Geological Society, London, Special Publications

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Notes

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SUMMARY: Late Proterozoic and Palaeozoic (pre-Permian) palaeomagnetic data from all regions involved in, or adjacent to, the Caledonian–Appalachian orogenic belt are reviewed. Between about 1100 and about 800 Ma the Laurentian and Baltic shields were close together, prior to the opening phase of the Caledonian–Appalachian Wilson cycle. The problems of tectonic interpretation of Palaeozoic palaeomagnetic data from within and around the belt derive mostly from differences of typically 10°–20° between the pole positions. These can variously be interpreted in terms of (i) relative displacements between different continents or terranes, (ii) differences in ages of remanence and (iii) aberrations due to inadequacy of data or geomagnetic complexity, and it is not always easy to discriminate between these alternatives. If the Pangaea A2 reassembly of continents around the northern and central Atlantic is taken as the end-product of Caledonian–Appalachian orogenesis, the following conclusions can be drawn.

1   Lower Palaeozoic palaeolatitude differences between the N American and British–Scandinavian margins of the Caledonides are small; hence any convergence must have been mainly E–W.
2   There are additional differences which could be due to major pre-Carboniferous strike-slip (more than 1000 km), although later strike-slip on this scale is no longer considered likely.
3   The Lower Palaeozoic apparent polar wander paths for Northern Scotland and N America disagree on face value, but must be reconciled if their conventionally assumed geographic relation is correct.
4   Lower Old Red Sandstone data from Britain and Norway disagree, but this is more likely to be due to magnetic overprinting in the Norwegian rocks than to remnant oceans between the regions of Old Red Sandstone facies.
5   Armorica seems to have been far to the S, adjacent to Gondwana, in Ordovician time. The latest view is that it collided with Euramerica in early Devonian time to form the Old Red Continent.
6   The timing of Gondwana's collision with the Old Red Continent is controversial; it is within either the late Devonian or the Carboniferous. If it occurred early in that time range, much of Hercynian–Alleghanian orogeny post-dated it.

Palaeomagnetic data from the continental crust were crucial in the recognition of Wegenerian continental drift which consists principally of the fragmentation and dispersal of Pangaea from Mesozoic times onward. However, limitations of precision and the indeterminacy of longitude which arises from the axial symmetry of the time-averaged palaeomagnetic field prevented the deduction of adequate and unique maps of the sequence of events. Simpler and more precise palaeomagnetic and tectonic data from the oceanic crust were required to achieve precise reassembly of relative positions and, once these were available, the principal role of continental data was to place those reassemblies into a latitude–longitude framework.

The application of continental palaeomagnetism to Palaeozoic continent distribution is even more hazardous than is the case for Mesozoic and younger periods for a number of reasons.

1   There is no additional constraint from contemporary oceanic crust, since none is preserved other than as ophiolite fragments.
2   The definition of Palaeozoic lithospheric fragments—plates and terranes—is not always clear.
3   There are insufficient data to chart the progress of all these fragments relative to the pole.
4   In general, older rocks are palaeomagnetically more complex. Whether by involvement in orogeny or by long-term exposure to geomorphological processes, older rocks are more likely to have been at least partially remagnetized. The dissection of the various magnetizations coexisting in such rocks is never straightforward and is sometimes impossible.
5   Problems of dating magnetizations are severe. Not only are there problems of dating the rocks themselves and of relating biostratigraphic and

radiometric ages into an internally consistent scale, but there are also problems in relating magnetization components to datable events in the formation and subsequent history of those rocks, e.g. in red beds.

It follows that useful palaeomagnetic constraints on the evolution of an orogenic belt are best derived from sequences of precise dated palaeomagnetic field estimates from individual lithospheric fragments. Precision is vital because relative movements of the order of hundreds of kilometres or less are of key interest to students of the geology of orogeny. Sequences of data are necessary because the required order of precision is rarely attained in single rock formations. Dating is vital because relative ages of events are a key element in the pattern of tectonic evolution.

In the case of the Appalachian–Caledonian orogen the definition of terranes within the belt is still a matter of debate, the identity and character of much of the SE margin is uncertain and the geological record on the cratons available for palaeomagnetic sampling is far from adequate; it also emerges that much of the apparent polar wander (APW) that is found corresponds to a change in palaeo-orientation rather than palaeolatitude.

Hence the approach we take here is to assume that the major fragments of continental lithosphere in the lower Palaeozoic were Baltica, Gondwanaland, Laurentia and Siberia, which would progressively be sutured along the Caledonian, Appalachian, Hercynian and Uralian orogenic belts to form a Pangaea at least by late Palaeozoic times. We shall consider the motion of each of these blocks in so far as they are relevant to the Appalachian–Caledonian orogen, and we shall also consider marginal regions of those 'continents' within the orogen, and those possible microcontinental fragments caught up within the belt, for which there are any palaeomagnetic data.

The palaeomagnetic expression of plate convergence related to the Caledonides was first illustrated schematically as differences between 'European' and 'N American' Palaeozoic polar wander paths relative to the geometrical fits of Bullard *et al.* (1965) and of Smith & Hallam (1970) now called Pangaea A, by Briden *et al.* (1973) and McElhinny (1973). The obvious place to try to measure the amount of separation was the British Isles, which is the only place where the whole width of the belt is exposed on land, but early attempts (Briden *et al.* 1973, Piper 1979) were rather inconclusive owing to scatter in the data. A direct comparison of poles from two contemporaneous volcanic suites in Ireland

(Deutsch 1980) and a more generalized estimate based on sequences of data, some of it more refined than hitherto, by Briden *et al.* (1984) are more satisfactory. Van der Voo and co-workers (Van der Voo 1979, Hagstrum *et al.* 1980, Perroud *et al.* 1984) have extended the comparisons to embrace 'Armorica', which is hypothetically an Armorica plate consisting not only of the Armorican massif but of most of Hercynian Europe, probably the Avalonian terranes of northeastern N America and possibly southern England and Wales.

Morris (1976) pointed out that the long-known discrepancy between European and N American Ordovician–Devonian data on the base map of Bullard *et al.* (1965) was consistent with major transcurrent movement roughly along the present Atlantic margin.

Features such as these have been incorporated into palaeocontinental world maps on a variety of scales and generalizations (Smith *et al.* 1973, 1981, Zonenshayn & Gorodnitskiy 1977a, b, Kanasewich *et al.* 1978, Morel & Irving 1978, Scotese *et al.* 1979, Bambach *et al.* 1980, Turner & Tarling 1982, Scotese 1984, Livermore *et al.* 1985).

We have endeavoured to confine our considerations to data which can be considered reliable in terms of their sampling, magnetic cleaning and dating. We have not applied stringent numerical criteria for rejection. This would lead to the elimination of a large proportion of the data (*cf.* the small number of grade A poles listed by Briden & Duff (1981)). Moreover, rigid criteria are not favoured because it is unclear what number of samples is required to eliminate bias; samples may not actually be independent in the statistical sense, and small confidence limits may indicate high quality or simply failure to sample secular variation adequately. Further, the methods and standards of analysis vary between laboratories, e.g. in the averaging of palaeomagnetic directions or VGPs and in the calculation of error limits. Rather, those poles considered most reliable by palaeomagnetists familiar with the results from each continent or continental fragment have been sought. The poles used all conform to the minimum rejection criteria set out by McElhinny (1973).

Laurentia

Laurentia comprises N America, Greenland, W Spitzbergen, Rockall and NW Scotland. Its reassembly in the configuration of Bullard *et al.* (1965) is generally consistent with geological constraints, most importantly the continuity of

Archaean ('Lewisian') and Proterozoic ('Grenville') basement and lower Palaeozoic cover (Durness and Beekmantown sequences) across the Atlantic. Of course, in Lower Palaeozoic time Laurentia would have presented a somewhat different outline from now, since its margins have subsequently been much modified.

The polar wander path for the interval between 1150 and 820 Ma is documented by a comparatively high density of pole positions comprising the Keweenawan track and the Grenville track. The Keweenawan track is determined by poles from Keweenawan volcanics, intrusives and sediments, and is supported by data from the Proterozoic Grand Canyon sequence. The later Grenville track is derived almost entirely from intrusions which cooled slowly in the Grenville Province after the peak metamorphic event, often resulting in complex multi-vector palaeomagnetic records. The Grenville poles are now regarded as representative of Laurentia because similar poles have been identified outside the Grenville Province. The precise connection of the Grenville track with the Keweenawan track is equivocal. The continuous joined paths shown in Fig. 1 are from recent reviews (Buchan *et al.* 1983, Roy 1983), with the two tracks connected near the equator and the Grenville poles forming a counterclockwise loop (S poles) in the eastern hemisphere. The age calibration of the Keweenawan track is uncertain by ± 50 Ma (Roy 1983), and the Grenville track is perhaps better dated by $^{40}Ar/^{39}Ar$ dating of mineral separates (Buchan *et al.* 1983). The poles in the highest latitudes on the Keweenawan track may be the result of asymmetry between mean directions of palaeo-

magnetic fields of opposite polarity during Keweenawan time (Nevanlinna & Pesonen 1983).

Palaeomagnetic poles from the Stoer Group and the Torridon Group of the NW Highlands of Scotland fall on the Keweenawan track when rotated into the N American frame of reference using a reconstruction (Smith *et al.* 1983) in the style of Bullard *et al.* (1965). This implies that the age of magnetization of these sediments is between 1100 and 1050 Ma, contrasting with the Rb–Sr closure ages of 968 Ma for the Stoer Group and 777 Ma for the Torridon Group. This discrepancy is open to a number of interpretations.

The polar wander track for Laurentia between 820 Ma ago and early Palaeozoic time is highly problematical because of the low density of pole determinations for this interval. Published interpretations have been criticized because they are based mainly on undated secondary magnetizations (McCabe & Van der Voo 1983, Roy 1983). A substantially larger data base is required for this interval before any consensus on the nature of the Laurentia polar wander path for this interval is reached.

Notwithstanding increasingly intensive study over the past 30 years, the Palaeozoic APW path for N America remains controversial. Almost all pole positions from upper Ordovician and younger rocks lie within 20° of the Permo-Carboniferous poles suggesting *either* that N America moved less relative to the poles in that time than any other fragment that has been palaeomagnetically studied *or* that the remanence of these rocks is dominated by Permo-Carboniferous overprints so that the mid-Palaeozoic APW of America is not yet fully discovered. Such a conclusion is implicit in the interpretation of Seguin & Gahé (1985). The remagnetization hypothesis was first proposed by Creer (1968) and has been convincingly documented in several specific cases (e.g. Roy *et al.* 1967, French & Van der Voo 1977, Irving & Strong 1984a, Kent & Opdyke 1985). More generally, it is suggested by the observations that Cambrian poles are spread along a line from the equatorial W Pacific to the vicinity of Permo-Carboniferous poles (Roy *et al.* 1983).

Those poles from Ordovician, Silurian and Devonian rocks which do not group close to Permo-Carboniferous poles are instead scattered roughly along the 30°N latitude line between about 160°E and 80°E with no clear chronological order to them (Roy *et al.* 1983), suggesting that overprinting was not restricted to Permo-Carboniferous time. Seguin & Michaud (1985) reached this conclusion in the case of sediments from the St Lawrence Lowlands.
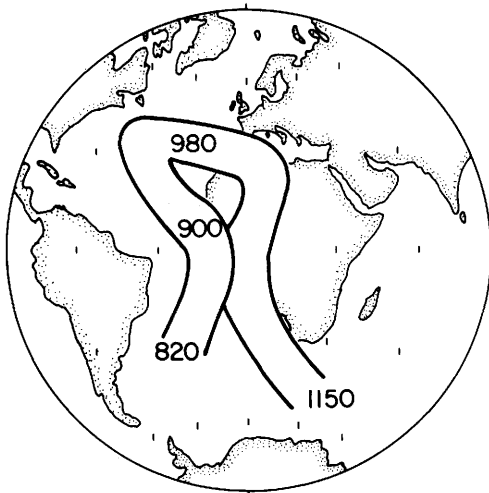

FIG. 1. Combined Keweenawan and Grenville APW paths (ages in Ma) (Redrawn after Buchan *et al.* 1983.)

Although more elaborate paths which imply extremely rapid and complex APW have been proposed (Dankers 1982), the path drawn by Van der Voo *et al.* (1980) (see also Van der Voo 1981) which is updated in Fig. 2 has been widely accepted as the best available estimate of the motion of the craton.

On this basis divergent data from lower Carboniferous and older rocks from the Appalachians have been interpreted as evidence for large-scale sinistral transcurrent motion (Kent & Opdyke 1979, Van der Voo *et al.* 1979, Kent 1982) and/or rotation (Spariosu & Kent 1983) of terranes within the Appalachians. However, this interpretation has been disputed (Roy 1982), and not all data from the belt conflict with that from the craton (Roy *et al.* 1983, Seguin *et al.* 1985). Moreover, Irving & Strong (1984b) have recently argued that what was originally interpreted as a pole position divergent from that applicable to the craton may instead be typical of the craton, while in other cases the presumed primary NRMs of cratonic rocks are now realized to be late Palaeozoic overprints (Kent & Opdyke 1985). Hence the notion of large-scale transcurrent motion in Carboniferous and later time is now discounted and hence, paradoxically, many of the best estimates of the N American APW path may have been derived from its deformed margin rather than its stable interior. If so, this may be because the rocks from the orogenic belt were

indurated and thus protected from the promotion of diagenesis by circulating groundwater, while the cratonic rocks were vulnerable to the effects of such processes (Irving & Strong 1984b, Seguin & Michaud 1985).

The lower Palaeozoic and Devonian APW paths for Scotland N of the Iapetus suture (Fig. 3A, B) are updated from Briden *et al.* (1984) and are extended into the lower Carboniferous. The data are entirely from igneous rocks, which are mostly intrusive, and high-grade metamorphic rocks. Although only a minority of the poles are dated directly, correlation is generally fairly well constrained by stratigraphic control and petrological affinity. As in N America red sediments appear to have been totally remagnetized in Permo-Carboniferous times (Tarling *et al.* 1976), and these data are omitted. Briden *et al.* (1984) sought to demonstrate that within these parts of Scotland there was no significant difference between the data from N and S of the Great Glen (compare Figs 3A and 3B), contrary to the conclusions of Van der Voo & Scotese (1981).

In Fig. 4 the N American data (Fig. 2) are rotated to Europe after Bullard *et al.* (1965). Comparison with Fig. 3 shows that on this reassembly the *bulk* of N American poles lie in systematically higher latitudes than is the case for the Scottish poles. This is consistent with a configuration like that proposed by Kent & Keppie (1987, Fig. 1) and subsequent sinistral shear. However, the most reliable of the critical N American data do not show this discrepancy; in particular, the Silurian data from the Rose Hill and Wabash Formations (9 and W in Fig. 4) are not significantly different from the poles from some of the Newer Granites in Scotland (HG, R and SG in Fig. 3A). Also, the paths from both regions backtrack together in the Lower Carboniferous. Thus it is possible that there may be a common APW path for Laurentia from Ordovician times to the end of the Palaeozoic; if this is so, it has the advantages of (a) not violating the widely accepted geometrical and geological reassembly, (b) not requiring transcurrent displacements younger than Caledonian age and (c) not requiring displacements of areas usually regarded as essentially part of the craton (Spariosu & Kent 1983).

FIG. 2. Palaeozoic APW path for N America according to Van der Voo *et al.* (1980) where most of the data are listed. Additional data are as follows: pole 9 revised after French & Van der Voo (1979); W, Wabash limestone (McCabe *et al.* 1985); T, Terenceville Formation (Kent 1982); D, Deer Lake Group (Irving & Strong 1984a).

Baltica

We refer to Baltica as the region bounded by the Caledonian, Uralian and Hercynian belts, and therefore consisting principally of Scandinavia and the Russian–central European platform, with Britain (S of the Iapetus suture) possibly at its
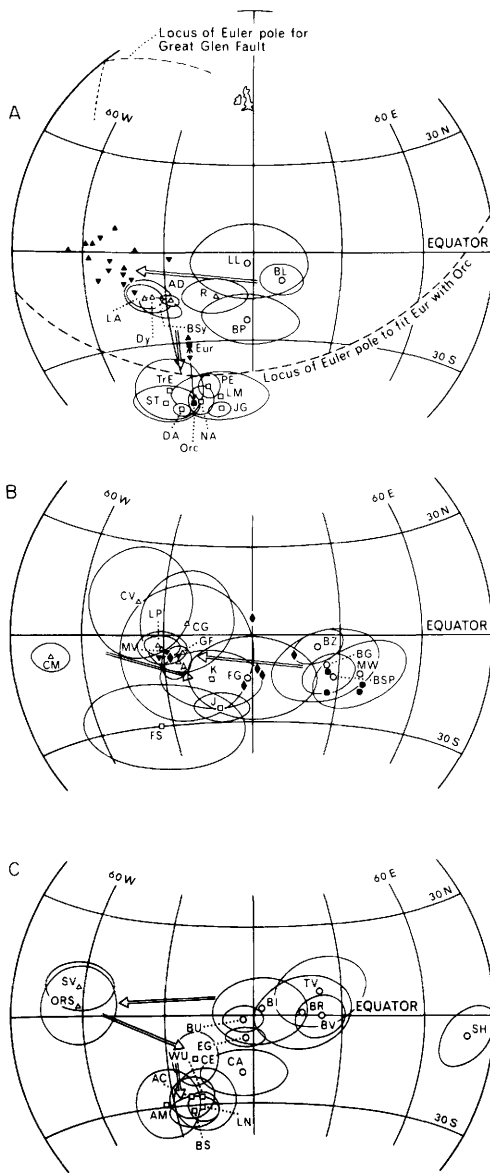
FIG. 3. Palaeozoic APW paths for three regions of the British Isles (A) N of the Great Glen fault, (B) between the Great Glen fault and the Solway line, and (C) S of the Solway line, with mean poles from other relevant areas: O, poles from Ordovician formations; △, Silurian–early Devonian; □, mid-Devonian and younger Palaeozoic. The 95% confidence limits are shown in all cases. Full symbols denote data from single sites. The data are from Briden *et al.* (1984), where the notation and sources are given, with additions as follows: FG, Foyers granite revised after Torsvik (1984); HG, Helmsdale granite (Torsvik *et al.* 1983); SG, Strontian grantie (Torsvik 1984); K, Kinghorn lavas (Everitt & Belshé 1960); CE, mean Carboniferous of England and Wales (Irving 1964).

western extremity, and central and eastern Spitzbergen and Novaya Zemlya on its northern flank. However, it is not clear for what period of time Baltica, as thus defined, was a tectonic entity, and the palaeomagnetic data base is so uneven, mainly because of the partiality of the stratigraphic record, that relative motions between parts of the region cannot be well defined at present.

A high density of pole determinations for the interval from 1040 to 840 Ma is available for Baltica, mainly from the Sveconorwegian fold belt which probably correlates with the Grenville province. This polar wander path is shown in Fig. 5. The palaeomagnetic poles span the same interval as the Grenville track, but the interpretation depicted in Fig. 5 shows the Baltic poles describing a clockwise path in the eastern hemisphere, opposite to the sense of movement depicted for the Grenville track as interpreted by various N American workers. Imprecision in the dating and location of the poles may be a factor in this ambiguity, and the Baltica polar wander path requires more precise calibration by ^{40}Ar/^{39}Ar age determinations as has been done for the Grenville track. Peripheral parts of Baltica may have been accreted during Proterozoic time, but there are no palaeomagnetic data to delimit this.

In the Palaeozoic the palaeomagnetic data distribution within Baltica is reversed and is concentrated in the peripheral regions such as Britain. Hence the data are again inadequate to determine when the present relative configuration was attained. In particular, the position of Scandinavia relative to southern Britain is not
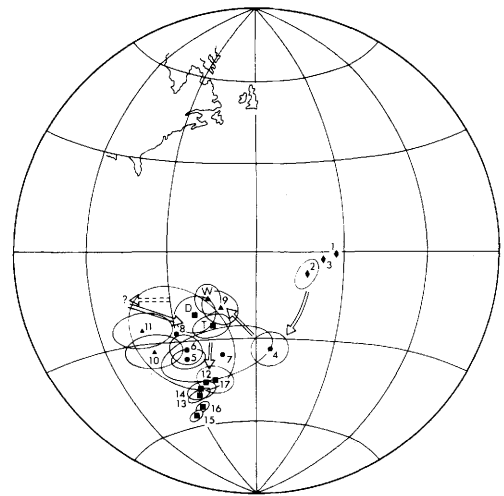

FIG. 4. N American data of Fig. 2 rotated to Europe after Bullard *et al.* (1965), plotted as South APW path and annotated for comparison with Fig. 3.
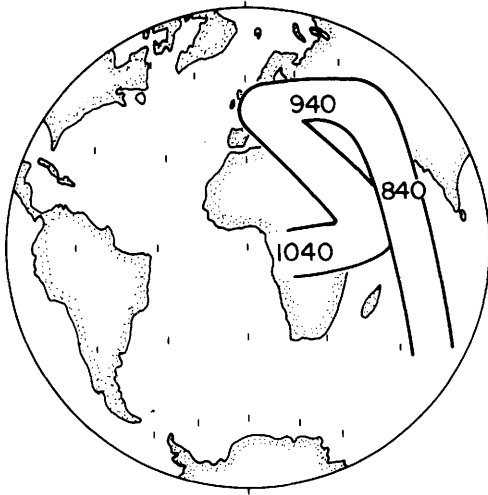
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FIG. 5. APW path for Baltica for the interval 1040–840 Ma. (After Stearn & Piper 1984.)

determined. Hence, most unfortunately, data are inadequate to throw light on the possible evolution of the 'third arm' of the Caledonides through central Europe except to indicate that the Russian Cambro-Ordovician and British Ordovician palaeolatitudes were similar but that their orientations were very different from the present; this may imply substantial closure and relative rotation in later Lower Palaeozoic time.

All Cambrian sediments from Britain that have been studied (Briden et al. 1971, 1973, Claesson & Turner 1980) seem to have been remagnetized. Southern Britain, however, does provide a number of reasonably constrained Ordovician and Silurian data. Although the Lower Devonian is only represented by the pole from the Anglo-Welsh Old Red Sandstone (Chamalaun & Creer 1964), McClelland Brown (1983) has confirmed this and demonstrated that the primary remanence has been distinguished from the strong Permo-Carboniferous overprint. Hence the APW path for southern Britain (Fig. 3C) heads westward as does the path for Scotland (Fig. 3A, B), although in the former case it may be exaggerated by about 20° of fairly local clockwise rotation which deflects the regional Caledonoid trend in the Old Red Sandstone of W Wales. As with Laurentia, the path then backtracks in the Lower Carboniferous before heading to higher latitudes (about 30°) in later Carboniferous times.

Scandinavia provides fragmentary data including only four of Lower Palaeozoic age. The three possibly Cambrian poles, from the Alnö and Fen complexes and the Nexø sandstone, differ greatly

and it is premature to suggest an APW path (Piper 1981). That from the Ordovician Sulitjelma gabbro is of uncertain regional significance because of its allochthonous tectonic situation. There are three poles from the Norwegian Old Red Sandstone, all located approximately 20°S, 345°E and thus differing from the results from Britain and seeming to imply a 'Tornquist's Sea' up to 1000 km wide at this time (Kent & Keppie 1987, Fig. 1). However, this interpretation involves major separations between components of the Old Red Sandstone continent when the Old Red facies was already widely developed. Since the British data are corroborated by evidence from contemporaneous extrusive and intrusive igneous rocks while the Russian and Norwegian data are all from sediments and fall on later Palaeozoic parts of the British APW path, an alternative explanation of this difference is that the original NRM in the sediments has been overprinted.

For the Russian platform (Khramov et al. 1981) there are Cambro-Ordovician data which are regarded as reliable, but Ordovician, Silurian and early Devonian data are believed to have been affected by partial or total overprinting in the late Palaeozoic. Thus although Khramov et al. (1981) elicited some control on the position of the Russian platform in the Ordovician and Silurian using data from the Urals, these are insufficient to provide a reliable APW path (Fig. 6A).

Armorica

Van der Voo (1979) and Hagstrum et al. (1980) suggested, largely on palaeomagnetic grounds but augmented by geological argument, that the Armorican massif, together with the Bohemian massif, England and Wales and the Avalonian terranes of NE America, was part of a somewhat larger lithospheric plate 'Armorica' throughout much of Palaeozoic time. They argued that Armorica was still in high southerly latitudes in the early Ordovician (see the end of the APW path in Fig. 6(B) and Fig. 8(A)) but moved northwards to collide with N America in the Taconic orogeny. Perroud et al. (1984) have revised the estimate of collision to coincide with the Acadian orogeny and also pointed out that Armorica could have been a 'mosaic of tectonic elements . . . more or less at the same latitude' rather than a single plate.

The incorporation of Central Britain between the Hercynian front and the Iapetus suture into Armorica rests upon inconclusive late Proterozoic and Cambrian palaeomagnetic data and upon
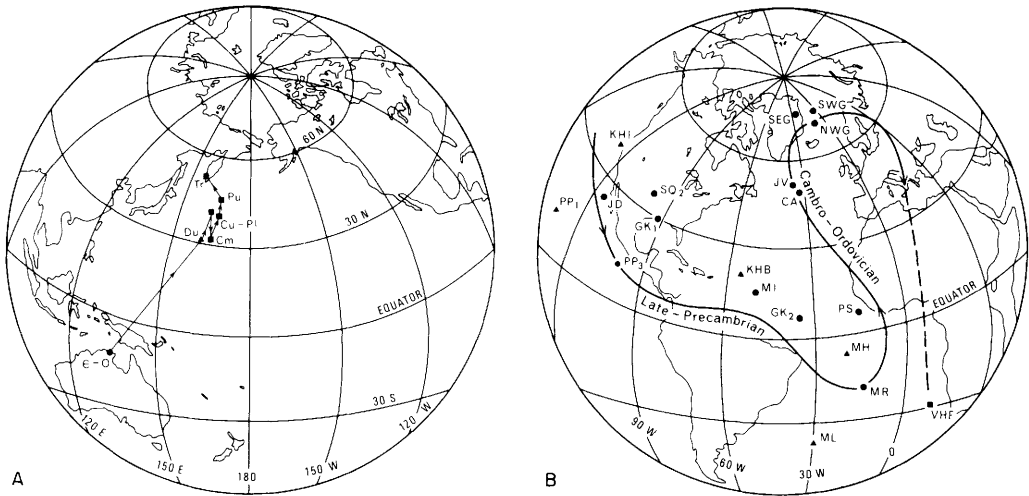
FIG. 6. Palaeozoic APW path for (A) the Russian platform (redrawn from Khramov *et al.* 1981) and (B) Armorica (Hagstrum *et al.* (1980) updated by Perigo *et al.* (1983) from where this map was redrawn). (Approximate stratigraphic ages and the middle Devonian to lower Carboniferous pole (VHF) from the Vosges, Harz and Franconian Forest (Bachtadse *et al.* 1983) have been added.)

uncharacteristically high inclinations (e.g. Thomas & Briden 1976) among a large body of Ordovician data which indicate lower latitudes (30°–43°S) than those of the Armorican massif (46°–76°S). Hence we regard central Britain as marginal to Baltica and not Armorica, and have discussed it in the previous section. This is contrary to the geologically based inferences of Ziegler (1984) that the London platform and Irish Sea horst belong to the same block as the Armorican and Bohemian massifs, unless we have been misled by the palaeomagnetic results from the latter regions. It should also be pointed out that the affinity of Avalonia and other marginal terranes of N America to Armorica is equivocal. However, the role of Armorica, even if it embraces no more than the stretch of Hercynian Europe from the Armorican to the Bohemian massif, is important to the tectonic evolution of the region as will be shown in the next section.

Relative positions of the crustal blocks

The palaeomagnetic data summarized in the foregoing sections provide control on the palaeo-latitude and orientation of each crustal fragment, with uncertainties which amount to several degrees of arc (i.e. at least several hundred

kilometres) at the 95% confidence level. The relative longitude remains indeterminate so that formal estimates of the separation of fragments will always be minima and will be measured by differences in palaeolatitude only; it is for this reason that compilers of Palaeozoic world 'maps' (e.g. Smith *et al.* 1973) often refer to them as 'composites' rather than true maps. Control on actual palaeolongitudinal separation relies on rather generalized geological constraints, such as the timing of the eventual suturing of two margins, together with the assumption that plate velocities have not been an order of magnitude larger than the present maximum. In particular, the need to assemble Pangaea by the end of the Palaeozoic is a major constraint.

The arrangement of Pangaea that is usually considered is the least-squares continental fit (Bullard *et al.* 1965, Smith & Hallam 1970), now often called Pangaea A, which fits a great deal of continental geological evidence as well as sea-floor spreading data. However, as has been realized for many years (van Hilten 1964), Permian and early Triassic palaeomagnetic data from Laurasia and Gondwanaland do not conform to this reconstruction but are better fitted with the northern continents displaced westward (anticlockwise) relative to Gondwana (Van der Voo & French 1974, Van der Voo *et al.* 1976, Van der Voo *et al.* 1984) in the arrangement called Pangaea A2 by Morel & Irving (1981). This route has been followed by Livermore *et al.* (1985).

Precambrian

Fragments of a late Proterozoic reconstruction can be glimpsed in the available palaeomagnetic data. If the correlation of the Stoer and Torridonian poles with the Keweenawan poles is correct, i.e. older than their Rb–Sr closure ages, the fragment of Precambrian crust in the NW Highlands of Scotland must be placed near the position proposed by Bullard *et al.* (1965). However, this conclusion remains uncertain in the absence of direct confirmation of the age of remanence.

Grenville poles and contemporaneous poles from Baltica are consistent with a reconstruction in which Baltica lies against Laurentia and the Grenville Province is continuous with the Sveconorwegian belt (Stearn & Piper 1984). Baltica is 15°–20° S of the Bullard *et al.* (1965) fit in a position similar to some suggested Devonian reconstructions (e.g. Kent & Keppie 1988).

Cambrian and Ordovician

As the discussion of the palaeomagnetic data shows, maps of Cambrian and Lower Ordovician time are necessarily very speculative, at least as far as the continents bounding the Caledonides are concerned. Smith *et al.* (1973, 1981), Scotese *et al.* (1979) and Morel & Irving (1978) have all produced tentative versions, and while they differ greatly they have in common the placement of most major fragments in low latitude. Likewise, maps for later Ordovician time show Laurentia and Baltica in low latitudes, with Iapetus lying at 0–30°S.

In Fig. 7(A) (Livermore *et al.* 1985), which relates to late Ordovician–early Silurian times, Baltica is positioned on the basis of data mostly from England and Wales. Interpolation of the APW path from the Russian platform would put Baltica in a different orientation but a similar latitude. Laurentia is positioned on the basis of N American data; the difference between Laurentia and Baltica data implies a latitudinal width of about 2000 km for the Iapetus ocean, which is twice as wide as that estimated from the difference between data from England–Wales and Scotland alone (Briden *et al.* 1984). Thus, taken at face value, the palaeomagnetic data would place Scotland in Fig. 7(A) in the middle of the Iapetus ocean which would pose major geological problems. Figure 7(A) is a cartographic expression of the discrepancies between the Scottish and N American data discussed at the end of the section on Laurentia. Some regions of the Appalachians are positioned on the S side of Iapetus in this map, in conformity with some palaeomagnetic data (Lapointe 1979, Rao & Van der Voo 1979). This emphasizes that early or middle Palaeozoic closure and transcurrent movement within the Appalachians remain a distinct likelihood notwithstanding doubts about the reality of *late* Palaeozoic transcurrent displacement. Armorica and the southern Appalachians are both shown at about 60°S.

The Ordovician sketch map due to Perroud *et al.* (1984) (Fig. 8A) is essentially the same as Fig. 7(A) except in its treatment of central Britain as part of Armorica rather than Baltica. That association is not well supported by the palaeomagnetic evidence which indicates that Britain was in a significantly lower palaeolatitude. Duff (1980) associated both regions with the Baltic shield and drew a common APW path, but this depended heavily on similarity between data from the Fen complex (Norway) and results of a bare reconnaissance nature from igneous rocks in Leicestershire and slates from N Wales.

Silurian and Devonian

In the first of their alternative maps for the Siluro-Devonian boundary (Fig. 7B) Livermore *et al.* (1985) show Iapetus still up to 1000 km wide or more. On this map Baltica is shown in a position indicated by poles from the Norwegian Old Red Sandstone and from Avalonia. Cratonic N America is positioned separately, using the poles from the Peel Sound Formation and the Bloomsburg Formation. These choices of data imply that Baltica was offset dextrally from its Bullard *et al.* (1965) position relative to Laurentia, i.e. prior to sinistral displacements along the Caledonian–Appalachian belt (*cf.* Van der Voo & Scotese 1981).

If, instead, Laurasia were oriented as a single unit based on British and N American data from the Caledonian–Appalachian belt, the southern margin of the N American craton would be at nearly 60°S. This raises difficulties in relation to the Gondwana data (Kent *et al.* 1984, Livermore *et al.* 1985) as well as indicating that a version of Pangaea was already assembled as early as end-Silurian time.

For the early Devonian, Perroud *et al.* (1984) (Fig. 8B) show Laurentia and Baltica in positions not unlike those shown in Fig. 7(B), but with Armorica already adjacent.

Carboniferous

Figure 7(C) shows a map proposed by Livermore *et al.* (1985) for Eifelian–Tournasian time. It is based on various assumptions about the palaeomagnetic data, faunal provinciality and the
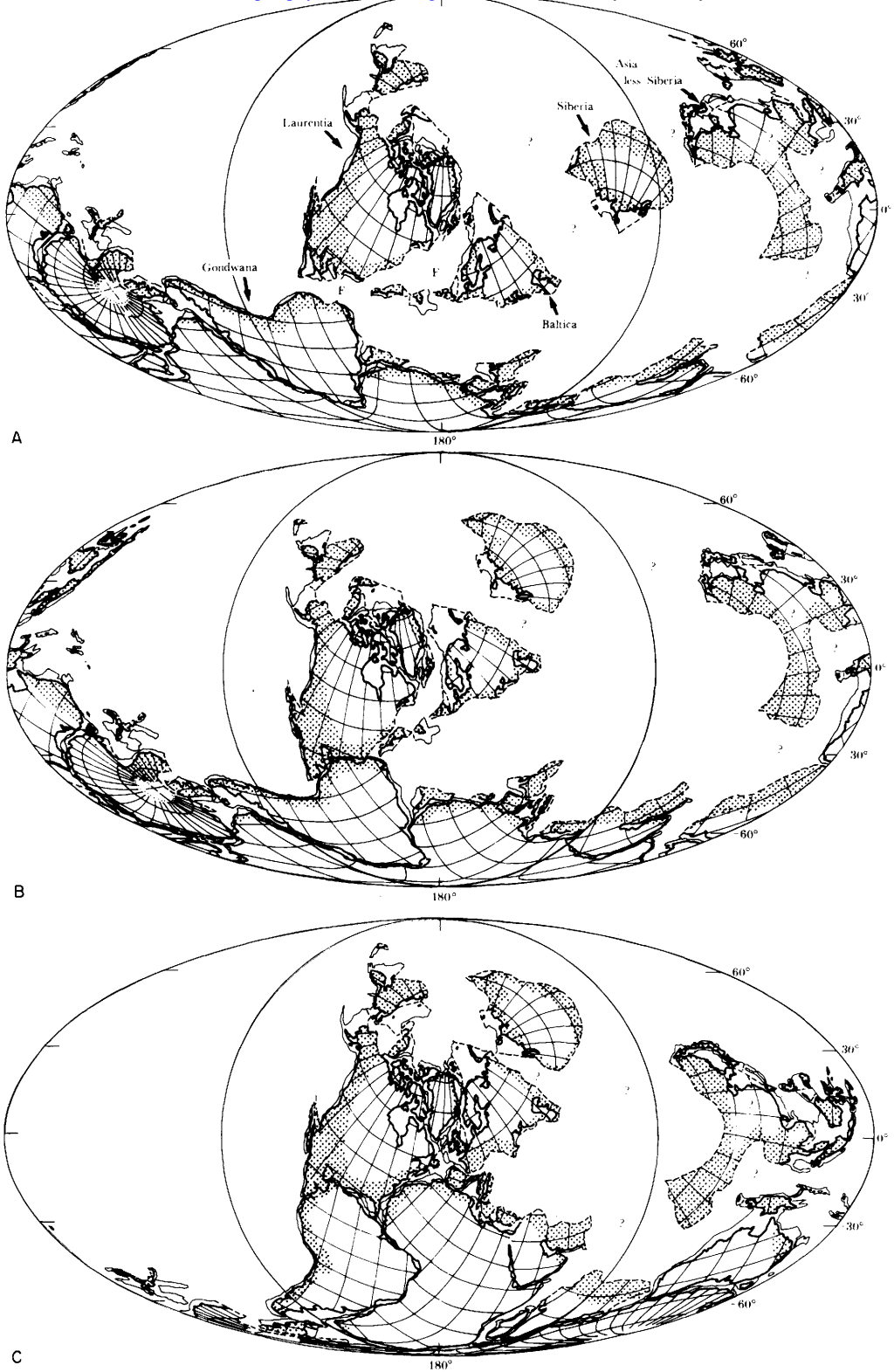
FIG. 7. Global reconstructions due to Livermore *et al.* (1985) (Mollweide elliptical projection) (stippled areas denote an approximate extent of orogenic deformation of the same age as the map or younger; F indicates that longitude separation is based on fossil evidence; ? in oceanic regions indicates uncertain longitudinal separation; ? in continental regions indicates that no palaeomagnetic data are available): (A) Caradoc–Wenlock time; (B) Ludlow–Emsian time; (C) Eifelian–Tournaisian time.
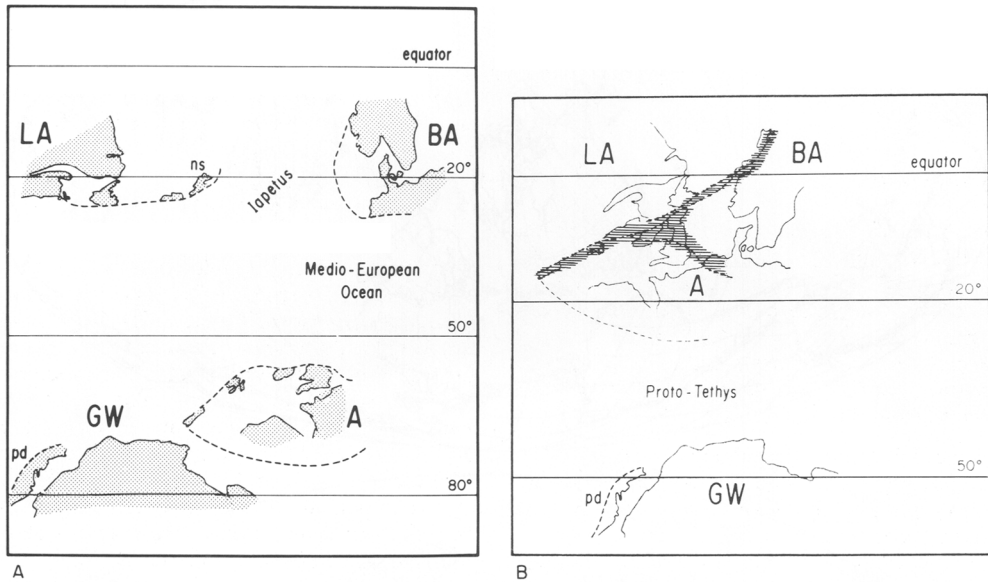
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FIG. 8. Sketch maps of the palaeocontinental positions proposed by Perroud *et al.* (1984) (A, Armorica; GW, Gondwana; BA, Baltica; LA, Laurentia; ns, northern Scotland; pd, Delaware Piedmont); shaded zones in (B) are areas of collision between plates: (A) Ordovician; (B) Devonian.

subsequent configuration of Pangaea, and depicts most of the continents already in one reassembly with Siberia arbitrarily not far removed from Russia and with eastern Asia arbitrarily positioned. Laurentia–Baltica is positioned on this map using data from Britain, Avalonia, central Europe and Iberia. This places it in a very similar position to that indicated by the revised data from the Mauch Chunk Formation (Kent & Opdyke 1985) and the data from the Canadian Maritimes (Roy & Morris 1983). Watts (1985) has shown that data from Spitzbergen are consistent with the position in Fig. 7(C).

Palaeomagnetic overprints

In this paper we have emphasized primary magnetizations and the difficulty of distinguishing them when secondary overprinting has occurred. However, the overprints themselves are of considerable importance as indicators of the diagenesis or metamorphism which causes them, and when the secondary remanence can be dated they are as useful as any other data for palaeomagnetic purposes.

For example, among the British data (Fig. 3B) is a sequence from the Aberdeenshire gabbros (Watts & Briden 1984) in which palaeomagnetic direction changes systematically with cooling age as determined independently by K–Ar studies

(Dewey & Pankhurst 1970). It seems that the NRM is either viscous PTRM acquired during cooling to about 500°C, as the original investigators suggested, or CRM acquired during the last stages of cooling, i.e. significantly later but still related to the post-orogenic cooling and still indicative of its progression in time and space. Thus the data can be used, as here, to contribute to the local APW path, although the absolute age of remanence may not be unambiguously known. Conversely, if the magnetization process were clear the data could also be used to refine the post-orogenic cooling pattern for this terrane and to provide temperature–time points for elucidation of its history of uplift and unroofing.

Late Palaeozoic overprinting of older rocks has been a major phenomenon and is of interest in its own right. It is likely to be related to diagenetic redeposition of iron oxides owing to groundwater circulation in the widespread arid climates of the Permo-Carboniferous (French & Van der Voo 1977, Scotese *et al.* 1982, McCabe *et al.* 1983, Irving & Strong 1984a, Seguin & Michaud 1985). In many rocks, particularly permeable sediments, overprinting amounts to total remagnetization. However, even massive igneous and metamorphic rocks from well outside the Hercynian–Alleghanian belt, where cooling effects would have been operative, have been affected (Roy *et al.* 1983, Briden & Mullen 1984). The data are useful additions to the late Palaeozoic data base

where precise ages can be attached to them, and the phenomenon is worthy of much magnetic and micro-mineralogical study of the processes that are involved.

Discussion

The maps in Figs 7 and 8 are extremely speculative because of the sparse data set and its uneven quality. The data amount to only a fraction of what is required for optimum palaeomagnetic control on evolution of the orogen. Nevertheless, limited but useful palaeomagnetic constraints upon the evolution of the belt can be deduced from the present data.

1 The Baltic and Laurentian shields may have been adjacent in the late Proterozoic before the opening phase of the Caledonian–Appalachian Wilson cycle.

2 In the Ordovician, Laurentia and Baltica were in similar palaeolatitudes and the convergence which caused the Scandinavian and British Caledonides must therefore have been principally along the lines of palaeolatitude.

3 The Armorican and Bohemian massifs comprised an 'Armorica' plate which was in high southerly latitudes in the early Palaeozoic but contiguous with Laurentia–Baltica by Devonian time; its convergence could coincide with and partially account for Acadian–Caledonian orogenic phases and perhaps for the 'third arm' of the Caledonides through central Europe.

4 Gondwanaland began to collide with the northern supercontinent in the late Devonian or early Carboniferous. Repercussions of this collision constituted Carboniferous orogeny in the southern Appalachians–Hercynides.

However, the data are neither sufficiently complete nor sufficiently refined to assist greatly in resolving such vital questions as (a) the nature of the central European Caledonides (Ordovician data from the Baltic shield and Russian platform, and Cambrian data from England are required for this purpose) and (b) the relative roles of dextral and sinistral displacements during orogenesis. To remedy this we require many more data, particularly from the cratonic and platform regions in which primary magnetizations are resolved from secondary overprints. This is a task requiring the highest standards of analysis—standards which have not always been attained even in some recent studies—and will need to be integrated with tectonic and mineralogical study. Such work may contribute to knowledge of the metamorphic and diagenetic history of the region as well as to its evolving reassembly.

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