# Silurian and Devonian Base Maps [and Discussion]

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# Silurian and Devonian base maps

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During the Silurian and Devonian, the sequence of continental collisions that were ultimately to result in the formation of the supercontinent of Pangaea had begun. By the Early to Middle Devonian North America (Laurentia), Acadia, Great Britain, and Northern Europe (Baltica) had collided to form the 'Old Red Sandstone' continent (Laurussia). Palaeomagnetic data, however, indicate that the configuration of the continents that made up Laurussia did not resemble the pre-breakup, Mesozoic reassembly. Rather, Britain, Baltica, and Acadia were displaced 10–20° to the south with respect to Laurentia. New palaeomagnetic data for Laurentia and Gondwana, suggests that the ocean separating the northern and southern continents was relatively narrow during the early Devonian, and may have been nearly closed by the late Devonian.

## INTRODUCTION

It has been over a decade since the publication of the first Siluro-Devonian reconstructions based on palaeomagnetic data (McKerrow & Ziegler 1972; Smith *et al.* 1973). In the intervening years, additional palaeomagnetic, biogeographical, and palaeogeographical information has become available that better constrains the positions of the continents during these Middle Palaeozoic times.

Though our understanding of the palaeogeography of the Siluro-Devonian has improved, there is not yet a consensus concerning the positions of the major continental blocks and the sequence of plate tectonic events that preceded the formation of Pangaea. It is encouraging, nevertheless, to note that reconstructions proposed by various authors during the intervening decade (Zonenshain & Gorodnitsky 1977; Morel & Irving 1978; Scotese *et al.* 1979; Van der Voo 1982; Turner & Tarling 1982; Scotese 1984) share much in common, and the most recent proposals appear to be converging on similar solutions.

In this paper a review is presented of the critical palaeomagnetic evidence used to produce the Silurian and Devonian reconstructions shown in figures 1–5. Though the palaeomagnetic data base for the Middle Palaeozoic has increased by nearly an order of magnitude since the publication of the Smith *et al.* (1973) reconstructions, there are still large gaps in the palaeomagnetic record. A summary of Silurian and Devonian palaeomagnetic data for the major continental blocks is given in tables 1–4.

Palaeomagnetic data alone, however, are not sufficent to produce accurate palaeocontinental reconstructions. Because palaeomagnetism does not provide any information concerning the longitudinal relationships of the continents, the relative positions and approximate longitudinal distances between continents must be inferred from other lines of evidence. The relative longitudinal positions of the continents can often be deciphered by studying the distribution of floras and faunas (McKerrow & Cocks 1976; Ziegler *et al.* 1981; Cocks & Fortey 1982).

Similarly the closure of ocean basins and the timing of continent–continent collisions, place important constraints on the relative position of these palaeocontinents and must be taken into account in any palaeoreconstruction.

As one might expect, the evidence from these independent lines of investigation do not always point to the same solution. With regard to Siluro-Devonian reconstructions, the major controversies that remain can be summarized by the following four questions: (i) when the Iapetus Ocean closed, what was the configuration of Laurentia (North America), Baltica (N Europe), and Great Britain? (ii) During the Silurian and Devonian what were the plate tectonic associations of the terranes that make up New England, Britain, and Variscan Europe (W France, Iberia, Germany, and Bohemia)? (iii) How wide was the ocean separating Laurussia (the 'Old Red Sandstone' continent) and Gondwana? (iv) Was there a late Devonian Pangaea?

## Palaeomagnetic evidence

### *North America*

Siluro-Devonian rocks of North America have yielded over 50 palaeomagnetic poles. The most reliable of these results (tables 1–4, see Appendix) have been obtained from the red beds associated with uplift and erosion of the Appalachian highlands (Rose Hill, Bloomsburg, and Catskill formations). Though other lithologies, such as limestones, have yielded stable magnetizations, the remanence carried in these units appears to have been reset during the late Palaeozoic Alleghenian orogeny (Scotese *et al.* 1982; McCabe *et al.* 1983).

Though the palaeomagnetic coverage for North America is fairly good, it is not evenly distributed across this time interval. Most of the results have been obtained from rocks that are either early Silurian or late Devonian in age; palaeomagnetic coverage is particularly sparse across the Siluro-Devonian boundary. At present, there is only a single early Devonian palaeomagnetic pole for cratonic North America (Dankers 1982). This determination, from late Siegenian red beds of the Canadian Arctic, is more similar to Silurian poles than late Devonian poles, suggesting that the 20° latitudinal shift in the position of North America from the early Silurian to the late Devonian (figures 1 and 4) may have occurred during a relatively brief interval in the early–middle Devonian.

Over half of the palaeomagnetic results from North America have come from the tectonically complex terranes that make up much of New England and Maritime Canada (Williams & Hatcher 1982). Though rocks from these areas have not yet yielded a reliable Silurian pole, results from the Devonian (tables 3 and 4) indicate that there is a distinctive 'Acadian' palaeomagnetic signature that differs from palaeomagnetic directions seen in contemporaneous rocks from the craton. Early and late Devonian palaeomagnetic inclinations from Acadia are steeper than their cratonic counterparts, suggesting that when parts of New England and Maritime Canada collided with North America (Acadian orogeny) they arrived 10–15° south of their present position (Kent & Opdyke 1980; Kent 1982).

These palaeomagnetic data require 1000–1500 km of sinistral–slip movement between cratonic North America and much of Maritime Canada. If this is the case, then several important questions are posed: 'when did this strike–slip movement take place?' and, 'where are the faults along which this motion occurred?'

Constraining the timing of the movement should be a simple matter of comparing cratonic and Acadian magnetic inclinations through time, and noting when the apparent difference between them is eliminated. There is a general consensus that by the late Carboniferous palaeomagnetic directions from cratonic North America and Acadia are identical; for older periods the evidence is less clear. This is because often comparisons must be made on the basis of only a few palaeomagnetic poles (for example, early Devonian). In addition, though there are intervals of time for which there are sufficient determinations, it is common to find that the results are unevenly distributed on either continent. In the case of the early Carboniferous one is left to compare 12 poles for Maritime Canada with only four poles from the craton (Scotese *et al.* 1984).

In addition to the late Carboniferous, the only other time interval for which a satisfactory comparison can be made is the late Devonian. The results of this comparison for Atlantic-bordering continents is discussed in detail by Van der Voo & Scotese (1981) and Van der Voo (1982, 1983). They conclude that during the late Devonian, Acadia, together with England and the Russian platform (Baltica), were displaced 10–20° south of the position they usually occupy in the Bullard fit. If North America and Acadia were still offset during the late Devonian, then the movement along this sinistral strike–slip fault must have taken place sometime during the Carboniferous (Van der Voo & Scotese 1981).

The orientation of cratonic North America during the late Devonian is the key to this alternative reconstruction of the Atlantic-bordering continents (figures 3–5). The latitudinal position of North America during the late Devonian is best defined by the results from the Catskill red beds of New York State (Kent & Opdyke 1978; Van der Voo *et al.* 1979). Some authors have suggested that these late Devonian directions may be an overprint of a more equatorial, late Palaeozoic palaeomagnetic signature. Such a remagnetization would eliminate the requirement for Carboniferous strike–slip movement, and would permit an earlier (Acadian?) phase of displacement.

Though palaeomagnetic poles from the Catskill red beds plot near Middle Permian poles for North America, there is no other evidence to suggest that they are secondary remagnetizations. On the contrary, a positive fold test and the occurrence of reversals argue for a primary remanence (Van der Voo *et al.* 1979).

### *Europe*

During the Early Silurian, Europe was composed of at least four separate plates: (i) Baltica, the Russian Platform east of the Polish trough; (ii) Variscan Europe, comprising France, Iberia, south-central Germany, and Bohemia; (iii) England and southeast Ireland, south of the suture of the Iapetus Ocean; and (iv) Scotland and northwest Ireland, north of the Iapetus suture. Both tectonic and palaeomagnetic evidence indicates that these areas had coalesced to form the European half of the 'Old Red Sandstone' continent by late Devonian times (Van der Voo 1982, 1983).

The Silurian and Devonian palaeomagnetic data from Baltica, England and Scotland have been recently reviewed by Briden & Duff (1982) and Briden *et al.* (1984). In these reviews the authors conclude that during the Silurian and early Devonian, Britain was located 20–30° south of the equator. Baltica, however, during the same time interval occupied more equatorial latitudes (figures 1–3). Two determinations from Norway (Storetvedt & Gjellestad 1966; Storetvedt *et al.* 1968) and five poles from the Russian platform (Khramov & Rodionov 1980; Khramov *et al.* 1981) suggest that during the late Silurian and early Devonian the palaeo-equator diagonally crossed Baltica from northern Norway, south to the Ukraine.

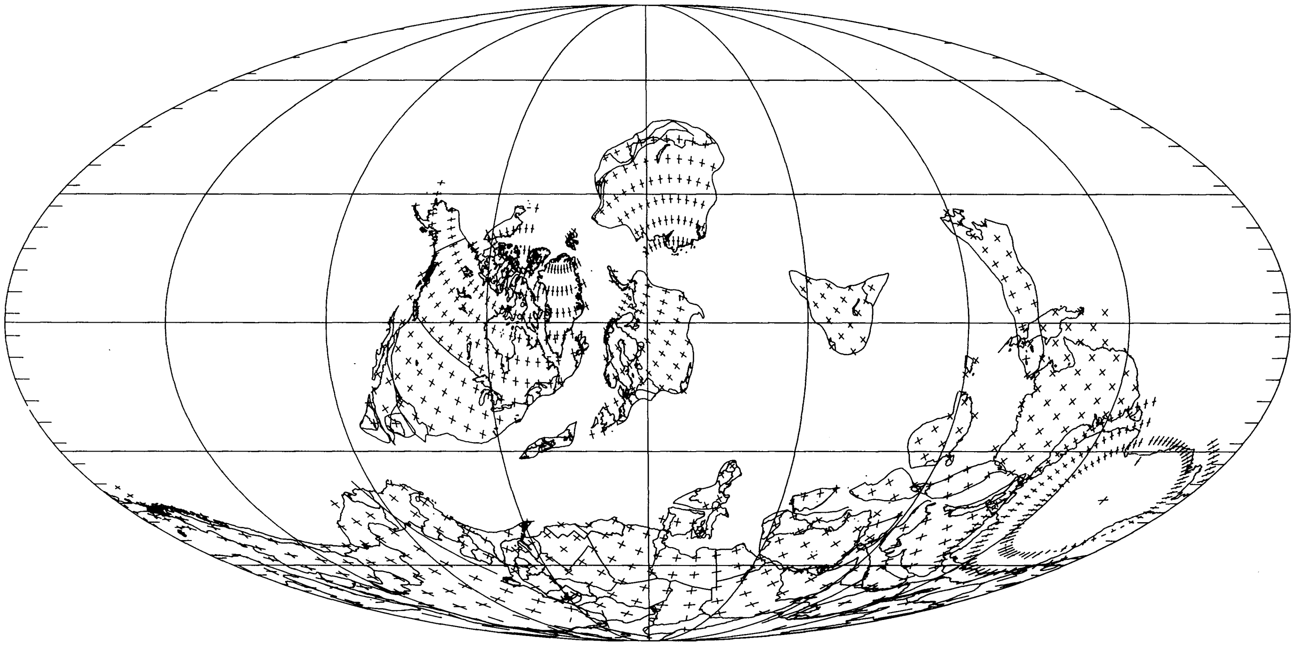

FIGURE 1. Early Silurian (late Llandovery–early Wenlock) reconstruction.

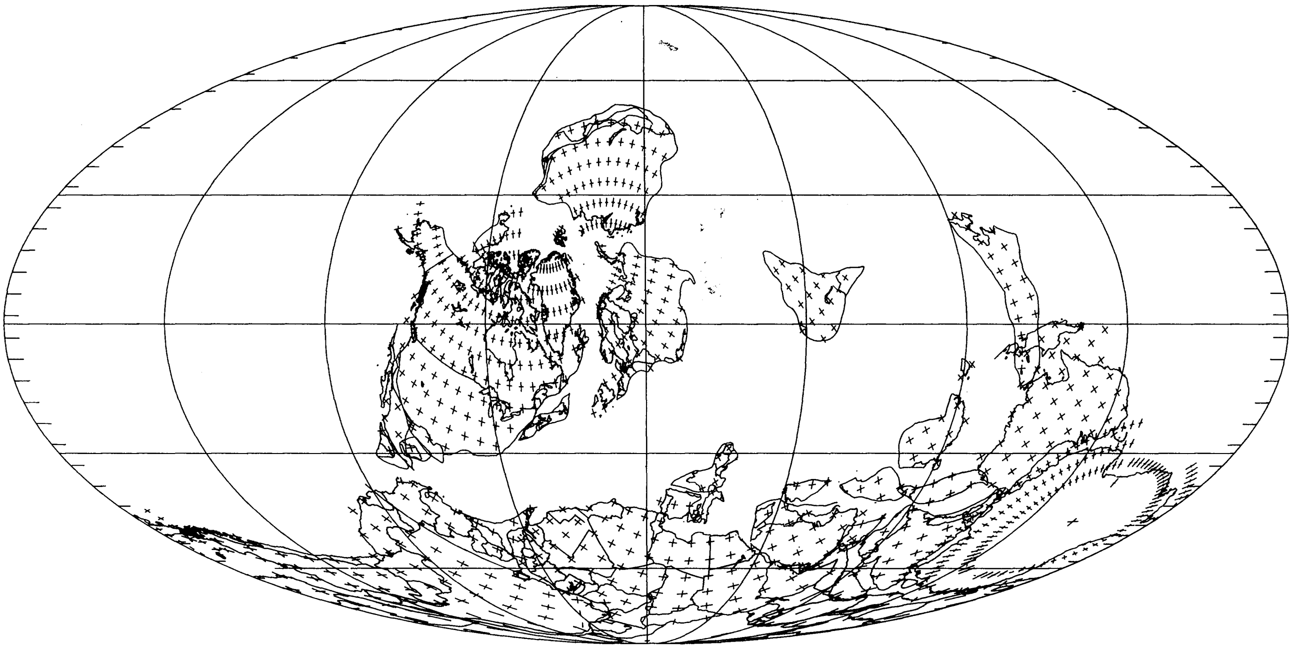

FIGURE 2. Late Silurian (late Ludlow–early Přídolí) reconstruction.

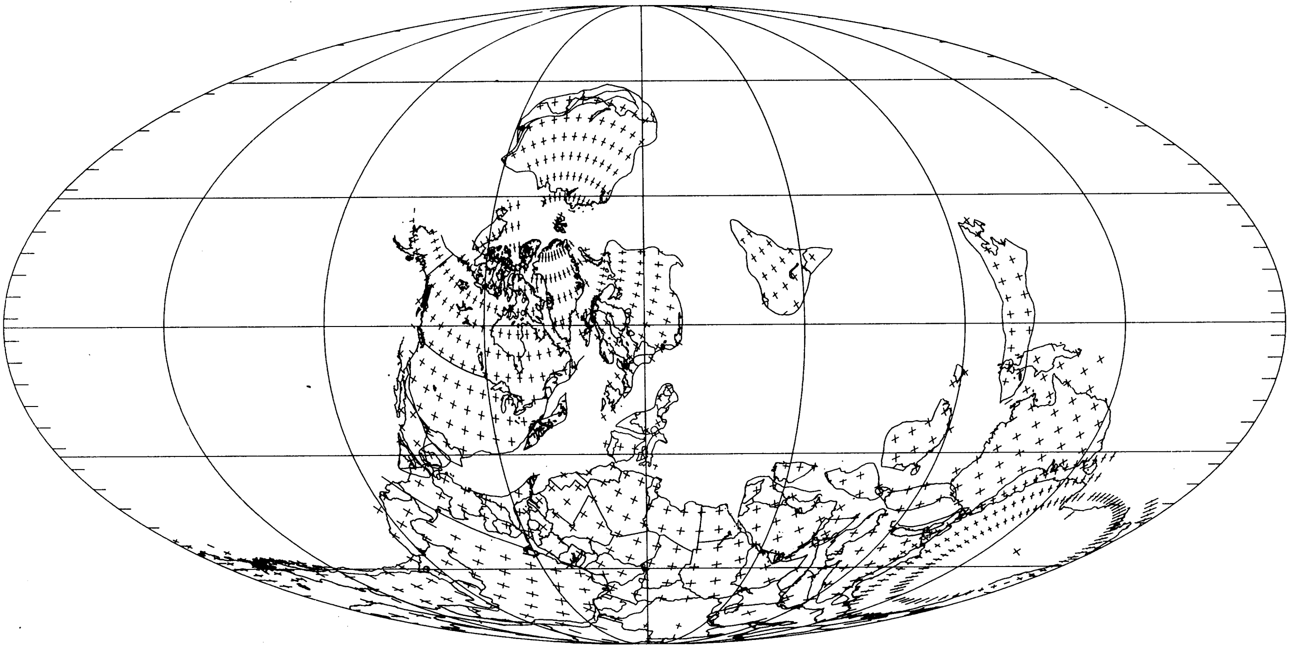

FIGURE 3. Early Devonian (late Gedinnian–early Siegenian) reconstruction.

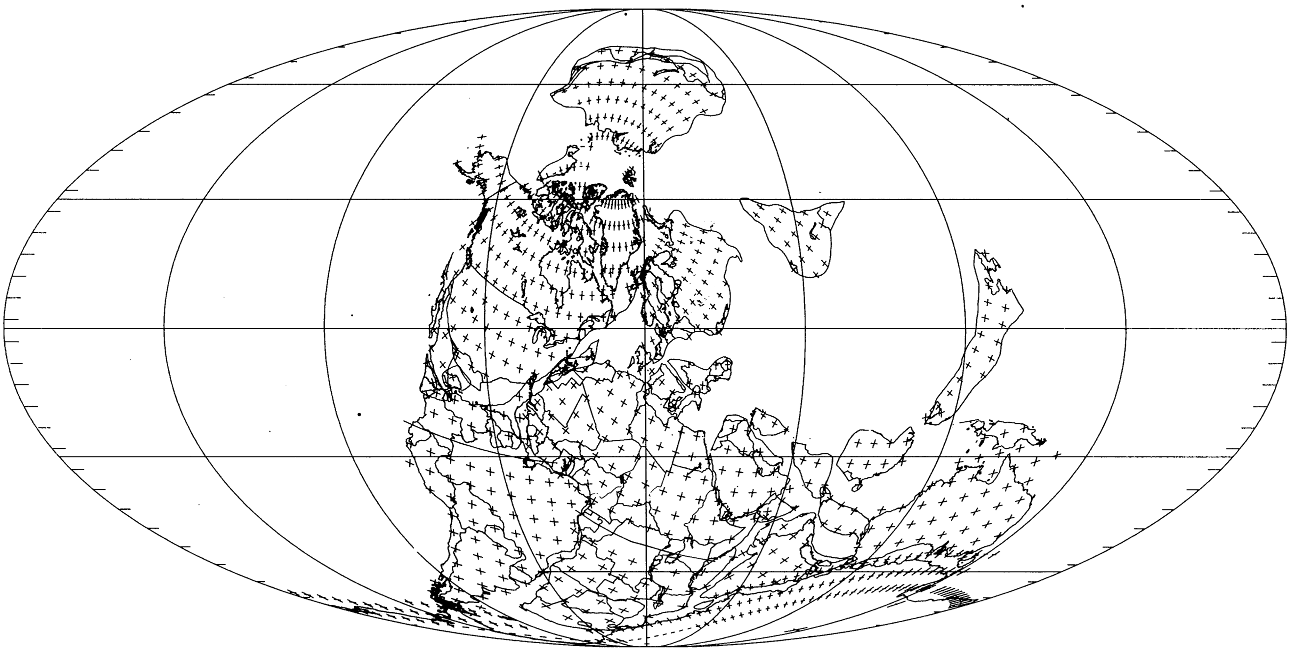

FIGURE 4. Late Devonian (late Frasnian–early Famennian) reconstruction. Model A.

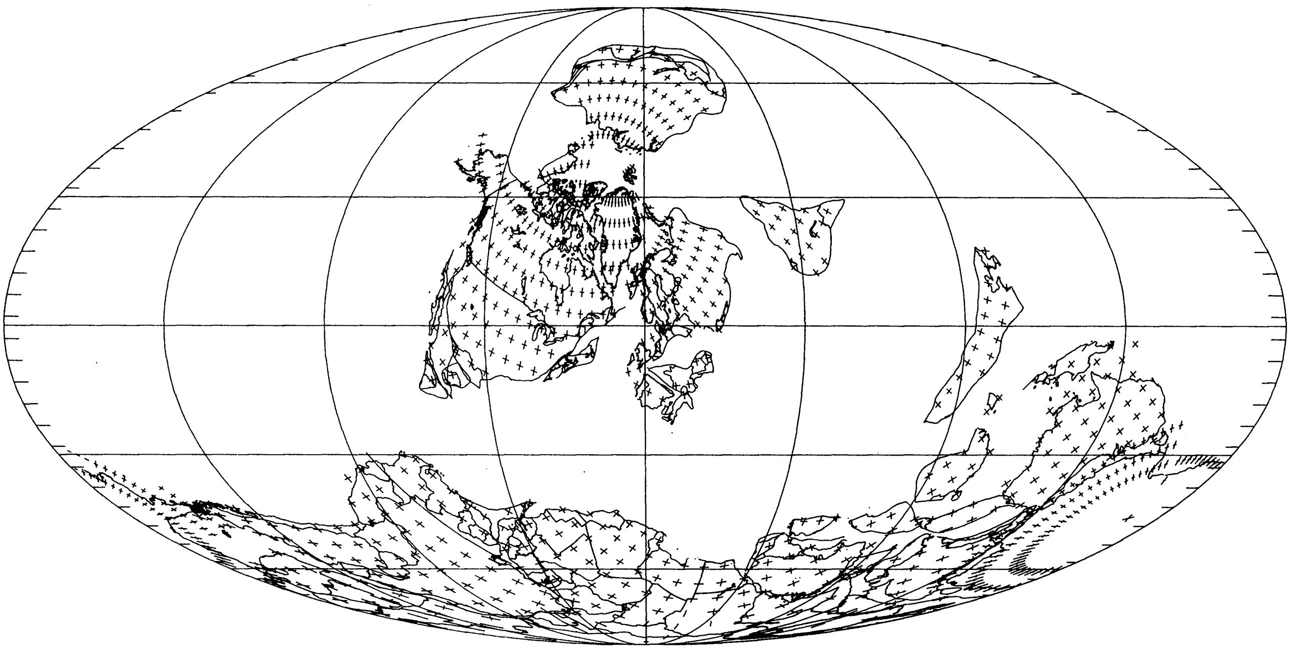

FIGURE 5. Late Devonian (late Frasnian–early Famennian) reconstruction. Model B.

During the Devonian, Baltica and England moved northward so that by late Devonian times, England occupied a more equatorial position (figures 3–5). Though the palaeomagnetic evidence is sparse (tables 3 and 4), it appears that the latitudinal offset between England and Baltica was also eliminated by the end of the Devonian.

In the preceding discussion, palaeomagnetic determinations from areas north and south of the Iapetus suture were considered together. Indeed the most recent review of British palaeomagnetic data (Briden *et al.* 1984) concludes that by the late Silurian–early Devonian, the Iapetus Ocean was too small to be measured palaeomagnetically. As they point out, this interpretation is geologically not controversial.

What is problematic, however, is the fact that southern Scotland, which in most tectonic models (Bird & Dewey 1971; McKerrow 1983) is considered to be part of the North American plate, does not appear to have the same Siluro-Devonian palaeomagnetic signature as North America. This discrepancy was noted by Van der Voo & Scotese (1981) who suggested that a major, and as yet geologically unrecognized, tectonic boundary must run through Britain. They proposed that the Great Glen Fault might be a likely candidate.

Recent palaeomagnetic studies of Silurian and Ordovician igneous and metamorphic rocks on either side of the Great Glen Fault (Turnell & Briden 1983; Watts 1982; Watts & Briden 1984) argue that the magnetic signatures on both sides of the fault are similar. In light of these results, large strike–slip movement along the Great Glen after the late Ordovician was thought to be unlikely (Briden *et al.* 1984).

This interpretation, however, does not resolve the discrepancy between North American and British palaeomagnetic data. If the Great Glen is not the site of a major tectonic boundary, then the fault, or series of faults, must lie to the north or south of the Great Glen. Although there are several major faults to the south (Highland Boundary Fault, Southern Uplands Fault, Iapetus suture), the palaeomagnetic poles from these areas look European rather than North American. Moreover, the Highland Boundary Fault is overlain by Devonian sediments, and therefore, cannot have post-Silurian displacements, and similar early Devonian sediments are present on both sides of the Southern Uplands Fault.

The fault could lie to the northwest of the Great Glen, somewhere offshore; but if it does, then why does the Lewisian basement fit so nicely against Greenland when the North Atlantic is closed? Also, if the Northern Highlands are displaced, then where do they fit along the eastern seaboard of North America? At present, none of the proposed sites of the fault are particularly attractive.

The final group of European palaeomagnetic results that need to be discussed briefly are those from Variscan Europe. Palaeomagnetic poles from rocks of late Devonian age place Iberia (Perroud 1983) and western France (Jones *et al.* 1979) at latitudes 10–15° south of the equator. This contrasts with late Ordovician palaeomagnetic directions from the same areas (Perroud 1983; Perroud *et al.* 1983) that are steeply inclined, indicating polar latitudes. From these data we can infer that during the Silurian and early Devonian, Variscan Europe rapidly traversed much of the southern hemisphere, and that by latest Devonian–early Carboniferous times it had begun to collide along the southern margin of the Old Red Sandstone continent (figure 4).

### *Gondwana*

The single greatest uncertainty in any Siluro-Devonian reconstruction is the position of the supercontinent of Gondwana. The Middle Palaeozoic portion of the apparent polar wander path for Gondwana is poorly constrained, and several alternative paths have been proposed (Briden 1967; Schmidt & Morris 1977; Morel & Irving 1978; Thompson & Clark 1982). The most direct path connects late Ordovician and early Carboniferous palaeomagnetic poles across central Africa.

Even if one assumes that the most direct apparent polar wander path is correct, the timing of Gondwana's northward movement along this path is still not well constrained. This uncertainty arises from the fact that several of the poles that define the path are poorly dated (for example, Mereenie sandstone) and the remainder do not lie along the apparent polar wander path in a simple temporal sequence (Kent *et al.* 1984).

Conflicting results from Africa (Msissi norite, Hailwood (1974); Gneignuira–Dikel Fm., Kent *et al.* 1984) place the northern margin of Gondwana at 45° S, or 15° S, respectively. These two alternative positions are shown in figures 4 and 5. If the Gneignuira–Dikel pole is primary, and not merely a late Palaeozoic overprint, then it is possible that a nearly Pangaean reassembly of the northern and southern continents, excluding Asia, may have been achieved by the end of the Devonian.

### *Asia*

Geological, tectonic, and biogeographical data now indicate that the Asian continent is actually a loosely welded agglomeration of separate palaeocontinents. Several of these palaeocontinents appear to have had long and independent plate tectonic histories before their incorporation into Asia (that is, Siberia and Kazakhstania) whereas others, N and S China, southeast Asia, Tibet, Afghanistan, Iran, India and parts of Turkey, have had strong ties to, and may have been derived from, Gondwana.

With the exception of Siberia, whose apparent polar wander path is fairly well known (Khramov & Rodionov 1980; Khramov *et al.* 1981), Asia is represented by only a handful of Siluro-Devonian palaeomagnetic poles. Included in this group are two late Devonian poles from Kazakhstan (Khramov & Sholpo 1967), two late Devonian poles from Iran (Wensink *et al.* 1978; Wensink 1979; Soffel & Forster 1980), one Devonian pole from Afghanistan (Krumsiek 1978), one early Silurian pole from N China (Khramov 1975), and a single late Silurian palaeomagnetic pole from Malaya (Haile 1980).

The position of S China, shown adjacent to northwest Australia in figures 1–5, is based on a Middle Cambrian pole from the South China platform (Lin *et al.* 1982), and the assumption that during the early and Middle Palaeozoic, South China was part of Gondwana. This assumption is supported by biogeographic evidence that links China and Australia during the late Cambrian. The positions of the remaining Asian palaeocontinents, with the exception of Siberia, have been interpolated between younger and older palaeomagnetic reference points.

## Discussion

The Devonian reconstructions shown in figures 3–5, differ considerably from the early Devonian reconstruction previously published by Scotese *et al.* (1979). The two major differences are the more southerly position of North America shown in figure 3, and the more northerly position of Gondwana shown in the Late Devonian reconstruction (figure 4).

As mentioned in the previous section, the more southerly position of North America is based on the recognition that early to Middle Devonian poles used in the Scotese *et al.* (1979) Emsian reconstruction, are not based on primary magnetizations, but rather on magnetic directions that had been reset during the Alleghenian orogeny (Scotese *et al.* 1982; McCabe *et al.* 1983). This fact, combined with a new early Devonian pole from the Canadian Arctic, permits the revisions illustrated in figures 3–5. As several critics of the Scotese *et al.* (1979) early Devonian reconstruction have pointed out (Boucot & Gray 1979; Heckel & Witzke 1979), the narrowing of the wide ocean between Gondwana and Laurussia (the Old Red Sandstone continent) produces a palaeogeography that is more consistent with the biogeographic patterns for the early Devonian (Barrett 1985).

During the early Devonian there were three major biogeographical realms: the Eastern Americas Realm, the Old World Realm, and the Malvinokaffric Realm. The Malvinokaffric Realm was restricted to south-central South America, southern Africa, and Antarctica, and is characterized by a low diversity, 'cold-water' fauna (Boucot 1975; Savage *et al.* 1979). The location of sites with reported Malvinokaffric faunas, when plotted on the early Devonian reconstruction (figure 3), are between 45 and 80° S. In contrast, the high diversity faunas of the Eastern Americas and Old World Realms appear to have been tropical (Boucot *et al.* 1969).

In the Scotese *et al.* (1979) early Devonian reconstruction, a severe palaeobiogeographical problem arose from the fact that both the Eastern Americas and Old World realms were split in half by the wide ocean barrier that separated the northern continents from Gondwana. Faunas belonging to the Eastern American Realm, that are found in the Appalachian basin, were separated from similar faunas in northern South America. Similarly, Old World faunas found in Britain and Baltica, were separated from similar occurrences in Variscan Europe. The existence of a wide ocean between Laurussia and Gondwana during the early Devonian is, therefore, biogeographically untenable (Barrett 1984). By narrowing the ocean basin between

Laurussia and Gondwana the reconstruction presented in this paper (figure 3) remedies this problem.

In general there is good agreement between the observed and expected distribution of climatically sensitive facies when plotted on these Siluro-Devonian reconstructions. Throughout this interval Laurentia and Baltica, which were covered by broad carbonate platforms, remain within 30° of the equator. The late Silurian evaporites of the Michigan Basin were produced while the eastern half of cratonic North America languished under the south tropical dry belt. The Devonian evaporites which occur along the western edge of the craton as far north as the Arctic circle, and as far south as the Williston basin in Montana, record the rapid northward movement of Laurentia under the dry, north subtropical high.

There were no widespread tillites during the Siluro-Devonian. However, isolated reports of diamictites from South America (early Silurian, Bolivia and Argentina (Ahfeld & Branisa 1960); early Devonian, Brazil (Hambrey & Harland 1981)) are consistent with the cool temperate and polar positions of these areas shown in figures 1 and 3. During the early to Middle Devonian, carbonates and patchy reefs, which had been absent since the Cambrian, appeared along the northern fringes of Gondwana (Africa (Hollard 1968); western France (Paris & Robardet 1977); Iran and Afghanistan (Ziegler *et al.* 1979)). The presence of early Devonian evaporites in western Australia, and the recent discovery of calcretes in southern China (Yunnan province; Boucot *et al.* 1982) are consistent with the subtropical location of these areas shown in figure 3.

One of the few areas where palaeomagnetic and palaeoclimatic latitudinal indicators do not agree, is Siberia. Early Devonian reefs occur at the unlikely latitude of 55° N, and evaporites plot 10–20° north of their predicted position.

## CONCLUSIONS

In this concluding section, we return to the four questions posed in the Introduction and discuss the answers, or at least the constraints, provided by Silurian and Devonian palaeomagnetic and biogeographical information.

(i) When the Iapetus Ocean closed, what was the configuration of Laurentia (North America), Baltica (N Europe), and Great Britain?

The closure of the Iapetus Ocean appears to have been a diachronous event, with evidence of closure first seen in the late Llandovery and Wenlock of Greenland (Hurst *et al.* 1983) and Scandinavia (Gee & Sturt 1983), followed by closure across the suture in Britain (Wenlock–Siegenian (Thirwall 1983; Leggett *et al.* 1983)), and final closure between Acadia and Laurentia in the early Devonian (Robinson & Hall 1980). Late Silurian and Devonian palaeomagnetic evidence suggests that though the Iapetus Ocean had closed, the configuration of the continents that composed the Old Red Sandstone continent was considerably different from the configuration shown in most North Atlantic reconstructions (Bullard *et al.* 1965; Sclater *et al.* 1977). In this alternative reconstruction (figures 1–5), Baltica, much of Britain, and the terranes of New England and Maritime Canada (Acadia, Avalon, and Meguma) are located 10–15° south of the position they usually occupy.

This interpretation suggests that there must have been considerable post-collisional strike–slip movement within this reassembly. However the location of the faults (Bradley 1982) and the timing of the motion, have not been satisfactorily resolved. The good agreement between late Palaeozoic palaeomagnetic results from the Atlantic-bordering continents indicate that these post-collisional readjustments were completed by the late Carboniferous (Scotese *et al.* 1984).

(ii) During the Siluro-Devonian, what were the plate tectonic associations of the terranes that make up New England, Maritime Canada, Britain, and Variscan Europe?

Palaeomagnetic data from New England, Maritime Canada, and Britain indicate that the terranes that comprise these areas moved as independent blocks with respect to the Laurentia and Baltica during the Silurian and early Devonian. By the late Devonian these terranes had become fixed to Baltica; however, as described in answer to the preceding question, Acadia, Britain, and Baltica were still displaced with respect to Laurentia.

The plate tectonic affinity of the terranes that made up Variscan Europe depends on which late Devonian reconstruction of Gondwana is correct (figures 4 and 5). If the reconstruction that places the northern margin of Gondwana at high southern latitudes is correct, then Variscan Europe crossed the southern hemisphere as an independent block during Siluro-Devonian times, opening a wide ocean between south-central Europe and Gondwana. If, on the other hand, the more tropical orientation of Gondwana is correct, then Variscan Europe may have always been adjacent to the northern margin of Gondwana. Biogeographical evidence for the Silurian and early Devonian, favours the second alternative (Cocks & Fortey 1982).

(iii) During the Silurian and Devonian, how wide was the ocean separating the 'Old Red Sandstone' continent (Laurussia) from Gondwana?

Biogeographical and palaeoclimatic evidence requires an oceanic barrier between England and the northern margin of Gondwana (Brittany) during the late Silurian (Cocks & Fortey 1982). *Clarkeia*, a brachiopod typically associated with Gondwanan faunas, occurs in Brittany (Melou & Racheboeuf 1977) indicating that this part of Europe was still biogeographically linked with Gondwana. Palaeoclimatically, England also differs from the Variscan Europe and Gondwana. During the Middle Silurian, England was covered by 'Bahamian-type' carbonates, whereas, the stratigraphy of Variscan Europe and the northern margin of Gondwana is dominated by deep water clastics.

This ocean barrier probably narrowed during the late Silurian and early Devonian. New palaeomagnetic data that places North America in a more southerly position (Dankers 1982) closes the ocean between Laurussia and Gondwana at these times. However, poor palaeomagnetic constraints regarding the position of Gondwana during the Middle Palaeozoic make it difficult to answer this question without equivocation.

Biogeographical patterns suggest that during the early Devonian any ocean basin that existed between these continents was not wide enough to act as a barrier to migration of shallow shelf benthic faunas. At present it is not possible to answer this question for the late Devonian. As figures 4 and 5 illustrate, both a wide and narrow intervening ocean are palaeomagnetically permissible.

By the early Carboniferous (Visean), the northern margin of Gondwana was in collision with Baltica across much of Variscan Europe. To close the ocean basin shown in figure 5, Gondwana would have had to have moved northward at an unusually high rate for a large continental plate (over 15 cm per year). Though this is not impossible, given the range of Phanerozoic plate velocities it seems unlikely.

(iv) Was there a late Devonian Pangaea?

While there is no one conclusive line of evidence that requires the formation of a late Devonian Pangaea, the trend of the arguments discussed in the preceding sections seems to point in that direction. This is not to say that Pangaea was complete, or that most of the tectonic activity associated with this phase of continental collision and plate reorganization was over. Rather, it was just beginning. Late Devonian times marked the end of an era of plate tectonics characterized by wide intercontinental oceans, high stands of sea level, and ageing passive margins. No such wide oceans would appear again until the Mesozoic–Cainozoic breakup of Pangaea.

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## APPENDIX

TABLE 1. EARLY SILURIAN (LLANDOVERY–WENLOCK) PALAEOMAGNETIC SUMMARY

| | pole position | formation; reference | palaeolatitude<br>† | <br>‡ | note |
|---|---|---|---|---|---|
| | | (*a*) Gondwana | | | |
| Australia | 30.0° S, 31.0° E | Tumblagooda ss.; Embleton & Giddings (1974) 14.405* | 18° S | 15° S | (1) |
| | 71.0° S, 7.0° W | Ainslie volcanics; Luck (1973) 14.368* | 17° S | 15° S | (2) |
| | 38.2° S, 34.6 ° E | mean pole Tasman; Goleby (1980) | 4° S | 15° S | (3) |
| India | 12.0° N, 20.5° E | Marhaum formation; Klootwijk (1979) | 37° S | 40° S | — |
| | | (*b*) North America | | | |
| Craton | 19.0° N, 129.1° E | Rose Hill fm.; French & Van der Voo (1979) | 26° S | 25° S | — |
| | 22.0° N, 141.0° E | Rockwood fm.; Van der Voo *et al.* (1983) | 18° S | 25° S | (4) |

### Table 1. (*cont.*)

| | pole position | formation; reference | palaeolatitude † | palaeolatitude ‡ | note |
|---|---|---|---|---|---|
| | | (*c*) Europe | | | |
| England | 16.0° N, 62.0° E | Moel-y-Golfa andesites; Piper (1978) 16.167§ | 28° S | 20° S | — |
| | 14.5° N, 54.2° E | Shelf inlier dolerite intrusions; Piper (1978) 16.166§ | 7° S | 20° S | — |
| | 18.4° N, 45.8° E | Snead phacolith; Piper (1978) 16.169§ | 40° S | 20° S | — |
| | 8.1° S, 128.7° E | Somerset and Glouc. lavas; Piper (1975) 15.131§ | 29° S | 20° S | — |
| | 9.0° S, 107.0° E | Tortworth traps; Morris *et al.* (1973) 14.385§ | 19° S | 20° S | — |
| Scotland | 16.5° N, 145.8° E | Borrolan (younger group); Turnell & Briden (1983) | 11° S | 5° S | (5) |
| | 12.0° N, 142.0° E | Moine metamorphics (intermediate blocking temperature); Watts (1982) | 16° S | 5° S | (6) |
| | 16.0° N, 138.0° E | Moine metamorphics (high blocking temperature); Watts (1982) | 11° S | 5° S | (6) |
| | | (*d*) Asia | | | |
| Siberia | 7.0° S, 103.0° E | early Silurian mean pole; Khramov *et al.* (1981) | 23° S | 25° S | — |
| N. China | 39.0° N, 25.0° E | Khramov (1975) | 23° N | 20° N | — |

† The palaeolatitude calculated from the inclination of the remanent magnetization.

‡ The palaeolatitude of this area, to the nearest 5°, as illustrated on figure 1.

§ These numbers refer to the pole list compiled by McElhinny (1968*a*, *b*, 1969, 1972) and McElhinny & Cowley (1977, 1978, 1980).

### Table 2. Late Silurian (Ludlow–Přídolí) palaeomagnetic summary

| | pole position | formation; reference | palaeolatitude † | palaeolatitude ‡ | note |
|---|---|---|---|---|---|
| | | (*a*) Gondwana | | | |
| Australia | 41.5° S, 40.5° E | Mereenie ss.; Embleton (1972) 14.376§ | 22° S | 20° S | (7) |
| | 54.0° S, 89.0° W | Laidlaw and Douro volc.; Luck (1973) 14.384§ | 11° S | 20° S | — |
| | 80.0° S, 20.0° E | Mugga Mugga porphyry; Briden (1966) 8.127§ | 25° S | 20° S | (8) |
| | 47.3° S, 2.4° W | mean pole Tasman; Goleby (1980) | 5° S | 20° S | (9) |
| | | (*b*) North America | | | |
| Craton | 32.0° N, 102.0° E | Bloomsburg fm.; Roy *et al.* (1967) 9.125§ | 17° S | 25° S | — |
| | 17.0° N, 125.0° E | Wabash reef; McCabe *et al.* (1985) | 20° S | 20° S | — |
| Avalonia | 25.0° N, 100.0° E | Wigwam red red, Botwood group; Lapointe (1979) | 15° S | 15° S | (10) |
| | 28.0° N, 85.0° E | Mascarene 'C'; Roy & Anderson (1981) | 13° S | 20° S | — |
| | | (*c*) Europe | | | |
| Craton | 21.0° N, 159.0° E | Ringerike ss.; Storetvedt *et al.* (1968) 10.129§ | 6° S | 10° S | — |
| England (see early Devonian summary) | | | | | |
| | | (*d*) Asia | | | |
| SE Asia | 17.0° N, 79.0° E | Upper Setul ls.; Haile (1980) | 67° N | ? | — |
| Siberia (interpolated between early Silurian and early Devonian poles) | | | | | |

† The palaeolatitude calculated from the inclination of the remanent magnetization.

‡ The palaeolatitude of this area, to the nearest 5°, as illustrated on figure 2.

§ These numbers refer to the pole list compiled by McElhinny (1968*a*, *b*, 1969, 1972) and McElhinny & Cowley (1977, 1978, 1980).

TABLE 3. EARLY DEVONIAN (GEDINNIAN–EMSIAN) PALAEOMAGNETIC SUMMARY

| | pole position | formation; reference | palaeolatitude | | note |
|---|---|---|---|---|---|
| | | | † | ‡ | |
| | | (*a*) Gondwana | | | |
| Africa | 38.4° S, 43.8° E | Lower Gneiguira group; Kent *et al.* (1984) | 13° S | 40° S | (11) |
| Australia | 64.0° S, 45.0° E | Bowning group; Luck (1973) 14.369§ | 24° S | 25° S | — |
| | 49.0° S, 106.8° W | early Devonian Tasman; mean pole; Goleby (1980) | 13° S | 25° S | (12) |
| | 50.4° S, 86.5° W | Tasman overprint; Goleby (1980) | 7° S | 25° S | (13) |
| India | 30.0° S, 12.0° W | Rudrapayag volcanics; Athavale *et al.* (1977) | 17° S | 45° S | (14) |
| S. America | 30.0° S, 47.0° W | Picos and Passagem beds; Creer (1970) 12.135§ | 63° S | 70° S | — |
| | | (*b*) North America | | | |
| Craton | 25.0° N, 99.0° E | Peel Sound formation; Dankers (1982) | 10° N | 15° N | (15) |
| Avalonia–Acadia | 19.8° N, 128.8° E | Hersey formation; Kent & Opdyke (1980) | 23° S | 25° S | (16) |
| | 23.7° N, 113.7° E | Eastport formation; Kent & Opdyke (1980) | 21° S | 25° S | — |
| | 23.5° N, 86.7° E | Dockendorf grp. volc.; Brown & Kelly (1980) | 15° S | 15° S | (17) |
| | 29.0° N, 82.0° E | Traveller's felsite; Spariosu & Kent (1983) | 10° S | 20° S | (18) |
| | 24.9° N, 93.5° E | Freels granite; Murthy (1983) | 10° S | 20° S | (19) |
| | 25.0° N, 86.0° E | Cape Breton granite; (CB3); Rao *et al.* (1981) | 13° S | 20° S | — |
| | | (*c*) Europe | | | |
| Craton | 19.0° N, 160.0° E | Roragen sandstone; Storetvedt & Gjellestad (1966) 8.124§ | 5° S | 5° S | — |
| | 35.0° N, 160.0° E | late Silurian–early Dev. mean pole; Khramov *et al.* (1981) | 3° S | 5° S | — |
| Scotland | | | | | |
| Grampian Highlands | 29.0° N, 160.0° E | Foyer's plutonic complex; Kneen (1973) 14.380§ | 3° S | 0° | — |
| | 5.0° N, 156.0° E | Garabal Hill, Glen Fyne complex; Briden (1970) 12.138§ | 24° S | 0° | — |
| | 8.0° N, 154.0° E | Arrochar complex; Briden (1970) 12.139§ | 21° S | 0° | — |
| | 2.0° S, 141.0° E | Lorne lavas; Latham & Briden (1975) 14.377§ | 30° S | 0° | — |
| | 23.0° N, 115.0° E | Salrock group; Morris *et al.* (1973) 14.382§ | 1° S | 0° | — |
| Midland Valley | 1.0° S, 145.0° E | O.R.S. lavas; McMurray (1970) 12.137§ | 28° S | 0° | — |
| | 1.0° N, 121.0° E | O.R.S. lavas; Creer & Embleton (1967) 9.124§ | 16° S | 0° | (20) |
| | 5.0° N, 140.0° E | O.R.S. lavas; Sallomy & Piper (1973) 14.378§ | 22° S | 0° | — |
| N. England (Iapetus Suture) | 3.7° S, 141.0° E | Cheviot granites; Thorning (1974) 14.373§ | 31° S | 15° S | (21) |
| Variscan Europe | | | | | |
| Spain | 22.0° N, 139.0° E | San Pedro red beds; Perroud (1984) | 19° S | 25° S | — |
| | | (*d*) Asia | | | |
| Siberia | 15.0° N, 116.0° E | late Silurian–early Devonian mean pole; Khramov *et al.* (1981) | 33° N | 35° N | — |

† The palaeolatitude calculated from the inclination of the remanent magnetization.

‡ The palaeolatitude of this area, to the nearest 5°, as illustrated on figure 3.

§ These numbers refer to the pole list compiled by McElhinny (1968*a*, *b*, 1969, 1972) and McElhinny & Cowley (1977, 1978, 1980).

TABLE 4. MIDDLE AND LATE DEVONIAN (GIVETIAN–FAMENIAN) PALAEOMAGNETIC SUMMARY

| | pole position | formation; reference | palaeolatitude<br>† | palaeolatitude<br>‡ | note |
|---|---|---|---|---|---|
| | | (*a*) Gondwana | | | |
| Africa | 0.5° S, 25.0° E | Msissi norite; Hailwood (1974) 14.361§ | 44° S | 10° S | (22) |
| | 28.6° S, 44.5° E | Upper Gneiguira group; Kent *et al.* (1984) | 18° S | 15° S | (23) |
| Australia | 60.2° S, 68.1° E | Ross River overprint; Kirschvink (1978) 16.161§ | 32° S | 50° S | (24) |
| | 67.0° S, 94.0° E | Housetop granite and aureole; Briden (1967) 9.123§ | 52° S | 55° S | (25) |
| | 54.0° S, 96.0° E | Mulga Downs; Embleton (1977) 16.153§ | 51° S | 50° S | — |
| | 28.0° S, 88.6° W | Lochiel formation; Embleton & Shepherd (1977) 16.152§ | 5° S | 50° S | — |
| | | (*b*) North America | | | |
| Craton | 46.8° N, 116.6° E | Catskill red beds, N.Y.; Kent & Opdyke (1978) 16.157§ | 1° S | 5° S | (26) |
| | 43.5° N, 124.2° E | Catskill red beds, Penn.; Van der Voo *et al.* (1979) | 4° S | 10° S | (27) |
| Avalonia–Acadia | 26.4° N, 109.3° E | Perry volcanics, New Brunswick; Black (1964) 8.120§ | 19° S | 10° S | (28) |
| | 34.7° N, 120.5° E | Perry red beds, New Brunswick; Black (1964) 8.121§ | 10° S | 10° S | (28) |
| | 24.0° N, 128.0° E | Perry volcanics, Maine Phillips & Heroy (1966) 9.120§ | 19° S | 10° S | (29) |
| | 32.0° N, 118.0° E | Perry red beds, Maine Robertson *et al.* (1968) 10.126§ | 12° S | 10° S | (30) |
| | 23.0° N, 126.0° E | Massachusetts metavolcanics; Schutts *et al.* (1976) 15.128§ | 22° S | 15° S | (31) |
| | 27.4° N, 123.5° E | Terrenceville fm.; Kent (1982) | 15° S | 10° S | — |
| | 18.0° N, 150.0° E | Ste Cecile–Sebastien gran.; Seguin *et al.* (1982) | 16° S | 10° S | (32) |
| | 32.0° N, 125.0° E | 'hornfels'; Seguin *et al.* (1982) | 11° S | 5° S | (33) |
| | 28.0° N, 77.0° E | Compton formation; Seguin *et al.* (1982) | 10° S | 5° S | (34) |
| | 29.0° N, 93.0° E | St George (B); Roy *et al.* (1979) | 14° S | 5° S | — |
| | 35.0° N, 97.2° E | Deadman's Bay dikes (2); Murthy (1983) | 2° S | 5° S | (35) |
| | 24.7° N, 147.2° E | White rock overprint; Spariosu *et al.* (1984) | 14° S | 10° S | (36) |
| | | (*c*) Europe | | | |
| Craton | 22.0° N, 170.0° E | Kvamshesten ss.; Lie *et al.* (1969) 12.134§ | 6° S | 10° N | — |
| | 32.0° N, 161.0° E | late Devonian mean pole; Khramov *et al.* (1981) RP 5.9–5.12‖ | 10° N | 10° N | — |
| Scotland<br>Northern Highlands | 50.0° N, 138.0° E | Stornoway red beds; Storetvedt & Steele (1977) 16.138§ | 22° N | 15° N | (37) |
| | 42.0° N, 143.0° E | Caithness O.R.S. (A); Waage & Storetvedt (1973) 14.363§ | 14° N | 15° N | (38) |
| | 54.0° N, 164.0° E | John O'Groats ss. (A); Storetvedt & Carmichael (1979) | 23° N | 15° N | — |
| | 50.0° N, 165.0° E | Lower and Middle O.R.S.; Tarling *et al.* (1976) 15.129§ | 19° N | 15° N | (39) |
| | 48.9° N, 171.8° E | Helmsdale granite (A); Torsvik *et al.* (1983) | 17° N | 15° N | (40) |

| | pole position | formation; reference | palaeolatitude † | palaeolatitude ‡ | note |
|---|---|---|---|---|---|
| Grampian Highlands | 30.0° N, 166.0° E | Foyers Middle O.R.S.; Kneen (1973) 14.380§ | 3° S | 15° N | — |
| | 21.0° N, 158.0° E | Derry Bay felsite; Morris (1976) 15.127§ | 15° S | 15° N | (41) |
| England | 23.0° N, 136.0° E | Cross Fell Minette dikes; Piper (1979) | 7° S | 10° S | — |
| | 32.0° N, 166.0° E | Hendre dolerite; Piper (1978) 16.162§ | 5° S | 10° S | (42) |
| | 33.0° N, 169.0° E | Blodwell keratophyre; Piper (1978) 16.162§ | 4° S | 10° S | (42) |
| | 32.0° N, 158.0° E | Bristol O.R.S.; Morris *et al.* (1973) 14.359§ | 5° S | 10° S | — |
| Variscan Europe | 30.0° N, 148.0° E | Armorican massif; Jones *et al.* (1979) | 7° S | 10° S | — |
| | 35.5° N, 141.9° E | Diabase, E. Germany; Rother (1971) 14.374§ | 7° S | 10° S | — |
| | 29.7° N, 189.0° E | Hercynian sediments and volcanics; Bachtadse *et al.* (1983) | 9° S | 10° S | — |
| | | (*d*) Asia | | | |
| Siberia | 20.0° N, 140.0° E | late Devonian mean pole; Khramov *et al.* (1981) | 41° N | 50° N | — |
| Kazakhstan | 43.0° N, 160.0° E | late Devonian red beds; Khramov & Sholpo (1967) | 32° N | 25° N | — |
| Iran | 0.2° S, 32.1° E | Geirud lavas; Wensink *et al.* (1978) | 50° S | 30° S | — |
| | 66.0° N, 83.4° W | Kerman 'Old Red'; Soffel & Forster (1980) | 14° S | 35° S | — |
| Afghanistan | 37.0° N, 177.0° E | Krumsiek (1978) | 3° S | 45° S | — |
| Japan | 38.9° N, 199.7° E | Sakari area; Minato & Fujiwara (1965) | 45° N | ? | — |

† The palaeolatitude calculated from the inclination of the remanent magnetization.

‡ The palaeolatitude of this area, to the nearest 5°, as illustrated on figure 4.

§ These numbers refer to the pole list compiled by McElhinny (1968*a*, *b*, 1969, 1972) and McElhinny & Cowley (1977, 1978, 1980).

‖ McElhinny (1973).

## *Notes to tables* 1–4

(1) Very poor age control. The Tumblagooda formation is composed of 1800 m of unfossiliferous sandstone that lies unconformably upon Precambrian gneiss and is overlain by Permian glacial deposits. There are a few trace fossils. A middle Cambrian to early Silurian age has been assigned by the authors.

(2) According to Goleby (1980) the Ainslie volcanics are late Wenlock, rather than early Devonian in age. Goleby suggests that the position of this pole with respect to the apparent polar wander path for Australia may indicate that this pole may be Devonian in age.

(3) This pole is the mean of results from the Rockdale fm., Millambri fm., Belubula shale, and Narragnal limestone. A detailed description of the palaeomagnetic behaviour of these units has not been presented, and it is difficult to know whether or not these results are reliable. In addition, these determinations are from sites that lie to the NE of an ophiolite belt separating the Tasman orogenic belt from cratonic Australia.

(4) This result has been published only in abstract form.

(5) This pole is the mean of the 'younger' group of poles from sites 3, 5, 6 and 7. The Borrolan group intrudes Precambrian–Cambrian age sediments that were metamorphosed during the early?–middle Ordovician, and are cross cut by the Assynt nappe of the Moine thrust (late Ordovician–early Silurian). Associated intrusives have been dated (Pb) at 430 Ma (early Silurian).

(6) This pole is the mean of the 'younger' group of poles from sites 1, 8, 9, and 10 of the Moine metamorphics. Chrontours indicate a cooling age of 410–440 Ma (Silurian). The difference between the intermediate and high

blocking temperature components may reflect apparent polar wander during the cooling episode, or tilting associated with uplift and cooling.

(7) A good discussion of the problems of the Mereenie sandstone can be found in Kent *et al.* (1984).

(8) According to Goleby (1980), the Mugga Mugga porphyry is earliest Ludlovian in age.

(9) This pole is the mean of results from the Canowindra phy., upper Avoca V. shale, Ghost Hill fm., and Mumbil fm. See note 3 for additional comments.

(10) This result was restudied by the author (C.R.S.) and a multiple component remanence was revealed. One of the directions fails the fold test, however a second direction passes the fold test and has an inclination of 15° after tilt correction.

(11) According to the author, 'the sampling was done on a structural surface which may represent a continental interval between marine Silurian and Emsian, i.e. during the early Devonian.' It is interesting to note that though stratigraphically older, the inclinations are shallower than the directions from the upper part of the group.

(12) This pole is the mean of results from the Tenandra fm., Cunningham fm., Cowra granodiorite, and dolerite intrusives from SE Australia. These results may be the most believeable of Goleby's poles because the same direction is also seen as secondary overprints in older units. See note 3 for additional comments.

(13) This pole is based on secondary components of magnetization which are thought to date from the Tasman orogeny.

(14) This pole is based on results from sites located between the Main Boundary thrust and the Main Central thrust of the Himalayas and are likely to be tectonically disturbed. The Rudrapayag volcanics make up the lower part of the Garwhal grp and are part of the Chamoli fm. which is thought to be correlative with the Devonian Muth quartzite.

(15) Though there are reversals present, no fold test was possible. The author rejects a very large percentage of his samples, and no explanation is given for several anomalous directions. The tilt correction, if applied, was not described.

(16) The authors suggest that these results represent a primary magnetization on the basis of contact tests, the presence of reversals, and the fact that several lithologies, with different magnetic minerals, possess similar directions. For a detailed rebuttal see Roy (1982).

(17) The previous result from this unit (Brown 1979) has been revised owing to an error in application of tilt correction. This result represents Acadian overprint direction.

(18) Stratigraphic age is Siegenian despite Rb–Sr date of 360 Ma.

(19) This pole was calculated by C.R.S. from directions given in figure 8 of original paper.

(20) This result combines results from north and south of the Highland Boundary fault and includes a determination from the Lorne Lavas.

(21) This result is from post-collisional granites that lie along the Iapetus suture. K–Ar dates of 366–368 have been obtained from associated andesite and rhyolite volcanics. These intrusives are overlain by late Devonian sandstones and therefore may be middle or early Devonian in age.

(22) The Msissi norite is unconformably overlain by late Devonian sediments (Famenian).

(23) This result is based on only 12 samples from three sites. There are no field tests constraining the age of magnetization, and it is possible that these units were remagnetized during the late Palaeozoic.

(24) Though these units are latest Precambrian–Cambrian in age, they carry a secondary component of magnetization that is thought to have been acquired during the Tasman orogeny.

(25) The precision parameter, $K$, decreases upon unfolding, and the author considers the direction to be a Tertiary remagnetization.

(26) Three formations were sampled that range in age from late Givetian (Manorkill and Plattekill formations) to middle Frasnian (Walton fm.).

(27) A positive fold test was obtained from these red beds, and reversals are present in four samples.

(28) The age of the Perry fm. is Frasnian–Famenian. Demagnetization consisted of AF treatment to 300 Oe (1 Oe = 79.6 A m$^{-1}$).

(29) This result has been published only in abstract form.

(30) Pre-folding and post-folding components were identified. It was difficult to resolve the individual components because the magnetic spectra of the two components appear to overlap. Rhyolite cobbles fail conglomerate test.

(31) These metamorphic rocks are Ordovician in age, but appear to carry a Devonian thermal overprint. K–Ar dates range from 340–370 Ma.

(32) This granite has a K–Ar date of 362 Ma.

(33) This result is from the contact aureole surrounding the Ste Cecile–Sebastien granite. The direction after tilt correction is nearly anti-polar to the direction obtained from the Compton fm. after tilt correction.

(34) The direction after tilt correction was used to calculate the pole for these metasediments. The protoliths have been dated as Eifelian.

(35) Though the directions from these basalts are generally steep, a shallow, southerly direction is also present that is thought to reside in haematite, and may represent a younger chemical remagnetization.

(36) Though the results from this early Palaeozoic formation fail the fold test, the direction before tilt correction is thought to represent an Acadian overprint.

(37) The age of the Stornoway fm. is problematic. Because the directions from these red beds look like European Permo-Triassic directions, the beds are thought to be remagnetized.

(38) The pole for the Caithness red beds was recalculated by using $D = 205$, $I = -27$ obtained from the figure in the original paper. The position of the pole changes from 20.5° S, 33.0° W to 42.0° S, 37.0° W.

(39) These units are Emsian or younger in age. No pole was given by original author. This pole was calculated by Van der Voo & Scotese (1981).

(40) The '*A*' direction, which is by far the best resolved component, agrees with other directions seen in red beds north of the Great Glen Fault.

(41) The Derry Bay felsite may be the extrusive equivalent of the Glen Saul intrusive that has been dated as early Ordovician.

(42) These intrusives are certainly post-Caradoc, and may be younger than the cleavage which has been dated as late Silurian. These intrusives are overlain by late Viséan sediments.

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## *Discussion*

T. S. Westoll, F.R.S. (*University of Newcastle upon Tyne, U.K.*). A most remarkable similarity between the Devonian fish-faunas of Australia and those of Europe and the Arctic is now evident. The well-known early Upper Devonian faunas of Gogo have clear close relationships with those of Bergisch Gladbach and the Baltic area, while those of the Upper Devonian of SE Australia (with representatives in Antarctica) are remarkably close to those of east Greenland – even the Ichthyostegalia may link the latter areas. Among the genera concerned is *Phyllolepis*, a bottom-dwelling placoderm that may well have been blind and is normally found in non-marine contexts. Tarling has taken note of these points in considering the possibility of closer proximity of Australia to the Arctic region in Devonian times. There are obviously many unsolved problems in reconstructing the relative positions of continental areas and the routes and possible barriers to migration. It is worth noting that at least some of the epicontinental waters may have been of moderately high salinity, though with very different chemical contents to sea water, resembling rather the waters of playa lakes.

C. R. Scotese. During the Silurian and early Devonian, North America and Australia occupied equatorial latitudes and were both bathed by a warm, broad equatorial gyre. If the larval stages of these Devonian fish were marine, then this equatorial current would have carried them westward from Australia to Laurentia.

By the late Devonian, most of the wide, deep marine barriers between Gondwana and the 'Old Red Sandstone' continent may have been eliminated. If this was the case, then a fresh water migration route along the margins of this pre-Pangean reassembly may have been possible.

W. G. Chaloner, F.R.S (*Royal Holloway and Bedford Colleges, Virginia Water, Surrey, U.K.*). Noting the suggested movement of the pole into and through Africa within the period under discussion, one sees that plant localities of late Devonian age (for example in S Africa) would have fallen within the polar circle. How do you picture the growing conditions, round the year, for a terrestrial flora in the proximity of the Gondwana pole? To put it in more everyday terms, could one have enjoyed a summertime picnic on the Gondwanan continent, within the polar circle, in Devonian time?

C. R. Scotese. The growing conditions in southern Africa, and other areas of Gondwana near the south pole, would have depended on two important factors: (i) the tilt of the Earth's axis; and (ii) the amount of polar ice. Seasonal growth rings in Carboniferous temperate floras indicate that the tilt of the Earth's axis produced the same seasonal effects then, as it does today. The Late Devonian world could not have been too different.

Regarding the amount of ice cover, evidence suggests that though there may have been isolated mountain glaciers (possibly in Brazil), there were no polar ice caps. However, a broad spectrum of palaeofaunal and palaeoclimatic indicators would seem to indicate that the polar climate was not warm, but rather 'cool'. If I could have gone on a picnic at that time and place, I certainly would have brought along a jacket and a sweater.