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Evidence for late Paleozoic and Mesozoic non-dipole fields provides an explanation for the Pangea reconstruction problems

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Abstract

Paleomagnetic pole positions have long been calculated with the assumption that the ancient geomagnetic field was purely that of a geocentric dipole, but in recent years it has become a concern that this assumption is not always valid because of long-term contributions from non-dipole fields, in particular octupole fields. We tested for the presence of a zonal octupole field in the Late Carboniferous, Permian, Mesozoic and Early Tertiary, by comparing the observed paleomagnetic paleolatitude distributions for the Laurentian (North America and Greenland) and European landmasses with those predicted from the mean paleopoles. Such a test is possible for a good-sized continent (not subsequently deformed) when numerous and reliable paleomagnetic results exist from sites that cover a wide range of paleolatitudes. If the field were purely dipolar, coeval results should form a coherent dataset, such that a regression line through the individual points in an observed versus predicted paleolatitude plot has a slope of 1. If the slopes of regression lines are systematically different from 1.0 for successive time intervals, and granted that the Earth's radius stayed the same, then it is likely that non-dipole fields can be held responsible. Regression line slopes ($\pm$ standard errors) for three intervals analyzed are 0.78 ± 0.04 (200–300 Ma), 0.93 ± 0.11 (120–200 Ma) and 0.82 ± 0.06 (40–120 Ma). As might be expected with a non-dipole contribution to the total geomagnetic field, paleomagnetic results from the most northerly areas of Laurentia and Europe (i.e. Ellesmere, Greenland and Svalbard) show clearly anomalous paleolatitudes. Because of the agreement between the equatorial locations determined independently by paleomagnetism and equatorial rain-forest occurrences [D.V. Kent, P.E. Olsen, Earth Planet. Sci. Lett. 179 (2000) 311–324], we argue that long-term quadrupole fields are less likely than octupole fields to be the cause of the paleolatitude discrepancies. Estimates of the magnitude of the octupole/dipole field ratio are not very precise, but center around 0.1, which could cause errors in conventional paleopole determinations (using the dipole formula) of 7.5°; because of the antisymmetry of octupole fields a comparison of paleomagnetic poles from mid-northern and mid-southern hemisphere locations could thus be off by as much as 15°. The well-known misfit between the paleomagnetic results from the Laurentia–European and Gondwana continents in a classical Pangea A configuration could be explained by such errors due to octupole fields. This explanation would negate the need to seek tectonic (Pangea B-type) solutions for the misfit. These solutions have generally remained unacceptable in terms of the geology of the Gondwana–Laurussia borderzone.

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1. Introduction

In the early days of publishing paleomagnetic results, papers stated explicitly the underlying assumption that the time-averaged geomagnetic field must be purely that of a geocentric axial dipole for the calculated paleomagnetic pole to have validity. In the decades since the 1960s, this assumption has become more tacit, although it has always been known that non-dipole fields contribute significantly to instantaneous geomagnetic field configurations in the historical past [1–3]. To what extent non-dipole fields also are sustained over long (i.e. geological) periods of time has been less certain (e.g. [4–15]) but in recent years analyses of paleomagnetic inclination distributions have refocused attention to this issue [16]. Because the existence of non-dipole fields introduces errors in paleopole positions, tectonic conclusions based on paleopoles and apparent polar wander paths (APWPs) can therefore be systematically in error.

One major tectonic enigma that may be solved by invoking non-dipole fields involves the discrepancy between reconstructions of Pangea based on paleomagnetic data [17–20] and those based on other evidence. Because the Permian–Early Triassic paleopoles from Gondwana do not agree with those from Laurentia and Europe (Laurussia) in a classical Pangea fit (Pangea A1 [21]), paleomagnetists have proposed alternative reconstructions. All these alternatives have in common that Gondwana is placed at more northerly paleolatitudes with respect to Laurussia, either by tightening the fit in the Gulf of Mexico area (Pangea A2 [22]) or, in order to avoid overlap between Gondwana and Laurussia, by placing Gondwana farther east, such that northwestern South America is located adjacent to the Appalachian margin of Laurentia (Pangea B [17,18]). More extreme (Pangea C, D) reconstructions have South America located to the south of southeastern Europe or even Asia [23,24]. For a detailed review of the paleomagnetic context of Pangea fits, see [25]. It is safe to say, however, that none of these alternatives have become widely accepted [26], not in the least because there is consensus that the Atlantic Ocean opened from a Pangea A configuration. This implies that if Pangea B existed before, a transition to Pangea A is required that involved a large (∼3500 km in mostly east–west sense) dextral megashear between the northern and southern continents. The likely locations of this megashear are not characterized by the geological features one would expect in a transpressional/transtensional environment.

Another enigma, but one for which there is no obvious tectonic explanation, is the discrepancy between paleopoles from northerly areas in Laurentia and Europe (e.g. Greenland, Svalbard) with those from the central parts of these landmasses. While it was considered possible until a few years ago that the results from Greenland and Svalbard were perhaps not meeting modern criteria for reliability, recent work [27,28] has been based on modern laboratory and analytical techniques and yet has confirmed the deviating nature of the Permian and Triassic results. The paleolatitudes observed in Greenland and Svalbard are lower than those predicted by extrapolation from mainland Laurentia and Europe. If this were due to relative tectonic movements, Greenland and Svalbard would have to be farther south, which is impossible given the continuity of the Laurussian continental landmass in Permo-Triassic times.

A third example of discordance between paleomagnetic inclinations and generally accepted tectonic conclusions can be found in Central Asia [29–32], where the Tertiary paleolatitudes of terranes such as the Tien Shan, Tarim, Qiangtang, Kun Lun or northern Tibet are much lower than those extrapolated from Europe. If one assumes that Siberia, as the core of Asia, has remained fixed with respect to Europe, this would mean large (∼10–20°) northward displacements with respect to Siberia for times subsequent to magnetization acquisition, and would imply considerable crustal shortening in north-central Asia. The evidence for this shortening, however, is lacking and this has led to the suggestion [30] that non-dipole fields may have been responsible. Alternatively, Cogné et al. [32] have proposed that Siberia and Europe did not remain fixed with respect to each other, transferring the inherently necessary tectonic compression to the area adjacent to the Ural Mountains.

The above-mentioned problems suggest that the purely dipolar model of the magnetic field must be questioned, as was suggested already early on [5]. Yet, comparisons of zonal distributions of climate- and precipitation-controlled facies with paleomagnetic paleolatitudes [25,33–35] are quite satisfactory in equatorial regions. This may be explained by examining the possible components of a non-dipole field: zonal and non-zonal, and quadrupolar, octupolar and higher-order fields. Most analyses of non-dipole fields in Quaternary or Tertiary times have found that they are predominantly zonal, if averaged over geological time intervals [7]. Higher-order fields have generally not been found to be sufficiently large to be a problem. A zonal quadrupole field, denoted by the Gaussian coefficient g_2 (dropping the superscript 0 for convenience), is symmetrical about the equator and causes maximum paleolatitude discrepancies at the equator. In contrast, a zonal octupole field (g_3) causes no paleolatitude deviation at the equator and is antisymmetrical with respect to the equatorial plane. In their analysis of global Precambrian and Paleozoic inclination distributions, Kent and Smethurst [16] found a significant and persistent octupolar contribution, with $G3 = g_3/g_1$ of about 0.25, whereas they could not estimate the quadrupolar field because they merged northern and southern hemisphere and normal and reversed polarity results. For Mesozoic and younger time, the octupolar component was not evident, but could have been present nevertheless to some extent.

This suggests that we should devise a different test for non-dipole contributions to the total field for Late Carboniferous and younger times. For a fairly large-sized continent such as Laurussia with numerous paleomagnetic results, a search for non-dipole (particularly octupole) components is possible by comparing predicted and observed paleolatitude patterns. It should also be noted that uncertainties in the fit between North America and Europe [36], being predominantly east–west, are orthogonal to the effects of a zonal non-dipole field, where the uncertainties are mainly north–south; this means that the choices for rotation parameters to reconstruct Laurussia have very little impact on our analysis.

2. Methodology

The first requirement for our analysis is an abundant paleopole dataset. We have used the

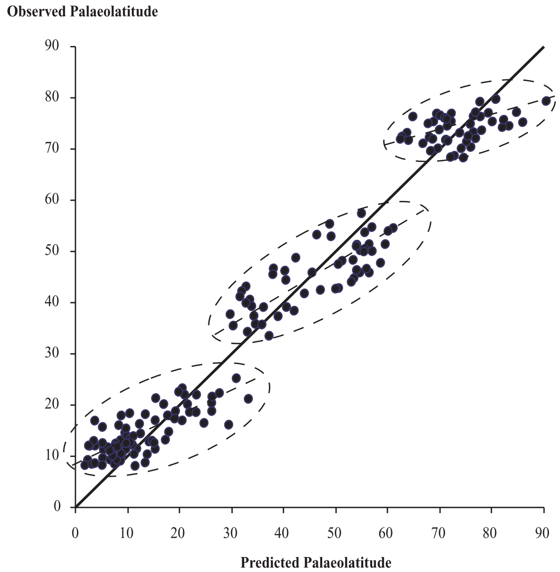
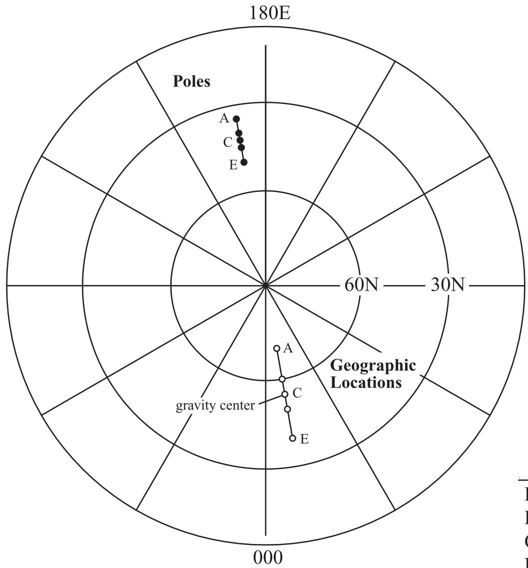
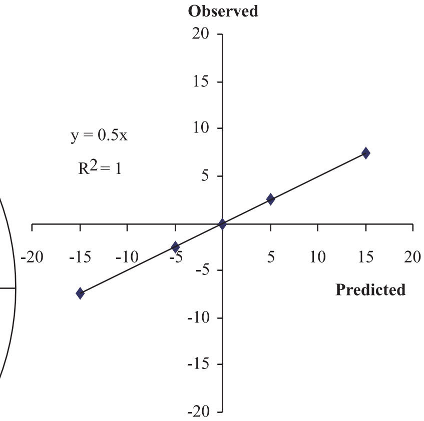


Fig. 1. Three hypothetical paleomagnetic datasets for a continent that drifted progressively northward. The mean poles of each of the three datasets have predicted and observed paleolatitudes that are identical and, hence, yield three points on a line with a slope of 1. Predicted paleolatitudes for these means (where the dashed straight lines and the solid line intersect) are calculated for the 'center of gravity' of all sites from which paleomagnetic results within the dataset are derived, whereas predicted paleolatitudes for individual results are calculated for their own site location. A regression line through a given dataset (dashed line) should also have a slope of 1 if the paleopoles are randomly and evenly distributed about their mean; in contrast, slopes significantly different from 1 (as shown in this hypothetical example) will be observed when a systematic bias occurs in the paleolatitude patterns, such as caused by non-dipole fields.





Site	Pole	Paleolat. Obs.	Centered
E 40, 10	50, 190	0	-7.5
D 50, 10	45, 190	5	-2.5
C 55, 10	42.5, 190	7.5	0
B 60, 10	40, 190	10	+2.5
A 70, 10	35, 190	15	+7.5

Fig. 2. A hypothetical dataset consisting of five paleopoles from five sites (A–E) as listed in the table and portrayed in the equal-area net. Points representing the predicted and observed paleolatitudes are shown to have a regression line with a slope of 0.5, and have been centered on the coordinate origin by subtracting the paleolatitude value (7.5°) of the mean pole C (see text for further explanation).

300–40 Ma paleopoles discussed in the companion paper [36] from North America and Europe. Results with low reliability ($Q < 3$ [25]) as well as all results from displaced terranes have been excluded. Results from Greenland, Ellesmere and Svalbard were not included in this reference dataset, but they have been included in the non-dipole analysis of this study. The North American and European continents were reconstructed as explained by Torsvik et al. [36]. Upon rotation according to the reconstructions, mean paleopoles have been determined with a 20 Myr moving window, at 1 Ma increments. In the paleolatitude analysis described below, an individual paleolatitude observation is compared with the paleolatitude predicted from the mean paleopole that is closest in time (≤ 1 Ma).

For an individual paleopole that matches exactly the mean pole with which it is being compared, the predicted and observed paleolatitude must agree perfectly. Such a result would plot in a diagram of predicted versus observed paleolatitudes (e.g. Fig. 1) on the line with slope of 1.0 (45°). Because Laurussia was steadily moving northward during the Mesozoic, those paleopoles that perfectly match the successive mean poles of the APWP would therefore by themselves all fall on this same line, whereas other results somewhat deviating from the means would scatter about. Fig. 1 shows three groups of hypothetical results, the mean of which each lies on the line with slope of 1.0, but with each group having an internal distribution that is elongated along a (dashed) line with slope possibly different from 1.0 (shown as less than 1.0 in the hypothetical data of Fig. 1). Of course, if the paleopoles in a given dataset are randomly and evenly distributed around the mean, then the slope of this (dashed) line through the predicted versus observed paleolatitudes will be about 1.0. In other words, our analysis rests on the assumption that noise and inaccuracies in the individual paleopoles are randomly distributed, such that a departure from unity slope means that we must seek a systematic departure from the expected (dipolar) model.

Because our time windows are only 20 Myr long, a given window may not contain a sufficient number of paleopoles to yield a meaningful paleolatitude analysis. Instead, we have opted to stack the data for three larger time intervals (300–200, 200–120 and 120–40 Ma), while 'centering' all the individual distributions. This centering is done as follows. The mean paleopole of a given window is used to calculate the corresponding 'reference' paleolatitude at the center of gravity of all sites that contribute to that mean. This center of gravity is calculated simply as the Fisherian mean of the site coordinate vectors. The value of the reference paleolatitude is subtracted from both the observed and predicted paleolatitudes, which moves the mean to the coordinate origin.

This process is further illustrated in Fig. 2 with another hypothetical dataset. For ease of examination, the five sites as well as the five paleopoles are all placed on the same meridian. The five sites span 30° of latitude (paleo- as well as present-day), and if the magnetic field recorded at these sites would be perfectly dipolar, they would all give the same paleopole. In our hypothetical set, they do not behave in this ideal fashion and,

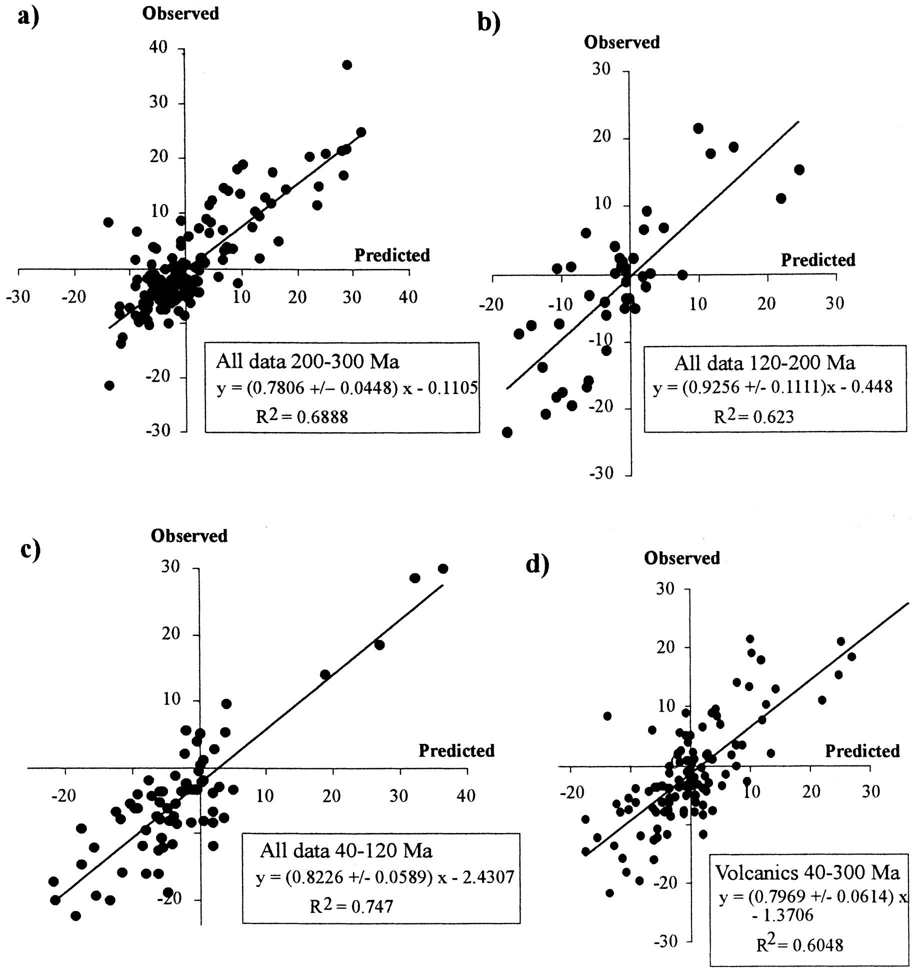


Fig. 3. Predicted and observed paleolatitude values for all Laurussian results (listed in the tables of the **EPSL Online Background Dataset**[1] of [36]) after centering the (moving-window) paleopole means at the coordinate origin and grouping (a–c) into three age bins (300–200, 200–120 and 120–40 Ma). (d) shows results from igneous rocks only for the 300–40 Ma interval to test whether sedimentary rocks have an influence through inclination error on the slopes of the regression lines in (a)–(c). Slopes are shown ± standard errors and for (a), (c) and (d) they are significantly different from 1, suggesting long-term non-dipole contributions to the total geomagnetic field.

moreover, it can be seen that four of the five paleopoles deviate systematically, not randomly, from the mean (pole C) derived from a site at the center of gravity. Centering of this dataset implies that we subtract the paleolatitude of the mean pole (7.5°) from the observed and predicted paleolatitudes. The resulting plot of observed versus predicted paleolatitudes has a slope of 0.5, confirming a systematic cause of the discrepancies.

3. Results

The plots of Fig. 3 display the results of our analysis, following the methodology just described. As mentioned earlier, results from Greenland, Ellesmere and Svalbard are included in the analyses, but not in the mean paleopoles of Torsvik et al. [36]. The dataset is divided into three larger age bins (Fig. 3a–c) and all three plots show a regression line slope less than 1.0, which implies that on average lower (higher) paleolatitudes are observed in locations to the north (south) of the center of gravity than would be expected. Such systematic deviations in the typical range of paleolatitudes covered by Laurussia (10°S–50°N) during Late Carboniferous through Early Tertiary times can be ascribed either to non-dipole fields or to a systematic misalignment of the remanent magnetizations with respect to the ancient time-averaged field. The standard errors associated with the regression slopes are generally small (see Fig. 3), and only for the 120–200 Ma bin is the slope not significantly different from 1.

It is well understood that persistent misalignments of magnetizations could be caused by inclination error or by a superposition of secondary magnetizations (not removed during demagnetization) and primary magnetizations that are all of one polarity only (the 'overprint' effect). Note, however, that if the ancient magnetizations have both normal and reversed polarity, the overprint effects cancel.

The fourth frame of Fig. 3 uses the results from intrusive and extrusive rocks only for the entire interval of 300–40 Ma, because these results are presumably not subject to a systematic inclination error and therefore provide a test that will allow us to choose between two of the just-listed causes for the paleolatitude deviations. It is clear that this volcanics-only dataset also has a slope less than 1 (0.8), comparable to those of the other three datasets that also include sediments. We also analyzed the 300–200 Ma (Permo-Triassic) volcanics-only data separately and again found a slope (0.72) well less than 1. We are confident therefore that inclination error is not the cause of the anomalies. We also discount the 'overprint' effect, for reasons given in Section 4.

4. Discussion

The most likely explanation for the discrepancies between observed and predicted paleolatitudes can be found in the contribution of a long-term non-dipole field to the total time-averaged geomagnetic field. As mentioned in Section 1, a long-term quadrupole contribution would displace the paleomagnetically determined equator from the real equatorial location as determined from paleoclimate and precipitation patterns. Such a misfit, however, is not generally observed [33,34] and was most recently negated by excellent and precise paleolatitudinal results from the Late Triassic basins along eastern North America [35]. Moreover, because of the symmetry of the effects of a quadrupole field about the equator, we would not expect to find a slope much different from 1 in equatorial latitudes, such as prevailed for Laurussia during the Permian. In contrast, the lowest slope would occur in low paleolatitudes if an octupole field made a significant contribution; this is indeed observed, as can be seen by comparing the 300–200 Ma regression line slope with those for younger times, when Laurussia had moved to more intermediate paleolatitudes.

Systematic contamination by overprints of present-day field magnetizations on ancient remanences of one polarity only (e.g. during the long Kiaman reversed interval of the late Paleozoic), will yield inclination patterns that are similar to those of a combined quadrupole–dipole field. This is because the 'overprint' effect is causing inclination deviations in the same sense in the northern and the southern hemisphere, provided that the continents involved drifted northward during their dispersal from Pangea to today's positions (as indeed nearly all Pangea continents did). And, notably, the effect would also be clearly present in rocks magnetized on the magnetic equator, just as would be observed in the effects of a contribution from a zonal quadrupole field. The effects of an overprint would always cause a downwards deviating inclination for the reverse polarity Late Carboniferous–Permian interval in Laurussian rocks, because the normal polarity present-day field overprint is steeply down to the north, and the late Paleozoic reversed directions are shallow and to the south. However, there would be no reason to expect that this effect is systematically variable and a function of latitude in Laurussia. Yet, our results with slopes of less than 45° in Fig. 3 show a systematically variable effect. For these reasons, we argue that the overprint effect is not the cause of the systematic paleolatitude bias.

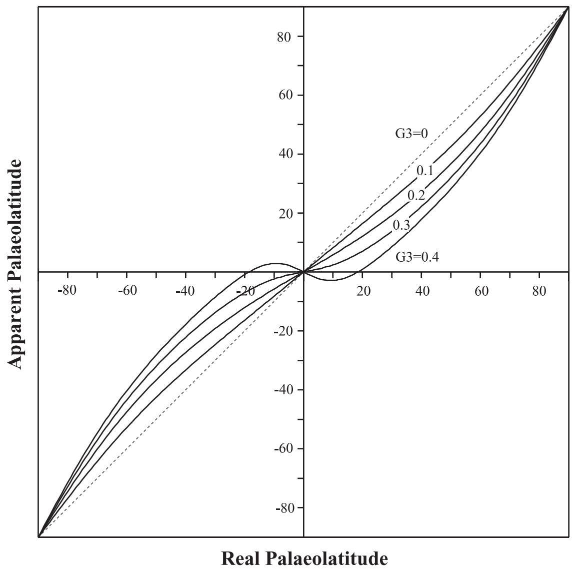


Fig. 4. Real and apparent paleolatitudes plotted with varying octupole contributions added to the dipole field ($G_3 = g_3/g_1$, see text), according to Eqs. 6.25–6.26 in [7]. An apparent paleolatitude is based on the dipole formula without taking octupole fields into account. A slope of 0.8 (~40°) in low latitudes corresponds to a G3 ratio of about 0.1, which best represents the results from Fig. 3.

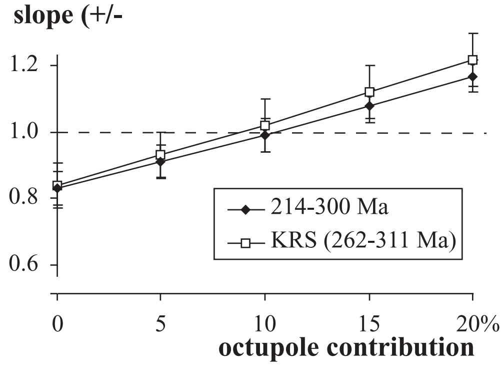


Fig. 5. Slope values of the regression lines through predicted versus observed paleolatitudes (as in Fig. 3) are plotted as a function of the octupole contribution (in %) that was used to calculate the predicted paleolatitudes. Filled diamonds include all paleopoles with ages between 300 and 214 Ma, whereas open squares include only the results from the Kiaman reversed superchron (KRS). For both datasets, an octupole contribution of 10% best fits the data.

A slope of about 0.8 at low latitudes corresponds to an octupole/dipole ($G3 = g_3/g_1$) ratio of about 0.1, as can be seen in Fig. 4. Obviously the slopes of each of the different g_3/g_1 ratios depicted in Fig. 4 steepen with increasing latitude, and a precise comparison would require not only much less scattered data distributions than those of Fig. 3, but also a knowledge about the range of true paleolatitudes covered by the observations. The data points in Fig. 3 are rather scattered, so that a precise estimate of $G3 = g_3/g_1$ cannot be computed from them. We have, however, recalculated all paleopoles in the interval 300–214 Ma with variable G3 ratios (using 0.05 increments up to 0.2), and determined the new slopes of the data distribution using the same technique as used for Fig. 3. Fig. 5 shows that a slope of 45° is attained for G3 = 0.1, which supports our best estimate given above. Fig. 5 also shows these slopes with variable G3 for the dataset of the Kiaman superchron, with a nearly identical distribution that also yields G3 = 0.1 as optimal, illustrating the similarity of the analysis for an exclusively reversed and a mixed polarity interval. Nevertheless, we must stress that these are average values for the intervals used and that G3 may well have temporally fluctuated about this mean value.

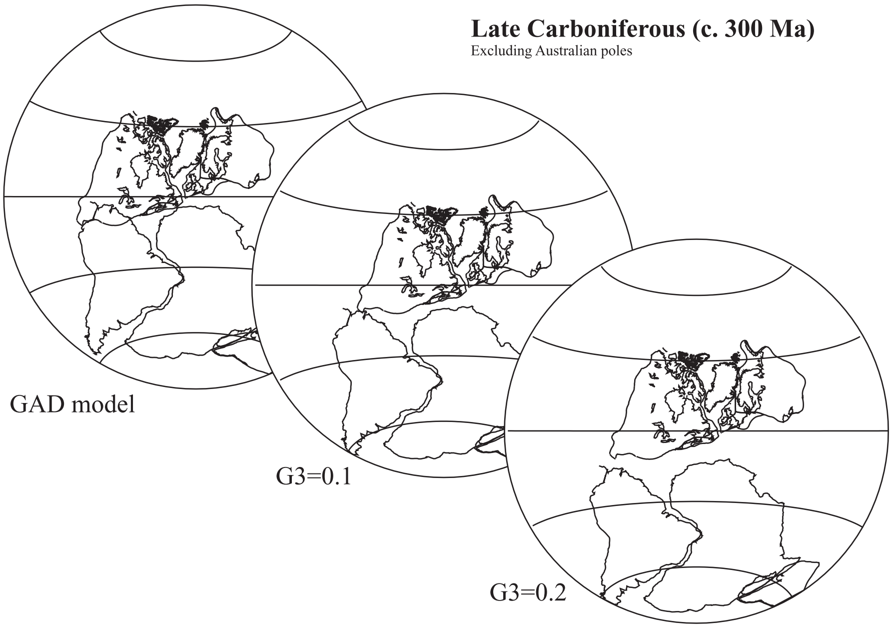


Fig. 6. Pangea reconstructed according to the paleomagnetic data (Tables 1 and 2 in the **EPSL Online Background Dataset**[1]) for the Late Carboniferous ($\sim 300 \pm 10$ Ma), where the paleopoles are calculated with (left) a pure geocentric axial dipole field (GAD), (middle) a dipole field plus a 10% octupole field ($G3 = g_3/g_1 = 0.1$), and (right) with $G3 = 0.2$. Paleolongitudes of Laurussia and Gondwana are not adjusted, and this causes overlap for the continents with the GAD model. Gondwana paleopoles (Table 2 in the **EPSL Online Background Dataset**[1]) do not include Australian results for reasons explained in the text; if these were to be included, only the $G3 = 0.2$ model would not show continental overlap.

It can be seen in Fig. 4 that for $G3 = g_3/g_1 = 0.1$ the paleolatitude deviation in mid-latitudes will be $\pm 7.5°$. The deviation will be such that the predicted paleolatitude will be, on average, that much higher than the observed one. In the northern and southern hemispheres, the effects are of the same magnitude, but with opposite signs, implying that a Late Permian–Early Triassic paleolatitude comparison between, say, Tanzania or northwestern Argentina, on the one hand, and Norway, on the other hand, would possibly be off by 15°. The locations mentioned have indeed provided paleomagnetic results, which have been used in evaluating Pangea reconstructions. As mentioned earlier, an alternative fit such as Pangea B involves moving Gondwana more northerly by a distance of about 10° with respect to its position in a Pangea A1 reconstruction.

We argue that octupole contributions of about 10–20% of the total long-term averaged geomagnetic field in the late Paleozoic to early Mesozoic may remove the need for alternative Pangea reconstructions that have remained unacceptable to most geologists familiar with the Gondwana–Laurussia borderzone. To test this, we have compiled Late Carboniferous (300 ± 10 Ma) and Late Permian–Early Triassic (250 ± 10 Ma) paleomagnetic data from the Gondwana continents in Tables 1 and 2 in the **EPSL Online Background Dataset**[1]. Next we have recalculated the paleopoles, using a formula that includes either a 10% or a 20% contribution of a zonal octupole field ($G3 = 0.1$ or 0.2). Laurussia paleopoles were similarly recalculated individually and combined into a continent-wide mean (Table 1 in the **EPSL Online Background Dataset**[1]). Rotations of the continents into their reconstructions used the Euler parameters of Lottes and Rowley [37]. Australian

[1] http://www.elsevier.nl/locate/epsl, mirror site: http://www.elsevier.com.locate.epsl

poles [38] have been included, but had a large effect, by themselves suggesting G3 values greater than 0.2. It could thus be argued that the Australian results bias the outcome significantly. They could be excluded on the grounds that local rotations in easternmost Australia [38], uncertainties in reconstruction parameters, possible quadrupole contributions, and other problems first need to be sorted out properly, which is outside the scope of this paper. Our present analyses have been performed with and without the Australian paleopoles, and have included all available results with $Q \geq 3$ from South America, Africa, India and Madagascar.

The outcome of this is illustrated in Figs. 6 and 7 for the two time intervals (300 ± 10 and 250 ± 10 Ma). The Gondwana and Laurussia continents were positioned in the paleolatitudes indicated by their mean paleopoles that included G3 = 0, G3 = 0.1 and G3 = 0.2, and in Fig. 7 their relative longitudes were adjusted to resemble as best as possible a Pangea A configuration, without having continent–continent overlap. For the Late Carboniferous, an octupole contribution of 10% is more than sufficient to bring the continents into a Pangea A-type fit, provided that the Australian paleopoles are not included (as shown in Fig. 6). With the Australian results included, a G3 of 0.2 is required to produce a Pangea A-type fit (not shown). For the Late Permian–Early Triassic, a 20% octupole field is required, regardless of whether the Australian paleopoles are included or not. The latter interval is known to be the interval that produces the largest deviations between Gondwana and Laurussia mean paleopoles in Pangea A [25] and, consequently, appears to require the largest G3. From this limited testing, we conclude that octupole fields are quite viable as a possible explanation for Pangea reconstruction problems. A more complete analysis for a much larger slice of Phanerozoic time is planned for the near future.

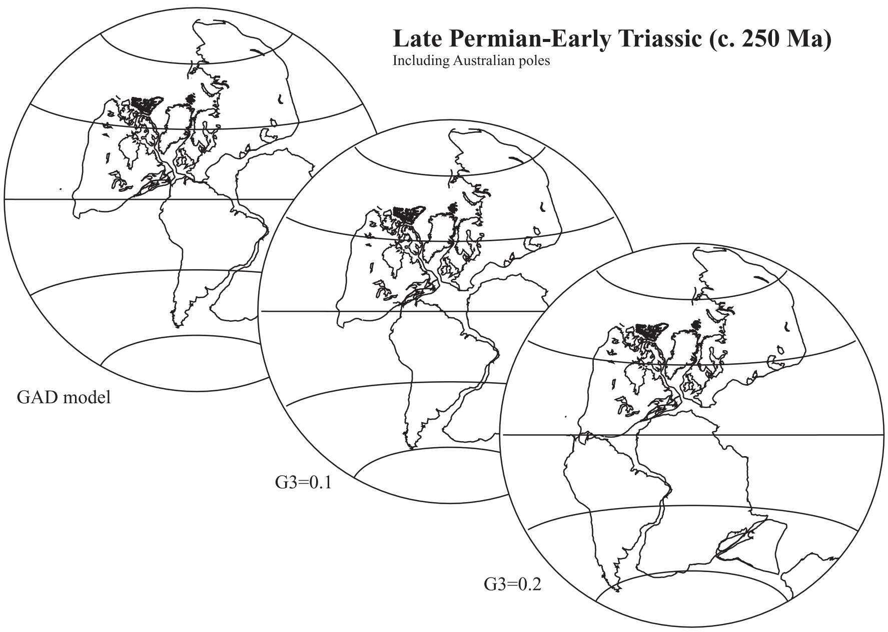


Fig. 7. Late Permian–Early Triassic (~250 ± 10 Ma) reconstructions, as in Fig. 6, but with the paleolongitudes of Laurussia and Gondwana adjusted, so as to avoid continent–continent overlap. Australian paleopoles are included in this analysis (see Table 2 in the **EPSL Online Background Dataset**[1]). The GAD model produces a Pangea C configuration [24], a 10% octupole contribution (G3 = 0.1) produces a Pangea B configuration [17] and a 20% octupole field contribution allows a Pangea A-type [22] configuration.

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