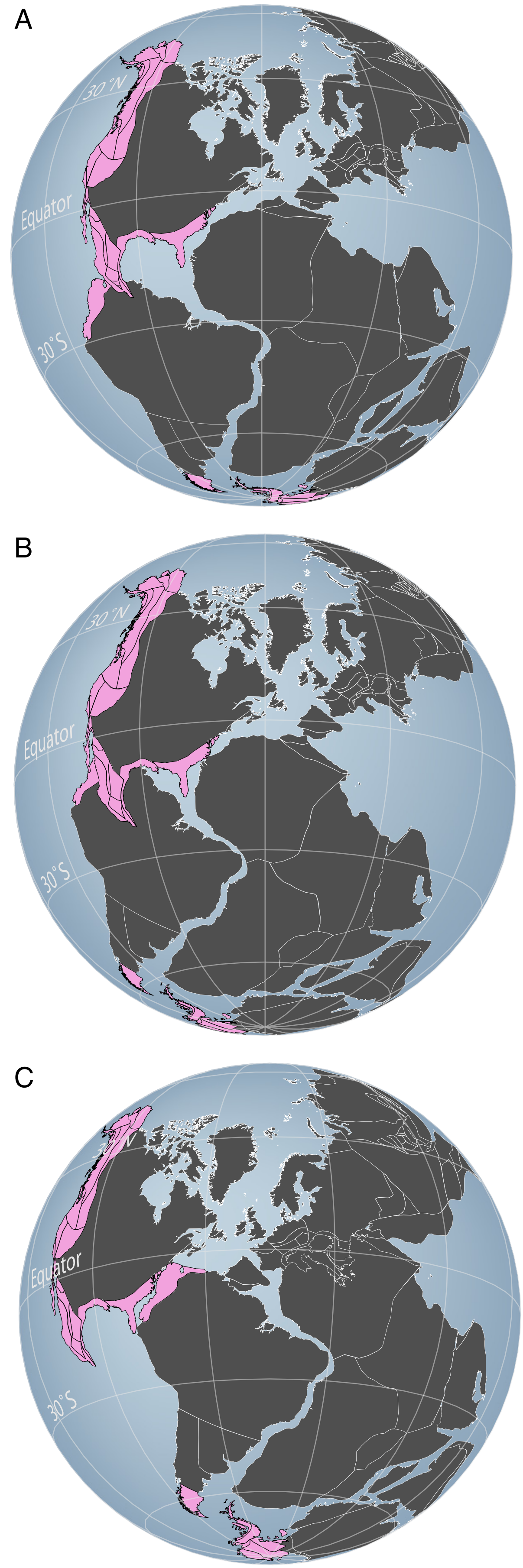


Fig. 5. A comparison of alternative Pangea reconstructions, redrafted after Livermore et al. (1986). (A) Pangea A-1 of Bullard et al. (1965). (B) Pangea A-2 of Van der Voo and French (1974). (C) Pangea B of Irving (1977) and Morel and Irving (1981). The (pink) highlighted regions are not correctly positioned, but we have kept them in their present-day configuration so as to be comparable with other published illustrations. With permission from Nature.

(Yucatan, Cuba, etc.) in the Gulf of Mexico. Consequently, most subsequent central Atlantic reconstructions (Klitgord and Schouten, 1986; Labails et al., 2010; Lottes and Rowley, 1990) have selected reconstruction parameters intermediate between the "loose" A-1 fit of Bullard et al. (1965) and the "tight" A-2 fit of Van der Voo and French (1974). Nonetheless, the A-1 and A-2 models remain useful as reference points; the term "Pangea A" will be used as a broad reference to these models in general.

4. Alternatives to A-type reconstructions

4.1. Pangea B

By the late 1970s there was widespread agreement that the paleogeography of Early Jurassic time – just prior to the opening of the central Atlantic – was essentially that of Pangea A. This was perhaps most convincingly demonstrated by detailed correlations of conjugate sea floor magnetic anomalies and marine fracture zones (see Klitgord and Schouten, 1986), but Early Jurassic paleomagnetic data were also shown to be in good agreement with Pangea A. However, the relevance of this paleogeography in earlier Mesozoic and late Paleozoic time, from which no in situ seafloor survives, was disputed on paleomagnetic grounds by Irving (1977), Westphal (1977), Kanasewich et al. (1978), Morel and Irving (1981), and others later.

Irving (1977) conducted an analysis using Pangea A reference latitudes: arbitrarily selected reference localities on the margins of the peri-Atlantic continents that would have been juxtaposed in Pangea A. If these continents are restored to the paleolatitudes dictated by their independent paleomagnetic data for a particular time, the reference latitudes can be compared, and significant relative differences can be interpreted as a failure of the Pangea A reconstruction for that specific time. Irving found that the paleomagnetic data agreed with Pangea A for the Early Jurassic, but could not be rectified with the model in Permian or Triassic time (Fig. 6a). Specifically, he found significant disagreement (~10°) between the North American and European reference latitudes for the Triassic, and a significant and persistent difference in the North American and Gondwanan reference latitudes for pre-Jurassic time. The relative difference of the latter implied that, during the Permian and much of the Triassic, Gondwana must have been farther north, relative to North America, than its position specified by Pangea A. This was particularly problematic because, in Pangea A, northwestern Africa is fit snugly against the eastern seaboard of North America and is juxtaposed with southwestern Europe, and South America is positioned directly south of North America; significant northward displacement of Gondwana, relative to these northern continents, would therefore result in implausible cratonic overlap (Fig. 6B).

To resolve this problem, Irving (1977) returned to the conceptual ideas of Van Hilten (1964) and De Boer (1965). Again noting the longitude indeterminacy of paleomagnetic data, he shifted Gondwana east, relative to the northern continents, where it could occupy the more northerly position indicated by the paleomagnetic data, without resulting in continental overlap. The result is a paleogeography where Africa is beneath central Europe and South America is juxtaposed with the eastern seaboard of North America (Fig. 5C). Also, the western Tethys is replaced with northern Africa and southern North America is flanked by open ocean. Irving (1977) called this configuration Pangea B and he considered it relevant from the mid-Carboniferous to the end Permian/earliest Triassic, in accordance with the paleomagnetic data. However, the geological and geophysical data overwhelmingly indicate that the Atlantic opened from Pangea A, requiring Pangea B to transform to Pangea A during the Middle–Late Triassic. In a proposal evocative of the Tethys Twist, Irving (1977) hypothesized that this transformation occurred via a ~3500 km dextral megashear between Gondwana and Laurussia. He further speculated that the westward displacement of Gondwana caused North America to move northward, relative to Europe, thereby causing the difference he observed in their reference latitudes during the Triassic.

The initial proposal of Pangea B was shortly followed by the paleomagnetic studies of Kanasewich et al. (1978) and Morel and Irving

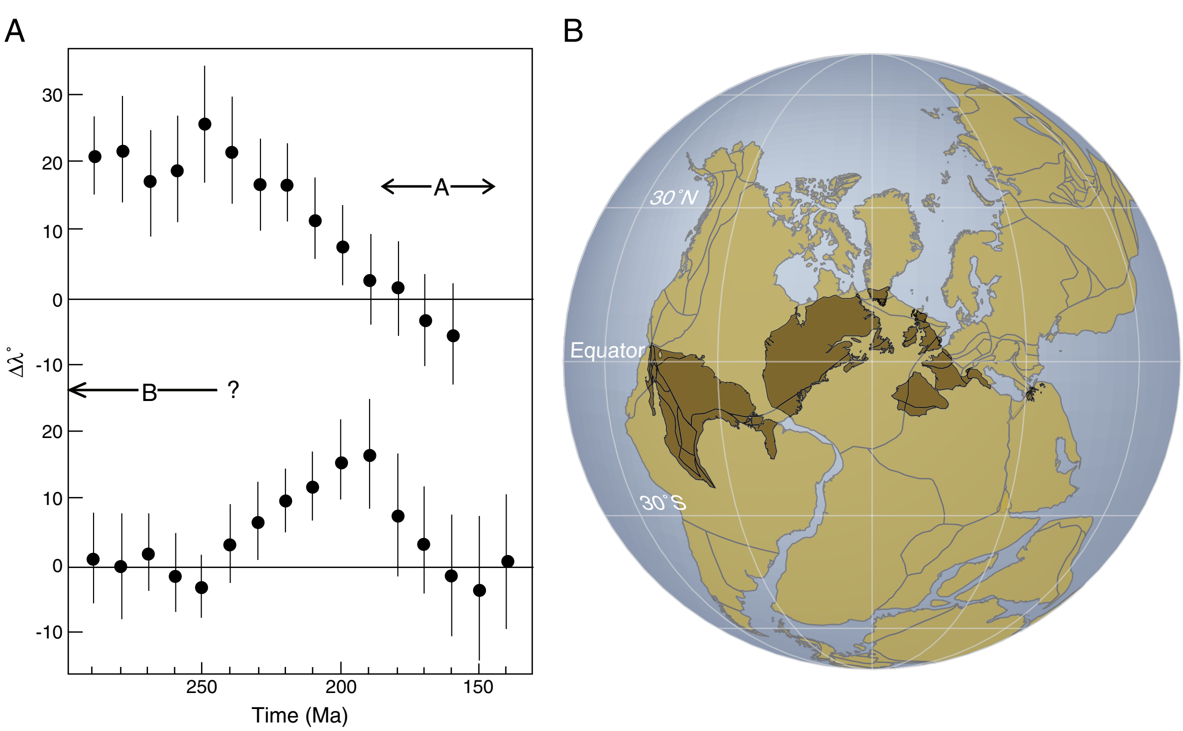


Fig. 6. The rationale for Pangea B. (A) Latitude differences (Δλ°) between Pangea A reference latitudes in North America and Gondwana (top panel) and North America and Europe (bottom panel) as a function of time. The interpreted duration of Pangea B and A are denoted. From Irving (1977) with permission from Nature. (B) Continental overlap that results if an A-type reconstruction is forced, using the 260 Ma paleomagnetic data of Morel and Irving (1981) to reconstruct Laurussia and Gondwana.

(1981), which re-affirmed the general conclusions of Irving (1977), namely the necessity of Pangea B in the Carboniferous and Permian, by re-evaluating the agreement between late Paleozoic and Mesozoic paleomagnetic data from the major continents, when rotated into different Pangea reconstructions. These conclusions were later reiterated by Torcq et al. (1997) and, most recently, by Rapalini et al. (2006), but were based on limited datasets. Torcq et al. (1997) compared an updated (to 1996) Permo-Triassic paleomagnetic dataset from Laurussia against a comparatively dated dataset from Gondwana, which included only two post-1980 results. Notably, with the updated dataset from North America, they did not detect a significant difference between the Triassic paleopoles of North America and Europe, as observed by Irving (1977) and Morel and Irving (1981). The study of Rapalini et al. (2006) incorporated several additional post-1980 paleopoles from Gondwana, but exclusively from Argentina and Peru; paleomagnetic data from the other Gondwana blocks were not included in the analysis, which compared the South American Permo-Triassic data against the North American APWP of McElhinny and McFadden (2000).

Westphal (1977) also determined that the paleogeography of the Permian was effectively that of Pangea B, but arrived at this conclusion by different means. He performed a spherical harmonic analysis using Permian paleomagnetic data from Laurussia and Gondwana and found that he could best align the center of the apparent offset dipoles, calculated from the data of each landmass, by rotating them into a Pangea B geometry. Although novel, this analysis must be considered dubious. A reliable spherical harmonic analysis requires a robust dataset, ideally one with a global distribution of observations; the small amount of geographically restricted data utilized in this study is most certainly inadequate. Additionally, the apparent persistence of the offset dipole may imply that the Permian paleomagnetic data used do not constitute a time-averaged field, and therefore may not be comparable, or representative of the Permian. Finally, the physical interpretation of the generating field is non-unique; the effects of an offset dipole can be equally well expressed by a series of non-dipole fields. Given the latter observation, a persistent "offset dipole", if a lasting geomagnetic characteristic, could be a manifestation of a long-term non-dipole element in the paleomagnetic field, which calls into question the fundamental assumption implicit in traditional paleomagnetic reconstructions. We will return to this last point in Section 5.

4.2. The Intra-Pangean megashear

Pangea B – being built to accommodate the paleomagnetic data – presents several serious geologic problems. Ross (1979) and Hallam (1983) showed paleobiogeographic, stratigraphic, and structural evidence to be in greater accord with Pangea A. The paleontologic argument includes the recognition of strong faunal affinities among Permian invertebrates in southern North America and northwestern South America, and similarities between late Paleozoic flora and fauna of northern Africa and western Europe–eastern North America, rather than central Asia. The stratigraphic argument similarly links comparable late Paleozoic sedimentary facies between southern North America and northwestern South America, and between northern Africa and western Europe–eastern North America. However, the most serious challenge to Pangea B is the structural argument against it, which cites an absence of evidence for the proposed ~3500 km dextral megashear in the Triassic. Although it must be emphasized that an absence of evidence is not equivalent to an evidence of absence, it does pose a critical question about the validity of the model. Given the magnitude of the proposed structure, and the irregular geometry of the plate boundary between Laurussia and Gondwana, it would be expected that the Pangea B to A transformation would leave abundant structural relics. Specifically, dextral motion upon the plate boundary would subject southwestern Europe to regional transpression, whereas the southern margin of North America would experience regional transtension, in addition to local expressions of transpression/transtension along bends in the trace of the shear zone, or en echelon structures (Hallam, 1983; Smith and Livermore, 1991; Weil et al., 2001). However, as discussed by Hallam (1983) and Smith and Livermore (1991), the mid-Permian to Middle Triassic was a tectonically stable interval; evidence for extension in southern North America or compression in southwestern Europe is minimal. Oft-referenced in discussions of the Pangean megashear, the conclusions of Arthaud and Matte (1977), namely that the Laurussia–Gondwana boundary may have acted as dextral shear zone, are only applicable to late Paleozoic time — too old to be pertinent to the Triassic transformation proposed by Irving (1977) and Morel and Irving (1981) (see also, Gates et al., 1986). Moreover, the displacements estimated on the principal faults are an order of magnitude smaller than required by the proposed transformation (Arthaud and Matte, 1977; Gates et al., 1986; Smith and Livermore, 1991). Finally, the adoption of Pangea B would require a fundamental reconsideration of conventional models of late Paleozoic orogenesis, as the Appalachian–Mauritanide–Variscan belt would have developed from a very different incipient framework than generally accepted. In Pangea B, the Ouachita–Marathon margin is open to the Panthalassa, the Appalachians are juxtaposed with the northern Andes, and the European Variscan margin is opposite western Africa (Fig. 5C).

4.3. A revision in timing

Beginning with Muttoni et al. (1996), several more recent paleomagnetic investigations have concluded that while the Carboniferous–Early Permian paleomagnetic data from Laurussia and Gondwana are suggestive of a Pangea B paleogeography, the Late Permian–Triassic paleomagnetic data can be reconciled with Pangea A (Muttoni et al., 2003; 2009, Rakotosolofo et al., 2006). The obvious implication borne from this conclusion is that the transformation from Pangea B to A must have been initiated and largely completed within the Permian period, contrary to the Triassic-age assigned to the event by earlier work (as discussed above).

The analysis of Muttoni et al. (1996) chiefly differs from the preceding studies by the use of Permian–Triassic paleopoles from the Southern Alps as proxy data for West Gondwana, according to the argument that Adria has acted as an African promontory, already during the late Paleozoic. Torcq et al. (1997), for example, explicitly omitted the paleomagnetic data from Adria in their analysis, arguing that the coherence between Adria and stable Africa was not well-demonstrated (see also Dercourt et al., 1986; Vai, 2003). Nevertheless, Muttoni et al. (1996) showed that a mean paleopole compiled from Early Permian results from the Southern Alps was statistically indistinct from an Early Permian paleopole compiled from data from West Gondwana. This comparison, however, is predicated on the reliability of the latter dataset, which is comparatively old (pre-1980 results, except one pole from 1981) and of poor quality; indeed its low quality was the stated purpose of using the Adria data as a proxy. With an Early Permian to Early Jurassic APWP, built from the merged Southern Alps–West Gondwana datasets, and the North American APWP of Van der Voo (1993), Muttoni et al. (1996) concluded that Pangea A was untenable during the Early Permian; Pangea B was necessary. However, by Late Permian/Early Triassic time the Pangea A-2 model of Van der Voo and French (1974) was able to accommodate the data, and by the Late Triassic the A-1 model was permissible (Fig. 7). Thus, they advocated an "evolutionary model" of Pangea, one in which the supercontinent underwent progressive internal change.

Following this contribution – and aiming, in part, to address arguments subsequently raised against it – Muttoni et al. (2003) presented additional paleomagnetic data from the Southern Alps and re-affirmed their earlier conclusion that the paleomagnetic evidence support Pangea B during the Early Permian, but Pangea A during the

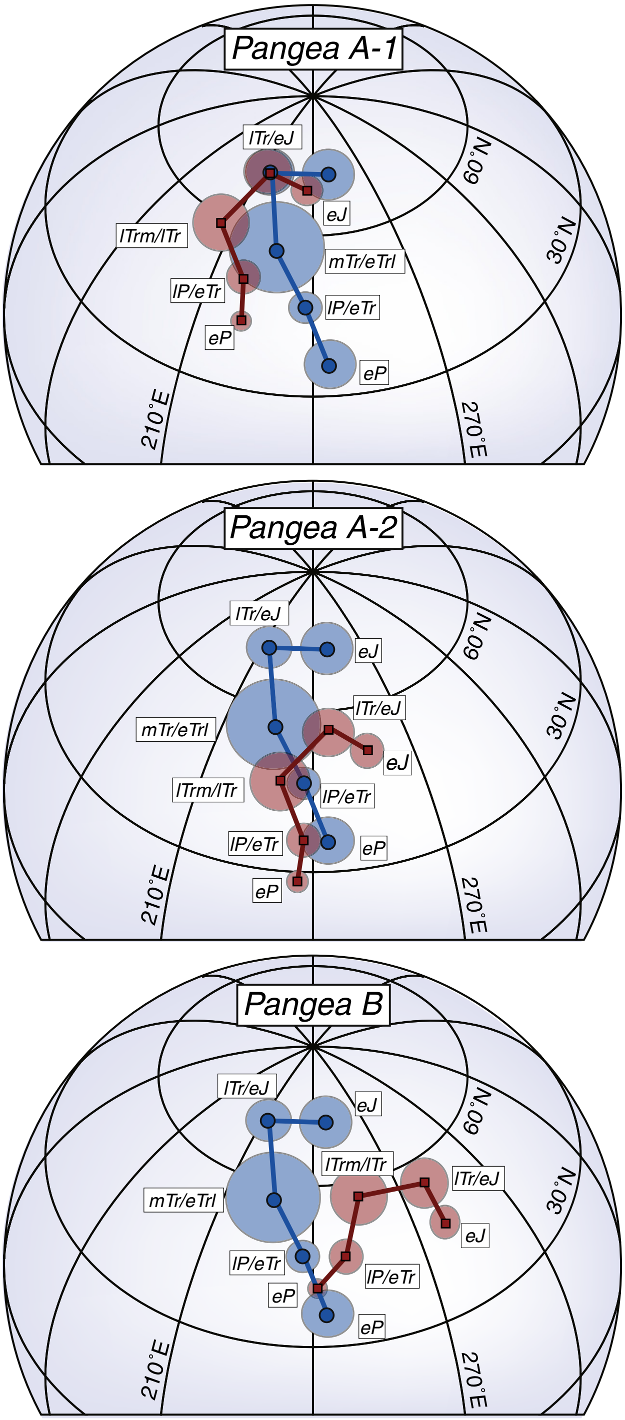


Fig. 7. Late Paleozoic–early Mesozoic apparent polar wander paths of Muttoni et al. (1996) for Laurussia (red) and West Gondwana (blue), according to Pangea A-1, A-2, and B reconstructions. Muttoni et al. (1996) noted that the models appear to best-fit the data at different times and proposed an evolution of Pangea from B (Early Permian) to A-2 (Late Permian–Early Triassic) to A-1 (Late Triassic–Jurassic). Note that the Early Permian data are strongly discordant in a Pangea A-1 fit, and that the Pangea A-2 reconstruction better fits the trends of the paths, but fails to align mean poles of the same age. From Muttoni et al. (1996) with permission from Elsevier.

Late Permian. To sidestep the argument that inclination shallowing in sediments (discussed in Section 6) could have biased the findings of Muttoni et al. (1996), Muttoni et al. (2003) used only igneous-based paleomagnetic poles in their analysis. They reiterated the assertion that Adria has moved in concert with stable Africa since the late Paleozoic, and showed an agreement between Early Permian volcanic-based paleopoles from the Southern Alps and Morocco. Again, however, the African poles used for comparison were comparatively old (pre-1980 results) and of questionable quality. The authors built a mean Early Permian paleopole for Gondwana by merging the Southern Alps and Moroccan datasets and, by comparing this with an igneous-based mean Early Permian paleopole from Europe, showed that if Pangea were reconstructed according to the longitude constraints of an A-type model, it would still result in ~1000 km of crustal overlap between West Gondwana and Laurussia. They further argued that this result was insensitive to zonal non-dipole fields (discussed in Section 5), as the paleomagnetic inclinations analyzed were from a narrow band of low paleolatitudes from the same hemisphere.

Bachtadse et al. (2002) and Rakotosolofo et al. (2006) similarly calculated a mean Early Permian paleopole for Gondwana and, after comparing it with the mean Early Permian paleopole for Laurussia (Van der Voo, 1993), concluded that it supported a Pangea B paleogeography. Rakotosolofo et al. (2006) further claimed that unpublished Early Triassic paleomagnetic data from southern Peru were compatible with Pangea A-2, thereby corroborating a Permian-age for the Pangea B to A transformation, as proposed by Muttoni et al. (1996; 2003).

The broader tectonic and geodynamic implications of a Permian-age megashear were discussed by Muttoni et al. (2003; 2009). In particular, these authors drew an association between the timing of the Pangean transformation, the opening of the Neotethys Ocean, and lithospheric wrenching, basin development, and magmatism in central Europe and the Southern Alps during the Permian. The hypothetical plate circuit for Gondwana included a subduction zone to the south and west (Panthalassa trench), a spreading center to the east (Neotethys ridge), and the Intra-Pangean dextral megashear to the north (Fig. 8). Although a Permian megashear is more temporally coincident with documented dextral activity in Europe (Arthaud and Matte, 1977; Schaltegger and Brack, 2007) than a Triassic transformation, the hypothetical motion required still grossly exceeds estimates of the true net displacement. Furthermore, many Gondwana–Laurussia boundary zones lack significant structural relics indicative of dextral strike–slip motion that post-dates Carboniferous–Permian continental convergence. For example, the prevailing Permian paleostress field in northern Iberia is N–S compressive (NNE–SSW compressive in paleogeographic coordinates), reflecting final Variscan deformation due to the collision of Gondwana and Laurussia (Weil et al., 2001) (Fig. 9A). This paleostress field precludes significant, Permian-age, ENE–WSW oriented, dextral shear in the region, which would require WNW–ESE compressive stress (NW–SE compressive in paleogeographic coordinates) (Fig. 9B).

4.4. Pangea C

According to the longitude indeterminacy of paleomagnetism, Pangea B is perfectly acceptable with respect to the data of Irving (1977) and others, but it is also non-unique. Irving (1977) acknowledged this, noting that Gondwana could be placed to the west of North America, or farther to the east than its position in Pangea B, but he ultimately deemed these alternatives untenable, given the geologic difficulties already manifest in the “more conservative” Pangea B model, as discussed above. Despite this, Smith et al. (1981) argued that Pangea B did not fully conform to the paleomagnetic data, and presented an alternative paleogeographic model (“Pangea C”) in which Gondwana is displaced farther east, relative to its position with respect to Laurussia in Pangea B. In this reconstruction, northern South America is juxtaposed with southern Europe and Africa is situated beneath Asia; this affords further space for Gondwana to be nudged northward to conform to the paleomagnetic data, without resulting in overlap between continents. Pangea C faces the same

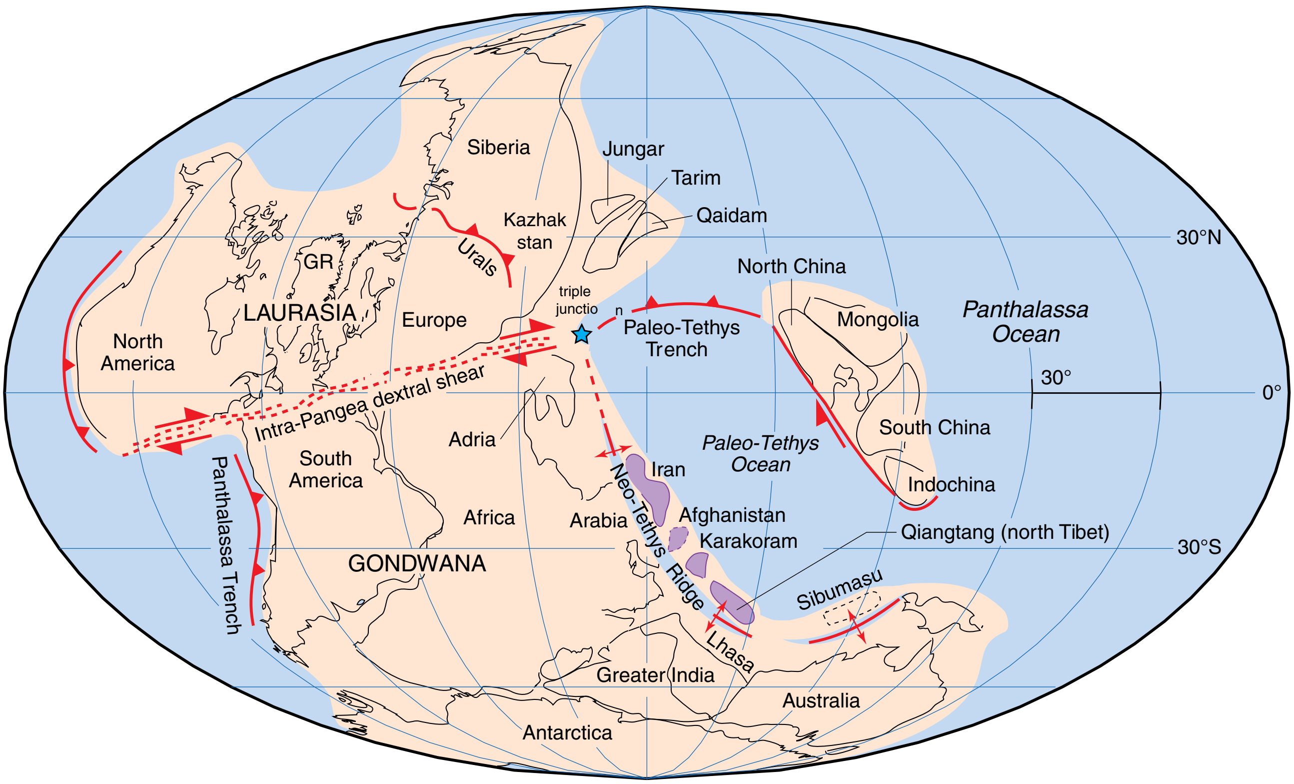


Fig. 8. Early Permian Pangea B reconstruction of Muttoni et al. (2009) displaying theoretical plate kinematics. With permission from GeoArabia.

problems as Pangea B, but exacerbated by the greater offset between Gondwana and Laurussia. For example, if Pangea C is assumed to transform to Pangea A within either the Permian or the Triassic (~50 Myr), the requisite ~6000 km displacement must have occurred at the remarkable average rate of 12 cm yr^{-1}. Furthermore, no major continent borders eastern North America in Pangea C, obliging advocates of Pangea C to explain the Alleghenian Orogeny in lieu of continent–continent collision. A variety of similar paleogeographic permutations of Pangea are obviously permissible according to the longitude indeterminacy of paleomagnetism, but are ultimately subject to the same geologic problems.

5. Non-dipole fields

5.1. A long-term zonal octupole?

In all of the paleomagnetic studies previously referenced, it is implicitly (or explicitly) assumed that the time-averaged paleomagnetic field can be approximated by a geocentric axial dipole (GAD). This is generally a necessary assumption, for without prior knowledge of the geomagnetic field structure, it is impossible to define a function relating inclination and latitude. By assuming that the paleomagnetic field was "always" a GAD, and that rocks can act as high-fidelity magnetic recorders on geologic timescales, changes in paleomagnetic direction can be interpreted as tectonic motion (or true polar wander). Thus, paleomagnetic plate reconstructions are made according to the assumption that the structure of the paleomagnetic field is perfectly well-known. Briden et al. (1971) turned this notion on its head. They took Pangea A-1 to be the true paleogeography of the Permo-Triassic and assumed that the paleomagnetic discrepancy with this reconstruction was due to a geomagnetic departure from a GAD. Comparing the limited data available at the time against theoretical inclination vs. latitude curves, the authors concluded that the Permo-Triassic geomagnetic field was, to a first approximation, a GAD, but that significant axially-symmetric non-dipole contributions were evident. They observed that the theoretical field with the best visual fit to the data appeared to be a prevailing dipole with a subsidiary zonal octupole of the same sign. Interestingly, they also observed a systematic incongruity in the Permian and Triassic inclinations of Europe and North America (later observed by Roy (1972), Irving (1977), and Morel and Irving (1981)), which they noted could not be explained by zonal magnetic fields.

Three decades later, amid revived debate about Pangea reconstructions, this concept was revisited by Van der Voo and Torsvik (2001) and Torsvik and Van der Voo (2002). Van der Voo and Torsvik (2001) analyzed 300–40 Ma paleopoles from North America and Europe for evidence of zonal non-dipole fields by comparing predicted and observed paleolatitudes derived from the data. Importantly, the primary uncertainty in the reconstruction of Laurussia is orthogonal to the effects of zonal non-dipole fields, so artifacts from fitting errors were of no significant consequence to their analysis. Their slope-fitting analysis revealed a consistent departure from the expectations of a GAD field (wherein predicted = observed paleolatitudes; yielding a slope of 1) that could be indicative of a long-term octupole component, representing ~10% of the total geomagnetic field. The authors demonstrated that by re-calculating paleolatitudes with a 10% octupole contribution in the late Carboniferous and a 20% contribution in the Late Permian–Early Triassic, Pangea A could be accommodated without significant continental overlap (Fig. 10). These conclusions were broadened by Torsvik and Van der Voo (2002), who conducted a similar analysis on Paleozoic and Mesozoic paleomagnetic data from Gondwana. Assuming a Pangea A reconstruction, they built running mean APWP pairs for Laurussia and Gondwana using several different geomagnetic field structures (varying octupole contributions; Fig. 11) and measured the great circle difference between concomitant mean poles for each APWP pair (due to the paleogeographic position of Gondwana on the south geographic pole for much of the Paleozoic, they could not apply the linear regression analysis comparing predicted vs. observed paleolatitudes used by Van der Voo and Torsvik (2001)). They found it generally

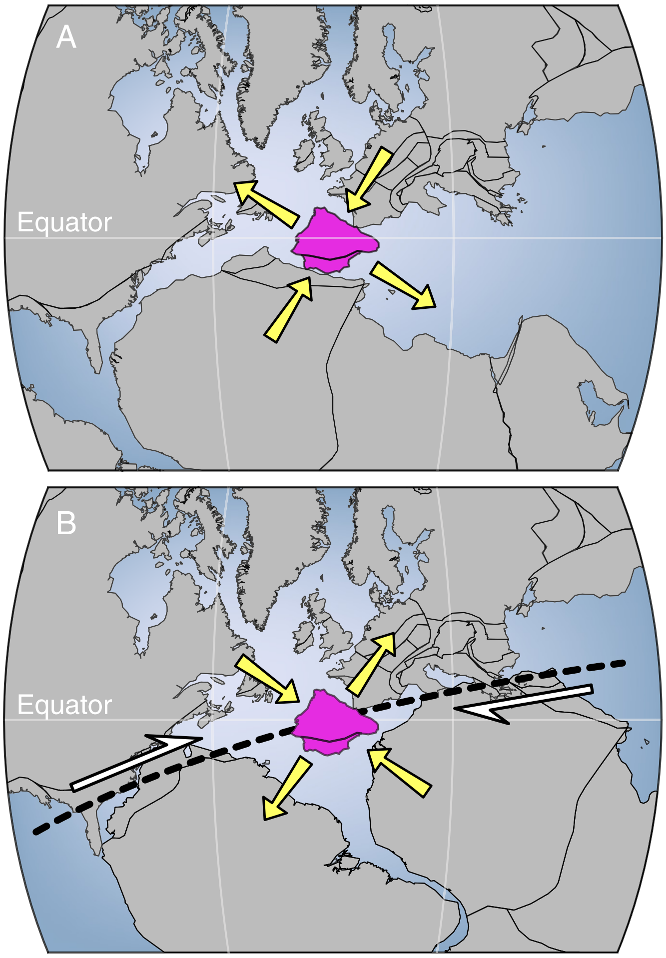


Fig. 9. (A) Early Permian paleostress field for northern Iberia as determined by Weil et al. (2001). (B) Paleostress field expected from the hypothetical Intra-Pangean mega-shear.
Redrafted after Weil et al. (2001) with permission from the Geological Society of America.

necessary to correct for an octupole contribution to achieve an optimal fit between the APWPs, but that the relative contribution of this optimal octupole component was time-varying. The relative contributions ranged from 20%–0% and generally diminished with time; the largest values were required in the late Paleozoic–early Mesozoic, again confirming that Pangea A could not be reconciled with the uncorrected paleomagnetic data. The authors noted that the late Paleozoic–early Mesozoic paleomagnetic poles from Gondwana were dominantly sedimentary-based, whereas the younger paleomagnetic poles were mostly derived from volcanic rocks. The implication of this observation is that inclination shallowing could be partly responsible for the apparently stronger octupole in the late Paleozoic–early Mesozoic, as it can produce equivalent effects in sediments. An igneous-only analysis suggested that inclination shallowing was not significant; but, notably, the data from Gondwana included few reliable igneous records. We will return to a discussion of inclination shallowing in Section 6.

5.2. Return to the GAD hypothesis

Paleomagnetism is the only available tool to make quantitative paleogeographic reconstructions for pre-Cretaceous time. Yet, this indispensible utility is predicated on the hypothesis of a static (on time-scales of ~10–100 ka) paleomagnetic field structure, ideally (and near-invariably assumed to be) a GAD. As aforementioned, without prior knowledge of the field structure, inclination cannot be used to solve for paleolatitude; and for pre-Pangean time this problem cannot be inverted (as per the approach of Briden et al. (1971)), as the gross paleogeography has only been established by paleomagnetic work underpinned by the GAD assumption. Thus, if the GAD hypothesis is abandoned, so, too, is our confidence in any pre-Pangean paleogeographic reconstruction derived from paleomagnetic results. It is prudent, therefore, to consider what persistent bias could manifest as an apparent octupole contribution; we will consider this in the next Section (7). Here we will briefly review recent work that suggests the hypothesis of a GAD may be relevant since the late Mesoproterozoic.

Analyses of paleomagnetic datasets 0–5 Ma – during which the contribution of tectonic plate motion is negligible – have demonstrated that the time-averaged field is approximately a GAD, with a subsidiary geocentric axial quadrupole representing ~2–5% of the total field (Johnson et al., 2008; McElhinny, 2004; Valet and Herrero-Bervera, 2011). Contributions from a persistent zonal octupole are generally regarded as insignificant (McElhinny, 2004), but may represent up to 5% of the total field (Johnson and Constable 1997; Johnson et al., 2008; Kelly and Gubbins, 1997). Similarly, Courtillot and Besse (2004) detected no significant evidence of an octupole contribution in their analysis of global 0–200 Ma paleomagnetic data, which they searched for hemispheric inclination anti-symmetry, relative to a synthetic global APWP. Bazhenov and Shatsillo (2010) devised an approach to investigate the structure of the paleomagnetic field from paleomagnetic data distributed across a large single plate and used this method to demonstrate that zonal non-dipole contributions to the Late Permian paleomagnetic field were unlikely to exceed ~10% of the total GAD. As previously discussed, Muttoni et al. (2003) also questioned the evidence of a significant zonal octupole field in the Early Permian and showed that paleomagnetic data from a narrow, low paleolatitude band in the same hemisphere exhibited the same discrepancy the octupole fields had been invoked to solve; such a distribution of sites should greatly minimize relative errors introduced by unrecognized octupole fields. Indeed, Van der Voo and Torsvik (2004) conducted a simpler test for evidence of an octupole bias in the Permo-Triassic paleomagnetic data of Western Europe and concluded that the results were ambiguous; no evidence of an octupole was found in the 280 Ma or 250 Ma data, while the 290 Ma data were consistent with a subsidiary octupole.

Repeating the paleomagnetic inclination frequency analysis introduced by Evans (1976) with an updated dataset, Kent and Smethurst (1998) concluded that the Precambrian and Paleozoic paleomagnetic fields may have included strong zonal quadrupole and octupole components (estimated at 10% and 25%, respectively) that diminished with time. Such a non-dipole field decay was apparent in the analysis of Torsvik and Van der Voo (2002), where the octupole contribution needed to optimize the fit between the Laurussian and Gondwanan APWPs was observed to diminish with time. However, the assumption of a random paleogeographic sampling that underlies the analysis of Kent and Smethurst (1998) has been shown to be invalid by Meert et al. (2003) and McFadden (2004). Moreover, recent comparisons of Proterozoic paleomagnetic inclinations and climate-sensitive paleolatitude proxies (Evans, 2006) and normal and reversed paleomagnetic data from the 1.1 Ga Keweenawan basalts (Swanson-Hysell et al., 2009) exhibit no remarkable departures from GAD expectations.

6. Bias in the paleomagnetic record

As an alternative to challenging the conventional paleogeographic model or the uniformitarian GAD hypothesis, Rochette and Vandamme (2001) and Van der Voo and Torsvik (2004), among

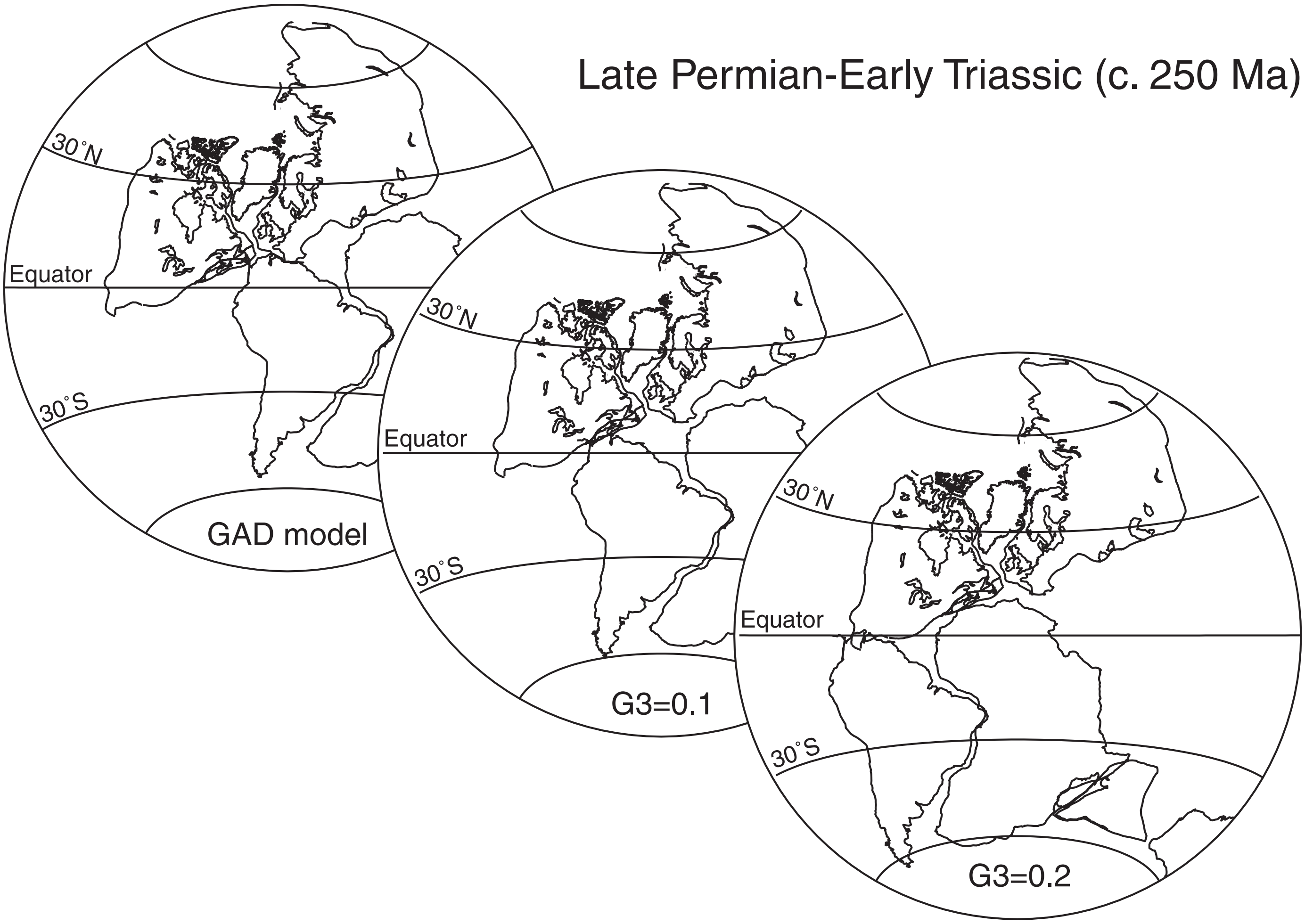


Fig. 10. Permissible Pangea reconstructions (i.e. those that do not require significant continental overlap) according to 250 Ma paleomagnetic data from Van der Voo and Torsvik (2001), assuming different geomagnetic field configurations. G3 = strength of zonal octupole field relative to an ideal dipole. Pangea A is permissible at 250 Ma if an octupole contribution of 20% is assumed.
From Van der Voo and Torsvik (2001) with permission from Elsevier.

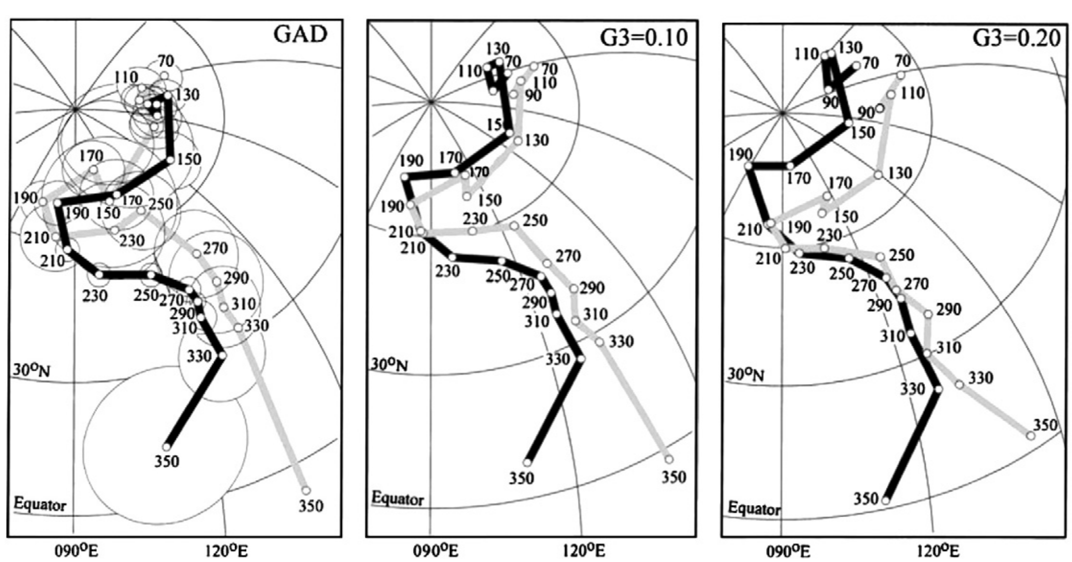


Fig. 11. Late Paleozoic–Mesozoic APWPs for Laurussia (black) and Gondwana (gray) constructed according to different assumed paleomagnetic field structures (i.e. including a varying octupole contribution). G3 = strength of zonal octupole field relative to an ideal dipole. The late Paleozoic–early Late Triassic interval exhibits a good-fit with an assumed G3 of 20%, but the fit of the later Mesozoic poles clearly worsens, suggesting that the G3 contribution (if any) may be time-variant.
From Torsvik and Van der Voo (2002) with permission from John Wiley and Sons.

others, have explicitly suggested that the discrepancy between the late Paleozoic–early Mesozoic paleomagnetic data of Laurussia and Gondwana could simply be a manifestation of bias in the paleomagnetic data. We use the term *bias* rather than *error* to denote a systematic quality; random errors, which are invariably present in any paleomagnetic dataset, are eliminated through the tiered treatment and averaging of data. With respect to the gross paleogeography of the late Paleozoic–early Mesozoic, the most corruptive data bias is that which is equatorially anti-symmetric, as Pangea straddles the equator during this time. As discussed above, an unrecognized subsidiary zonal octupole field can impart an anti-symmetric bias to paleomagnetic data, but it is not the only phenomenon capable of such. Indeed, the inclination shallowing of sediments inherently leads to an anti-symmetric bias, and can produce near-identical results to those of an octupole field (Fig. 12). Less intuitively, systematic errors in age assignment or unrecognized overprints or remagnetizations can yield a similarly anti-symmetric bias, albeit under specific circumstances. In the following, we explore each of these potential sources of bias in more detail, with a specific focus on their possible contributions to the late Paleozoic–early Mesozoic paleomagnetic discrepancy.

6.1. Inclination shallowing

Examples of sedimentary inclination shallowing have been well-documented in a variety of natural settings and rock-types (Arason and Levi, 1990; Bilardello and Kodama, 2010a,b,c; Celaya and Clement, 1988; Garces et al., 1996; Gilder et al., 2003a; Iosifidi et al., 2010; Kent and Tauxe, 2005; Tan et al., 2007; Tauxe and Kent, 1984; Zijderveld, 1975) and by numerous laboratory re-deposition experiments (Anson and Kodama, 1987; Deamer and Kodama, 1990; King, 1955; Levi and Banerjee, 1990; Lovlie and Torsvik, 1984; Mitra and Tauxe, 2009; Sun and Kodama, 1992; Tauxe and Kent, 1984; van Vreumingen, 1993). The bias appears to affect some sedimentary magnetic records which are defined by a depositional remanent magnetization (DRM) or a post-depositional remanent magnetization (pDRM). In the case of the former, the bias arises from the settling and compaction of inequant magnetized grains or sedimentary flocs in the gravitational field, which may overcome the vertical torque applied to the particles by the geomagnetic field. The shallow inclination bias of a pDRM is imparted by post-depositional compaction, wherein the long-axes of magnetic particles are preferentially rotated toward the horizontal plane, perhaps by riding passively on larger plate-like clays to which they are adsorbed. Interestingly, Rochette and Vandamme (2001) and Tan and Kodama (2002) have suggested that even a chemical remanent magnetization (CRM), potentially acquired millions of years after deposition, could "inherit" a shallow inclination bias by developing along the depositional/compacted fabric of the host rock, or by mimicking the fabric via alteration of preexisting grains; an early acquired CRM could also be subject to active compaction-driven shallowing.

Due to the great diversity of sediment characteristics and depositional conditions, in addition to the assortment of specific mechanisms by which a magnetization may acquire a shallow inclination bias, the magnitude of the bias in sedimentary rocks is variable. Yet, the bias can be expressed by a very simple relationship between the local geomagnetic field inclination (I_f) and the acquired inclination (= the measured inclination, I_m), namely that of King (1955): $\tan(I_m) = f \tan(I_f)$, where f is the shallowing coefficient, which can range from 0 (complete shallowing) to 1 (no shallowing) (Fig. 12). For a given value $0<f<1$, this relationship implies that the greatest inclination bias will occur at mid-latitudes, whereas no value $f>0$ can modify the inclination at the equator or poles (where the inclination is horizontal and vertical, respectively). According to the compilation of Bilardello and Kodama (2010a), f values from magnetite-dominated sedimentary rocks have been found to range from 0.54 to 0.79, with a mean of 0.65, whereas hematite-dominated sedimentary rocks have yielded f values from 0.4 to 0.83, with a mean of 0.59. The minimum f values equate to maximum inclination errors of ~17° (at $\lambda = |34°|$) for magnetite and ~25° (at $\lambda = |38°|$) for hematite. In a normal (reverse) polarity field, inclination error is negative (positive) in the northern hemisphere and positive (negative) in the southern hemisphere, thus it is inherently anti-symmetric about the equator (Fig. 12). Obviously, then, paleomagnetic errors due to inclination shallowing can be exacerbated by comparing biased directions from the two hemispheres.

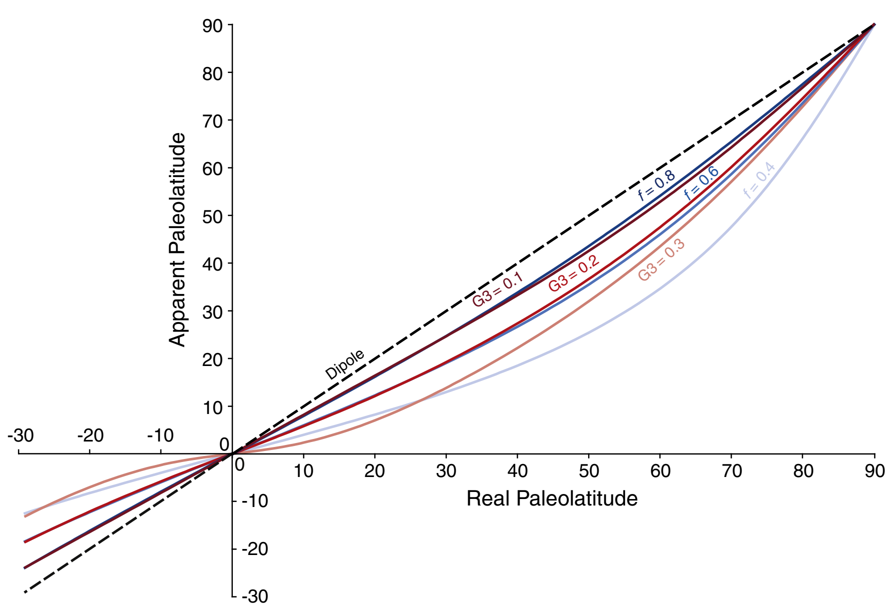


Fig. 12. The effects of a zonal octupole field and inclination shallowing on paleomagnetic determinations of paleolatitude. The dashed black line indicates the reference paleolatitude expected from an ideal dipole (apparent paleolatitude = real paleolatitude). The warm-colored lines illustrate the effects of an increasing octupole contribution: G3 = strength of zonal octupole field relative to an ideal dipole. The cool-colored lines illustrate the effects of increasing inclination shallowing (f = shallowing coefficient, see text). The effects are highly similar (compare the G3 = 0.2 and f = 0.6 curves) and most pronounced at mid-latitudes.

Inclination shallowing is particularly ruinous in that it is generally undetectable from routine paleomagnetic analysis. In studies conducted on one homogeneous formation, or on similar lithologic units, many, if not all, sample inclinations may be similarly biased, whereas magnetic declinations are not affected by inclination shallowing. Two independent methods have been developed to identify and correct for inclination shallowing, neither of which can generally be retroactively applied to published paleomagnetic datasets. The magnetic anisotropy method (Jackson et al., 1991) is built on the premise that an unbiased magnetic recorder must be effectively magnetically isotropic. A sedimentary rock subjected to inclination shallowing, therefore, can be recognized by its departure from magnetic isotropy. The magnetic anisotropy of a rock is a function of both the the magnetic anisotropy of the individual particles and the degree of axial alignment among the particles. If both of these parameters are quantified, they can be used to correct the inclination of a sample. Unfortunately, when magnetic anisotropy is quantified in paleomagnetic studies, which is atypical, it is usually in the form of the anisotropy of magnetic susceptibility, which is an integrative measure of all the magnetic sources (including diamagnetic and paramagnetic contributions), and not exclusively a measure of the orientation of the remanence carrying particles. Moreover, determining the anisotropy of individual particles is an especially time-consuming and tricky operation that is rarely performed (although Bilardello et al. (2011) show that, for hematite, a mean particle anisotropy value of 1.38 may be reliably assumed because its anisotropy is controlled by magnetocrystalline forces). The alternative approach to eliminating inclination bias, the so-called "elongation–inclination" (E/I) method (Tauxe and Kent, 2004), assumes that the distribution of directions in datasets that perfectly capture the full expression of secular variation will exhibit a latitude-dependence that is time-invariant. This latitude-dependence is due to the non-linear relationship between directions and virtual geomagnetic poles (VGPs): as VGP populations are commonly assumed to be circularly symmetric, the distribution of directions cannot be circular, except at very high-latitudes. The distribution of directions faithfully mapped from a circular distribution of VGPs will be elliptical, with the long axis oriented along the meridional (up–down) plane (Fig. 13A); the elongation of this elliptical distribution is latitude dependent, reaching a maximum at the equator. By contrast, a distribution of directions that have been subjected to inclination shallowing will be "squashed", so that the observed elongation is less than expected, or, alternatively, greater than expected but re-oriented so that the elongation is zonal (horizontal) (Fig. 13B). Thus, by comparing the distribution of measured directions with the predictions of a statistical paleosecular variation model, inclination shallowing can be detected and reversed (Fig. 13C). Interestingly, this technique can also be used to detect contributions from octupole fields, which would exaggerate the meridional elongation of directional datasets. The impediment to this method is the requirement that secular variation be fully expressed in the directional dataset; Tauxe et al. (2008) demonstrate that >100–150 independent site-means are necessary to conduct a meaningful E/I analysis. Such large paleomagnetic datasets are exceedingly rare, even among recently published studies. It is possible that the E/I technique can yield reliable shallowing estimates from smaller datasets (~100 samples), where sampling is stratigraphically homogenous and the sedimentation rate is not too high (Bilardello et al., 2011). However, it should be noted that such datasets do not allow for the elimination of sample-level random error, which reduces the effectiveness of the E/I technique.

Despite the difficulty in retroactively identifying inclination shallowing in published results, and the tedious laboratory (for the remanence anisotropy method) or laborious field (for the E/I method) work required to rigorously correct for it, headway has recently been made in the context of late Paleozoic–early Mesozoic paleomagnetism. Kodama (2009) applied the anisotropy of remanence method to the Late Pennsylvanian Glenshaw Formation in Pennsylvania and determined that the magnetite-dominated sequence of limestone and siltstone had a ~10° shallow inclination bias. Bilardello and Kodama (2010b) similarly applied this method (although using a different measurement technique) to Late Mississippian–Early Pennsylvanian hematite-dominated redbeds in the Canadian Maritimes. They ascertained that the Shepody and Maringouin Formations had a shallow inclination bias of ~10° and ~4°, respectively. As discussed by Bilardello and Kodama (2010b,c), the corresponding corrected Carboniferous paleopoles place North America farther south, as the sampling areas were situated in the southern hemisphere at this time and inclination shallowing acts as a low-paleolatitude bias. This correction actually worsens the overlap between North and South America in a Carboniferous Pangea A reconstruction. However, it is likely that if the North American sedimentary-based Carboniferous paleopoles are biased by inclination shallowing, so, too, are the paleopoles from Gondwana. Furthermore, because West Gondwana was situated at mid-latitudes during the mid-to-late Carboniferous, a set of f values, comparable to those from the North American results, would result in a greater inclination error (Fig. 12). In considering the maximum possible effects of inclination error on the Carboniferous reconstruction of Pangea, Bilardello and Kodama (2010c) employed the minimum

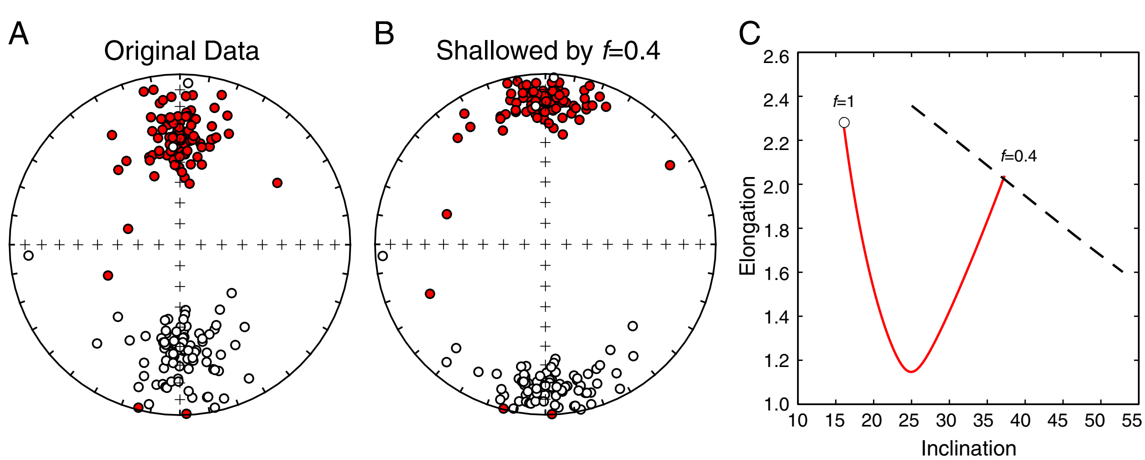


Fig. 13. Illustration of the Elongation/Inclination (E/I) technique for identifying and correcting a shallow inclination bias in a sedimentary-based paleomagnetic record. (A) Data generated from paleosecular variation model TK03.GAD at λ = 20°. (B) Data from (A) after shallowing by $f = 0.4$; note that the direction of elongation in the distribution of data-points has changed from north–south (up–down) to east–west (horizontal) as a consequence of shallowing. (C) Finding the best match to the theoretical E/I curve of Tauxe and Kent (2004) (black dashed line) by assuming different f values and evaluating the change to the data (red line). The best fit, where the red and black lines intersect, is found to be $f = 0.4$.

observed f values to correct the sedimentary-based results from Gondwana, and found that Pangea A could easily be accommodated.

The E/I method has been successfully applied to Late Triassic/Early Jurassic continental sedimentary sequences in North America and Greenland (Kent and Olsen, 2008; Kent and Tauxe, 2005). Kent and Tauxe (2005) examined the paleomagnetic records from the Dan River, Newark, and James Land basins and showed that they have average inclination errors of ~4°, 10°, and 15°, respectively; these correspond to average paleolatitude errors of ~2°, 6°, and 14°. Kent and Olsen (2008) similarly demonstrated that paleomagnetic inclinations from the Hartford basin have an average shallow inclination bias of ~14° (~8° error in paleolatitude). In both studies, the corrected inclinations were found to be in closer accord with the paleomagnetic data from proximal and concomitant igneous rocks, as well as with the paleolatitudes implied by regional paleoclimate data. Although these corrections pertain to magnetizations too young to be directly applicable to the paleogeographic problem of interest here, they importantly affirm the presence of a pervasive shallow inclination bias in typical clastic sedimentary rocks. The Late Carboniferous to Triassic (320–200 Ma) paleomagnetic record from North America, for example, is dominated by results derived from such rocks; in the compilation of Torsvik et al. (submitted for publication) they constitute 60 of the 72 paleomagnetic poles from this interval. The E/I method has also been applied to an Early Permian result from Brazil (Brandt et al., 2009) and to Carboniferous results from Ukraine (Meijers et al., 2010), which yielded paleolatitude corrections of ~1–5°. However, the dataset of Meijers et al. (2010) does not meet the requisite ~100 site/sample means necessary for a rigorous E/I analysis (they used <100 specimens), and the corrections may thus be unreliable.

Because paleomagnetic results derived from sedimentary sequences have not been routinely subjected to tests for a shallow inclination bias, the extent of the bias in any given APWP is difficult to estimate. Kent and Irving (2010) side-stepped this problem in their construction of a Triassic through Paleogene APWP for North America by excluding all sedimentary-derived paleomagnetic poles that were not explicitly checked/corrected for inclination error. Correspondingly, the paleolatitudes that they determined for North America were higher than those calculated from other APWPs, especially those dominated by results derived from sedimentary rocks. Unfortunately, very few igneous-based paleomagnetic results exist for the Early and Middle Triassic, so Kent and Irving (2010) began their analysis at 230 Ma (they retained only one pre-Late Triassic paleomagnetic pole in their dataset). To correct for shallow inclination bias in the paleomagnetic records of earlier time, when igneous-based and inclination-corrected sedimentary poles are scarce, it is necessary to make some assumptions. Torsvik et al. (submitted for publication) assumed an average shallowing coefficient of $f = 0.6$ for all clastic sedimentary sequences and showed an improved agreement in the APWPs of Laurussia and Gondwana through the late Paleozoic–early Mesozoic by correcting for it. In a preceding study, Rochette and Vandamme (2001) concluded that an average shallowing coefficient of $f = 0.5$ could reconcile the paleomagnetic poles from Laurussia and Gondwana in a Pangea A-type fit. To verify the veracity of these average shallowing estimates, in lieu of direct diagnostic tests, Domeier et al. (2011b) conducted a VGP distribution analysis on a set of Permian to Middle Triassic paleomagnetic poles from North America. Following the aforementioned assumption that unbiased VGPs should be circularly symmetric, and that the redbeds from which the poles were derived shared a common shallowing coefficient, they calculated a range of inclination corrections which would "unflatten" the observed (elongate) distribution of combined VGPs. The authors compared the variably-corrected North American APWP against a new igneous paleomagnetic pole and found a good agreement with the use of shallowing coefficient $f = 0.54$, which falls between the assumed values of Rochette and Vandamme (2001) and Torsvik et al. (submitted for publication).

6.2. Age bias

Pangea consistently drifted northward (~8 cm/yr) during the late Paleozoic–early Mesozoic (Steinberger and Torsvik, 2008; Torsvik et al., submitted for publication; Fig. 14). It is obvious, therefore, that a paleomagnetic pole from this time interval with an erroneous age assignment can be expected to generate an error, in the sense that a predicted paleolatitude for the erroneous age will differ from what it should be. However, a globally uniform age bias would result only in absolute paleolatitude errors, where no relative differences would be detectable in the paleomagnetic poles of correctly restored continental blocks. Instead, paleomagnetic discrepancies will arise from regional age bias, such as that arising from systematic errors in intercontinental correlation. For example, the significant difference in the Triassic paleopole positions of North America and Europe (restored to Laurussia) observed by Irving (1977) and Morel and Irving (1981) has been recognized as an artifact of intercontinental correlation error (Kent and Tauxe, 2005, Livermore et al., 1986).

To explain the observed late Paleozoic–early Mesozoic paleomagnetic discrepancy between Laurussia and Gondwana in terms of an age bias, there must be a hemispheric disparity in the age estimate errors (i.e. a hemispheric bias). For example, the age estimates from Laurussia could be erroneously young, relative to the (approximately correct) age estimates from Gondwana. In other words, a comparison of (relatively) old paleomagnetic data from Laurussia and (relatively) young paleomagnetic data from Gondwana will result in a paleogeographic overlap of the landmasses, due to their common and progressive northward drift through late Paleozoic–early Mesozoic time. For example, Rochette and Vandamme (2001) argued that the paleomagnetic discrepancy observed by Torcq et al. (1997) in their 244 Ma A-type reconstruction was due to a hemispheric age bias; the 244 Ma pole of Laurussia was weighted by Permian-age poles, whereas the 244 Ma pole of Gondwana was weighted by Late Triassic-age data (or even Cretaceous age data; see next section). This disparity would act to drive the apparent 244 Ma paleolatitudes of Laurussia and Gondwana toward one another, resulting in continental overlap if an A-type reconstruction is maintained. Rochette and Vandamme (2001) concluded that an A-type reconstruction was permissible in the Triassic, according to the results of Torcq et al. (1997), if the 244 Ma pole of Gondwana was compared with the 214 Ma pole of Laurussia (which may be more equivalent in true age).

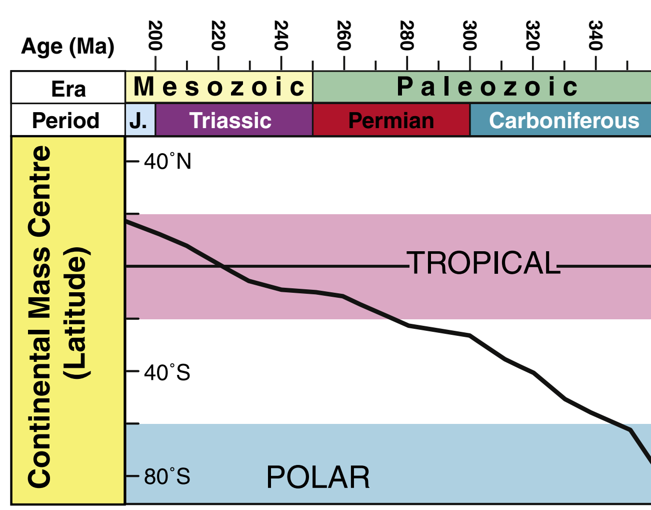


Fig. 14. Paleolatitude of the center-of-mass of Pangea in late Paleozoic–early Mesozoic time, as determined by Torsvik et al. (submitted for publication), showing a steady (~8 cm/yr) northward drift. Center-of-mass is determined from the mean weighted latitude of all continents at any given time and is independent of longitude. Simplified from Torsvik et al. (submitted for publication).

More generally, Van der Voo and Torsvik (2004) revealed the presence of an age bias in the Permian paleomagnetic record of stable Europe, by comparing several mean 250 Ma and 280 Ma paleopoles, calculated from populations of data with varying age estimate reliability (Fig. 15). For both intervals, they found that the mean paleopoles derived from data with higher-quality age estimates yielded higher European paleolatitudes, which suggests that the low-quality age estimates may be biased toward younger dates. Unfortunately, in applying their highest age quality filter, the pole-set of Van der Voo and Torsvik (2004) was reduced from six poles to one (83% rejected) at 250 Ma, and from 27 poles to three (89% rejected) at 280 Ma. These drastic reductions in pole quantity prevent such a filter from being routinely applied, especially to less ample or lower-quality paleomagnetic datasets, such as those from Gondwana. In this respect, an age bias can be one of the most challenging data-pathologies to deal with, as only meticulous attention to newly published or re-assessed age estimates and timescale revisions can resolve unrecognized and enduring age disparities. Fortunately, the marked improvements in isotopic dating over the previous decades have allowed age estimates to be made (or revised) with increasing precision and reliability, so that recent paleopole compilations are much less corrupted by relative age errors than older datasets.

6.3. Contaminated magnetizations

Secondary magnetizations are well-known in the study of paleomagnetism, mostly as a nuisance in the form of a minor overprint, and often parallel to the present day field (PDF). In most cases, the magnetization of interest, the characteristic remanent magnetization (ChRM), must be separated from these secondary magnetizations by demagnetization techniques. If the secondary magnetization is not completely eliminated (or the ChRM completely isolated), the calculated ChRM direction will be corrupted by incorporation of the secondary component(s). Because secondary magnetizations, like a PDF overprint, can be consistently oriented and regionally/lithologically pervasive, an unrecognized or incompletely removed secondary magnetization has the potential to significantly bias a paleomagnetic result. If a consistently-oriented secondary magnetization contaminates an assemblage of ChRM directions of mixed polarity, the bias may cancel out, as the normal and reversed directions would be diametrically modified. Correspondingly, the contamination would then be detectable by the reversal test, which would reveal the normal and reverse mean directions to be non-antipodal. However, in an assemblage of ChRM directions of single polarity, such a bias would not cancel, and a reversal test would not be applicable. This is relevant to the discussion at hand, due to the presence of a long interval of reversed polarity from ~318 to 265 Ma, the Kiaman Reversed Superchron.

Given the low paleolatitude of Laurussia during the late Paleozoic, a primary Kiaman magnetization contaminated with a normal-polarity PDF overprint will be biased downward, toward positive inclinations. The paleogeographic corollary of this bias is an apparent southward shift of Laurussia. Such a bias would affect Kiaman-age magnetizations from Gondwana in an identical manner, resulting in erroneously high southerly paleolatitudes. The effect of a normal-polarity overprint superposed on a late Paleozoic–early Mesozoic magnetization of normal polarity would thus result in paleolatitude estimates for both Laurussia and Gondwana that were too northerly. Van der Voo and Torsvik (2004) tested the Permian paleomagnetic data of Europe for an overprint bias by comparing mean 250 Ma and 280 Ma paleopoles calculated from well-demagnetized vs. poorly demagnetized data, following the assumption that the poorly demagnetized data were more likely to be contaminated by PDF overprints (Fig. 15). For the earlier interval (280 Ma), which falls within the Kiaman, the European paleolatitude derived from the well-demagnetized data was 5° higher than the one derived from the poorly demagnetized results, which supports the contention of a PDF contaminant in the latter. For the younger, mixed polarity interval (250 Ma), the poorly demagnetized data yielded a paleolatitude estimate 3° higher than that derived from the well-demagnetized data, but this analysis was based on very few poles.

Finally, it is worth noting that a complete remagnetization, if unrecognized as such, can affect a paleomagnetic dataset in the

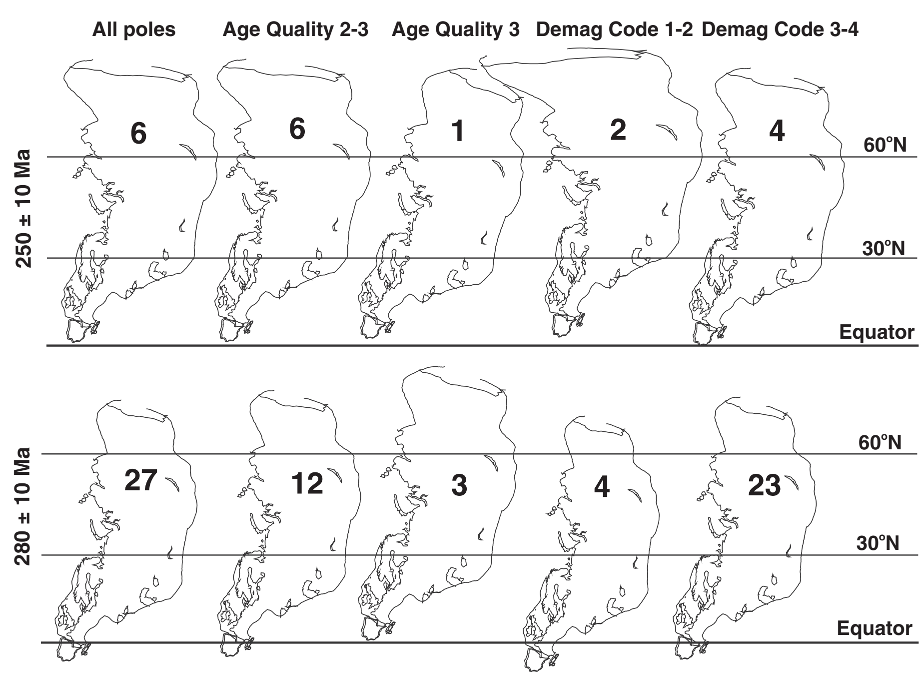


Fig. 15. The paleogeographic position of Eurasia at 280 Ma and 250 Ma according to different data selection criteria by Van der Voo and Torsvik (2004). The bold values denote the number of paleopoles used in each instance to calculate the paleolatitude. For both intervals, the selection of data with the most reliable ages (U–Pb or ^{40}Ar–^{39}Ar methods) results in a northward shift in the estimated paleolatitude. This can be explained by the assignment of erroneously young absolute ages by the outdated geochronologic methods. Selecting the most well-demagnetized data similarly results in a northward shift at 280 Ma, which can be explained by a present-day field magnetization contamination in the less well-demagnetized data. From Van der Voo and Torsvik (2004) with permission from American Geophysical Union.

same manner as an "old-age" bias (where the assigned age is older than the true age of the magnetization). Where field stability tests are not applicable, remagnetized units may be difficult to recognize, especially if the secondary magnetization is not conspicuously different in orientation from the expected direction. This is especially relevant to paleomagnetic data from redbeds, which may acquire their ChRM from a chemical process, millions of years after deposition. As an example of this potential bias, we return to the critical remarks of Rochette and Vandamme (2001) on the conclusions of Torcq et al. (1997). Torcq et al. (1997) used three Moroccan paleomagnetic poles with estimated ages of 238 Ma in the calculation of the 244 Ma mean paleomagnetic pole for Gondwana, which was then used in support of an argument for Pangea B. However, Rochette and Vandamme (2001) noted that in the 50+ sites represented by these three Moroccan paleomagnetic poles, all site mean directions have yielded normal polarity (except one dubious result), and the poles are indistinct from mid-Cretaceous African results. The predominance of normal polarity could therefore be interpreted as an indication that the units were remagnetized during the Cretaceous Normal Superchron, which would imply that the 244 Ma mean paleopole of Gondwana, as calculated by Torcq et al. (1997), is biased by Cretaceous data.

7. Approaching resolution

To succinctly summarize the previous sections: the paleomagnetic data from Laurussia and Gondwana have been repeatedly shown to be incompatible with a Pangea A-type paleogeography for the late Paleozoic, and by some accounts, for the Early to Middle Triassic as well. However, the magnitude and duration of this incongruence have been diminishing with continued study, a trend which suggests that it may simply be a long-lived data artifact. Indeed, it has been demonstrated that several subtle biases may cooperatively act to corrupt the paleomagnetic dataset in such a way as to drive the apparent paleogeographic positions of both Laurussia and Gondwana toward lower latitudes (i.e. toward the equator). This hypothesis is an important potential solution to this paleomagnetic problem, which otherwise requires either a fundamental restructuring of Pangea (unsupported geologically), or adoption of a non-uniformitarian non-dipole geomagnetic field during the late Paleozoic–early Mesozoic (implicitly calls into question all prior conclusions from pre-Mesozoic paleomagnetic work). In the following, we re-evaluate the above hypothesis by re-calculating and comparing the APWPs of the major peri-Atlantic continental blocks in light of the most recent paleomagnetic data, newly refined continental fits, and theoretical inclination shallowing corrections. As we are here concerned with the first-order fit between Laurussia and Gondwana, we omit paleomagnetic data from East Gondwana (Antarctica, Australia, India–Pakistan, Madagascar), which would otherwise introduce additional uncertainty when reconstructed to West Gondwana (due to their less-than-perfectly known reconstruction parameters). However, we note that discrepancies between late Paleozoic–early Mesozoic paleomagnetic data from East Gondwana and West Gondwana/Laurussia remain an important unresolved problem that merits future investigation. One possibility that already appears to be rather evident is that the paleomagnetic results obtained from the detrital sedimentary formations of East Gondwana are very likely in need of inclination-correction. With a complete absence of results from this interval from Antarctica, only Australian igneous rocks are – in principle – suitable for comparisons.

7.1. Data quality

"Data quality" is difficult to evaluate, as it is a subjective measure, but the use of even a crude quality-criterion can be useful in illuminating the impact of any bias that may be present in the form of unreliable or corrupt data. As an example, we consider the difference in the APWPs of North America, Europe, and West Gondwana, as constructed from the updated paleomagnetic dataset of Torsvik et al. (submitted for publication) (Table 1), relative to those constructed by Morel and Irving (1981), following the assumption that newer results are generally of higher quality due to improved laboratory techniques and analytical treatments. We have elected to use the dataset of Morel and Irving (1981) because many of the more recent studies which assert support for Pangea B have focused on a limited interval of time, such as the latest Permian–earliest Triassic (Torcq et al., 1997) or the Early Permian (Bachtadse et al., 2002; Muttoni et al., 2003; Rakotosolofo et al., 2006), rather than considering the complete late Paleozoic–early Mesozoic time frame of interest here. Because the quantity and quality of the available paleomagnetic data are highly variable across this interval, it is important to consider all results in the context of their temporal neighbors; isolated comparisons can be seriously misleading, as expounded in our discussion of the potential sources of bias. Moreover, the conclusions of several of these more recent studies are predicated on the use of data collected prior to 1980 (as noted in Section 4); this data was already included in the study of Morel and Irving (1981).

We constructed the APWPs using a 30-Myr moving window, as was originally done by Morel and Irving (1981), and all APWPs were rotated into African coordinates, according to Bullard et al. (1965) (Table 2; Fig. 16). Unfortunately, significant changes in the reference timescale prevent a direct comparison between specific mean poles of the "new" and "old" paths, but qualitative comparisons of their shapes and trends are nonetheless informative. In the newer APWPs of both North America and Europe there is a clear eastward shift in the Permian segments, relative to the older paths of Morel and Irving (1981), and the trend of the Late Permian–Early Triassic curvature is inverted (Fig. 16A, B). Conversely, the newer path for Gondwana is displaced west, and slightly north, relative to the older one. The Permian segments of the Gondwana paths are more congruous with one another, but the Triassic section of the newer path is more westward convex. These changes result in greater accord between the North America–Gondwana and Europe–Gondwana paths for the Permian–Early Triassic; the great circle distance (GCD) between the paths is reduced on the order of ~5°–10° for this interval (Fig. 16D, E), and their trends are visibly more congruent. We again emphasize that these improvements are free of differences in APWP construction or continental-reconstruction parameters; they are due solely to data selection, which in turn is reflective of the impact of data-quality.

To further consider the reliability of the Torsvik et al. (submitted for publication) compilation, we have conducted a simple data-filtering exercise. We re-calculated the APWPs as before, having excluded all results with ≤29 samples and/or ≤three sites and/or a global paleomagnetic database DEMAG code of ≤two (Table 1). While these specific filter thresholds are admittedly arbitrary, smaller data-sets are less likely to average secular variation, and poorly demagnetized samples are less likely to be purged of secondary magnetizations, so the sample/site quantity and DEMAG code parameters are particularly well-suited for such a quality-filtering exercise. We elected not to apply any age-quality filters (as per Van der Voo and Torsvik, 2004), as the datasets of North America and Gondwana still contain too few high-quality age data for the filtered results to be useful. Moreover, age reliability was already considered in the pole selection by Torsvik et al. (submitted for publication). Upon filtering, the APWPs of North America and Europe change rather little, both exhibiting a minor northeastward shift in the Late Carboniferous–Early Permian (Fig. 16C). The APWP of Gondwana becomes less-well defined with filtering, losing much of its sinuosity, but it does not exhibit any consistent shift in position. The GCDs between the North America–Gondwana and Europe–Gondwana APWPs reveal a small reduction with filtering, supporting the contention that the APWP

Table 1
325–195 Ma paleomagnetic poles from Laurussia and West Gondwana, compiled by Torsvik et al. (submitted for publication). The following criteria were applied in pole selection: to be included, a pole must (1) have a Q-factor of 3 or greater, (2) be tectonically coherent with a continental craton (an exception is made for the Colorado Plateau, where the poles are adjusted by a counterclockwise rotation of 5.4° (Bryan and Gordon, 1990)), (3) not be remagnetized, and (4) have a reliably known age. Poles added to or combined from the original compilation are listed in bold. Plat/Plon = paleopole latitude/longitude. α_{95} = the semi-angle of the 95% cone of confidence about the mean magnetization direction (underlined values are A_{95}, which is the 95% cone of confidence about the mean pole). Age = estimated paleopole age in Ma (based on the timescale of Gradstein et al., 2004). Notes: X (with italicized line) = entry removed during filtering exercise of Section 7.1. * = corrected for inclination shallowing by f = 0.6 in Section 7.3 and Section 8. "i" = inclination shallowing correction applied by original authors. # = corrected for Colorado Plateau rotation (see above). References: Global Paleomagnetic Database reference number (Ref no. in: http://www.ngu.no/geodynamics/gpmdb/) or original reference information.

Formation	Plat	Plon	α_{95}	Age	Notes	Reference
Laurussia						
North America						
Newark volcanics I	−63.0	263.1	2.3	197		1702
Connecticut Valley volcanics	*−65.5*	*267.5*	*11.1*	*197*	X	477
Moenave Fm	−62.5	251.0	2.8	197	#,i	Donohoo-Hurley et al. (2010)
Hartford Newark basalts and volcanics	−68.0	268.5	4.0	197		2278
Watchung basalts	−63.6	268.7	6.2	197		1339
Hettangian Newark red beds	−55.6	274.6	6.0	198	*	2312
Piedmont dikes	−61.5	234.0	7.9	199		1809
North Mountain basalt	−66.4	252.0	10.7	200		1932
Hartford basin	−66.6	268.2	3.2	201	i	Kent and Olsen (2008)
Newark Martinsville core	−67.8	275.8	5.0	204	i	Kent and Tauxe (2005)
Chinle Group, Redonda Fm	−58.5	256.9	8.0	204	*	2979
Chinle Fm	−58.7	250.9	10.7	204	#,*	2800
Chinle Fm, Redonda Member	*−57.8*	*259.3*	*4.2*	*204*	X,*	152
Newark Martinsville core	−64.9	276.6	6.5	204	i	Tan et al. (2007)
Newark Weston core	−58.1	271.8	2.5	207	i	Tan et al. (2007)
Newark Westonville	−66.9	267.2	5.0	207	i	Kent and Tauxe (2005)
Passaic Fm, baked sediments	−65.5	255.1	4.7	211		2791
Passaic Fm	−55.6	274.6	5.6	211	*	2312
Chinle Fm	−56.6	255.9	3.4	211	#,*	2380
Newark Somerset core	−61.7	274.7	4.0	211	i	Kent and Tauxe (2005)
Newark Basin both polarities	−57.6	269.6	3.0	211	*	1339
Taylor Mountain batholith	−61.4	282.2	5.2	212		Symons et al. (2009)
Newark Rutgers core	−60.1	277.1	3.1	214	i	Kent and Tauxe (2005)
Manicouagan Structure, Quebec	−60.1	271.8	7.0	215		434
Manicouagan Structure, Quebec	*−59.0*	*267.6*	*10.0*	*215*	X	443
Popo Agie Fm, Chugwater	*−56.1*	*276.0*	*14.0*	*215*	X,*	1334
Ankareh Fm	−50.5	267.6	7.8	215	*	Weil et al. (2010)
Chinle Fm, Bull Canyon Member	−57.4	267.7	5.6	216	*	2380
Newark Titusville core	−59.9	279.4	3.2	217	i	Kent and Tauxe (2005)
Chinle, Sangre de Cristo	−52.9	282.0	5.1	218	#,*	2979
Dockum Group, Trujillo and Tecovas Fms	−56.4	276.8	7.7	218	*	2944
Shinarump Member, Chinle Fm	−59.6	277.5	5.0	220	#,*	2489
Newark Basin, Lower redbeds	−53.4	281.7	5.0	220	*	2331
Dan River–Danville Basin	−58.5	279.5	2.0	221	i	Kent and Tauxe (2005)
Newark Nursery core	−60.5	281.6	5.0	221	i	Kent and Tauxe (2005)
Abbott Pluton	*−48.3*	*272.3*	*3.9*	*221*	X	1831

Table 1 (*continued*)

Formation	Plat	Plon	α_{95}	Age	Notes	Reference
Newark Princeton core	−54.1	285.2	4.0	227	i	Kent and Tauxe (2005)
Agamenticus Pluton	−48.4	278.5	3.2	228		1831
Upper Moenkopi drillcore	*−54.1*	*288.3*	*2.5*	*230*	#,X,*	160
Chugwater Fm	*−45.2*	*295.4*	*4.0*	*230*	X,*	1266
Upper Moenkopi Fm	*−52.5*	*290.7*	*3.1*	*230*	#,X,*	159
Moenkopi Fm (upper)	−56.5	283.2	4.5	230	#,*	2808
Chugwater Fm	−46.1	293.6	3.3	230	*	1271
Moenkopi Fm (Gray Mountain)	−54.6	284.5	5.0	234	#,*	1221
Moenkopi Fm, Anton Chico Member	−44.7	301.4	4.9	234	#,*	2979
Combined Moenkopi	−57.6	280.3	2.8	234	Com.,*	2489
Moenkopi Fm., CO	−55.6	285.8	4.9	234	#,*	571
Moenkopi Fm	*−41.1*	*305.6*	*5.3*	*234*	#,X,*	2632
Combined Red Peak	−47.3	294.0	5.8	230	Com.,*	1334
Lower Fundy Group	−44.3	271.6	7.2	246	*	Symons et al. (1989)
Dewey Lake Fm	−51.0	306.5	5.0	250	*	2303
Bernal Fm	*−49.9*	*298.1*	*8.0*	*255*	#,X,*	2489
Ochoan red beds	−54.8	299.3	15.0	258	*	688
Guadalupian red beds	−51.5	306.7	5.0	263	*	688
Illinois intrusives	−56.3	302.9	3.8	270		Domeier et al. (2011b)
Downey Bluff sill	*−53.0*	*308.7*	*3.8*	*272*	X	Reynolds et al. (1997)
Hicks Dome breccia	*−54.8*	*292.1*	*8.6*	*272*	X	Reynolds et al. (1997)
Toroweap Fm	*−51.9*	*303.0*	*10.0*	*277*	#,X,*	688
Leonardian subset	−51.7	302.1	5.0	277	*	688
Artinskian Pictou red beds	−42.1	306.5	3.6	280	*	2281
Churchland pluton	*−33.5*	*306.3*	*16.3*	*282*		1264
Fountain and Lykins Fms	*−44.6*	*305.3*	*13.1*	*283*	#,X,*	504
Abo Fm	−46.8	304.0	2.1	285	#,*	1311
Piedmont Mafic intrusions	−38.9	300.8	10.2	289		1527
Upper Casper Fm	−50.5	303.0	1.5	291	*	1455
Elephant Canyon Fm	*−37.5*	*296.6*	*5.0*	*292*	#,X,*	671
Cutler Fm, Lisbon Valley	*−40.1*	*307.7*	*7.1*	*292*	#,X,*	1341
Ingelside Fm	−43.1	307.9	2.0	292	#,*	1142
Cutler Fm	*−41.6*	*300.4*	*2.0*	*292*	#,X,*	671
Minturn and Maroon Fms	−40.1	300.5	2.8	298	#,*	1685
Upper Maroon Fm	*−55.3*	*279.8*	*12.8*	*299*	#,X,*	504
Dunkard Fm	−44.1	301.5	3.9	300	*	302
Laborcita Fm	−42.1	312.1	2.1	301	*	1311
Wescogame Fm	−44.1	303.9	3.4	301	#,*	1311
Lower Casper Fm	−45.7	308.6	1.8	303	*	1455
Glenshaw Fm	−28.7	299.8	3.1	303	i	Kodama (2009)
Riversdale Group	−36.0	302.0	6.0	310	*	1110
Shepody Fm, Nova Scotia	−29.0	298.3	7.7	317	i	Bilardello and Kodama (2010b)
Mauch Chunk	−22.6	294.4	8.3	320	i	Bilardello and Kodama (2010c)
Maringouin Fm, Nova Scotia	−29.7	296.4	15.3	322	i	Bilardello and Kodama (2010b)
Greenland						
Gipsdalen and Fleming Fjord Fms	−52.7	278.7	5.0	209	i	Kent and Tauxe (2005)
Stable Europe						
Kerforne dyke, France	−61.0	259.0	7.5	198		2743
Hettangian-Sinemurian limestone	*−55.0*	*280.0*	*9.0*	*201*	X	3141
Paris Basin sediments	−51.0	285.0	3.0	201		3029
Andesites, Ukraine	−50.0	286.4	4.5	204		Yuan et al. (2011)
Rhaetian sediments, Germany, France	−50.0	292.0	8.0	208	*	3141
Merci mudstone, Somerset	−50.0	308.0	5.1	215	*	3311
Sunnhordland dike	*−50.0*	*305.0*	*4.6*	*221*	X	Walderhaug (1993)

Table 1 (*continued*)

Formation	Plat	Plon	α_{95}	Age	Notes	Reference
Gipskeuper sediments	−49.0	311.0	6.0	226		3141
Taimyr Sills, Siberia	−47.1	301.6	2.9	228		Walderhaug et al. (2005)
Heming limestone, France	−54.0	321.0	3.0	234		2411
Musschelkalk carbonates, Poland	−53.0	303.0	12.0	234		3253
Bunter and Musschelkalk, Germany	−49.0	326.0	15.0	239	*	158
Upper Buntsandstein, France	−43.0	326.0	5.0	243	*	1028
Volpriehausen Fm, Germany	−49.0	348.2	3.8	246	*	Szurlies (2004)
Taimyr basalts, Siberia	−59.3	325.8	7.8	248		Walderhaug et al. (2005)
German Trias, Lower Buntstein	−50.6	345.6	3.3	249	*	Szurlies et al. (2003)
Taimyr Siberian Traps, Siberia	*−59.0*	*330.0*	*10.0*	*250*	X	2832
Siberian Traps, Siberia	−56.2	326.0	3.3	251		Gurevitch et al. (2004)
Kotuy River Siberian Traps, Siberia	−52.7	328.4	13.9	251		Pavlov et al. (2007)
Siberian Traps NSP1 pole	−56.4	321.7	2.1	251		Pavlov et al. (2007)
Sudetes sediments, Poland	*−50.0*	*343.0*	*5.0*	*251*	X,*	3161
Stolbovaya River Siberian Traps, Siberia	−53.3	330.2	5.3	251		Pavlov et al. (2007)
Big Nirundaiver intrusion, sediments, Siberia	−54.3	323.0	5.0	251		Pavlov et al. (2007)
Moyero River Siberian Traps, Siberia	−58.5	314.5	2.7	251		Gallet and Pavlov (1996); Pavlov et al. (2007)
Siberian Traps Mean recalculated, Siberia	−52.8	334.4	9.7	251		Kravchinsky et al. (2002), recalculated
Dome de Barrot red beds, France	−46.0	327.0	2.7	255	*	652
Massif des Maures, France	−51.0	341.0	4.0	255	*	1408
Late Permian sediments, Urals	−45.6	350.2	3.5	260	*	Bazhenov et al. (2008)
Esterel sediments, France	*−47.0*	*331.0*	*5.0*	*261*	X,*	165
Brive Basin sediments, France	−49.0	343.0	4.0	261	*	3144
Permian red beds, Lodeve, France	*−53.0*	*331.0*	*0.0*	*264*	X,*	1207
Lodeve Basin, France	−49.0	334.0	1.5	264	*	1813
Upper Lodeve sandstone, France	*−47.0*	*336.0*	*4.6*	*264*	X,*	168
Saxonian red sandstone, France	*−51.0*	*324.0*	*4.0*	*264*	X,*	2361
Esterel extrusives, France	−51.5	322.0	6.1	264		165
Cracow volcanics B	−50.0	344.0	4.1	269		Nawrocki et al. (2008)
Lunner dikes, Norway	−51.0	343.0	2.5	271		Dominguez et al. (2011)
Lunner dikes, Norway	−53.0	344.0	5.9	271		3188, redated
Bohuslan dikes combined, Sweden	−51.0	345.0	8.6	275		1155
Scania melaphyre dikes, Sweden	−54.0	352.0	11.0	279		2222
Bohemian quartz porphyry, Germany	*−37.0*	*341.0*	*7.0*	*280*	X	3145
Mauchline lavas, Scotland	*−47.0*	*337.0*	*14.0*	*280*	X	3093
Bohemian Massif igneous, Germany	−42.0	346.0	10.0	280		2356
Oslo volcanics, Norway	*−47.0*	*337.0*	*1.0*	*281*	X	915
Ringerike lavas, Norway	−44.6	337.4	13.4	281		1830
Sarna alkaline intrusion, Sweden	*−38.0*	*346.0*	*6.9*	*281*	X	1735
Trachytes, Ukraine	−49.4	359.7	6.5	283		Yuan et al. (2011)
Moissey volcanics, France	−41.0	352.0	6.7	285		1205
Intrasudetic Basin volcanics, Poland	−43.0	352.0	3.2	285		3161
North Sudetic Basin sediments, Poland	*−44.0*	*4.0*	*5.1*	*285*	X,*	3161

Table 1 (*continued*)

Formation	Plat	Plon	α_{95}	Age	Notes	Reference
Krkonose Basin oil shales, Czech Republic	*−40.0*	*346.0*	*2.0*	*285*	X,*	2444
Lower Lodeve sandstone	*−44.0*	*350.0*	*7.7*	*285*	X,*	168
Mount Hunneberg Sill, Sweden	*−38.0*	*346.0*	*6.3*	*285*	X	2211
North Sudetic Basin volcanics, Poland	*−42.0*	*354.0*	*8.1*	*285*	X	3161
Lodeve Basin, France	−42.0	349.0	2.0	285	*	1813
Lodeve B Component, France	*−49.0*	*342.0*	*17.0*	*285*	X,*	2454
Intrasudetic basin sediments, Poland	*−37.0*	*340.0*	*6.8*	*285*	X,*	3161
Krakow volcanics, Poland	*−43.0*	*345.0*	*7.9*	*285*	X	275
Bohemian red beds, Czech Republic	*−41.0*	*345.0*	*4.0*	*285*	X,*	167
Lower Silesia volcanics, Poland	*−40.0*	*352.0*	*13.2*	*285*	X	465, recalculated
Exeter Lavas, UK	−50.0	330.0	4.0	286		461
Black Forest volcanics, Germany	−49.0	356.0	5.9	286		170, recalculated
Exeter Lavas, UK	*−48.0*	*343.0*	*10.0*	*286*	X	411, recalculated
Black Forest rhyolites, Germany	*−42.0*	*353.0*	*1.0*	*286*	X	2941
Thuringer Forest sediments, Germany	*−41.5*	*340.0*	*5.8*	*287*	X,*	1792
Stabben Sill, Norway	*−32.0*	*354.0*	*2.4*	*291*	X	1540
Saar-Nahe volcanics, Germany	*−41.0*	*349.0*	*15.9*	*291*	X	712
Nahe volcanics, Germany	*−46.0*	*347.0*	*13.0*	*291*	X	940
Sudetic Mountain granitoids, Poland	−42.0	346.0	13.0	293		2446
Great Whin Sill, UK	*−44.0*	*339.0*	*4.8*	*294*	X	585
Hadrian's Wall–Pennines Sill and Hett Dike (Whin Sill), UK	*−32.9*	*347.1*	*3.5*	*294*	X	Liss et al. (2004)
Holy Island Sill and Dyke (Whin Sill), UK	*−35.4*	*346.8*	*6.3*	*294*	X	Liss et al. (2004)
Nideck–Donon volcanics, France	*−47.0*	*348.0*	*4.0*	*294*	X	1010
Lower Nideck volcanics, France	*−42.0*	*348.0*	*19.0*	*294*	X	174
Cracow volcanics A, Poland	−44.0	355.0	4.8	294		Nawrocki et al. (2008)
Alnwick Sill, High Green and St. Oswalds Chapel Dyke (Whin Sill), UK	*−47.1*	*337.1*	*8.1*	*294*	X	Liss et al. (2004)
Scania dolerites, Sweden	−38.0	348.0	6.5	294		2222
Scania dolerite dikes, Sweden	−37.0	354.0	11.0	294		2211
Thuringer Forest volcanics, Germany	*−37.1*	*350.0*	*7.1*	*295*	X	1792
Silesia volcanics, Poland	*−43.0*	*354.0*	*13.6*	*296*	X	465
Arendal diabase dykes, Norway	*−42.5*	*339.6*	*7.1*	*297*	X	175
Ny-Hellesund sills, Norway	*−39.0*	*341.0*	*2.9*	*297*	X	626
Peterhead dyke, Scotland	−41.0	342.0	1.3	297		1535
Donets basin, Ukraine	*−43.0*	*345.0*	*3.0*	*297*	X,*	Iosifidi et al. (2010)
Svedlodarsk, Karamysh Fm, Donbas	*−48.4*	*349.8*	*2.4*	*299*	X,*	Meijers et al. (2010)
Mount Billinger sill, Sweden	−31.0	354.0	4.0	299		2211
Donets basin, Ukraine	*−42.0*	*359.0*	*4.0*	*301*	X,*	Iosifidi et al. (2010)
Debaltsevo Donbas, Ukraine	*−48.2*	*342.3*	*2.0*	*303*	X	Meijers et al. (2010)
Wackerfield dyke, England	*−49.0*	*349.0*	*3.0*	*303*	X	180
Queensferry sill, Scotland	*−38.3*	*354.0*	*5.2*	*305*	X	2447
Westphalian–Stephanian red beds, Czech Republic	*−38.0*	*343.0*	*9.0*	*305*	X,*	167
Tashkovska Donbas, Ukraine	*−38.4*	*339.5*	*2.9*	*312*	X	Meijers et al. (2010)
West Gondwana						
Amazonia						
Anari and Tapirapua Fms, Brazil	−65.5	250.3	3.8	197		3316

(continued on next page)

Table 1 (*continued*)

Formation	Plat	Plon	α_{95}	Age	Notes	Reference
French Guyana dikes, Brazil	−81.2	235.1	4.0	198		3378
Bolivar dykes, Venezuela	*−66.9*	*245.6*	*4.9*	*203*	X	150
Dolerite dykes, Suriname	−82.0	320.0	10.0	232		701
Mitu Group red beds, Peru	−71.4	303.6	5.7	249	*	3524
Independencia Group	−80.7	7.0	6.6	260	i	Rapalini et al. (2006)
Multiple Fms., E. Cordillera, Bolivia	−81.8	344.2	3.5	280	*	Gilder et al. (2003a, b)
Copacabana Group sediments, Peru	−68.2	321.3	5.2	280	*	Rakotosolofo et al. (2006)
Santa Fe Group, Brazil	−65.7	330.9	4.1	300	i	Brandt et al. (2009)
Itarare Subgroup, Tubarao Group, Brazil	*−57.0*	*357.0*	*11.2*	*310*	X,*	798
Colorado						
Mendoza sediments and volcanics	−51.0	223.0	6.0	195		Iglesia-Llanos et al. (2006)
Los Colorados Mendoza	−81.8	298.3	7.6	216		Vizán et al. (2004)
Amana Fm, Paganzo Group, Argentina	*−83.0*	*317.0*	*7.0*	*240*	X,*	1132
Puesto Viejo Fm Volcanics, Mendoza	−76.0	312.4	7.3	245		Domeier et al. (2012)
Puesto Viejo Fm Sediments, Mendoza	−87.0	325.0	4.9	245	*	Domeier et al. (2012)
Sierra Chica, La Pampa	−80.1	348.6	3.3	263		Domeier et al. (2011a)
Upper Choiyoi Group, Mendoza	−73.7	315.6	4.1	264		Domeier et al. (2012)
Horcajo, Uspallata Basin, Argentina	−72.4	264.8	12.0	267		2475
Tambillos, Uspallate Basin, Argentina	−80.6	308.3	6.5	270		2475
De la Cuesta Fm., Famatina, Argentina	*−77.2*	*343.6*	*12.2*	*275*	X,*	Spagnuolo et al. (2008)
La Colina Fm, Paganzo	*−80.6*	*268.8*	*2.8*	*283*	X,*	Geuna and Escosteguy (2004)
Middle Paganzo II, Los Colorados Lower Beds, Argentina	*−59.5*	*357.5*	*2.5*	*283*	X,*	620
La Colina Fm, Los Colorados 1, Argentina	*−74.0*	*313.0*	*3.1*	*283*	X,*	166
Cerro Colorado	−79.3	290.6	11.0	275	*	Geuna and Escosteguy (2004)
Rincon Blanco, Paganzo Basin, Argentina	−75.0	291.5	6.7	275	Com.	Geuna and Escosteguy (2004)
La Tabla Fm, Chile	−51.0	347.0	5.7	310		1420
Pular and Cas Fms, Chile	*−57.0*	*350.0*	*9.6*	*310*	X	1420
La Colina, Las Mellizas, Paganzo, Argentina	−67.2	343.7	5.6	310		Geuna et al. (2010)
South Africa						
Red sandstone Fm, Zambia	*−68.0*	*50.5*	*4.6*	*222*	X,*	323
Cassanje Series, Angola	*−54.0*	*80.0*	*6.0*	*249*	X,*	1960
Karroo Basin	*−50.9*	*86.3*	*7.6*	*251*	X,*	De Kock and Kirschvink (2004)
K1 Dwyka Varves, Zimbabwe, Zambia, Tanzania	*−26.5*	*26.5*	*5.6*	*282*	X,*	435
Dwyka Group combined	−25.0	67.0	12.0	315	*	3489
Meseta						
Argana Flows. Morocco	−69.2	55.5	6.0	201		Ruiz-Martínez et al. (submitted for publication)
Moroccan Intrusives, Morocco	*−71.0*	*36.0*	*7.0*	*201*	X	148
Central Atlantic Magmatic Province, Morocco	−73.0	61.3	19.0	201		Knight et al. (2004)
Taztot Trachyandesite, Morocco	*−38.7*	*56.8*	*4.6*	*273*	X	723
Chougrane red beds, Morocco	*−32.2*	*64.1*	*4.7*	*273*	X,*	723
Djebel Tarhat red beds, Morocco	*−24.0*	*63.8*	*7.8*	*273*	X,*	1080
Volcanics, Mechra ben Abou, Chougrane, Morocco	*−36.0*	*58.0*	*20.9*	*281*	X	1859
Somalia						
K3 beds, Galula coalfield, Tanzania	−46.0	40.0	5.0	257	*	324
Northwest Africa						
Ighrem and Foum Zguid dykes, Morocco	−73.0	64.7	4.1	200		Palencia-Ortas et al. (2011)
Zarzaitine Fm, Algeria	−70.9	55.1	2.6	207	*	2932
Abadla Fm., Upper Unit, Algeria	−29.2	60.0	4.5	273	*	3275
Abadla Fm., Lower Unit, Algeria	−29.1	57.8	3.6	275	*	3275
Mezarif Basin sediments, Algeria	−29.3	56.4	3.4	275	*	Merabet et al. (2005)
Upper El Adeb Larache Fm, Algeria	*−38.5*	*57.5*	*2.8*	*287*	X,*	2540
Lower Tiguentourine Fm, Algeria	*−33.8*	*61.4*	*4.1*	*290*	X,*	2728
Merkala Fm., Tindouf Basin, Algeria	−32.4	56.6	2.3	304	*	Henry et al. (1999)
Lower El Adeb Larache Fm, Algeria	−28.7	55.8	3.5	307	*	2540
Illizi Basin sediments, Algeria	−28.3	58.9	4.6	309	*	3484
Reggane Basin, Harsi Bachir Fm, Algeria	−32.8	55.7	2.0	310	*	Derder et al. (2009)
Djebel Reouina Fm., Tindouf Basin, Algeria	−28.4	56.9	1.7	315	*	Merabet et al. (1999)
Oubarakat,El-Adeb Larache Fms, Algeria	−28.2	55.5	4.5	317	*	3481
Reggane Basin, Algeria	−26.6	44.7	5.3	320	*	3402
Northeast Africa						
Upper Triassic Sediments, Southern Tunisia	*−54.9*	*43.3*	*11.5*	*222*	X,*	3020
Al Azizia Fm. Combined, Libya	−57.0	40.3	6.0	231	Com.	3408
Jebel Nehoud Ring Complex, Kordofan, Sudan	−40.8	71.3	6.0	280		3504
Arabia						
Abu Durba sediments, SW Sinai, Egypt	−25.6	64.0	7.2	307	*	2784

separation is, at least in part, an artifact of data-quality. However, the GCD reductions are typically near-negligible, implying that the remaining separation is due to additional factors, and that the unfiltered dataset of Torsvik et al. (submitted for publication) is relatively free of bias due to low-quality data.

7.2. Euler rotations

In testing various Pangea reconstructions with paleomagnetic data, the most significant variables are the Euler parameters. Euler rotations exert a much greater control on the relative positions of the APWPs than data selection or the choice of APWP construction method, as is evident in the differences in relative APWP position according to Pangea A-1, A-2, and B. Yet, the sensitivity of APWPs to Euler parameter adjustments internal to these general frameworks is often overlooked. For example, most paleomagnetic tests of Pangea reconstructions focus only on the fit between Gondwana and Laurussia, implicitly assuming that the other required Euler parameters are comparatively

Table 2
Reconstruction parameters used or discussed in the text. [a,b,c] = parameter used in the construction of apparent polar wander paths in panels (A,B,C) of Fig. 17. European paleopoles of <220 Ma are rotated to North America according to Euler poles interpolated from the 220 Ma and 190 Ma reconstruction poles.

North America to Northwest Africa	Lat	Lon	Angle (deg)	Reference
Pangea A-1[ab]	67.6	346.0	74.8	Bullard et al. (1965)
Pangea A-2	57.3	339.0	89.0	Van der Voo and French (1974)
Pangea B	36.2	356.0	77.4	Morel and Irving (1981)
Labails et al. (2010) model[c]	64.3	345.3	78.1	Labails et al. (2010)
New reconstructions (inc. corrected, $f=0.6$)				
210 Ma	63.2	352.9	79.0	This paper
220 Ma	63.5	339.8	79.1	This paper
230 Ma	65.3	345.9	75.6	This paper
240 Ma	66.3	346.3	74.1	This paper
250 Ma	66.0	341.1	72.0	This paper
260 Ma	65.9	347.4	75.0	This paper
270 Ma	63.4	345.3	77.9	This paper
280 Ma	65.1	345.5	74.4	This paper
290 Ma	67.9	350.7	70.3	This paper
300 Ma	61.8	335.9	76.6	This paper
310 Ma	59.9	338.2	80.6	This paper
Europe to North America[a]	88.5	27.7	−38.0	Bullard et al. (1965)
Europe to North America (310–220 Ma)[bc]	78.6	161.9	−31.0	Alvey (2009)
Europe to North America (190 Ma)[bc]	69.0	154.8	−23.6	Torsvik et al. (submitted for publication)
Greenland to Europe[a]	73.0	96.5	22.0	Bullard et al. (1965)
Greenland to Europe[bc]	65.1	126.1	18.9	Alvey (2009)
South America to Africa[a]	44.0	329.4	57.0	Bullard et al. (1965)
Amazonia to South Africa[bc]	50.0	327.5	55.1	Torsvik et al. (2009)
Colorado to South Africa[bc]	47.5	326.7	57.3	Torsvik et al. (2009)
Arabia to Africa[a]	36.9	18.0	−6.0	Bullard et al. (1965)
Arabia to South Africa[bc]	37.1	17.2	−8.9	Torsvik et al. (submitted for publication)
Northwest Africa to South Africa[bc]	33.6	26.0	2.3	Torsvik et al. (submitted for publication)
Northeast Africa to South Africa[bc]	40.5	298.6	−0.7	Torsvik et al. (submitted for publication)
Somalia to South Africa[bc]	9.9	143.0	−0.2	Torsvik et al. (submitted for publication)
Moroccan Meseta to Northwest Africa[c]	29.4	347.9	5.1	Labails et al. (2010)

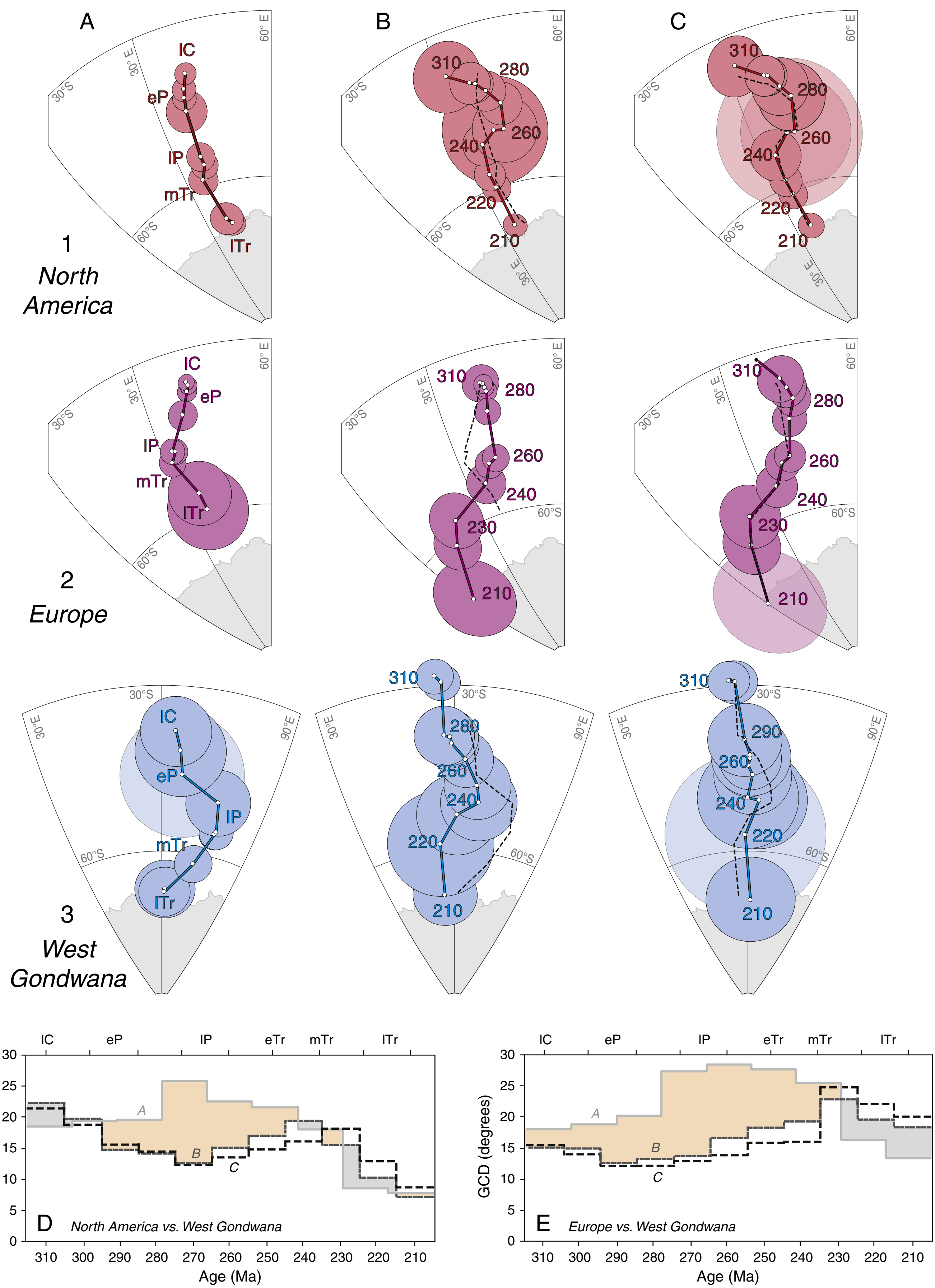
unimportant. A direct comparison of paleomagnetic poles requires rotation to a common reference frame, so a comparison of data from Laurussia and West Gondwana invariably necessitates definition of at least three Euler parameters: Europe vs. North America, South America vs. Africa, and Laurussia vs. Gondwana. The first two parameters are independent of the Pangea A-1, A-2, and (most) B model distinctions, which are defined by the Laurussia vs. Gondwana fit. However, significant inaccuracies in either the Laurussia or the West Gondwana reconstruction could compromise any comparative analysis of the Pangea models. This is especially true for the Europe vs. North America parameter, as the paleomagnetic dataset from Europe is the largest and most reliable for the late Paleozoic–early Mesozoic. In addition to these first-order variables, important internal deformation/rotations have been recognized within some continents (Nuernberg and Mueller, 1991; Torsvik et al., 2008, 2009, submitted for publication), further compounding the uncertainty in relative APWP position that may be independent of the Laurussia–Gondwana fit.

To demonstrate the significance of these parameters, we have re-calculated the APWPs of Laurussia and Gondwana using the unfiltered compilation of Torsvik et al. (submitted for publication) and a series of recently re-determined Euler parameters (Table 2), and compare them with the same APWPs constructed with the conventional Euler parameters of Bullard et al. (1965). Bullard et al. (1965) treated the continents as rigid plates, so reconstruction of the APWPs requires only the three rotations listed above (Fig. 17A). In reconstructing Laurussia according to more recent work, we adopt the Europe vs. North America parameter of Torsvik et al. (2006), which is supported by continental lithospheric extension estimates determined from gravity inversion and seismic refraction profiles (Alvey, 2009). For West Gondwana, we have elected to use the reconstruction parameters of Torsvik et al. (2009), which are based on a relocation of the South Atlantic continent–ocean boundaries (COBs) by analysis of a variety of geophysical data and geological information. Following the earlier work of Nuernberg and Mueller (1991), Torsvik et al. (2009) divide South America into four domains (Amazonia, Parana, Colorado, and Patagonia) and Africa into five domains (NW Africa, NE Africa, Somalia, Lake Victoria Block, and southern Africa), which results in a much improved fit between the restored COBs. We initially keep the Laurussia vs. Gondwana parameter constant (retaining that of Bullard et al., 1965), so that any change in the GCD between the APWPs of Laurussia and Gondwana in our first comparative analysis must be due solely to the Europe vs. North America and/or South America vs. Africa parameters (Fig. 17B). Only minor differences are observed in the APWPs of Gondwana (as constructed according to Bullard et al. (1965) and Torsvik et al. (2009), respectively), but the APWPs of Laurussia are considerably different. The Laurussian path constructed according to Torsvik et al. (2006) exhibits a significant and consistent shift eastward, which is due entirely to the difference in the rotation of Europe. In terms of GCD, the APWPs constructed according to the more recent parameters are an average of 7° closer than those constructed according to Bullard et al. (1965) (Fig. 17D); this improvement represents ~46% of the initial difference between the paths.

Turning next to the fit between Laurussia and Gondwana, we compare the reconstruction parameter of Bullard et al. (1965) with the recently proposed parameter of Labails et al. (2010) (Table 2), which is based on a redefinition of the African COB by Sahabi et al. (2004). We also follow Labails et al. (2010) in applying a minor rotation to the Moroccan Meseta, relative to NW Africa, which improves the congruence of the North America–Africa fit. Because we retain an African coordinate frame, the minor changes to the APWP of Gondwana are due only to this rotation of the Moroccan Meseta (Fig. 17C). The modified rotation of Laurussia results in a northeast shift of its APWP, bringing it into closer proximity with the APWP of Gondwana. This improvement is reflected in the overall reduction of the GCD between these paths, excepting the intervals of 290 Ma and 260 Ma, in which the mean poles are now found to be primarily separated in a North–South direction (orthogonal to the initial separation). The mean 290 Ma and 260 Ma poles of Gondwana are both situated at what appear to be short periods of relatively fast and brief APW; it is likely that these are artifacts of undersampling (or sampling with a poor temporal distribution: there are no Gondwana poles in the dataset between 300 and 290 Ma), and we do not consider these intervals of APWP mis-fit to be critical inadequacies of the Labails et al. (2010) fit. With the adoption of this fit, the GCD between mean poles is consistently less than 10°, and the average separation of 6° is close to the commonly assumed ~5° minimum uncertainty threshold of paleomagnetism (Fig. 17D). Overall, the adoption of these new Euler parameters results in a ~58% reduction in the GCD between the APWPs of Laurussia and Gondwana, relative to our starting point with the parameters of Bullard et al. (1965), an improvement which is independent of data selection or other factors.

7.3. Inclination shallowing corrections

The previous exercises have all but demonstrated that the late Paleozoic–early Mesozoic paleomagnetic Pangea problem is an artifact arising from the inclusion of low-quality data and usage of coarse and/or inaccurate Euler parameters. However, after adopting the updated


A
B
C
1
North America
2
Europe
3
West Gondwana
lC
eP
lP
mTr
lTr
310
280
260
240
230
220
210
290
30°S
60°S
30°E
60°E
90°E
D
North America vs. West Gondwana
E
Europe vs. West Gondwana
GCD (degrees)
Age (Ma)
eTr

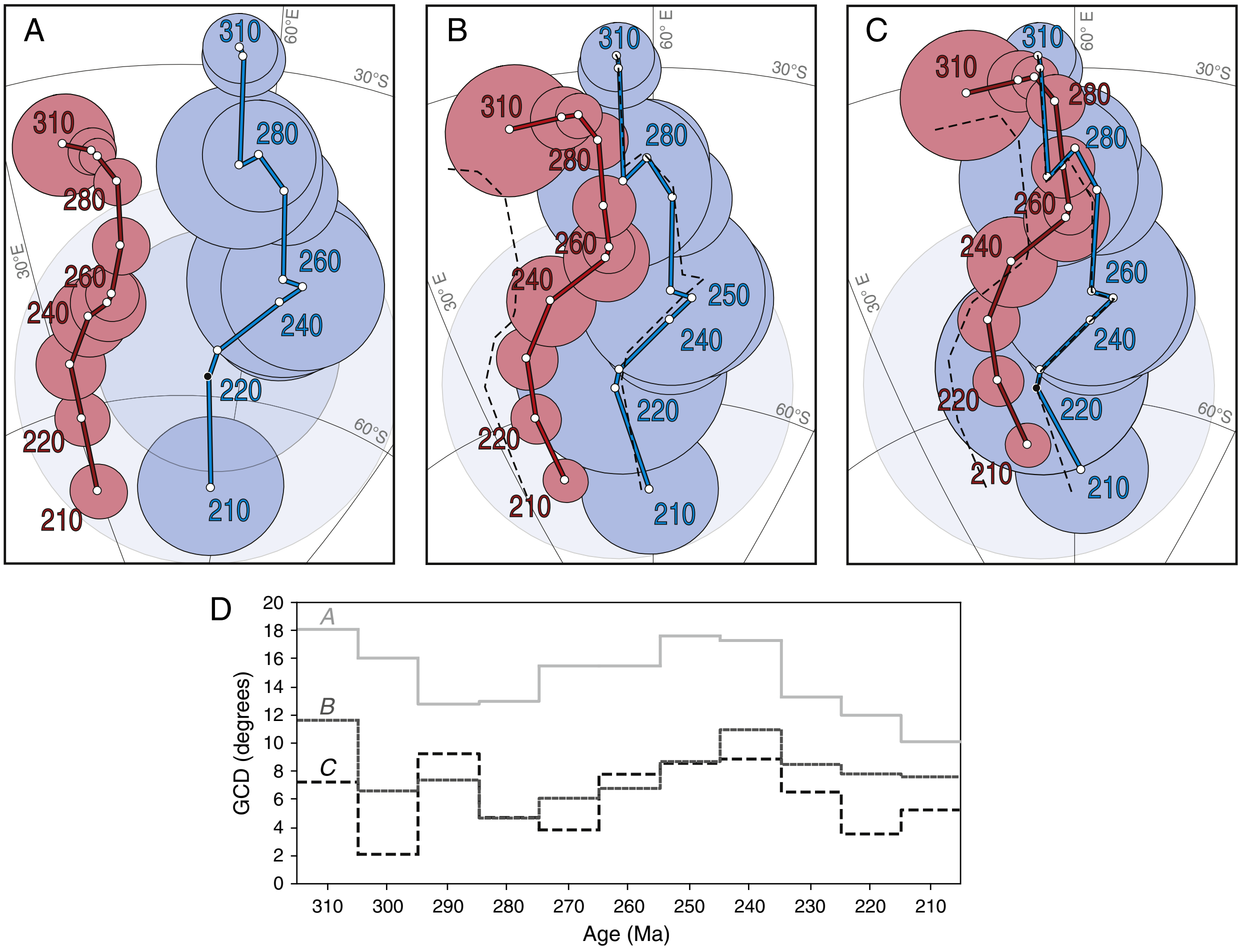


Fig. 17. The significance and influence of Euler rotations as illustrated from a comparative APWP analysis. Panels A–C depict the APWPs of Laurussia (red) and Gondwana (blue) from the paleomagnetic data in Table 1 and using a moving window of 20-Myr. Mean poles with an A_{95} greater than 10° are transparent and poles with a solid symbol are determined from less than 4 results. (A) APWPs according to the Euler parameters of Bullard et al. (1965). (B) Same as panel (A), but using the Laurussia reconstruction parameters of Torsvik et al. (2006) and the West Gondwana reconstruction parameters of Torsvik et al. (2009) (the central Atlantic remains reconstructed according to Bullard et al. (1965)). (C) as in (B), except adopting the central Atlantic reconstruction parameter and the Moroccan Meseta rotation of Labails et al. (2010). The dashed lines in panels (B) and (C) depict the trend of the APWP from the previous (direct left) panel for comparison. Euler parameters are listed in Table 2. (D) GCD between the APWPs of each panel.

rotation schemes discussed above and using the most recent compilation of paleomagnetic data, a significant, albeit smaller, separation remains between the APWPs for the Late Permian–Middle Triassic (Fig. 17C). The paleomagnetic datasets of the interval 270–220 Ma contain a relatively high fraction of sedimentary-based results that have not been checked/corrected for inclination shallowing, suggesting that this bias may be prominent for these times (Fig. 18). In the dataset of Laurussia, 81% (21 of 25) of the constituent paleomagnetic poles for the 250–230 Ma window are derived from sedimentary sequences which have not been corrected for inclination shallowing, the highest proportion in the entire 310–210 Ma interval. In the dataset of Gondwana, 87% (8 of 9) of the constituent paleomagnetic poles for the 260–240 Ma window are derived from uncorrected sedimentary sequences, the highest proportion in its 310–210 Ma dataset.

To check these datasets for the presence of a shallow inclination bias, we have re-calculated the APWPs after removing all clastic sedimentary-based poles that are uncorrected for inclination shallowing (Fig. 19A, B). Accordingly, the 260–240 Ma segment of the Laurussian APWP shifts to the southeast with this treatment, implying that the unfiltered dataset is significantly biased by shallow inclinations in this interval. A less pronounced, but discernable eastward shift is also observed for the 280–270 Ma interval, in which very recent results from igneous rocks in Laurussia take on some prominence (Dominguez et al., 2011; Yuan et al., 2011). Interestingly, a northeastward shift is observed in the 300–290 Ma interval, due to the presence of part of Laurentia in the southern hemisphere at that time, and owing to the valuable inclination-corrected results obtained by Bilardello and Kodama (2010b). The filtered dataset of Gondwana is less illuminating, due to the severe reduction in the quantity of

Fig. 16. The importance of data quality as illustrated from a comparative APWP analysis. Columns A, B, and C depict data from Morel and Irving (1981), Table 1, and a filtered version of Table 1, respectively. The details of the filter are described in the text. Rows 1, 2, and 3 exhibit the APWPs of North America, Europe, and West Gondwana, respectively. Each APWP is constructed from a 30-Myr moving window, as originally done by Morel and Irving (1981), and rotated into African coordinates according to Bullard et al. (1965). Mean poles with an A_{95} greater than 10° are transparent. Mean poles with a solid symbol are determined from less than 4 results. The dashed lines in columns (B) and (C) depict the trend of the APWP from the previous (direct left) panel for comparison. (D) Great circle distance (GCD) between North America and West Gondwana for columns A, B, and C. (E) GCD between Europe and West Gondwana for columns A, B, and C. The orange area highlights the improvement (decreased GCD) between results from columns A and B, whereas the light gray shows intervals of increased GCD.

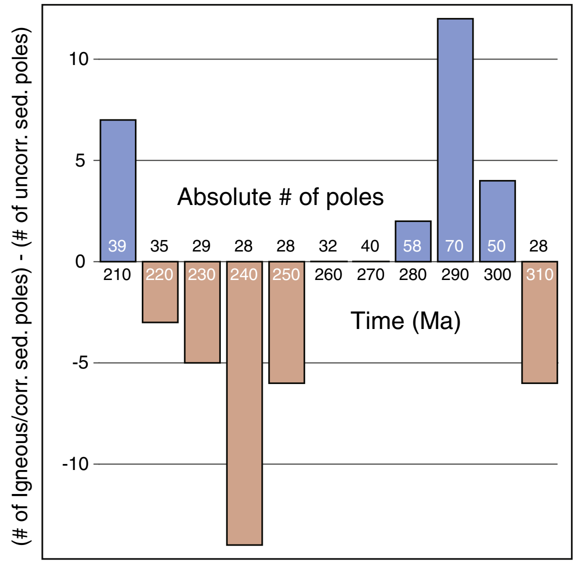


Fig. 18. Difference calculated as: (1) the number of igneous-based/inclination-corrected sedimentary-based paleopoles minus (2) the number of uncorrected sedimentary-based paleopoles (as in Table 1), plotted against time. Time (in Ma) is listed below the central horizontal axis. Each 10-Myr bin includes data from a 20-Myr moving window (for direct comparison with the APWPs) centered on the time listed. The absolute number of poles in each bin is listed above the central horizontal axis.

data; only the 210 Ma and 270 Ma mean poles are built from more than five results (including several new paleopoles from Argentina (Domeier et al., 2011a, 2012)), and the average pole quantity for the 20-Myr moving windows in the 310–210 Ma time-frame is 3.8. Consequently, the filtered APWP is erratic and unreliable for the interval of interest (260–230 Ma).

Following the observations from this filtering exercise, and the identification of a widespread shallow inclination bias in the Permian–Middle Triassic paleomagnetic data of North America by Domeier et al. (2011b), we apply an average shallow inclination correction ($f=0.6$) to all sedimentary-based results that are prone to inclination shallowing, as also done by Torsvik et al. (submitted for publication) (Fig. 19C). The application of this correction to the APWP of Laurussia appears to under-correct the most strongly biased intervals (300–290, 250–230 Ma), while coinciding reasonably well with the filtered mean poles of the remaining intervals (280–260, 220–210 Ma), suggesting that the correction is not excessive. The change evident in the APWP of Gondwana is more pronounced, partly due to the greater proportion of sedimentary-based results in its dataset, but also because Gondwana occupied higher latitudes than Laurussia during the late Paleozoic–early Mesozoic and the correction yields the greatest change at mid-latitudes. We are unfortunately unable to evaluate the pertinence of this correction to the Gondwana dataset, again due to the low-quality of the filtered APWP, but we see no reason to expect that the mechanics of shallowing should have a hemispheric distinction. With the application of this correction, the average GCD between the APWPs is reduced to 4.7°, and only for the 310–290 Ma interval is the separation larger than the uncertainty on the position of the mean Gondwana poles (Fig. 19D). Importantly, this separation is inverted relative to the original problem; the 300–290 Ma mean poles from Gondwana are west of the equivalent mean poles from Laurussia, a separation which does not introduce any unacceptable cratonic overlap, but rather requires a greater distance between the continents than expected by the Labails et al. (2010) fit.

It is worth noting that our use of an average inclination correction is not strictly correct. As aforementioned, f is a function of numerous variables (grain size, sedimentation rate, post-depositional history, timing of magnetization acquisition, size and composition of magnetic carrier, etc.) and will therefore be formation-specific (or even horizon-specific if such variables are prone to substantial intraformational change). However, it will be some time before formation-specific f values are known for the bulk of the (currently uncorrected) sedimentary-based results. In the absence of these specific values, application of an average correction likely offers a more realistic estimate of the true trend of the APWPs, assuming the average correction is reasonably close to the "true" (and unknown) average value. In the compilation of Bilardello and Kodama (2010a), the average f value (from magnetite- and hematite-bearing rocks) is 0.61, with a standard deviation of 0.11, very close to the value of $f=0.6$ assumed above. This assumed value is conservative with respect to the hematite-only average ($f=0.59$), the values determined from re-deposition experiments (not included in the compilation of Bilardello and Kodama (2010a)), and the averaged value calculated from the VGP distribution analysis of Domeier et al. (2011b). Moreover, the appropriateness of the applied average value is independently substantiated by the improved agreement between the sedimentary-based poles and the igneous-only results in the APWP of Laurentia, as described above.

To consider what variability could be anticipated in the position of the APWPs, given the so-far observed variation in f values, we conducted the following numerical exercise: each sedimentary-based paleomagnetic pole (without a known f) was corrected with a random value of f that was drawn from a normal distribution with a mean of 0.61 and a standard deviation of 0.11. 10-Myr mean poles were then recalculated with a 20-Myr moving window, as before (igneous-based poles and previously corrected sedimentary-based poles were still used in the calculation of mean poles); the procedure was repeated 1000 times (Fig. 20). The resulting assemblages of re-estimated poles show various distributions, according to the number of sedimentary-based constituents and the geographic distribution of their sampling sites. Importantly, the re-estimated poles do not fall outside the A_{95} of the original means (which have a constant assumed value of $f=0.6$). This reveals that the variation in formation-specific (and unknown) f values is relatively unimportant, assuming that the average correction is close to the "true" average. This is because pole-specific corrections will only result in local and random mean pole adjustments, whereas a change in the average correction will result in a systematic shift of the entire APWP. Given the f values so-far determined, we contend that the average correction $f=0.6$ is very reasonable, and offers a first-order estimate of the true APWP positions. Future adjustments to the average value and incorporation of pole-specific f values should be made to these initial estimates.

8. Reconstructions

Having confirmed that the paleomagnetic data can be reconciled with an A-type Pangea reconstruction through the 310–210 Ma interval, we now adopt the complimentary approach to reconstructing Laurussia and Gondwana. We assume the Laurussia vs. Gondwana reconstruction parameter to be unknown, and instead reconstruct these landmasses independently according to their paleomagnetic records at each 10-Myr interval between 310 and 210 Ma. For the reconstruction parameters internal to Laurussia and Gondwana, we retain those used in Section 7.2. As longitude is unconstrained by paleomagnetism, the east–west fitting of Laurussia to Gondwana is determined by visual inspection in all instances (Table 2). In each case, we attempt to rotate the landmasses into the closest permissible fit; permissible reconstructions are those that require no more than a few hundred kilometers of overlap of modern COBs. A minor overlap of modern COBs is expected in pre-drift reconstructions, as some extension occurs before continent break-up. For example, the pre-drift (max. closure) fit of Labails et al. (2010) results in ~100 km of COB overlap between North America and NW Africa. Our delimitation of the central Atlantic COBs follows

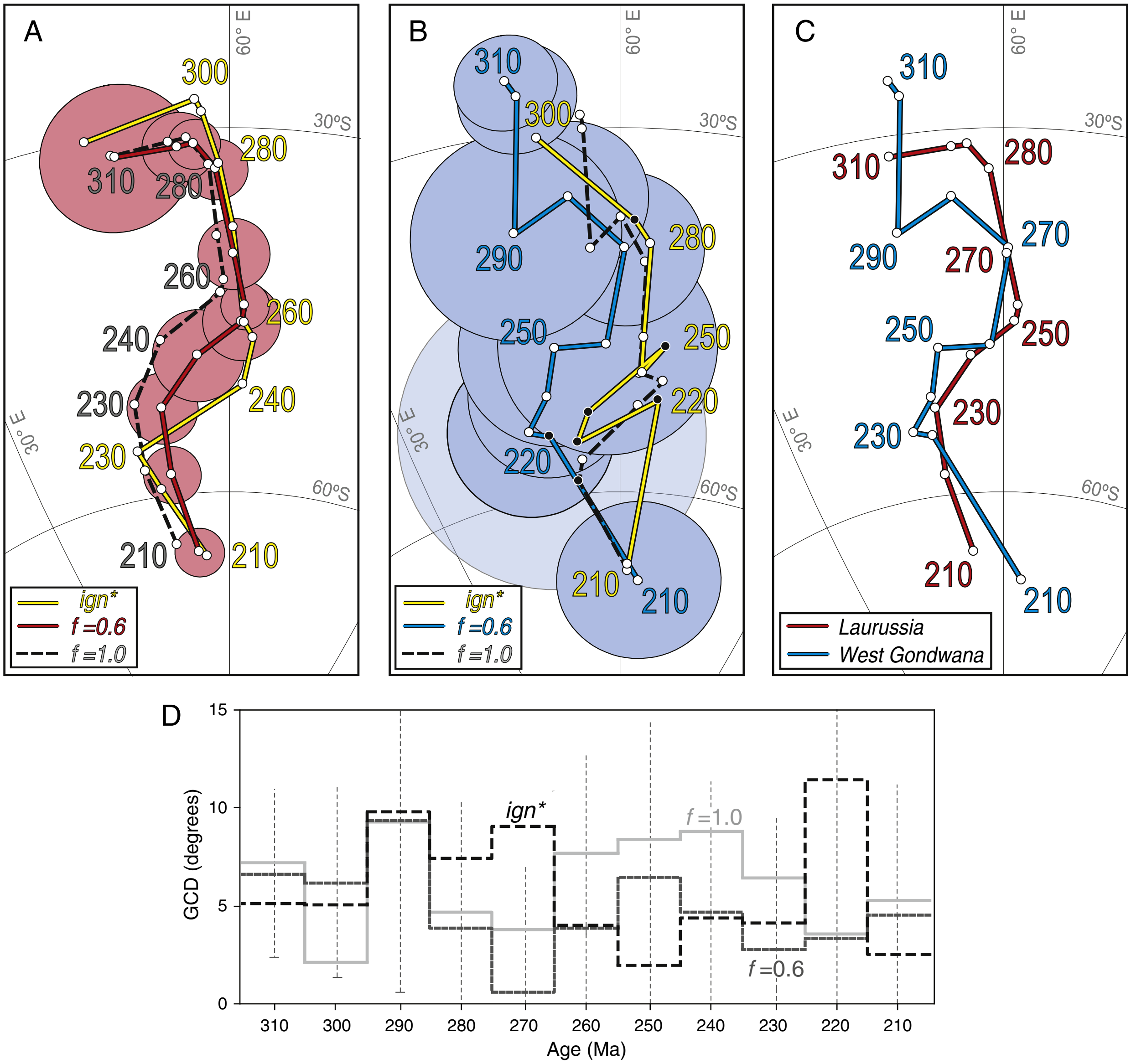


Fig. 19. Tests and corrections for inclination shallowing in the APWPs of (A) Laurussia and (B) Gondwana. In these panels, the APWPs are built from the data in Table 1 and constructed using a 20-Myr moving window and the rotation parameters used in Fig. 17C. The dashed black paths are calculated from the raw data ($f=1$; i.e. no shallowing correction), the yellow paths are calculated from the same data after removing all poles derived from detrital/clastic sedimentary rocks (leaving results derived from igneous and carbonate rocks), and the solid colored paths are calculated after applying a blanket inclination correction ($f=0.6$) to all poles derived from clastic sedimentary rocks. Mean poles with an A_{95} greater than 10° are transparent and poles with a solid symbol are determined from less than 4 results. (C) The solid colored paths (inclination corrected) from panels (A) and (B) for direct comparison. (D) GCD between the APWPs for each treatment. The vertical dashed lines show the extent of the A_{95} error on the Gondwana mean pole estimates, relative to the GCD between poles of the inclination corrected paths. No statistically distinct separation is observed between 280 and 210 Ma.

that of Labails et al. (2010). Following this approach, we can broadly determine which reconstruction is in closest accord with the paleomagnetic data for a given interval in the late Paleozoic–early Mesozoic. We consider the results using both the raw and inclination-corrected ($f=0.6$) datasets (Table 3). It is worth re-iterating here that our use of an average inclination correction is not strictly correct, and the veracity of the derived reconstructions is ultimately dependent on the validity of the assumed (average) correction.

If the raw datasets are used in the Late Carboniferous (310 Ma), reconstruction of the landmasses according to an A-type geometry results in a large COB overlap (350–550 km) between Laurussia (specifically eastern North America and Iberia) and NW Africa. There is also a tight fit between the southern margin of North America and northern South America, so any small relative sinistral translation applied to the landmasses (to reduce central Atlantic COB overlap) will result in cratonic overlap between the Americas, unless Pangea B is adopted. By the latest Carboniferous (300 Ma), a clockwise rotation and northward drift of Laurussia, relative to Gondwana, yields a small paleo-Gulf, ~200–300 km wide, and an excellent fit between Laurussia and NW Africa (~100–250 km of COB overlap) in an A-type geometry. At this time, most of Laurussia has drifted into the northern hemisphere and northwestern Africa is a few degrees south of the equator. With the application of inclination correction (for 310–300 Ma), Gondwana is pulled south, away from Laurussia, resulting in a central Atlantic COB separation of ~200–600 km and a much larger paleo-Gulf between North and South America (~300–900 km wide) (Fig. 21). The applied inclination shallowing correction may therefore be excessive in this interval.

Laurussia and Gondwana continued drifting northward during the Early Permian (290–270 Ma, Fig. 14). If the raw data are used during

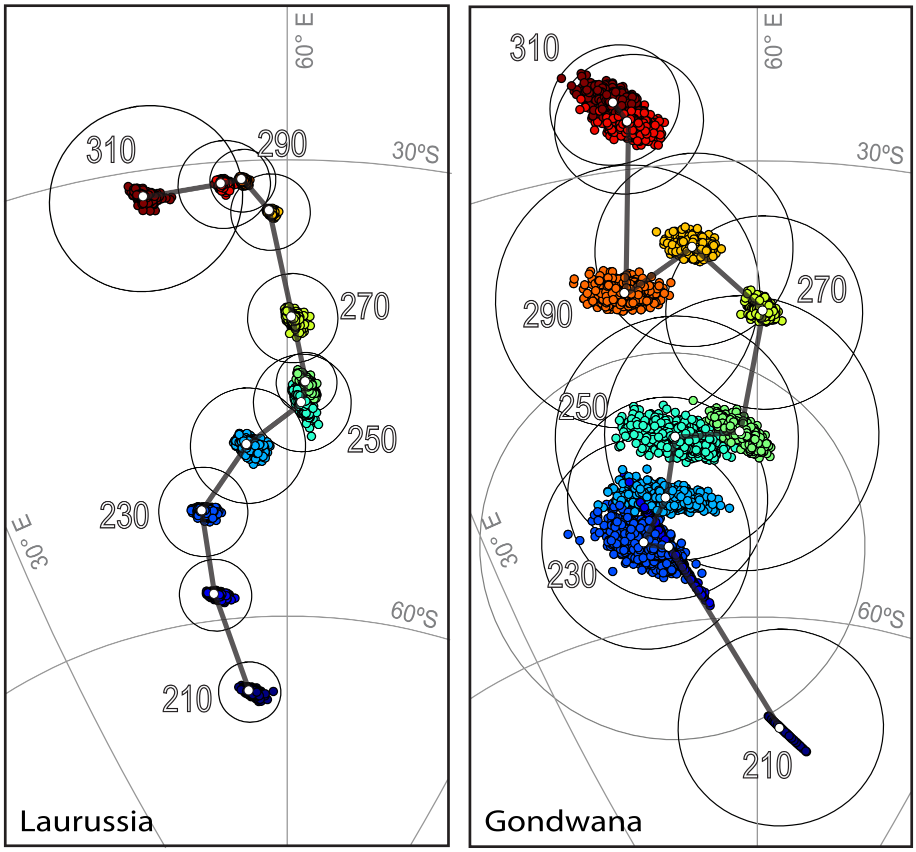


Fig. 20. Numerical examination of potential variation in mean pole positions assuming the so-far observed variation in inclination shallowing coefficients (f), as compiled by Bilardello and Kodama (2010a). The left (right) panel shows re-estimations of the mean pole positions in the APWP of Laurussia (Gondwana). Each panel shows the mean poles re-estimated by: (1) assigning all uncorrected sedimentary-based paleopoles a value of f drawn randomly from a normal distribution with a mean of 0.61 and a standard deviation of 0.11, and (2) re-calculating the mean poles by re-averaging the newly-corrected sedimentary-based poles with the igneous-based and previously corrected sedimentary-based poles. The process is repeated 1000 times (i.e. each mean pole is re-estimated 1000 times). The color scheme was applied to distinguish pole assemblages of different age. The white poles and their A_{95} depict the result using a constant value of $f = 0.6$ (i.e. the mean poles and A_{95} from Fig. 19C). The distribution of re-estimated poles is controlled by the relative number of constituent uncorrected sedimentary-based poles, and the geographic distribution of their sampling sites. Note that none of the re-estimated poles falls outside of the A_{95} on the $f = 0.6$ means.

this interval, and an A-type reconstruction is forced, the COB overlap between Laurussia and NW Africa is large (~300–700 km; greatest at 290 Ma). The North–South America fit is loose at 290 Ma but becomes increasingly tight with decreasing age (tight at 270 Ma). Again, application of a small relative sinistral translation between Laurussia and Gondwana (to relieve some central Atlantic COB overlap) is not possible due to consequent overlap of the Americas and northern Gondwana–southern Europe. With inclination correction, a tight to slightly loose fit (minor to no COB overlap) is achieved between Laurussia and NW Africa, and a wide paleo-Gulf is observed between North and South America (~300–900 km) (Fig. 22).

In the Late Permian, Laurussia and Gondwana continue to drift north and rotate counter-clockwise. Laurussia resides entirely in the northern hemisphere and NW Africa extends to ~10° N (Fig. 23). At 260 Ma, use of the raw data results in large central Atlantic COB overlap (~400–700 km) if an A-type geometry is assumed, and the fit between North and South America remains tight. The inclination corrected data yield an excellent central Atlantic fit and a wide paleo-Gulf (Fig. 23). At the Permian–Triassic boundary (250 Ma), an A-type reconstruction does not appear permissible with the raw data; it would yield ~500–800 km of COB overlap between Laurussia and NW Africa and minor cratonic overlap between North and South America. As before, relative sinistral translation between Laurussia and Gondwana results in additional overlap until a B-type geometry is reached. The $f = 0.6$ correction appears to over-compensate for any bias present in this interval, as it results in a ~350 km separation of the central Atlantic COBs and the paleo-Gulf exceeds 900 km in width.

In the Early to Middle Triassic, Laurussia and Gondwana continue to rotate counter-clockwise, but with minimal northward drift. If an A-type fit is forced with the raw data, the overlap of the central Atlantic COBs peaks in this interval (~600–1000 km at 240 Ma), and significant cratonic overlap between southern North America and northern South America is again observed. The inclination corrected data yield a tight COB fit (no overlap) and a wide (~500–800 km) paleo-Gulf (Fig. 24). In the early Late Triassic (230 Ma), the central Atlantic COB overlap begins to lessen (~300–700 km) with use of the raw data; by 220–210 Ma the overlap is further reduced (~300–600 km). North and South America are tightly fitting to overlapping throughout the Late Triassic; at 230 Ma this overlap is large (~300–400 km). With inclination correction, the central Atlantic fit becomes tight at 230 Ma (minor COB overlap), and the paleo-Gulf is moderately wide (~400–700 km). For 220 Ma, the corrected data yield a good fit of the central Atlantic COBs (0–200 km) and a wide paleo-Gulf (~600 km). No appreciable change is observed with the application of inclination correction at 210 Ma. Both Laurussia and Gondwana continue to slowly rotate counter-clockwise through the Late Triassic, and again begin to drift northward.

In summary, an A-type Pangea reconstruction is permissible for the entire 310–210 Ma interval if the paleomagnetic data from Laurussia and Gondwana are corrected for inclination shallowing (by $f = 0.6$). The specific reconstruction achieved by restoration of

Table 3
Mean 310–210 Ma paleopoles for Laurussia and West Gondwana determined from Table 1. Mean poles were calculated by means of a 20 Myr moving window at 10 Myr intervals. N = number of paleopoles used in the calculation of the mean pole. Plat/Plon = paleopole latitude/longitude. All poles are reported in South African coordinates, using the rotation parameters described in the caption of Fig. 17C (and listed in Table 2). A_{95} = the semi-angle of the 95% cone of confidence about the paleopole.

		Raw poles			Inclination corrected (f = 0.6)		
Age	N	Plat	Plon	A_{95}	Plat	Plon	A_{95}
Laurussia							
210	32	−64.2	50.3	2.1	−65.0	54.4	2.0
220	32	−57.8	47.2	2.3	−58.4	51.1	2.4
230	24	−52.3	47.4	2.8	−52.9	50.9	2.9
240	21	−47.4	51.8	4.1	−48.8	56.1	3.7
250	20	−43.8	59.1	3.9	−46.1	61.4	3.2
260	25	−43.0	59.4	2.3	−44.9	61.7	1.9
270	23	−39.1	58.7	2.8	−40.6	60.5	2.9
280	39	−33.2	58.0	2.6	−33.5	58.7	2.6
290	59	−30.8	55.9	2.1	−31.3	56.6	2.1
300	39	−31.0	54.2	2.9	−31.5	55.1	3.0
310	14	−31.7	48.6	6.1	−31.8	49.0	6.3
West Gondwana							
210	7	−66.6	61.6	6.0	−67.4	63.9	6.7
220	3	−59.0	53.6	15.9	−55.1	50.0	12.7
230	5	−57.3	54.5	9.5	−54.6	47.3	6.9
240	7	−53.0	62.5	6.7	−51.9	50.4	6.6
250	8	−50.9	65.7	7.3	−48.1	52.1	8.0
260	7	−50.4	62.6	8.5	−48.0	58.5	9.0
270	17	−41.3	62.8	5.7	−40.1	60.6	6.4
280	19	−37.6	60.1	5.8	−35.7	54.9	6.5
290	11	−40.1	56.9	8.0	−38.3	49.0	8.7
300	11	−30.1	56.5	3.7	−26.7	50.6	4.9
310	14	−28.9	56.3	3.3	−25.3	49.6	4.3

Fig. 21. Paleogeographic reconstruction for the Late Carboniferous (310 Ma) using the inclination corrected data of Laurussia and Gondwana (Table 3) to restore the landmasses independently. Euler rotations internal to Laurussia and Gondwana are those used in Fig. 17C. The optimal longitude fit between Laurussia and Gondwana was determined by visual inspection (Table 2), as paleomagnetic data offer no constraints on longitude, and was applied by rotating Laurussia along fixed latitude lines, relative to Gondwana. Arbitrary (undefined) longitudes are depicted at 30° intervals for reference. The darker brown areas depict (present-day) submerged continental crust which extends to the continent ocean boundary (COB). The boundaries of the central Atlantic COBs are taken from Labails et al. (2010). The layers are transparent so that crustal overlap is evident by darker shades of color. The Piedmont–Florida terrane has been placed in its present-day position to allow for a comparison between the Atlantic-bordering COBs. In this particular reconstruction (310 Ma), the central Atlantic COBs are separated by ~200–400 km, indicating that the inclination correction (f = 0.6) may well have been excessive in this interval.

Laurussia and Gondwana according to their independent paleomagnetic data is similar to the fit of Bullard et al. (1965), but with a slightly tighter central Atlantic closure, as in the re-assembly of Labails et al. (2010) (Table 2). Even if the paleomagnetic data are *not* corrected for inclination shallowing, an A-type reconstruction is arguably acceptable for the Late Carboniferous (310–300 Ma), the late Early to Middle Permian (280–270 Ma), and the Late Triassic (220–210 Ma). It is only in the Early Permian (290 Ma) and the Late Permian–Middle Triassic (260–230 Ma) that a forced A-type reconstruction will result in untenable continental overlap (again, only in the case that the paleomagnetic data are not corrected for inclination shallowing). Rather than advocate a rapidly evolving paleogeography (alternating between Pangea B and A), we contend that this apparent failure of the A-type model in the Early Permian and Late Permian–Middle Triassic is a manifestation of a recurring data-artifact. Following our earlier arguments and the observation that the paleomagnetic data of the 250–230 Ma interval include a disproportionate number of results derived from clastic sedimentary rocks (Fig. 18), we favor the interpretation that this data-artifact equals a shallow inclination bias.

9. Conclusions

A prominent discrepancy between late Paleozoic–early Mesozoic paleomagnetic data and the most commonly assumed paleogeographic model of Pangea has been recognized (and has persisted) for half a century. Three theoretical solutions have been proposed to resolve this problem: an alternative paleogeographic reconstruction (notably Pangea B), modification to the GAD hypothesis for (at least) late Paleozoic–early Mesozoic time, and eradication of, or correction for, systemic bias in the paleomagnetic data. The former two hypothetical solutions require substantial revision to widely used and well-supported models, whereas the latter solution implies that these models can be reconciled by the use of only the highest-quality data. We have confirmed that the late Paleozoic–early Mesozoic paleomagnetic data from Laurussia and Gondwana can be reconciled with a conventional A-type Pangea reconstruction, using an updated paleomagnetic dataset, recently refined Euler parameters, and theoretical inclination shallowing corrections. Our review of previous work and our comparative analysis of APWPs with/without results derived from clastic sedimentary rocks details support for the presence of a significant shallow inclination bias in such rocks. The longitudinally best-fitting reconstruction of Laurussia and Gondwana, after independently restoring these landmasses to paleolatitudes determined by their respective paleomagnetic data, yields a central Atlantic fit similar to the A-type reconstruction of Bullard et al. (1965). These findings indicate that Pangea can be reconciled with the paleomagnetic data without requiring serious paleogeographic re-structuring or non-dipole fields. We have generated a series of new reconstructions based on our preferred dataset, which may act as a first-order reference to be updated as new data and formation-specific inclination shallowing corrections become available.

Acknowledgments

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Fig. 22. Paleogeographic reconstruction for the Early Permian (280 Ma) using the inclination corrected datasets for Laurussia and Gondwana (Table 3). In this reconstruction, the central Atlantic COBs are closer to each other, relative to Fig. 21, but still separated by ~100–150 km, so the applied inclination correction may again have been somewhat excessive. The paleo-Gulf of Mexico is wide, very similar to the A-1 configuration of Bullard et al. (1965).

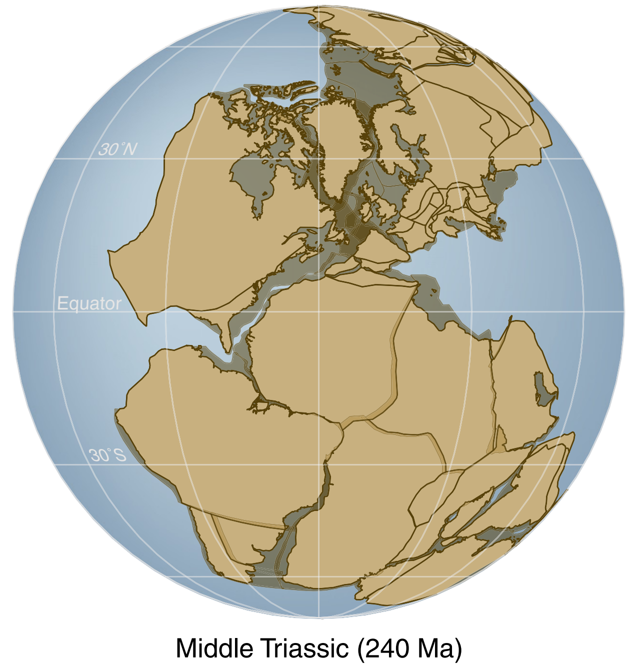

Fig. 24. Paleogeographic reconstruction for the Middle Triassic (240 Ma) using the inclination corrected datasets for Laurussia and Gondwana (Table 3). A loose fit is observed in the central Atlantic, and a sizable paleo-Gulf is present between Laurentia and northern South America. Comparison with Fig. 21 reveals that Pangea has drifted north and rotated counter-clockwise since the Late Carboniferous.

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Fig. 23. Paleogeographic reconstruction for the Late Permian (260 Ma) using the inclination corrected datasets for Laurussia and Gondwana (Table 3). A good fit is observed between the central Atlantic COBs (minor overlap). A significant paleo-Gulf is still present, again in agreement with the A-1 model.

Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.tecto.2011.10.021.

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