Geophys. J. Int. (2003) **152,** 68–78

Pre-drift extension of the Atlantic margins of North America and Europe based on paths of Permo–Triassic apparent polar wander

Myrl E. Beck Jr and Bernard A. Housen

Department of Geology, Western Washington University, Bellingham, WA 98225, USA

Accepted 2002 July 19. Received 2002 July 9; in original form 2002 February 14

SUMMARY

We reconstruct the relative configuration of North America and Europe prior to separation using paths of apparent polar wander (APW) for the interval 300 to 200 Ma. The Bullard *et al.* (1965) reconstruction closely superimposes the 300 Ma points on the two APW paths but leaves the 200 Ma points far apart. Conversely, anomaly-based reconstructions for later times approximately superimpose the 200 Ma ends of the paths but leave the older ends far apart. This indicates that separation of the interiors of the two continents began during the interval 300 to 200 Ma, long before surficial rifting commenced in the late Mesozoic. This in turn requires pre-rift extension in the two continental margins. Extension appears to have occurred in two phases of approximately equal magnitude but significantly different direction; the change in direction occurred at about 200 Ma. The earlier (300 to 200 Ma) episode of extension appears to have involved a strong element of sinistral shear. Based on our preferred reconstruction, the total amount of pre-rift extension of the two continental margins may have been as much as 1400 km.

Key words: APW, continental rifting, continental stretching.

1 INTRODUCTION

Three independent lines of evidence provide constraints on pre-drift continental reconstructions: continental outlines and associated geological correlations, ocean-floor magnetic anomalies, and curves of apparent polar wander (Frei & Cox 1987). Reconstructions of the North Atlantic bordering continents using each of these methods are similar but far from identical. As recognized by several authors, differences between the results of these several approaches are due in large part to marginal extension immediately prior to and during rifting. Thus, because of extension, one should not expect to find exact correspondence between reconstructions based on palaeomagnetism and reconstructions based on the shape of continental margins. This follows because the former reflect the relative position of the undisturbed cratons (from which most palaeomagnetic poles are derived), whereas the latter are based on the relationship between continental margins that may have extended significantly during breakup. For this reason any valid palaeomagnetic reconstruction should yield some degree of continental overlap, with the amount of overlap providing a rough estimate of extension accompanying rifting (e.g. Fig. 1).

The tectonic significance of the lack of close agreement between palaeomagnetic and other types of reconstructions has been discussed recently by Torsvik *et al.* (2001). These authors employ a large, not highly selected data set to characterize apparent polar wander (APW) for North America and Europe, using a 20 My running mean. Their analysis is well argued and should be consulted in conjunction with this article.

Our approach to this problem is similar but simpler and yields somewhat different results. In particular, it yields a quantitative estimate of pre- and syn-rifting extension that is surprisingly large. Because it relies on curve-fitting and thus requires fairly large sets of high-quality data for accuracy, analysis is limited to the relative motions of North America and Europe and ignores other plates and lithospheric fragments (most notably Iberia and Greenland).

In illustrations throughout this paper, North America is held fixed. In illustrations other than those showing the present configuration of the continents, Greenland is rotated into North American coordinates after Bullard *et al.* (1965).

2 METHODS AND APW PATHS

Our analysis consisted of two steps. First we compiled lists of reliable palaeomagnetic poles for stable Europe and North America. The time interval considered was Permian through earliest Jurassic; ∼300 to 200 Ma. We chose this interval because it encompassed the initial steps leading to the breakup of continents around the North Atlantic, and also because, as will be seen, the distribution of palaeomagnetic poles for this interval can be fit reasonably well by a single small-circle path. To compile the list, we consulted the IAGA database, examining all poles for stable regions of North America and Europe that have been published since 1970. Several poles not

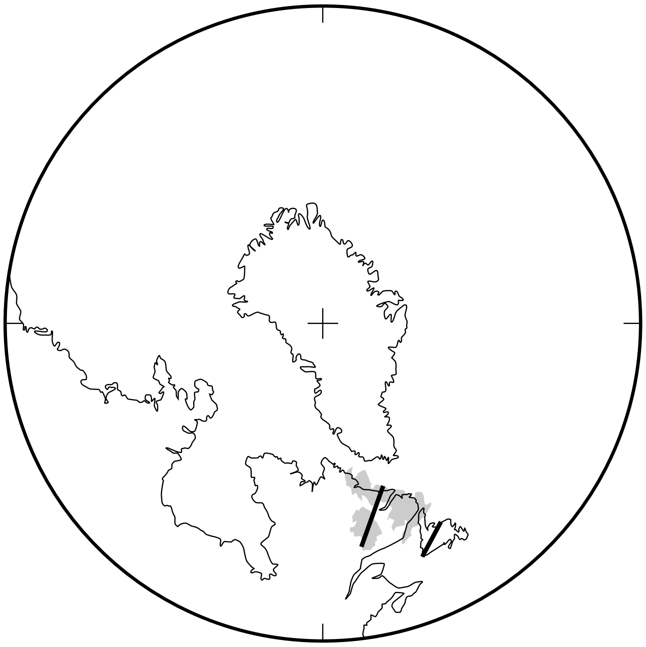

Figure 1. Restoring northern Europe to its pre-drift location relative to North America using the purely palaeomagnetic reconstruction of Frei & Cox (1987) results in unacceptable overlap. Lines crossing Newfoundland and the British Isles represent the Iapetus suture, after Phillips *et al.* (1976) and Williams *et al.* (1972).

yet included in the IAGA list also were used. We rejected any pole from rocks about which there appeared to be substantial uncertainty regarding either age or structural setting. Some useful data no doubt were omitted, but for this type of analysis it is important to err on the side of caution. Poles included are listed in Tables 1 and 2. In Table 1, poles from southwestern US (essentially the Colorado Plateau region) have been rotated clockwise 10.5° about a rotation pole located at 35°N. 102°W (Kent & Witte 1993; Steiner 1998; Beck & Housen, submitted). Alternative calculations using smaller rotation angles degraded the fit of North American poles to a small circle, but changed the overall results of our analysis very little.

The second step was the purely mechanical one of fitting small circles to the list of poles; results summarized in Table 3 and illustrated in Fig. 2.

Table 1. Permian to earliest Jurassic palaeomagnetic reference poles for stable North America.

#	Unit	Age	λ	ϕ	N	A_{95}
1	Moenave Fm	200	60.6	71.3	22	4.7
2	Newark igneous rocks	200	63.0	83.2	10	2.3
3	Newark baked sediments	200	59.7	68.8	23	4.7
4	Newark volcanics, CT, NJ	200	66.3	97.3	3	5.0
5	Upper Newark Fm	205	54.8	94.4	9	6.6
6	Church Rock Fm/Chinle Grp	205	57.5	82.6	8	8.4
7	Redonda Fm/Chinle Grp	215	57.9	102.8	5	7.1
8	Owl Rock Fm/Chinle Grp	215	57.0	86.1	13	3.1
9	Middle Newark Fm	215	56.9	97.5	9	6.2
10	Manicouagan impact structure	215	59.6	90,2	10	6.1
11	Upper Shale Fm/Chinle Grp	220	54.8	103.2	16	5.5
12	Petrified Forest Fm/Chinle Grp	220	57.2	87.7	65	3.0
13	Garita Creek Fm/Chinle Grp	225	50.4	102.8	12	4.4
14	Bluewater Creek Fm/Chinle Grp	225	52.6	104.3	8	7.9
15	Lower Newark Fm	225	53.1	108.5	8	6.1
16	Maine plugs	225	48.3	97.1	12	2.3
17	Ankareh Fm, Wyoming	235	51.3	103.9	3	10.1
18	Cross diatreme, British Columbia	240	49	115	11	6
19	Anton Chico Mbr/Moenkopi Fm	240	39.6	129.4	38	3.6
20	Moenkopi Fm	245	52.4	117.9	3	2.7
21	Red Peak Mbr/Chugwater Fm	245	47.7	113.2	15	4.1
22	Bernal Fm	250	47.2	126.3	3	4.1
23	Dewey Lake Fm, New Mexico	250	57.6	106.5	5	7.5
24	Dewey Lake Fm, Texas	250	51.5	126.1	16	4.6
25	Ochoan seds, SW US	255	45.3	133.6	6	3.9
26	Pegmatites, Connecticut	260	35.4	131.9	5	7.4
27	Guadalupian seds, SW US	265	45.5	125.5	6	4.9
28	Pictou red beds	270	41.1	124.5	12	3.4
29	Cutler Formation, Colo & Wy	270	37.1	130.3	71	2.8
30	Ingelside Fm, Colorado	270	45.9	122.1	34	2.0
31	Leonardian seds, SW US	275	49.9	139.8	7	11.3
32	Abo Formation	275	49.7	118.3	84	2.1
33	Elephant Canyon Fm, Utah	280	36.7	130.9	3	7.8
34	Casper Fm., Wyoming	280	50.6	123.4	72	1.5
35	Wolfcampian seds, SW US	285	45.3	133.6	15	6.5
36	Laborcita Formation	290	43.3	132.2	114	1.0

λ, ϕ are north latitude and east longitude of palaeomagnetic pole. N, number of sites. A_{95} is radius of circle of 95 per cent confidence around pole. Age given to nearest 5 My. References: (1) Ekstrand & Butler (1989); (2) Smith & Noltimier (1979); (3) Kodama *et al.* (1994); (4) Prevot & McWilliams (1989); (5) Witte & Kent (1990); (6) Kent & Witte (1993); (7) Reeve & Helsley (1972); (8) Bazard & Butler (1991); (9) Witte *et al.* (1991); (10) Larochelle & Currie (1967); Robertson (1967); (11) Bazard & Butler (1991); (12) Steiner & Lucas (2000); (13) Molina-Garza *et al.* (1996); (14) Molina-Garza *et al.* (1998); (15) Witte & Kent (1989); (16) Fang & Van der Voo (1988); (17) Grubbs & Van der Voo (1976); (18) Wynne *et al.* (1992); (19) Molina-Garza *et al.* (1991); (20) Helsley & Steiner (1974), Molina-Garza *et al.* (1991), Purucker *et al.* (1980); (21) Van der Voo & Grubbs (1977), Shive *et al.* (1984), Herrero-Brevera & Helsley (1983); (22) Molina-Garza *et al.* (1996); (23) Molina-Garza *et al.* (2000); (24) Molina-Garza *et al.* (1989); (25) Peterson & Nairn (1971); (26) DeBoer & Brookins (1972); (27) Peterson & Nairn (1971); (28) Symons (1990); (29) Helsley (1971), Gose & Helsley (1972); (30) Diehl & Shive (1979); (31) Peterson & Nairn (1971); (32) Steiner (1988); (33) Gose & Helsley (1972); (34) Diehl & Shive (1981); (35) Peterson & Nairn (1971); (36) Steiner (1988).

3 WHY SMALL CIRCLES?

The method of characterizing APW by use of small circles (the palaeomagnetic Euler pole–PEP–concept) originated with Gordon *et al.* (1984). These authors reasoned that, if APW is the result of the movement of lithospheric plates with respect to the earth's spin axis, it follows that the mathematics used to describe plate displacements should apply equally to the apparent displacement of the palaeomagnetic pole. Gordon *et al.* (1984) showed that Permian through Cretaceous APW of North American could be described reasonably well by two small circles—that is, by two periods of uniform rotation, separated by a single episode of abrupt change (the so-called 'J1 cusp') at about 200 Ma Subsequently May & Butler (1986) suggested that a better fit can be obtained by adding another small-circle (and thus a second cusp, at about 160 Ma), although this has engendered considerable controversy.

The logic underlying the PEP concept seems impeccable, but its use has been criticized. Several authors (e.g. Beck 1989; Van der Voo 1993) have expressed doubt that plate motions can be characterized adequately by smooth motion about a single stationary Euler pole for periods as long as 10^7 to 10^8 yr, as postulated originally by Gordon *et al.* (1984). In view of the low momentum of even the largest plate, plus the range of geological 'edge effects' that can significantly

Table 2. Permian to earliest Jurassic palaeomagnetic reference poles for northern Europe.

#	Unit	Age	λ	ϕ	N	A_{95}/α_{95}
1	Sediments, Paris Basin (core)	200	57.4	106.9	16	*3.1*
2	Hettangian-Sinemurian seds	200	55.3	99.8	3	11.2
3	Rhaetian seds	207	50.3	112.0	5	8.1
4	Mercia Mudstone, England	212	49.6	128.4	27	*5.1*
5	Carnian seds	223	49.5	130.8	4	6.6
6	Muschelkalk, Poland	225	53.4	123.2	5	*12.3*
7	Entroque limestone	234	53.5	140.8	19	*3.4*
8	Lunner dikes, Norway	242	53.4	166.9	4	14.8
9	Voltzia ss, France	245	43.1	145.7	49	4.8
10	Massif des Maures pelites, Fr	255	51.2	160.7	9	4.3
11	Zechstein, Poland	255	50	163	18	4.9
12	Brive basin seds, France	260	48.8	162.5	15	2.6
13	Saxonian pelites, Fr	265	48.6	153.5	6	1.2
14	Saar-Nahe igneous rocks, Ger	265	44.6	167.6	6	*15.0*
15	Black Forest seds & volcs, Ger	270	48.5	174.7	18	5.0
16	Ny-Hellesund dikes, Norway	270	38.6	160.7	10	*2.9*
17	Thuringer Forest seds & volcs	270	41.2	170.5	17	6.4
18	Bohuslån dikes, Sweden	273	50.9	165.4	16	*8.6*
19	Bohemian intrusions	280	37.3	166.1	14	*5.6*
20	Lower Rotliegend seds, Poland	280	42	171	8	*5.0*
21	Autunian pelites, France	280	42.2	169.4	8	2.2
22	Oil shales, Poland	280	40.1	167.2	3	5.3
23	Sarna intrusion, Sweden	285	38.1	166.4	29	*6.9*
24	Mauchline lavas, Scotland	290	47.2	166.8	5	11.5

Age in Ma. λ, ϕ are north latitude and east longitude of palaeomagnetic pole. N, number of sites (*, number of specimens). A_{95}/α_{95} indicate radius of circle of 95 per cent confidence about mean VGP/mean direction. Italics indicate calculations done using directions. References: (1) Yang *et al.* (1996); (2) Edel & Duringer (1997); (3) Edel & Duringer (1997); (4) Briden & Daniels (1999); (5) Edel & Duringer (1997); (6) Symons *et al.* (1995); (7) Theveniaut *et al.* (1992); (8) Torsvik *et al.* (1998); (9) Biquand (1977); (10) Merabet & Daly (1986); (11) Nawrocki (1997); (12) Chen *et al.* (1997); (13) Merabet & Guillaume (1988); (14) Berthold *et al.* (1975); (15) Konrad & Nairn (1972); (16) Halvorsen (1970); (17) Mauritsh & Rother (1983); (18) Thorning & Abrahamsen (1980); (19) Thomas *et al.* (1997); Soffel & Harzer (1991); (20) Nawrocki (1997); (21) Merabet & Guillaume (1988); (22) Krs *et al.* (1992); (23) Smith & Piper (1979); (24) Harcombe-Smee *et al.* (1996).

Table 3. Best-fit small circles to APW paths for Europe and North America, 300 to 200 Ma.

	N Latitude	E Longitude	Radius	rms misfit
Europe	38.7	299.7	87.1	4.3°
N America	39.8	246.9	80.0	3.7

alter the balance of forces driving plate motions, periods of no more than a few million years would seem more reasonable. However, for 10^8 yr during Permo–Triassic time the PEP construction provides at worst a useful first approximation of APW (Fig. 2). The 20 My running-average APW points for the interval 300 to 200 Ma of Torsvik *et al.* (2001) also are well-fit by our small circles (Fig. 3); the rms deviations of the Torsvik *et al.* (2001) data are 1.96° for North America and 2.57° for Europe. Only at the 'young' (200 Ma) end of the path is there an important difference, almost certainly because the running-mean method artificially smoothes the abrupt change in APW direction that occurred at 200 Ma.

4 EFFECT OF RECONSTRUCTIONS ON APW PATHS

In this section we examine various well-known reconstructions (Table 4) to see which do the best job of superimposing the 300–200 Ma APW paths of North America and Europe. The APW paths with the continents in their present (unrestored) configuration is shown for reference in Fig. 4(a).

Rotating the European APW path into North American coordinates using the classical continental-outline fit of Bullard *et al.* (1965) produces excellent agreement of the older (300 Ma) ends of the APW paths, but the two curves diverge with time (Fig. 4b), possibly reflecting Permo–Triassic pre-rifting extension within one or both continental margins.

In contrast, reconstructions for later times more nearly superimpose the 200 Ma ends of the two APW paths but leave the older ends far separated. For instance, the Srivastava & Tapscott (1986) pole, thought to be appropriate for the initial opening of the North Atlantic (∼105 Ma), produces fair coincidence at the young (200 Ma) end of the APW but leaves the older (300 Ma) ends far apart (Fig. 4c). The reconstruction of Rowley & Lottes (1988), primarily an attempt to minimize overlap of continental fragments and tectonic features in the Arctic region, is similar (Fig. 4d), as is the 170 Ma reconstruction (Fig. 4e) of Royer *et al.* (1992). Not shown is the 'optimized' North Atlantic fit of Torsvik *et al.* (2001), which begins with the Bullard *et al.* (1965) reconstruction for the interval 300 to 214 Ma, then gradually evolves by interpolation to an anomaly fit at 54 Ma. From Fig. 4(b) the Bullard *et al.* (1965) fit is appropriate for 300 Ma but not for 214 Ma. From these examples it is clear that reconstructions based on matching continental outlines, geological features and/or magnetic anomalies do not provide a satisfactory fit of the APW paths.

Reconstructions based entirely on palaeomagnetic APW paths are equally unsatisfactory in that they produce an unacceptable degree of continental overlap (Figs 4f and g). Clearly there is a fundamental difference between reconstructions based on the superimposition of palaeomagnetic APW paths and those based on other methods; the difference arises primarily because the APW method calls for much greater angles of rotation (Table 4).

5 SHOULD THE APW PATHS SUPERIMPOSE?

If relative displacement between Europe and North America began later than 200 Ma, then there should be a single finite rotation that superimposes the European and North American 300–200 Ma APW paths and also restores the continents to their pre-drift position. However, as previously illustrated, precise superimposition of the European and North American 300–200 Ma paths produces unacceptable overlap of Europe on NE North America. The problem presumably lies with an underlying assumption; that all parts of Europe and North America remained stationary with respect to one another prior to 200 Ma. More likely the two continental interiors were actively separating, and what are now marginal areas of the North Atlantic were actively extending, during the interval 300–200 Ma.

The Bullard *et al.* (1965) rotation provides a close match of the 300 Ma ends of the North American and European APW paths (Fig. 4b). The Bullard reconstruction also very nearly aligns the Iapetus suture (Fig. 5) transecting Newfoundland and the British Isles (Phillips *et al.* 1976; Williams *et al.* 1972). Reconstructions for later times, based on oceanic magnetic anomalies, leave the

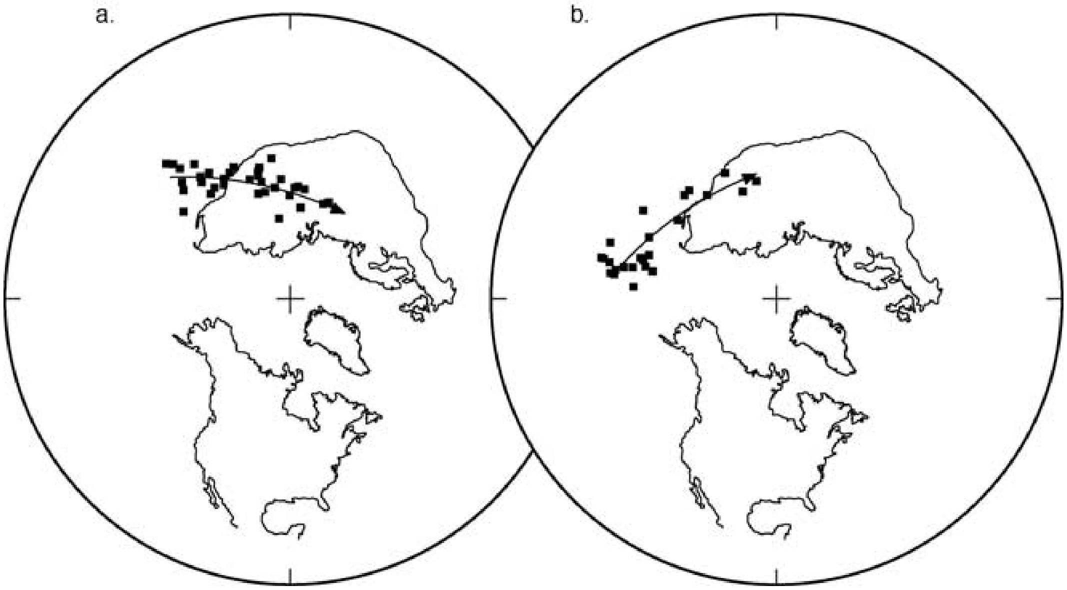

Figure 2. Permo–Triassic apparent polar wander (APW) paths for (a) North America and (b) Eurasia. Paths are arcs of best-fit small circles. Data summarized in Tables 1 and 2; small-circles in Table 3.

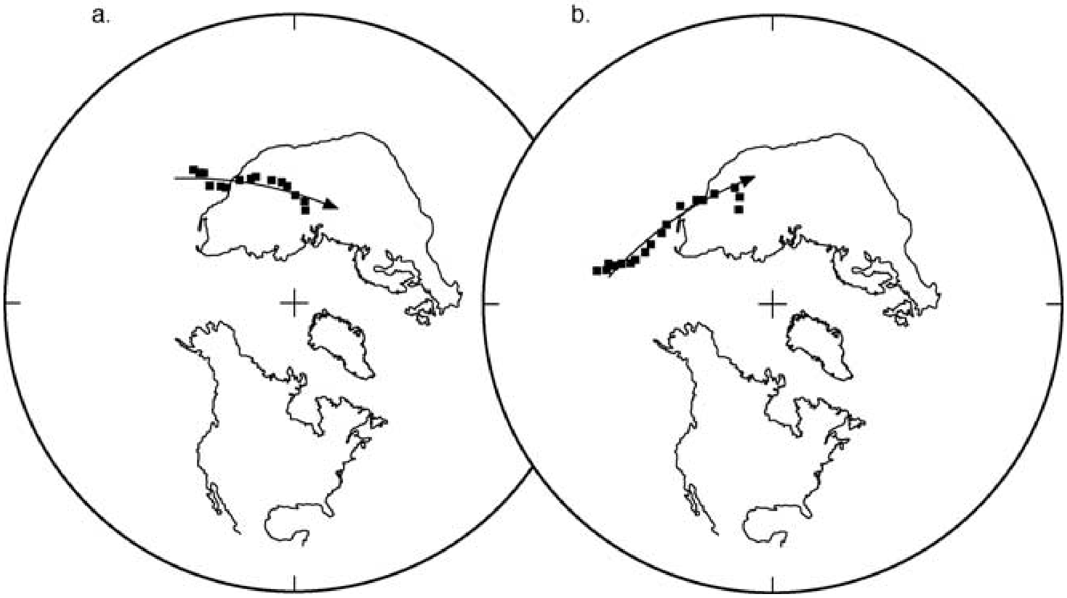

Figure 3. Best-fit small circles of Fig. 2, plotted together with the 300–200 Ma reference poles of Torsvik *et al.* (2001), for (a) North America and (b) Eurasia.

Table 4. Europe–North America total reconstruction parameters.

Fig.	Nlat	Elong	R	Reference
4b	88.4°	27,7°	38.1°	Bullard *et al.* (1965)
4c	79.5	151.9	25.6	Srivastava & Tapscott (1986)
4d	72.8	154.7	24.3	Rowley & Lottes 1988
4e	69.1	156.7	23.6	Royer *et al.* (1992)
4f	82	150	48	Frei & Cox (1987)
4g	77.2	134.2	44.3	This paper

Fig., illustration showing the degree to which the indicated rotation superimposes Permo–Triassic APW paths. Nlat, Elong are north latitude and east longitude of the reconstruction pole, respectively. R is the rotation angle (negative to place Europe in North American coordinates). Fig. 4(a) shows the APW paths in their present position.

300 Ma point on the respective APW paths far apart, although they are reasonably close for 200 Ma (Figs 4c–e). This suggests that the cratonic regions of Europe and North America were moving away from one another during Permo–Triassic time, although what are now the margins of both continents remained in contact. This obviously requires extension of one or both continental margins.

To estimate the amount and direction of stretching, one must first identify the correct 200 Ma reconstruction. Unfortunately, using only palaeomagnetic data the problem is indeterminate. For instance, Fig. 6 shows the 200 Ma points on the APW paths for Europe and North America, together with a segment of the bisecting great circle. From a geometric standpoint, any point on the great circle can serve as a rotation pole to precisely superimpose the 200 Ma

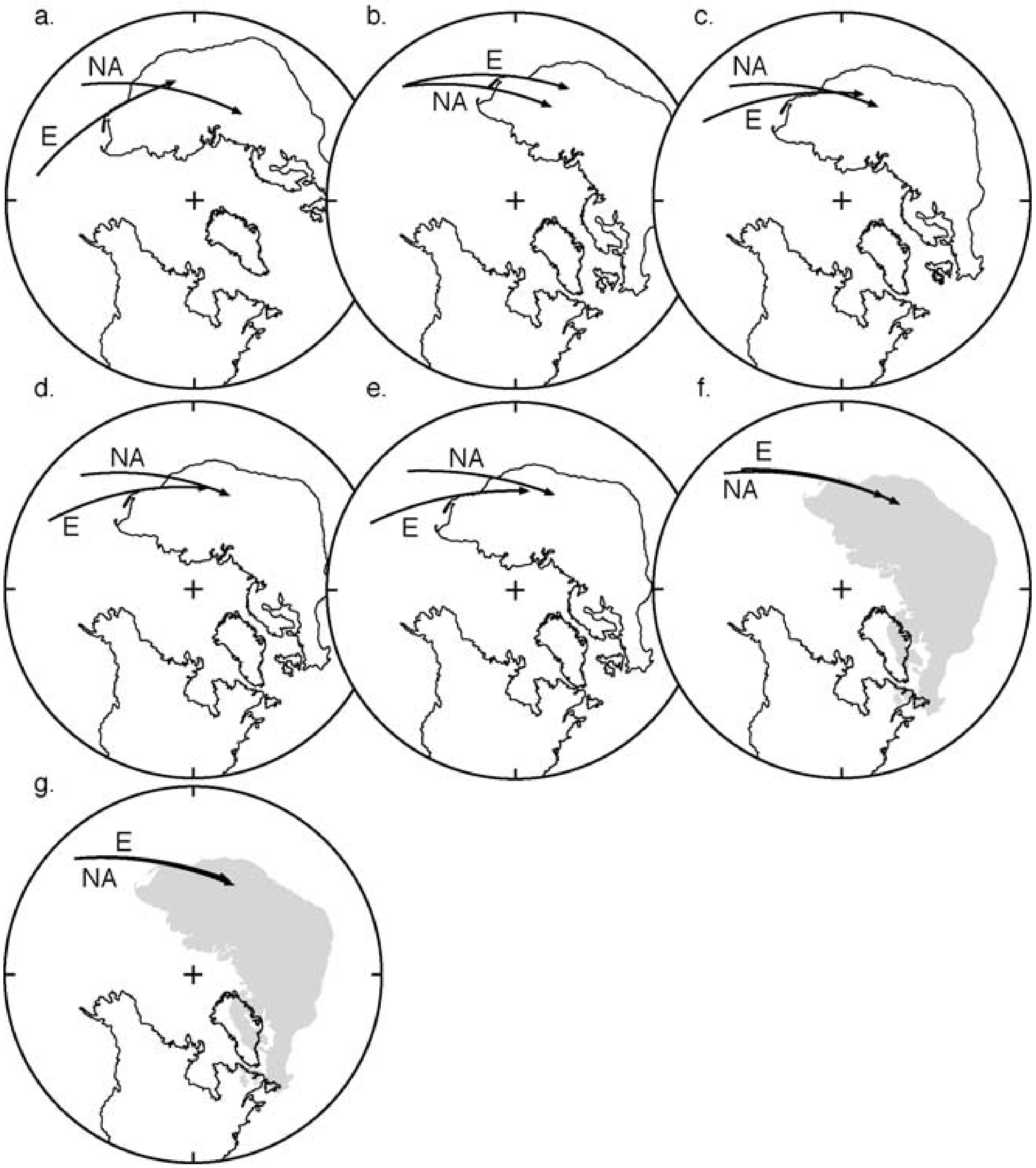

Figure 4. North American and Eurasian APW paths for various reconstructions: (a) present configuration; (b) corrected after Bullard *et al.* (1965); (c) corrected after Srivastava & Tapscott (1986); (d) corrected after Rowley & Lottes (1988); (e) corrected after Royer *et al.* (1992); (f) corrected after Frei & Cox (1987); (g) palaeomagnetic best-fit reconstruction from this paper.

ends of the two APW paths. To determine the correct pole other (non-palaeomagnetic) constraints are required.

The choice can be narrowed by using the amount of rotation as a rough constraint. The total rotation involved in a 200 Ma reconstruction probably ought to lie in the range ∼38 to ∼23°, these being the approximate rotation angles involved in the Bullard *et al.* (1965) reconstruction, which we take to be valid for 300 Ma, and the Royer *et al.* (1992) reconstruction at 170 Ma. After applying this constraint, the range of plausible rotation poles remains quite broad (Fig. 6).

To narrow the selection further we need to examine the effect of the rotation on the placement and alignment of northwestern Europe with respect to northeastern North America. For example, the extreme values of rotation can be eliminated; the maximum (38°) rotation clearly is too great (Fig. 7a), whereas the minimum (23°) rotation is far too small (Fig. 7b)

From the range of plausible rotation poles still remaining we have selected two:

The first (Fig. 8) superimposes the 200 Ma ends of the APW paths while minimizing the displacement of the British Isles from their pre-stretching position, taken to be the Bullard *et al.* (1965) fit (shown in Fig. 8b). Because it also minimizes the subsequent estimate of pre-200 ma continental extension we refer to this as the 'minimum' reconstruction. This is 76.3°N, 177.0°E, with a rotation angle of 32.8°.

Our 'preferred' 200 Ma reconstruction (Fig. 8c) requires more apparent displacement of the British Isles (and hence a larger estimate of pre-200 Ma continental stretching), but it more nearly maintains

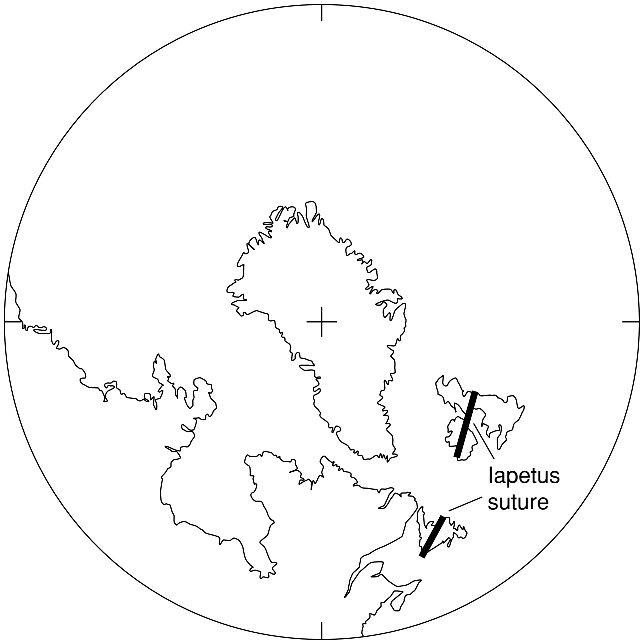

Figure 5. Bullard *et al.* (1965) reconstruction nearly aligns the Iapetus suture (shown as bold lines).

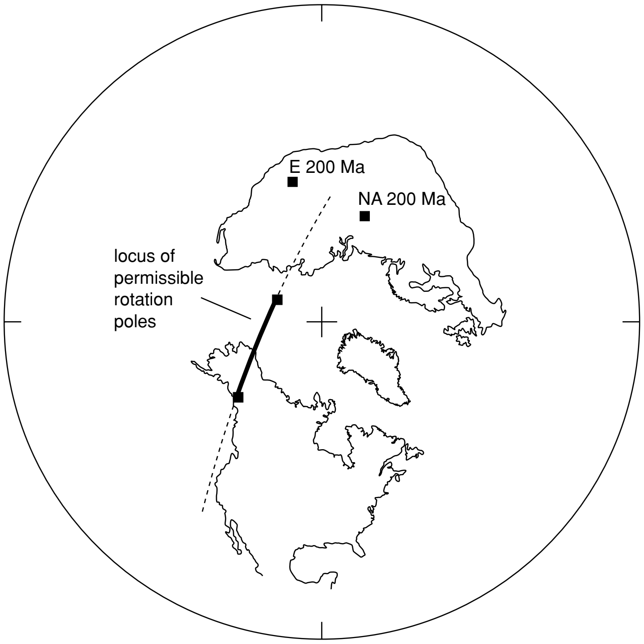

Figure 6. Attempt to superimpose the 200 Ma ends of the NA and Europe APW paths. Any point on the bisecting great circle is a possible rotation pole, but rotation poles located along either dotted segment are excluded by the geology.

the alignment of the Iapetus suture. This rotation pole is 77.0°N, 165.75°E, with a rotation angle of 35°.

6 PRE-RIFT EXTENSION: 300 TO 200 MA

If the difference between the Bullard reconstruction and the 200 Ma reconstruction is due to extension during the Late Permian and Triassic, it follows that the finite-difference rotation between these configurations gives an Euler pole that can be used to describe the extension. For the 'preferred' reconstruction this pole is 24.3°N. 9.3°E, with a total rotation of 9.4°; for the 'minimum' rotation it is 35.9°N, 177.0°, with a rotation angle of 10.6°. Extension amounts are approximately 800 km for the 'preferred' case and 500 for the 'minimum' case (Figs 9a and b).

An interesting feature of this inferred Permo–Triassic extension is that its direction was nearly parallel to the margins of the nascent North Atlantic Ocean. In this it resembles the modern tectonic geometry of the Gulf of California (e.g. Umhoefer 2000). Early relative motion between stable Europe and North America involved an element of sinistral shear (Figs 9a and b), as was noted previously by Frei & Cox (1987). This might be expected to have important geological consequences which, however, for the most part are beyond the scope of this paper. As an example, anti-clockwise rotations in the Newark basin of Pennsylvania determined palaeomagnetically by Kodama *et al.* (1994) might be attributable to this phase of sinistral shear.

7 PRE-RIFT EXTENSION: 200 TO 105 MA

If we accept the Srivastava & Tapscott (1986) reconstruction for the initiation of ocean-floor spreading in the North Atlantic at 105 Ma, then, as in the preceding section, it follows that continental extension between 200 Ma and 105 Ma can be modelled as a finite rotation of 9.6° about a pole located at 69.7N, 196.1E (Fig. 10a) for the preferred 200 Ma reconstruction, or 7.8° about 61.1°N, 216.5°E, 7.82° for the minimum reconstruction (Fig. 10b). With either reconstruction, extension during this younger phase was more nearly parallel to the subsequent direction of ocean-floor spreading and thus at a considerable angle to the direction of extension during the interval 300 to 200 Ma. This seems to require some sort of tectonic transition at about 200 Ma, perhaps coincident with the J1 cusp of Gordon *et al.* (1984) and the 'geologically instantaneous' emplacement of Central Atlantic magmatic province basalts (Hames *et al.* 2000), both dated at about 200 Ma.

8 DOES THE GEOLOGY AGREE?

Adding the two finite rotations gives a pole for the total extension of continental margins across the North Atlantic from 300 to 105 Ma. Using the preferred 200 Ma reconstruction this total-extension pole is 23.5°N, 186.1°E, with a rotation angle of 12.9°; using the 'minimum' 200 Ma pole it is 4.4°N, 174.5°E, 11.2°. The maximum amounts of extension are about 1450 km for the preferred model, and about 1150 km for the minimum model (Fig. 11).

The middle great-circle segment shown in Fig. 11(a). extending from Cabot Strait, separating Nova Scotia from Newfoundland, to the coastline near Bergen, Norway, is approximately 2250 km long. If this represents the full width of continental crust immediately prior to the onset of extension, then 1435 km of pre-rifting extension represents a total stretching of less than 65 per cent, which clearly is not excessive (see, for comparison, Snow & Wernicke 2000).

The history described above calls for two distinct episodes of crustal extension, with a change in extension direction at about 200 Ma. However, because the direction of extension appears to have changed by <30°, any resulting change in structural trends might be difficult to recognize. This is especially true if, as concluded by some authors, (e.g. Doré *et al.* 1997), pre-existing

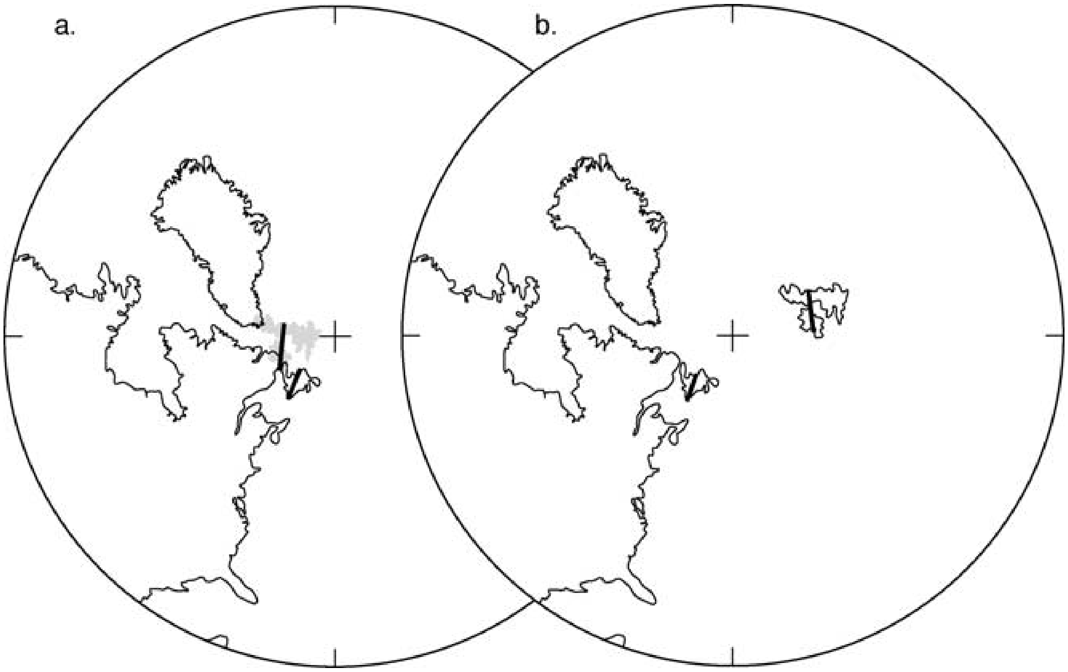

Figure 7. Extremes of 'permitted' segment of Fig. 6. (a) maximum rotation produces overshoot of alignment of the Iapetus suture. (b) minimum produces an extreme undershoot in suture alignment.

basement features exerted a strong effect on the location of Mesozoic extensional structures. However, evidence of crustal thinning in the form of sedimentary deposits of Permo–Triassic and Jurassic age ought to exist.

There is an abundance of literature on the stratigraphy of the continental shelf regions near Newfoundland and in the North Sea area, largely owing to petroleum exploration. Rifting of both Permo–Triassic and Jurassic-early Cretaceous age occurred in the European continental margin (e.g. Doré *et al.* 1999), resulting in thick accumulations of sedimentary rocks in the southern North Sea area (Cameron *et al.* 1992), the central North Sea area (Erratt *et al.* 1999), and elsewhere (see reviews in Tankard & Balkwill 1989; Fleet & Boldy 1999). Moreover, episodes of Permian, Triassic and Jurassic rifting are widely recognized in the British Isles (Whittaker 1985) and elsewhere in northwest Europe (Boldy 1995). Sedimentary deposits of these ages are sufficiently thick and widespread to be consistent with important crustal thinning.

However, evidence of pre-Jurassic rifting of the North American continental margin is limited. There are thick Upper Triassic sequences in various continental-margin basins on the Grand Banks and elsewhere nearby (e.g. Tucholke *et al.* 1989; McAlpine 1990), but phases of Permian and Early Triassic extension do not seem to have been recognized; indeed, Enachescu (1988) describes the Permian and Early Triassic of the Grand Banks as a time of erosion. Continental margin clastic basins throughout the Appalachians contain sedimentary material as old as Middle Triassic, but apparently not older (Olsen 1997). Thus, if crustal extension was active in the Permian and Early Triassic it seems mainly to have been confined to the area now forming the European continental margin.

9 SUMMARY AND CONCLUSIONS

Our analysis of North American and European Permian–Late Triassic apparent polar wander (APW) reaffirms that pre-drift reconstructions based on either continental outlines or early seafloor magnetic anomalies do an unsatisfactory job of superimposing the two APW paths. Similarly, reconstructions based solely on APW do not yield a satisfactory realignment of the respective continental margins; invariably the palaeomagnetic reconstructions result in unacceptable overlap of continental crust. This appears mainly to be the result of extension in the zone of incipient rifting, before the onset of seafloor spreading. The analysis suggests amounts of stretching that are surprisingly large; up to perhaps 1400 km between Newfoundland and Norway. This stretching appears to have comprised two distinct phases, with the earlier (pre-200 Ma) phase having an important oblique (sinistral) transtensional element.

In a related study, Van der Voo & Torsvik (2000) consider the problem of the existing lack of agreement between APW paths for Laurussia and Gondwana, which has led to a multitude of alternative Pangea reconstructions (e.g. Van der Voo 1993). They conclude that zonal harmonics of the geomagnetic field may be at fault; that is, that the time-averaged field was not strictly dipolar, as commonly assumed. Because the discrepancies considered in this paper (between portions of Laurussia) are mainly east-west, they would be little affected by zonal harmonics. However, in light of the surprisingly large extension apparently accompanying rifting in the North Atlantic, we wonder if the answer to the Pangea problem may also lie in deformation of the continental margins.

ACKNOWLEDGMENTS

Thanks to R. F. Burmester for many insightful discussions and to N. Bowerman for much-needed clerical assistance. J. Crider, as always, acted as the senior author's guide to the mysteries of Microsoft *Word*. Illustrations drafted by K. Short. Reviews by J. Geissman and G. Muttoni were helpful. This work was partially supported by NSF grant EAR-0073891.

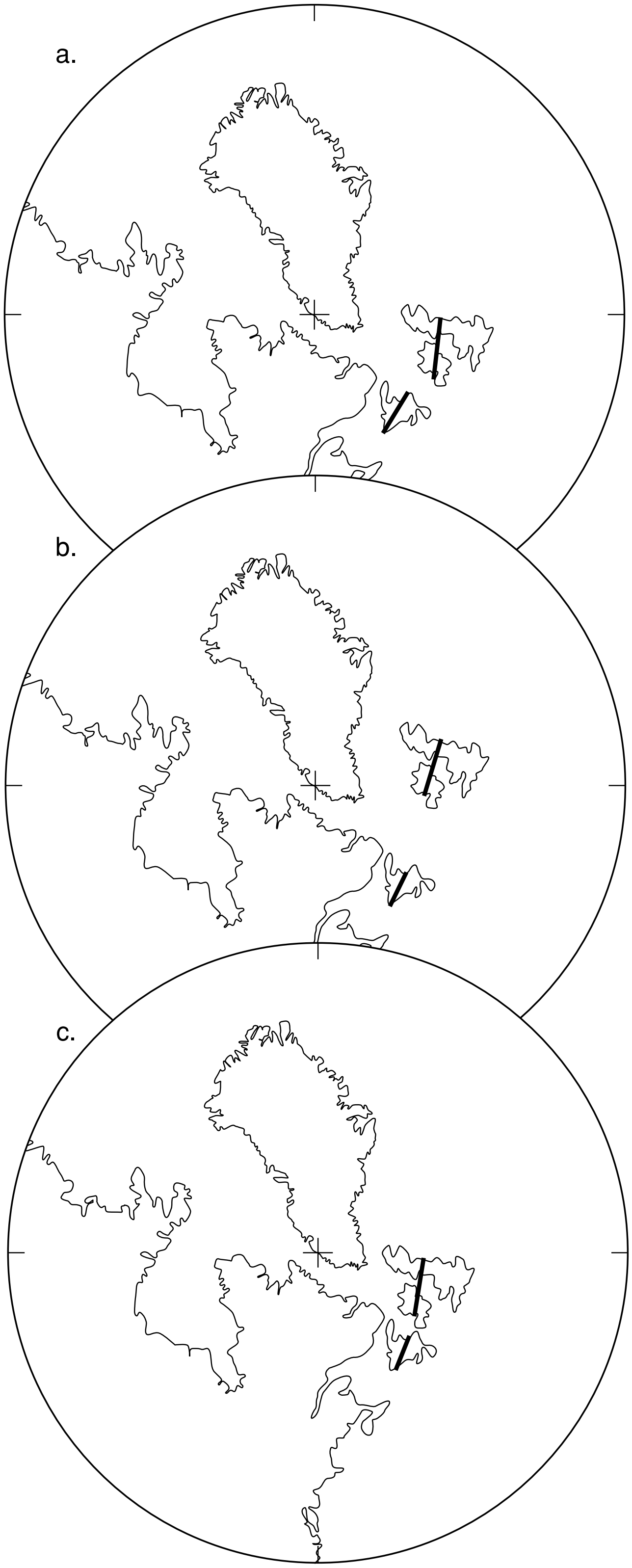

Figure 8. Acceptable 200 Ma reconstructions. (a) 'minimum' reconstruction minimizes displacement of British Isles from Bullard *et al.* (1965) position (shown by b), but fails to align Iapetus suture. (c) 'preferred' reconstruction gives best alignment of suture but requires more pre-drift extension than (a).

REFERENCES

Bazard, D. & Butler, R., 1991. Paleomagnetism of the Chinle and Kayenta formations, New Mexico and Arizona, *J. geophys. Res.,* **96,** 9847–9872.

Beck, M.E., Jr., 1989. Paleomagnetism of continental North America: Implications for displacement of crustal blocks within the Western Cordillera, Baja California to British Columbia, in *Geophysical Framework of the Continental United States, Memoir 172,* pp. 471–492, eds Pakiser, L. & Mooney, W., Geological Society of America, Boulder.

Berthold, G., Nairn, A.E.M. & Negendank, J.F.W., 1975. A palaeomagnetic investigation of some of the igneous rocks of the Saar-Nahe basin. *N.* (Buntsandstein superieur) du Massif des Vosges (France), *Can. J. Earth Sci.,* **14,** 1490–1514.

Biquand, D., 1977. Paléomagnetisme de la formation des 'gres-a-Voltzia' (Buntsandstein superieur) du Massif des Vosges (France), *Can. J. Earth Sci.,* **14,** 1490–1514.

Boldy, S.A.R., 1995. *Permian and Triassic rifting in northwest Europe, Special Publication 91,* Geological Society, London.

Briden, J.C. & Daniels, B.A., 1999. Palaeomagnetic correlation of the Upper Triassic of Somerset, England, with continental Europe and eastern North America, *J. geol. Soc. Lond.,* **156,** 317–326.

Bullard, E.C., Everett, J.E. & Smith, A.G., 1965. The fit of the continents around the Atlantic, *R. Soc. London Philos Trans., A.,* **258,** 41–51.

Cameron, T.D.J., Crosby, A., Balson, P.S., Jeffrey, D.H., Lott, G.K., Bulat, J. & Harrison, D.J., 1992. The geology of the southern North Sea, *United Kingdom Offshore Regional Report,* HMSO, London.

Chen, Y., Faure, M. & Cogne, J.P., 1997. Late Permian palaeomagnetic results from the Brive basin (Massif Central, France), *Tectonophysics,* **281**.

DeBoer, J. & Brookins, D.G., 1972. Paleomagnetic and radiometric age determination of (Permian) pegmatites in the Middletown District (Connecticut), *Earth planet. Sci. Lett.,* **15,** 140–144.

Diehl, J.F. & Shive, P.N., 1979. Palaeomagnetic studies of the Early Permian Ingelside Formation of northern Colorado, *Geophys. J. R. astr. Soc.,* **56,** 271–282.

Diehl, J.F. & Shive, P.N., 1981. Paleomagnetic results from the Late Carboniferous-Early Permian Casper Formation: implications for northern Appalachian tectonics, *Earth planet. Sci. Lett.,* **54,** 281–292.

Doré, A.G., Fitchler, C. & Olesen, O., 1997. Pattern of basement structure and reactivation along the NE Atlantic margin, *J. geol. Soc. Lond.,* **154,** 85–92.

Doré, A.G., Lundin, E.R., Jensen, L.N., Birkeland, O., Eliassen, P.E. & Fichler, C., 1999. Principal tectonic events in the evolution of the northwest European Atlantic margin, in *Petroleum Geology of Northwest Europe,* pp. 41–62, eds Fleet, A.J. & Boldy, S.A.R., The Geological Society, London.

Edel, J.B. & Duringer, Ph., 1997. The apparent polar wander path of the European plate in Upper Triassic—Lower Jurassic times and the Liassic intraplate fracturing of Pangaea: new palaeomagnetic constraints from NW France and SW Germany, *Geophys. J. Int.,* **128,** 331–344.

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

Enachescu, M.E., 1988. Extended basement beneath the intracratonic rifted basins of the Grand Banks of Newfoundland, *Can. J. explor. Geophys.,* **24,** 48–65.

Erratt, D., Thomas, G.M. & Wall, G.R.T., 1999. The evolution of the central North Sea Rift, in *Petroleum Geology of Northwest Europe,* pp. 63–82, eds Fleet, A.J. & Boldy, S.A.R., The Geological Society, London.

Fang, W. & Van der Voo, R., 1988. Paleomagnetism of Middle-Late Triassic plutons in southern Maine, *Tectonophysics,* **156,** 51–58.

Fleet, A.J. & Boldy, S.A.R., eds, 1999. *Petroleum Geology of Northwest Europe, Vols 1 & 2,* The Geological Society, London.

Frei, L.S. & Cox, A., 1987. Relative displacement between Eurasia and North America prior to the formation of oceanic crust in the North Atlantic, *Tectonophysics,* **142,** 111–136.

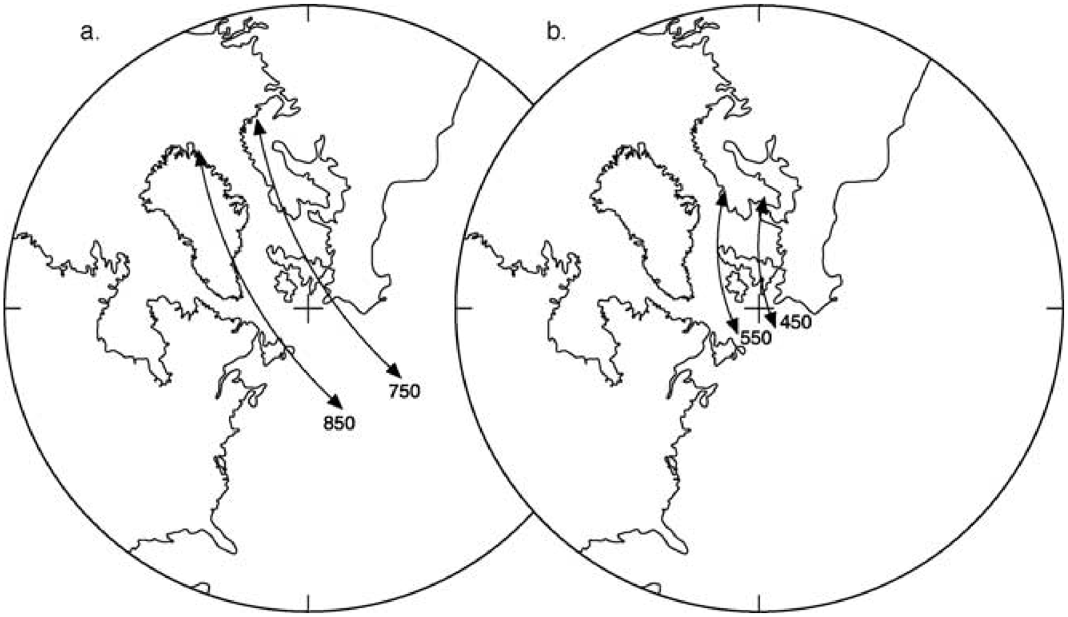

Figure 9. Extension 300–200 Ma. (a) 'preferred' reconstruction; (b) 'minimum reconstruction'. Arrows denote direction of extension, numbers are amounts of extension along each small circle, in km. Base map: Bullard *et al.* (1965) reconstruction.

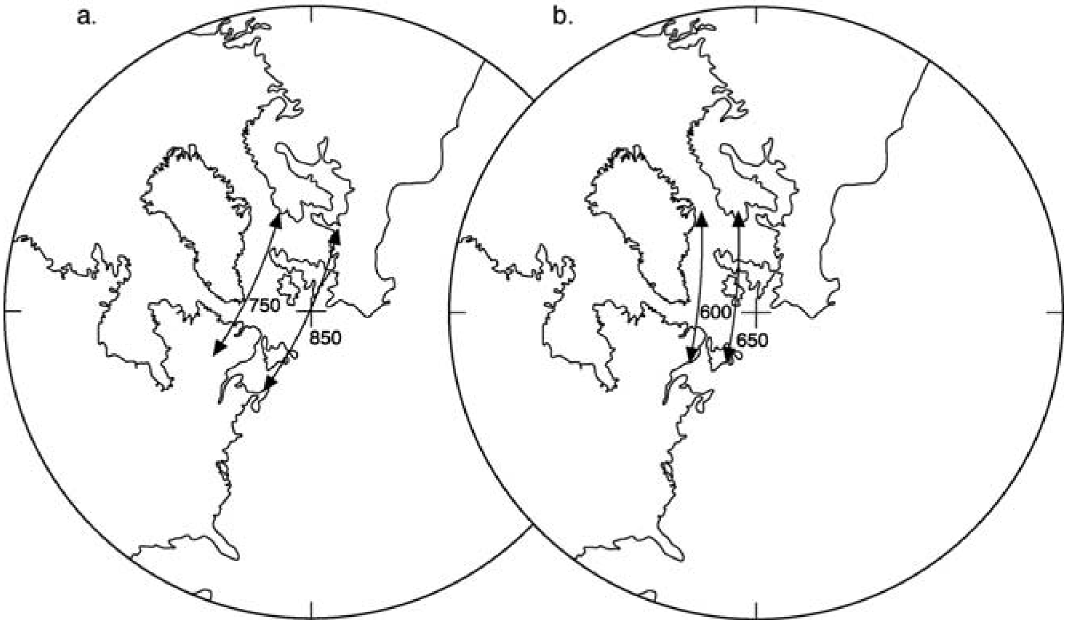

Figure 10. Extension 200–105 Ma. (a) 'preferred' reconstruction; (b) 'minimum' reconstruction. Arrows denote direction of extension, numbers are amounts of extension along each small circle, in km. Base map: Bullard *et al.* (1965) reconstruction.

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

Gose, W.A. & Helsley, C.E., 1972. Paleomagnetic and rock-magnetic studies of the Permian Cutler an Elephant Canyon Formations in Utah, *J. geophys. Res.,* **77,** 1534–1548.

Grubbs, K.L. & Van der Voo, R., 1976. Structural deformation of the Idaho-Wyoming overthrust belt (USA), as determined by Triassic paleomagnetism, *Tectonophysics,* **33,** 321–336.

Halvorsen, E., 1970. Palaeomagnetism and the age of the younger diabases in the Ny-Hellesund area, S. Norway, *Norsk Geologisk Tidsskrift,* **50,** 157–166.

Hames, W.E., Renne, P.R. & Ruppel, C., 2000. New evidence for geologically instantaneous emplacement of earliest Jurassic Central Atlantic magmatic province basalts on the North American margin, *Geology,* **28,** 859–862.

Harcombe-Smee, B.J., Piper, J.D.A., Rolph, T.C. & Thomas, D.N., 1996. A palaeomagnetic and palaeointensity study of the Mauchline lavas, south-west Scotland, *Phys. Earth planet. Inter.,* **94,** 63–73.

Helsley, C.E., 1971. Remanent magnetization of the Permian Cutler Formation of western Colorado, *J. geophys. Res.,* **76,** 4842–4848.

Helsley, C.E. & Steiner, M.B., 1974. Paleomagnetism of the Lower Triassic Moenkopi Formation, *Geol. Soc. Am. Bull.,* **85,** 457–464.

Herrero-Brevera, E. & Helsley, C.E., 1983. Paleomagnetism of a polarity transition in the Lower (?) Triassic Chugwater Formation, Wyoming, *J. geophys. Res.,* **88,** 3506–3522.

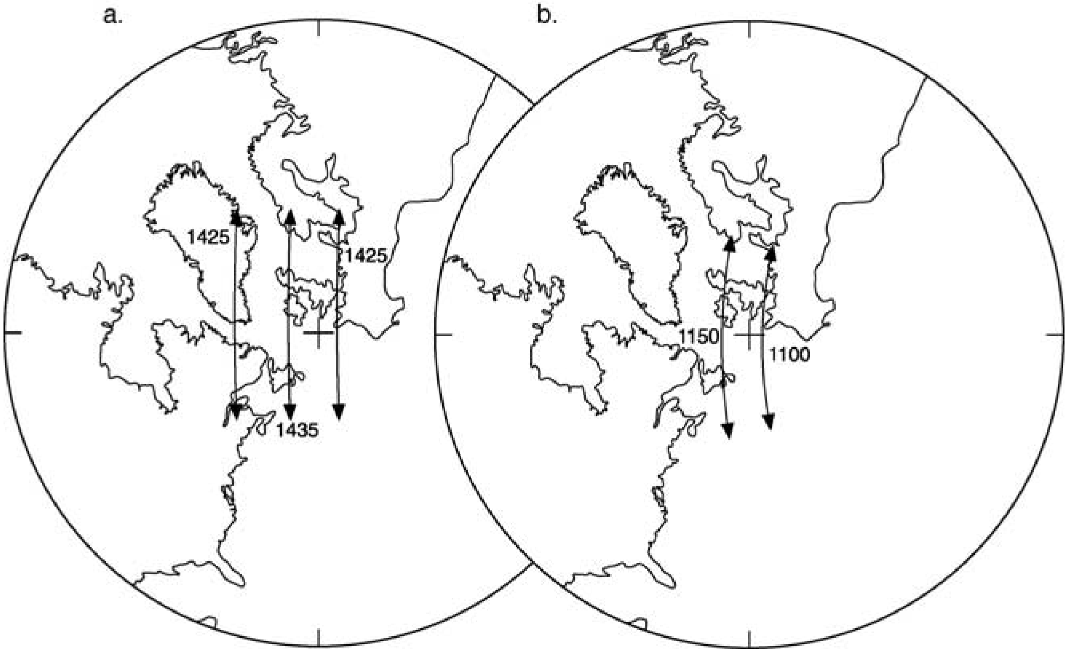

Figure 11. Total pre-drift extension, 300–105 Ma. (a) 'preferred' reconstruction; (b) 'minimum' reconstruction. Arrows denote direction of extension, numbers are amounts of extension along each small circle, in km. Base map: Bullard *et al.* (1965) reconstruction.

Kent, D.V. & Witte, W.K., 1993. Slow apparent polar wander for North America in the Late Triassic and large Colorado Plateau rotation, *Tectonics,* **12,** 291–300.

Kodama, K.P., Hedlund, C., Gosse, J. & Strasser, J., 1994. Rotated palaeomagnetic poles from the Sassamansville syncline, Newark basin, southeastern Pennsylvania, *J. geophys. Res.,* **99,** 4643–4653.

Konrad, H.J. & Nairn, A.E.M., 1972. The palaeomagnetism of the Permian rocks of the Black Forest, Germany, *Geophys. J. R. astr. Soc.,* **27,** 369–382.

Krs, M., Krsova, M., Konklikova, L., Pruner, P. & Valin, F., 1992. On the applicability of oil shale to palaeomagnetic investigations, *Phys. Earth planet. Inter.,* **70,** 178–186.

Larochelle, A. & Currie, K.L., 1967. Paleomagnetic study of igneous rocks from the Manicouagan structure, Quebec, *J. geophys. Res.,* **72,** 4163–4169.

Mauritsh, H.J. & Rother, K., 1983. Paleomagnetic investigations in the Thüringer Forest (G.D.R.), *Tectonophysics,* **99,** 63–72.

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

McAlpine, K.D., 1990. Mesozoic stratigraphy, sedimentary evolution, and petroleum potential of the Jeanne D'Arc basin, Grand Banks, Newfoundland., *Geol. Survey Canada Pap.* 89-17, Geological Survey of Canada, Ottawa.

Merabet, N. & Daly, L., 1986. Determination d'un pole paleomagnetique et mise en evidence d'aimantations a polarite normale sur les formation s du Permien superieur du Massif des Maures (France), *Earth planet. Sci. Lett.,* **80,** 156–166.

Merabet, N. & Guillaume, A., 1988. Palaeomagnetism of the Permian rocks of the Lodeve (Herault, France), *Tectonophysics,* **145,** 21–29.

Molina-Garza, R.S., Geissman, J.W. & Van der Voo, R., 1989. paleomagnetism of the Dewey Lake Formation (Late Permian), northwest Texas; end of the Kiaman Superchron in North America, *J. geophys. Res.,* **94,** 17 881–17 888.

Molina-Garza, R., Geissman, J.W., Van der Voo, R., Lucas, S.G. & Hayden, S.N., 1991. Paleomagnetism of the Moenkopi and Chinle Formations in central New Mexico: Implications for the North American apparent polar wander path and Triassic magnetostratigraphy, *J. geophys. Res.,* **96,** 14 239–14 262.

Molina-Garza, R., Geissman, J.W., Lucas, S.G. & Van der Voo, R., 1996. Palaeomagnetism and magnetostratigraphy of Triassic strata in the Sangre de Cristo Mountains and Tucumcari Basin, New Mexico, USA, *Geophys. J. Int.,* **124,** 935–953.

Molina-Garza, R., Geissman, J.W., Gomez, A. & Horton, B., 1998. Paleomagnetic data from Triassic strata, Zuni uplift, New Mexico; Further evidence of large-magnitude Triassic apparent polar wander of North America, *J. geophys. Res.,* **103,** 24 189–24 200.

Molina-Garza, R., Geissman, J. & Lucas, S., 2000. Paleomagnetism and magnetostratigraphy of uppermost Permian strata, southeast New Mexico, USA: correlation of the Permian-Triassic boundary in non-marine environments, *Geophys. J. Int.,* **141,** 778–786.

Nawrocki, J., 1997. Permian to Early Triassic magnetostratigraphy from the Central European Basin in Poland: Implications on regional and worldwide correlations, *Earth planet. Sci. Lett.,* **152,** 37–58.

Olsen, P.E., 1997. Stratigraphic record of the early Mesozoic breakup of Pangea in the Laurasia-Gondwana rift system, *Ann. Rev. Earth Planet. Sci.,* **25,** 337–401.

Peterson, D.N. & Nairn. A.E.M., 1971. Paleomagnetism of Permian redbeds from southwestern United States, *Geophys. J. R. astr. Soc.,* **23,** 191–205.

Prevot, M. & McWilliams, M., 1989. Paleomagnetic correlation of Newark Supergroup volcanics, *Geology,* **17,** 1007–1010.

Phillips, W.E.A., Stillman, C.J. & Murphy, T., 1976. A Caledonian plate tectonic model, *J. geol. Soc. Lond.,* **132,** 579–609.

Purucker, M.E., Elston, D.P. & Shoemaker, E.M., 1980. Early acquisition of characteristic magnetization in Red Beds of the Moenkopi Formation (Triassic), Gray Mountain, Arizona, *J. geophys. Res.,* **85,** 997–1012.

Reeve, S.C. & Helsley, C.E., 1972. Magnetic reversal sequence in the upper portion of the Chinle Formation, Montoya, New Mexico, *Geol. Soc. Am. Bull.,* **83,** 3795–3812.

Robertson, W.A., 1967. Manicouagan, Quebec, palaeomagnetic results, *Can. J. Earth Sci.,* **4,** 641–649.

Rowley, D.B. & Lottes, A.L., 1988. Plate-kinematic reconstructions of the North Atlantic and Arctic: Late Jurassic to present, *Tectonophysics,* **155,** 73–120.

Royer, J.-Y., Muller, R.D., Gahagan, L.M., Lawyer, L.A., Mayes, C.L., Nurnberg, D. & Sclater, J.G., 1992. A global isochron chart, *Univ. Texas Inst. for Geophys. Tech Rep.,* **117,** 275–278.

Shive, P., Steiner, M. & Huyke, D., 1984. Magnetostratigraphy, paleomagnetism, and remanence acquisition in the Triassic Chugwater Formation of Wyoming, *J. geophys. Res.,* **89,** 1801–1815.

Smith, T.E. & Noltimier, H.C., 1979. Paleomagnetism of the Newark Trend igneous rocks of the North Central Appalachians and the opening of the central Atlantic Ocean, *Am. J. Sci.,* **279,** 778–807.

Smith, R.L. & Piper, J.D.A., 1979. Palaeomagnetism of the Sarna alkaline body, *Geologiska Foreningens I Stockhnold Forhandlingar,* **101,** 167–168.

Snow, J.K. & Wernicke, B.P., 2000. Cenozoic tectonism in the central Basin and Range: magnitude, rate and distribution of upper crustal strain, *Am. J. Sci.,* **300,** 659–719.

Soffel, H.C. & Harzer, F., 1991. An Upper Carboniferous-Lower Permian (280 Ma) palaeomagnetic pole from the western margin of the Bohemian Massif, *Geophys. J. Int.,* **105,** 547–551.

Srivastava, S.P. & Tapscott, C.R., 1986. Plate kinematics of the North Atlantic, in *The Western North Atlantic Region,* pp. 379–404, eds Vogt, P. & Tucholke, B., Geological Society of America, Boulder.

Steiner, M.B., 1988. Paleomagnetism of the Late Pennsylvanian and Permian: A test of the rotation of the Colorado Plateau, *J. geophys. Res.,* **93,** 2201–2215.

Steiner, M.B., 1998. Age, correlation, and tectonic implications of Morrison Formation palaeomagnetic data, including rotation of the Colorado Plateau, *Modern Geology,* **22,** 261–281.

Steiner, M.B. & Lucas, S.G., 2000. Paleomagnetism of the Late Triassic Petrified Forest Formation, Chinle Group, western United States: further evidence of 'large' rotation of the Colorado Plateau, *J. geophys. Res.,* **105,** 25 791–25 808.

Symons, D.T.A., 1990. Early Permian pole: Evidence from the Pictou red beds, Prince Edward Island, Canada, *Geology,* **18,** 234–237.

Symons, D.T.A., Sangster, D.F. & Leach, L.L., 1995. A Tertiary age from paleomagnetism for Mississippi Valley-type zinc-lead mineralization in Upper Silesia, Poland, *Economic. Geol.,* **90,** 782–794.

Tankard, A.J. & Balkwill, H.R., eds, 1989. Extensional tectonics and stratigraphy of the North Atlantic Margins, *Am. Assoc. Petrol. Geol. Mem.,* **46,** 641.

Theveniaut, H., Besse, J., Edel, J.B., Westphal, M. & Duringer, P., 1992. A Middle-Triassic palaeomagnetic pole for the Eurasian plate from Heming (France), *Geophys. Res. Lett.,* **19,** 777–780.

Thomas, D.N., Rolph, T.C. & Friel, D.F., 1997. Permo-Carboniferous (Kiaman) palaeointensity results from the western Bohemian Massif, Germany, *Geophys. J. Int.,* **130,** 257–265.

Thorning, L. & Abrahamsen, N., 1980. Paleomagnetism of Permian multiple intrusion dykes in Bohuslan, SW Sweden, *Geophys. J. R. astr. Soc.,* **60,** 163–185.

Torsvik, T.H., Eide, E.A., Meert, J.G., Smethurst, M.A. & Walderhaug, H.J., 1998. The Oslo Rift: New palaeomagnetic and ^{40}Ar/^{39}Ar age restraints, *Geophys. J. Int.,* **135,** 1045–1059.

Torsvik, T.H., Van der Voo, R., Meert, J.G., Mosar, J. & Walderhaug, H.J., 2001. Reconstructions of the continents around the North Atlantic at about the 60th parallel, *Earth planet. Sci. Lett.,* **187,** 55–60.

Tucholke, B.E., Austin, J.A., Jr. & Uchupi, E., 1989. Crustal structure and rift-drift evolution of the Newfoundland Basin, *Am. Assoc. petrol. Geol. Mem.,* **46,** 247–263.

Umhoefer, P.J., 2000. Where are the missing faults in translated terranes?, *Tectonophysics,* **326,** 23–36.

Van der Voo, R., 1993. *Paleomagnetism of the Atlantic, Tethys and Iapetus Oceans,* Cambridge University Press, Cambridge.

Van der Voo, R. & Grubbs, K.L., 1977. Paleomagnetism of the Triassic Chugwater redbeds revisited (Wyoming, USA), *Tectonophysics,* **41,** 27–33.

Van der Voo, R. & Torsvik, T., 2000. Evidence for late Paleozoic and Mesozoic non-dipole fields provides an explanation for the Pangea reconstruction problems, *Earth planet. Sci. Lett.,* **187,** 71–81.

Whittaker, A., 1985. *Atlas of Onshore Sedimentary Basins in England and Wales; Post-Carboniferous Tectonics and Stratigraphy,* Blackie & Sons, Glasgow.

Williams, H., Kennedy, M.J. & Neale, E.R.W., 1972. The Appalachian structural province, in *Variations in Tectonic Styles in Canada, Geol. Assoc Canada Paper 11,* pp. 182–261, eds Price, R.A. & Douglas, R.J.W., Geological Association of Canada, St Johns.

Witte, W.K. & Kent, D.V., 1989. A middle Carnian to early Norian (c. 225 Ma) paleopole from sediments of the Newark Basin, Pennsylvania, *Geol. Soc. Am. Bull.,* **101,** 1118–1126.

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

Witte, W.K., Kent, D.V. & Olsen, P.E., 1991. Magnetostratigraphy and palaeomagnetic poles from Late Triassic-earliest Jurassic strata of the Newark basin, *Geol. Soc. Am. Bull.,* **103,** 1648–1662.

Wynne, J.B., Irving, E., Schulze, D.J., Hall, D.C. & Helmstaedt, H.H., 1992. Paleomagnetism and age of three Canadian Rock Mountain diatremes, *Can. J. Earth Sci.,* **29,** 35–47.

Yang, Z., Moreau, M.G., Bucher, H., Dommergues, J.L. & Trouiller, A., 1996. Hettangian and Sinemurian magnetostratigraphy from the Paris Basin, *J. geophys. Res.,* **101,** 8025–8042.