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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

# Palaeomagnetic Evidence for a Proterozoic Super-Continent [and Discussion]

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# Palaeomagnetic evidence for a Proterozoic super-continent

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The Precambrian apparent polar wander (a.p.w.) curve for Africa is now defined in a general way from *ca.* 2700 million years (Ma) to Palaeozoic times, and is compared here with palaeomagnetic results from other Precambrian regions. Loops present in the African and North American a.p.w. curves between 2000 and 1000 Ma can be matched in size and shape, and when superimposed show that the Afro-Arabian and North American regions were in continuity at this time. Data from other Gondwanaland continents are reviewed and seem to be consistent with the Smith–Hallam reconstruction to *ca.* 2100 Ma for South America, to *ca.* 1800 Ma for India, and possibly for Australia back to *ca.* 2100 Ma. The a.p.w. curve from the Baltic and Ukrainian Shields can be matched with that from Africa and North America such that there was crustal continuity prior to 1000 Ma with the Gothide and Grenville mobile belts in great-circle alignment. The limited palaeomagnetic data from the Siberian Shield do not allow it to be placed uniquely with respect to the other land masses but are consistent with a position in juxtaposition with the Baltic-Ukrainian Shields such that massive anorthosites and *ca.* 1000 Ma mobile belts are in alignment with those from elsewhere.

The palaeomagnetic evidence is consistent with a model in which the bulk of the Precambrian shields were aggregated together as a single super-continent during much of Proterozoic times, the most prominent feature of which is a great circle alignment of massive anorthosites (2250–1000 Ma) along a belt which also became a concentrated zone of igneous intrusion by rapakivi granites and alkaline intrusions, and culminated in generation of long linear mobile belts at 1150 ± 200 Ma and thick graben sedimentation. The predominance of this feature during much of the Proterozoic suggests that a simple mantle convection system pertained during this time. The proposed super-continent is not greatly different in form from the later short-lived super-continent Pangaea, formation of which may have involved relatively minor redistribution of the sialic regions in late Precambrian (probably post-800 Ma) and Palaeozoic times.

## 1. Proterozoic apparent polar wander paths

Proterozoic palaeomagnetic data are treated in this paper in terms of apparent polar wander (a.p.w.) paths forming swathes up to several tens of degrees wide (Beck 1970) to highlight general trends (Spall 1971 *a*) rather than isolated results, and with the aim of forming a general tectonic synthesis.

### (*a*) *Apparent polar wander path for Africa*

Present data (appendix 1) give a general idea of the path of the pole relative to Africa from about 2700 Ma and are plotted for the intervals 2700–1760 Ma and 1650–650 Ma in the two parts of figure 1 respectively. Poles 1–6 of figure 1 lie on a simple swathe which may represent apparent polar movement during the interval 2670–2340 Ma, but pole 4 (2340 Ma) is removed by 52° from pole 7 (2300 Ma) and the magnitude of this break and new age work (Harding, Crockett & Snelling 1974) suggesting that pole 4 may be younger (2250 Ma) than pole 7,

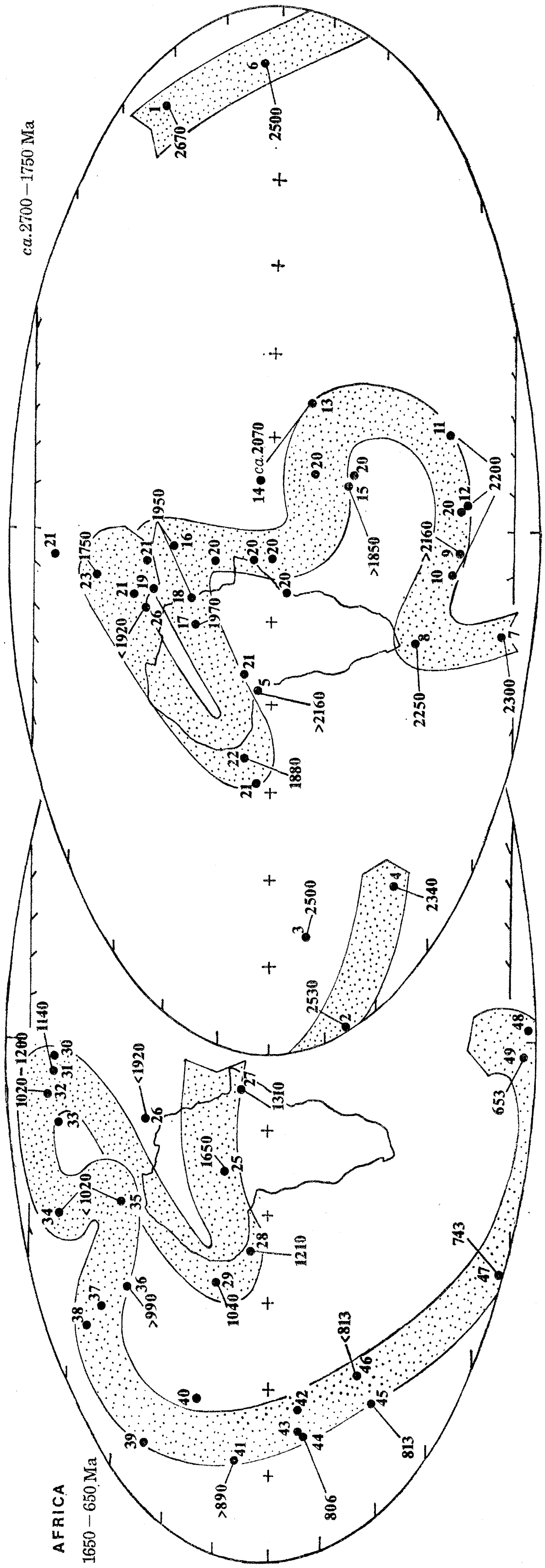


FIGURE 1. Precambrian apparent polar wander path for Africa. The numbered palaeomagnetic poles are listed in the compilation of appendix 1 and the preferred ages in millions of years are indicated.



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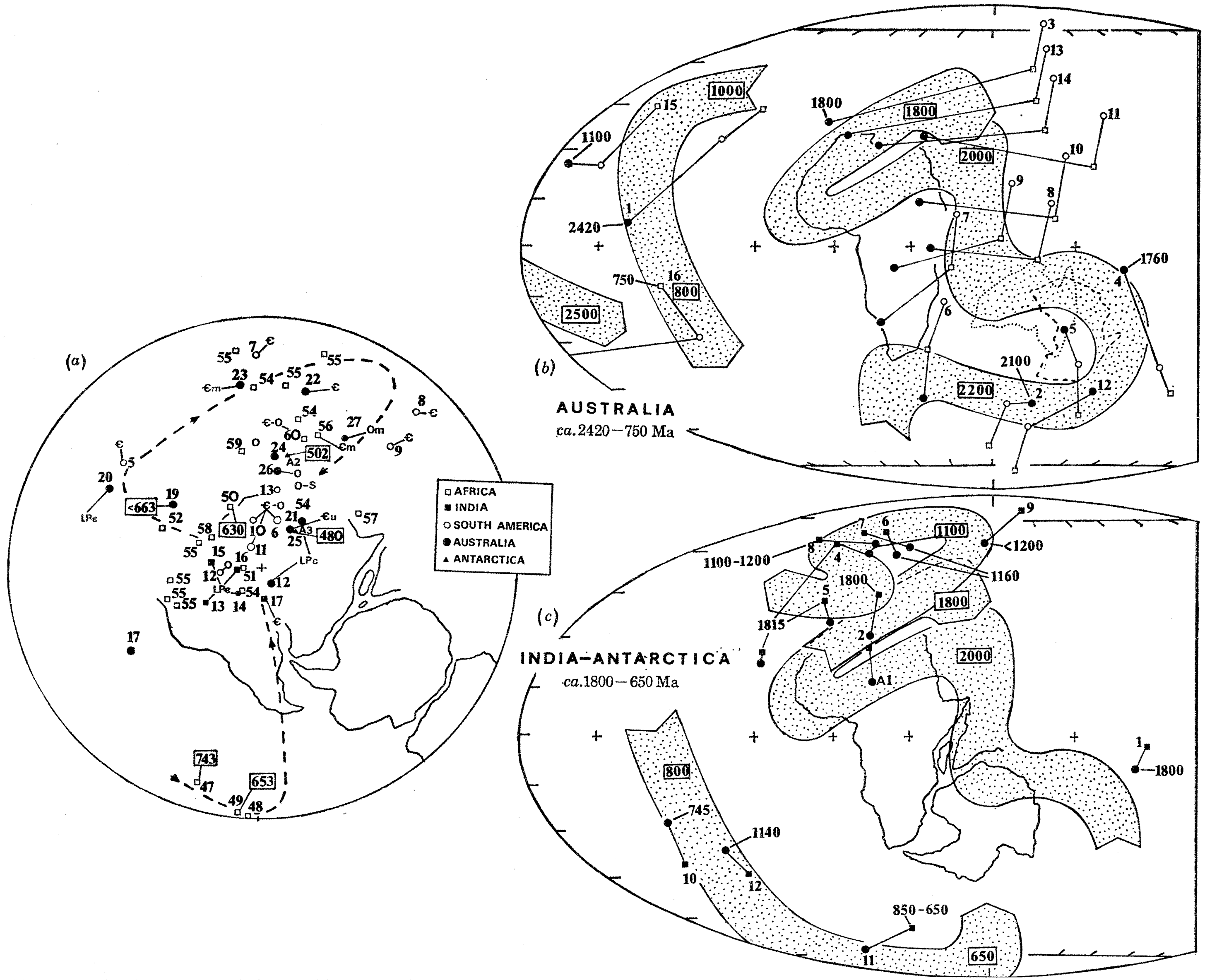


FIGURE 2. (*a*) Late Precambrian and Lower Palaeozoic poles from Gondwanaland continents listed in appendixes 1 and 2 and plotted after rotation according to the Smith–Hallam (1970) reconstruction. (*b*) Precambrian palaeomagnetic poles from Australia (listed in appendix 2) plotted relative to the African apparent polar wander path for the relevant time intervals after rotation according to the reconstructions of Carey (closed circles), Tarling (squares) and Smith & Hallam (open circles). (*c*) Precambrian palaeomagnetic poles from India and Antarctica (listed in appendix 2) plotted relative to the African apparent polar wander path for the relevant time intervals after rotation according to the reconstructions of Tarling (circles) and Smith & Hallam (squares).

leave the polarity of the 2670–2500 Ma segment in doubt. It is possible that we should be considering the antipoles of poles 1–3 in figure 1 but they are plotted in this way for clarity. Of the later part of the curve, a notable feature is the closed loop between *ca.* 1200 and 1000 Ma to which reference is made later. The segment of the a.p.w. curve between *ca.* 800 and 630 Ma is currently only suggested by three poles (47, 48 and 49) with poor age control and may need modification in the light of further results.

The form of the a.p.w. curve in Late Precambrian and Lower Palaeozoic times is only clarified in detail by consideration of other Gondwanaland data (McElhinny, Giddings & Embleton 1974 and McElhinny & Embleton, this volume). Late Precambrian results from Africa, India and Australia *ca.* 750 Ma in age are consistent with one another on the Smith–Hallam reconstruction of Gondwanaland. Late Precambrian to Ordovician pole positions from Australia (McElhinny *et al.* 1974) and South America (Thompson 1973) lie on a common swathe including a loop (figure 2*a*) to which can also be fitted poles from the Fish River Group (Lower Cambrian, poles 55) and Plateau Series (Lower Palaeozoic, poles 54) from Africa, poles 16 and 17 from India, and poles A2 (502 Ma) and A3 (480 Ma) from Antarctica.

### (*b*) *Pre*-750 Ma *palaeomagnetic data from other Gondwanaland Continents*

#### (i) *South America*

Three of four poles derived from dolerites intruding the Guyana Shield (poles 1–4, appendix 2 (iv)) with a probable age of 2070–2090 Ma lie on a swathe connecting *ca.* 2200 and *ca.* 2000 Ma pole positions from Africa after closure of the South Atlantic (44.0, 329.4, 57.0)† according to the Bullard, Everett & Smith (1965) fit (Piper & Lomax 1973), and notably close to a single pole from Africa (14) with a probable age of *ca.* 2070 Ma and other poles from West Africa of less well defined age. No other results are currently available until the Cambrian and Ordovician poles of Thompson (1973). The South American and African results are derived from opposite sides of the West African portion of the Pan-African belt and comprise the palaeomagnetic evidence that this belt is ensialic.

#### (ii) *Australia*

The Precambrian palaeomagnetic poles listed in appendix 2(i) are rotated in figure 2*b* according to the reconstructions of Smith & Hallam (1970: −3.6°, 40°, −31° and 1.3°, 324°, +58.4°), Tarling (1972: −6.0°, 40.6°, −31.6° and −0.2°, 316.6°, +39.7°) and Carey (1958: estimated to be +75.0°, 32.0°, −57.0°). The Carey reconstruction was used by Porath (1967) to suggest that Australian haematite ore poles (5–14) correlate with the African a.p.w. curve. Although these poles are mostly older than recognized by Porath and correlate with global development of bedded haematite ores reaching a climax between 2500 and 2000 Ma (Sutton 1973) to be largely displaced by redbed sedimentation after this, his essential conclusion is not invalidated because the spread of these poles is accommodated by 2500–2000 Ma African (figure 2*b*) and North American (§2, figure 3) poles; the other reconstructions for Australia would, however, accommodate these poles equally well.

Dated pole 1 (2420 Ma) does not lie close to any African data of comparable age; pole 2 (2100 Ma) shows good agreement, but pole 3 (1800 Ma) and pole 4 only crude agreement with data from elsewhere.

† In this paper rotational operations on poles are given in the form latitude (positive when north) and longitude (degrees east) of the Euler pole, and the angle of rotation (negative when clockwise).

(iii) *India*

Precambrian to Cambrian poles from the Indian subcontinent listed in appendix 2 (ii) use ages given by Athavale, Verma, Bhatta & Pullaiah (1970) except where other information has been forthcoming (Astwathanarayana 1968; McElhinny 1973). Pole positions relative to the African a.p.w. curve with the reconstructions of Smith & Hallam (+28.9, 42.2, −58.9) and Tarling (−23.2, 203.7, +66.3) are shown in figure 2*c*. Pole 3 from the Gwalior (Bijiwar) Traps (1815 Ma) agrees with the African curve *ca.* 1800 Ma and the Hart Dolerite pole from Australia (1800 Ma) and all of poles 2 and 11 straddle the African curve at positions appropriate to their assigned ages. Pole 10 from the Malani Rhyolites (745 Ma) falls on the African curve between 810 and 740 Ma and pole 11 from the Mundwara Complex (850–650 Ma) falls on the curve between 740 and 650 Ma. The Kaimur Series, which is older than the Malani Rhyolites, gives a pole (12) falling near to that from the latter; it cannot be matched with the African curve prior to 800 Ma however and is in conflict with an age of 1140 Ma quoted by McElhinny (1973).

Also included in appendix 2 and plotted in figure 2*c* by using the Smith–Hallam (+1.3°, 324°, +58.4°) and Tarling (−0.2°, 316.6°, +39.7°) reconstructions is a single Precambrian pole from Antarctica computed from palaeomagnetic data of Embleton & Arriens (1973) from dykes of East Antarctica. These have an assigned age of 1030 ± 200 Ma and the pole falls on the African swathe at *ca.* 1200 Ma.

## 2. Correlation between North American and Gondwanaland Precambrian palaeomagnetic data

Du Bois (1962) originally suggested that a loop was present in the North American a.p.w. curve between poles known to lie in the age range 1400–1000 Ma. This concept has subsequently been developed by Spall (1971*a*) and defined in detail by Robertson & Fahrig (1971) who refer to it as the 'Great Logan Loop'; subsequent assessment of the data (Irving & Park 1972 and Irving & McGlynn, this volume) has altered the loop in detail only. A comparable loop is also present in the African a.p.w. curve between *ca.* 1650 and 1000 Ma (appendix 1 and figure 1). When the loops are superimposed the Afro-Arabian and North American Precambrian regions are in contact in the configuration of figure 3. With a plastic overlay on a 30 cm globe it is estimated that the two a.p.w. curves have a closest fit after anticlockwise rotation of North America of 146° about a Euler pole at 73° N, 138° E. In figure 3*a* the North American poles between 1750 and 1000 Ma in age are rotated and plotted relative to the African curve for this interval to demonstrate the close agreement of the a.p.w. paths by means of this reconstruction. In figure 3*b* pre-1750 Ma poles are plotted and compared with the a.p.w. curve of comparable age from Africa.

Even bearing in mind the variable quality of the data used and the fact that the assigned ages have been obtained by a variety of methods of varying reliability, there is impressive agreement between the 2700–1000 Ma palaeomagnetic poles from North America and African curve. The palaeomagnetic record for both continents begins at *ca.* 2600 Ma and pole 1 from the Stillwater Complex lies close to the pole from the Modipe gabbro of Botswana (2630 ± 470 Ma) using this reconstruction. It is uncertain how much agreement should be expected between these old poles in view of the errors associated with their ages and because they are

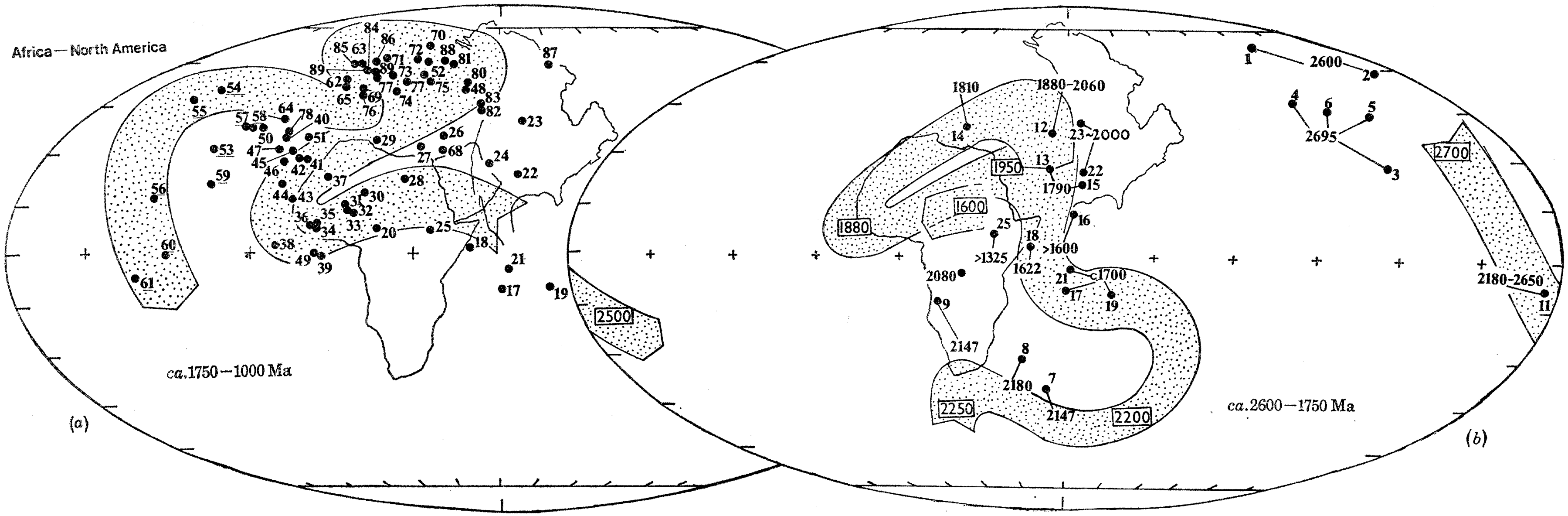


Figure 3. (*a*) Poles from North America falling in the age range 1750–1000 Ma plotted relative to the African apparent polar wander path after rotation according to the preferred Proterozoic reconstruction discussed in the text. Poles with numbers underlined are derived from rock units within the Grenville Province. (*b*) Pre-1750 Ma poles from North America plotted after rotation according to the same reconstruction. The poles are listed in appendix 3 and their preferred ages in millions of years are indicated.

derived from rock units within a crust which was considerably more mobile than in later geologic time (Sutton 1973). However, poles from the Soudan iron formation (2600 Ma) and Matachewan/Abana dykes (2690 Ma) also lie in the same vicinity as the Modipe gabbro pole, and pole 11 from Cobalt Group sediments (2650–2180 Ma) is in the same region as African poles *ca.* 2500 Ma in age. In addition pole 8 from the Nipissing diabase (2160 Ma) and pole 9 from Older Abitibi dykes (2147 Ma) lie near the African swathe at *ca.* 2150 Ma. Several pre-2150 Ma poles from North America (Irving & McGlynn, this volume) cannot yet be matched with African poles on this reconstruction, but the widespread agreement of pre-2400 and post-2150 Ma poles may imply that this is due to complex apparent polar movements rather than non-validity of the reconstruction.

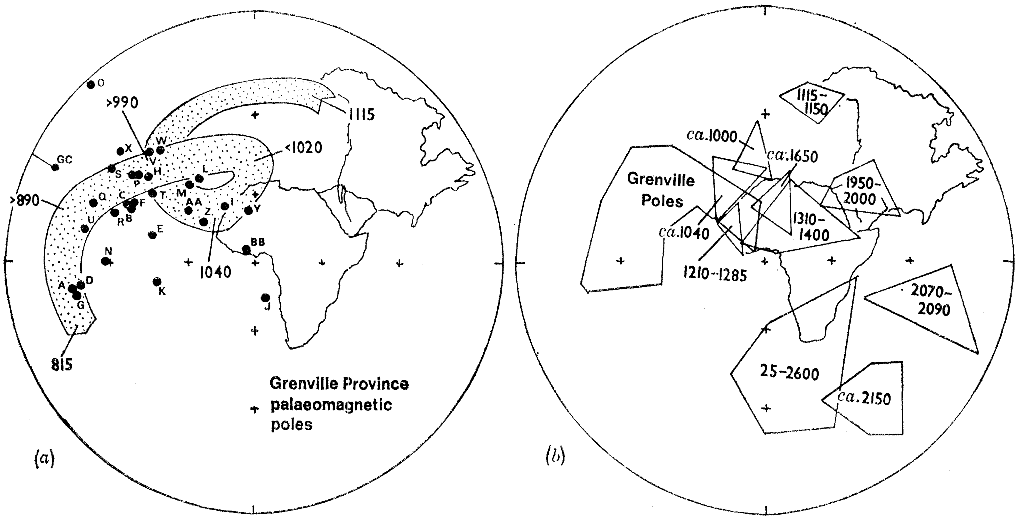


FIGURE 4. (*a*) Palaeomagnetic poles from rocks within the Grenville Province from the compilation of Irving, Emslie & Ueno (1974) plotted on the super-continent reconstruction (sterographic projection). The stippled swathe is the African a.p.w. curve between 1115 and 815 Ma (ages labelled on the figure) and is one of several possible curves depending on the age sequence of Africa poles 29, 35 and 36. The North American poles are from: A, Allard Lake; B, Frontenac dykes; C, Grenville gneisses; D and E, Haliburton basic rocks; F, Lake St Jean anorthosite; G and H, Morin anorthosite; I, Morin dykes; J, Magnetawan metasediments; K, L and M, Mealy Mt rocks; N, Larrimac and Bryson diorites; O, Tudor gabbro; P, Umfraville intrusive: Q, Wilberforce pyroxenites; R, S and T, Whitestone anorthosite; U, Whitestone diorite; V, Grenville front anorthosite; W, Michael gabbro; X, Seal and Croteau igneous rocks; Y, Seal group red beds; Z, AA, and BB, Shabogamo gabbro. GC is the pole from the Giles Complex of Australia (1100 Ma) on the Smith–Hallam reconstruction. From this correlation of Gondwanaland and Grenville poles the latter are interpreted as having ages younger than 1100 Ma (except possibly the Tudor Gabbro) although several may be older than 1040 Ma. (*b*) Fields of agreement between dated Precambrian poles from Africa, South America and North America. The 2070–2090 Ma field is defined by the pole from the Indin dykes (Irving & McGlynn, this volume), and the approx. 1650 Ma field by redating of Mackenzie and related igneous events of North America (Gates & Hurley 1973). The 1040 Ma field is confirmed by redating of African pole 29 (A. Kröner, private communication). The most poorly-defined region of agreement is that at 1210–1285 Ma where the date of 1210 Ma is the maximum of several plateau ages determined by the $Ar_{39}$–$Ar_{40}$ technique assigned to the single African pole (no. 28) falling here.

In assessing the agreement between African and North American Precambrian palaeomagnetic data it is possible to define in a qualitative way regions of agreement between dated African and North American poles. These fields of agreement are illustrated in figure 4*b*, and it is possible to match all pre-1000 Ma pole positions from Africa except numbers 7 and 8 with poles within 90 Ma (between 3 and 9 % of the age determinations) from North America.

Poles 55–61 from rock units within the Grenville Province are removed from those of comparable age from elsewhere in the Canadian Shield (figure 3). Irving, Park & Roy (1972*a*) and Palmer & Carmichael (1973) suggest that this results from attachment of the Grenville Province to the remainder of the Shield by dextral strike-slip motion at *ca.* 1100 Ma. However, Archaean and early Proterozoic rocks are found reworked within the Grenville Province (although this need not be fatal to the hypothesis), massive anorthosites are common both within the Province and the neighbouring Shield, and *ca.* 2000 Ma iron formations of the Labrador trough can be traced well inside the province where they are deflected at the line of the Grenville Front (Windley 1973); also basic bodies characterizing modern sutures are absent. Further work close to the line of the Grenville Front has produced Grenville-type pole positions from very close to the Grenville front where there seems to be no possibility of a plate suture, and Roy & Fahrig (1973) offer a new explanation; they suggest that these poles are evidence for a rapid excursion of the pole ('The Grenville Loop') not hitherto identified in North America, prior to, and connecting with, the Great Logan Loop. Figures 3 and 4 resolve this problem in a different way: the poles from the Grenville Province are coincident with the contemporary African a.p.w. curve. Although uncertainty surrounds the precise form of this curve, the Grenville poles clearly straddle the region defined by pole 29 (1040 Ma) and poles 34–46 with assigned ages between (> 990–1000 Ma and 806 Ma). This is consistent with the probable ages of the Grenville poles and leaves no grounds for interpreting the Grenville Province in terms of plate convergence.

It is probable that continental separation was complete by about 750 Ma since Fahrig, Irving & Jackson (1971) and Murthy (1971) report pole positions at 167° E, 8° N and 161° E, 3° S for late Precambrian dolerites of the Canadian Shield with ages indicated by K-Ar studies of 675 and 700 Ma respectively. These poles together with that from Upper Torridonian sandstone of northwest Scotland (*ca.* 750 Ma) plot on the reconstruction of figure 5 in positions remote from 800–700 Ma poles from Australia, India and Africa.

## 3. Comparison of data from Europe and Asia with the North America–Gondwanaland a.p.w. curve

### (*a*) *Palaeomagnetic data from the Baltic and Ukrainian Shields*

Several authors have analysed Precambrian palaeomagnetic data from the Baltic Shield (Neuvonen 1970; Spall 1973; Donaldson, Irving, McGlynn & Park 1973). Poles plotted in figure 5 have assigned ages quoted in original papers or taken from later studies. Poles (8, 9, 20 and 34) with probable ages in the range 2000–1850 Ma form a closely clustered group noted by Spall (1973), and recognition of this as a palaeofield axis for this time is substantiated by further work of Neuvonen (1973, poles 31 and 32 in figure 5). These are separated from poles falling in a second general group (1–5, 12, 16, 18, 19, 21, 25 and 30) with considerable spread of allocated ages; poles 16, 18, 19, and possibly 3 and 12, all have assigned ages older than 1650 Ma while poles 1, 4, 5, 25, 30 and possibly 21, have ages in the range 1400–900 Ma. The Ukrainian Shield is separated from the Baltic Shield by the Gothian-Ovruch mobile belt which did not consolidate until 1500–1150 Ma (Semenko *et al.* 1968) but there seems to be no compelling reason for differentiating between pole positions from the two regions (figure 5).

The 2000–1000 Ma Baltic–Ukrainian data cluster in a very similar way to contemporary results from Africa and North America, and for this reason alone it is reasonable to seek correlation between them. In particular if Ukrainian poles 26–29 are *ca.* 1700–1600 Ma in age as the majority of the isotopic evidence suggests, then the swathe connecting them with *ca.* 1300 Ma poles is 110° of arc or similar to the displacement of poles of comparable age on the North American curve. The 2000–1850 Ma poles from the Baltic Shield (8, 9, 20, 31, 32 and 34) belong to an earlier part of the curve and their displacement from *ca.* 1300 Ma poles

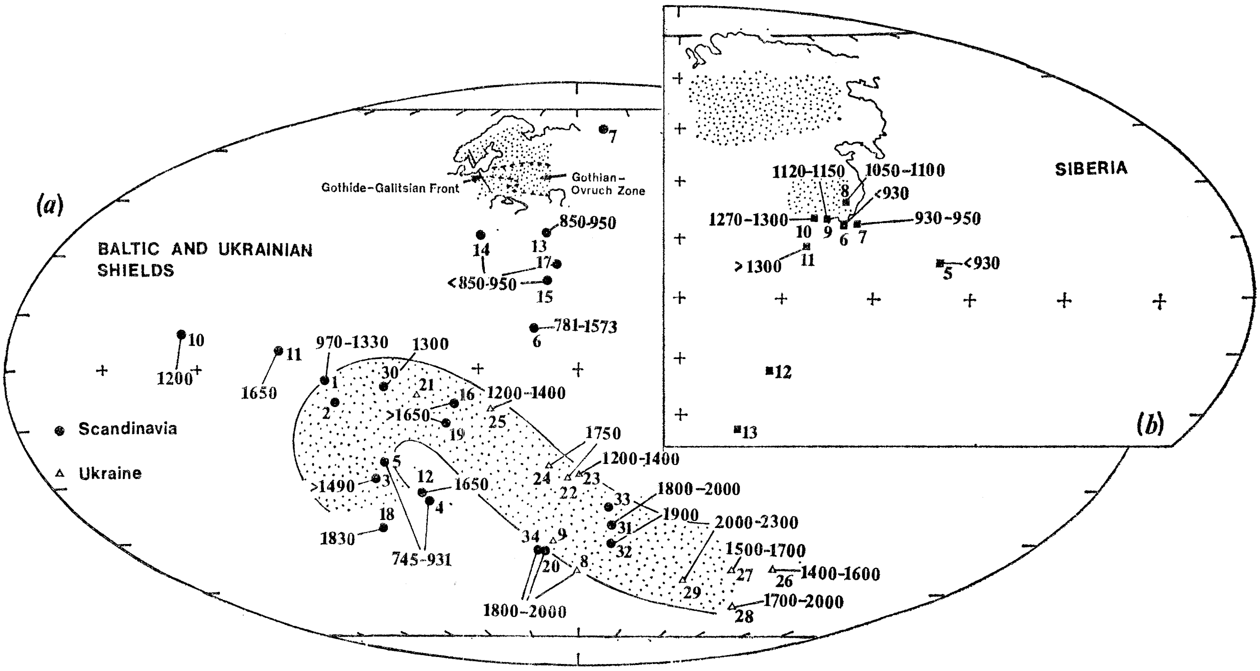


FIGURE 5. (*a*) Precambrian palaeomagnetic poles from the Baltic and Ukrainian Shields with assigned ages where they are known. Poles 1–29 are included in the compilation of Spall (1973) where they are referenced: 1 (SD), 2 (V), 3 (DV), 4 (JB), 5 (JD), 6 (HD), 7 (HF), 8 (JS), 9 (JSV), 10 (DS), 11 (M), 12 (F), 13 (BN), 14 (HN), 15 and 17 (EG), 18 (AV), 16 and 19 (K), 20 (TG), 21 (AG), 22 (KC), 23 (UG), 24 (KG), 25 (G), 26 (TM), 27 (BS), 28 (NC), 29 (BP). Other poles are from Neuvonen (1973, poles 30 and 31), Neuvonen (1974, pole 32), Cornwell (1968, pole 33) and Puranen (1960, pole 34). The stippled area is a simplified a.p.w. swathe which is matched with 2000–1300 Ma results from North America and Africa to derive the reconstruction of figure 6. (*b*) Precambrian palaeomagnetic poles from Siberia are coded: 5, 10/176; 6, 10/177; 7, 10/178; 8, 10/179; 9, 10/180; 10, 10/181; 11, 10/182; 12, 7/56, and 13, 7/77 where the numbers refer to listings in the *Geophysical Journal of the Royal Astronomical Society*.

(65° of arc) is again the same as on the North American curve. The loop identified from the combined Gondwanaland–North American data between *ca.* 2000 Ma and 1700 Ma may then explain why poles falling in two different age groups are found at the westerly end of the swathe if poles 3, 12, 16, 18, 19 and possible 11 (> 1650 Ma) belong to this loop. Recognition of these analogies in detail between the North American and Baltic–Ukrainian data allow the two a.p.w. curves to be superimposed such that the areas of Precambrian crust are in continuity (figure 6) preserving the colinearity of the Grenville and Gothide belts noted by Donaldson *et al.* (1973). Semenenko *et al.* (1968) continue this belt with the Galitsian belt of eastern Europe. As yet no feature comparable to the Great Logan Loop has been identified from Scandinavian data but this is not surprising since the top of the loop was executed within a few tens of millions of years only.

### (*b*) *Palaeomagnetic data from Siberia*

Precambrian palaeomagnetic data from Siberia include poles 5–11 plotted in figure 5*b* with assigned ages ranging from > 1300 to < 930 Ma; two other poles (12 and 13) have no age control. Clearly all of the ages of poles 5–11 are not consistent with this essentially 'quasi-static' pole position if this region was also part of the Proterozoic supercontinent. However, the pole moved only slightly relative to the Gondwanaland–North America region during the interval *ca.* 1650–1300 Ma (figures 1 and 3) and returned to a closely similar position after about 1040 Ma (figure 4) so we may superimpose these groups of poles from the two regions to obtain an estimate of relative positions of the Shield regions at this time. The reconstruction of figure 6 in which the Baltic–Ukrainian and Siberian Shields are in juxtaposition is probably the correct one because the Siberian massive anorthosites are then a direct continuation of the great circle arc of Proterozoic magmatism recognized in Gondwanaland, North America and the Baltic Shield (Piper 1974, figures 1 and 2). These anorthosites include bodies in the Stanovoi region (< 1800–2000 Ma), Aldan Shield (> 1550–1600 Ma), Dzhugdzhur Massif (2250 ± 150 Ma) and Anabar Massif (1734 Ma), and occur associated with a broad belt of Proterozoic alkaline magmatism (Butakova 1974). The Baikal, Sayany and Yenisey belts are dated *ca.* 1200 Ma (Semenenko *et al.* 1968) and Tugarinov (1968) recognizes a 1000–1100 Ma magmatic event in the eastern part of the Aldan Shield.

## 4. Geological and geophysical implications

### (*a*) *The Proterozoic super-continent*

The palaeomagnetic data reviewed here are consistent with the continental (sialic) regions existing in the form of a single unit as illustrated in figure 6. This super-continent as defined is supported by palaeomagnetic evidence from about 2000 Ma (*ca.* 2690 Ma in the case of Africa and North America) until late Precambrian times, although paucity of data from Siberia and a number of the segments of Gondwanaland render it uncertain whether these regions were continuously part of such a super-continent. With the age uncertainties assigned to Precambrian palaeomagnetic pole positions this is currently only one possible interpretation of the data. It is still possible to argue that small differences in pole positions or ages are a consequence of relative plate movements. To test this model against a plate tectonic model for the Proterozoic crust necessitates an assessment of the geological evidence. Also, it remains uncertain when the super-continent was dismembered, although differences illustrated in figure 6*b* between < 950–850 Ma palaeomagnetic poles from Scandinavia, comparable age data from Africa, and *ca.* 700 Ma data from North America, suggest that these areas had begun to move independently by Late Precambrian times.

### (*b*) *Proterozoic tectonic and magmatic features*

The most notable feature of the reconstruction of figure 6 is the alignment of major Proterozoic tectonic and magmatic elements as a broad belt spanning the length of the super-continent. Segments of this lineament have already been noted by several other workers (Bridgwater & Windley 1972; Sutton 1973; Hurley & Rand 1969). The tectonic episodes along this lineament occurred during the interval 1350–940 Ma and include the Namaqualand, Kibaran, Irumide, Grenville, Gothide-Galitsian and Baikal belts; magmatic features include massive anorthosites

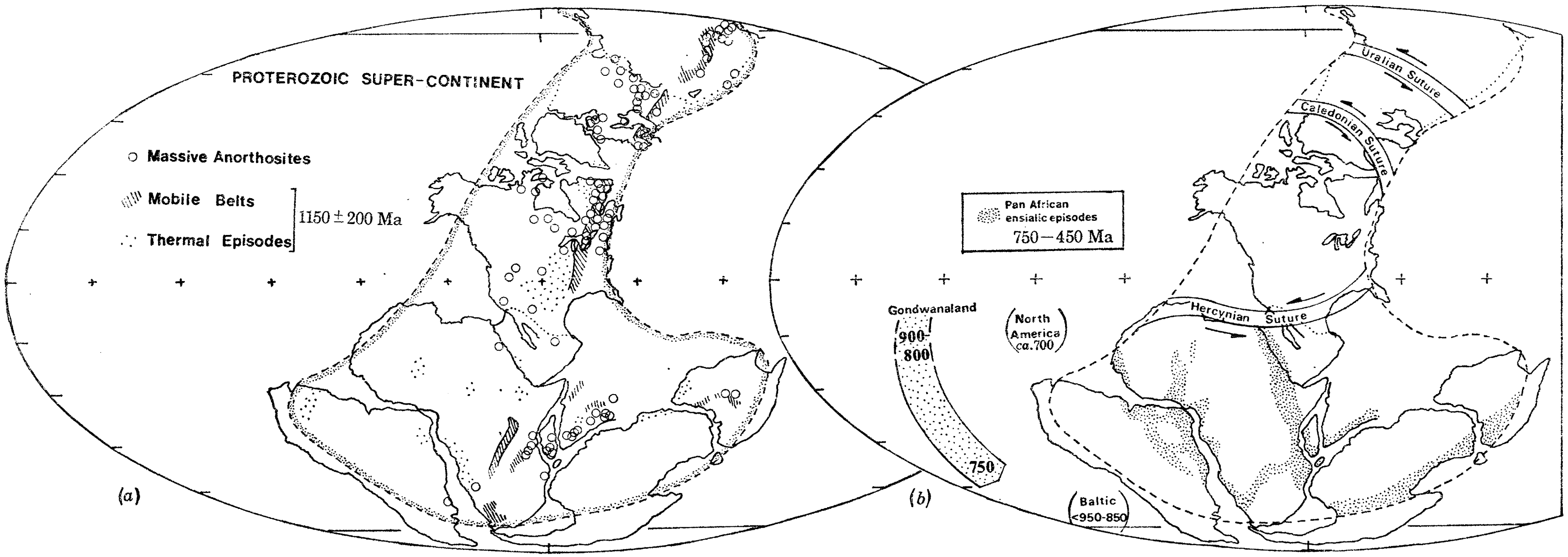


FIGURE 6. (*a*) Distribution of massive anorthosites, and 1150 ± 200 Ma thermal episodes and mobile belts on the Proterozoic super-continent. The distribution of anorthosites is simplified after the compilation in the New York State Museum and Science Service, Memoir 18. The true extent of the thermal episodes has been obscured by later overprinting and the distinction between a thermal episode and mobile activity is often not clear from available data. (*b*) Late events in the dismemberment of the Proterozoic super-continent. These involved break-up along sutures along which later orogenic belts developed, and movements *may* have been largely sinistral strike-slips as indicated diagrammatically by the arrows. Due to paucity of palaeomagnetic data, the timing of this break-up is uncertain; pole positions from Scandinavia rocks dated < 950–850 Ma, and North American rocks *ca.* 600 Ma are plotted relative to the Gondwanaland a.p.w. curve in this figure to show that it had probably commenced by these dates. The development of orogenic belts along the sutures was in part contemporaneous with formation of the 'Pan-African' ensialic mobile belts, the extent of which is indicated in this diagram.




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(*ca.* 2250–1000 Ma), rapakivi granites (⩾ 1650 Ma) and alkaline intrusive suites of uncertain age span. At a late stage in development of this lineament grabens developed near the axis in which thick suites of clastic sediments accumulated spatially associated with the 1150 ± 200 belts.

Identification of this super-continent implies a major difference between the relative movements involved in development of *orogenic belts* at plate margins and *mobile belts* by limited internal deformation across broad zones of crustal mobility (see Briden, this volume; Piper *et al.* 1973). The palaeomagnetic findings follow geologic observations made over a long period of time beginning with Holmes's (1948) observation that the Mozambique belt is essentially a tectonic overprint on an older basement, a point later emphasized by Clifford (1968) and Hepworth (1972). Palaeomagnetic evidence does not yet preclude major internal deformation of the super-continent and in particular available pre-1300 Ma results from western and southern Africa could accommodate relative rotations between the cratons of about 10 or 20° and lateral movements of up to about 1000 km within the later 1150 ± 200 Ma and Pan-African mobile belts. Only field observations can place lower limits on internal deformation within these belts, and in Africa direct correlation of older structural lineaments across these belts (Shackleton 1973, Fig. 2) and correlation sediments on the cratons with those in the mobile belts (Cahen 1970) seem to imply only very limited displacements across them. Absence of large amounts of strike-slip movement along the belts is also suggested by the limited length of the tectonic zones themselves; the Kibaran belt is flexed through a right angle at its northeast termination and the Irumide belt also apparently dies out along its length (Shackleton 1973, Fig. 1). In Namaqualand this episode involved principally a reactivation of granite gneiss basement with only minor associated tectonic activity. In common with the later Pan-African episode extensive zones of thermal overprinting and igneous intrusion with little or no tectonic activity accompanied development of the 1150 ± 200 Ma belts. The full extent of these zones has been obscured by the later thermal-tectonic events but at least includes western parts of the North American Shield (Stockwell 1968) and parts of central, west, and northeast Africa (Cahen & Snelling 1966; Coomer & Robertson 1974; Grant, Hickman, Burkholder & Powell 1972).

Elsewhere displacements may have been greater: Donaldson & Irving (1972) note structural elements within the Canadian Shield attributable to dextral strike-slip along the Grenville Front; although the strike slip involved does not appear to be of the magnitude envisaged by the authors, their explanation in terms of more limited strike slip is not invalidated.

Of much longer time significance than the 1150 ± 200 Ma mobile belts is the alignment of magmatic activity including massive anorthosites and associated rapakivi granites and extrusive silicic volcanic provices. As noted by Bridgwater & Windley (1973) and others this activity is not distributed throughout the Precambrian crust but is restricted to broad zones which become a single great-circle arc on the palaeomagnetic reconstruction. There is also a clear migration of this magmatism from the margins to the centre of the Proterozoic super-continent. Bridgwater & Windley (1973) recognize a migration of anorthosite-rapakivi granite magmatism from the margins of the North American–Baltic Shield–Ukrainian region at *ca.* 1700 Ma to the centre at *ca.* 1300–1200 Ma including the late anorthosites of Labrador, southwest Norway, and south Greenland (where they did not reach present levels of erosion); the scale of this inward migration is expanded by recognition that the massive anorthosites of southwestern Africa and Siberia were being intruded before 2000 Ma.

Evidence for this distribution of the sialic crust as early as *ca.* 3000 Ma comes from the distribution of deformed anorthosites (Windley & Bridgwater 1971) which appear to be restricted to belts similar to those of the later massive anorthosites and forming a single unit on the reconstruction. This feature is one of the earliest recognizable linear elements of the sialic crust (Sutton 1973). The distribution in time of geological events during the history of the Proterozoic super-continent is summarized in table 1. An important conclusion to derive from the present meeting is the recognition of continental margin and ophiolitic igneous suites only in late Precambrian time, including the Arabian, Uralian and Atlas regions.

Table 1. Time distribution of major events during the history of the Proterozoic super-continent

(Geologic information mostly from Bridgwater & Windley (1973) and Sutton (1973).)

| Ma | major stages in evolution of the crust | development of Proterozoic magmatic-tectonic lineament | palaeomagnetic evidence for the super-continent reconstruction |
|---|---|---|---|
| 3000 | development of the granitic crust green stone belts + granulites | highly-deformed anorthosites | |
| 2500 | restriction of mobile activity to belts between rigid cratons | | |
| 2000 | widespread development of mobile belts (but with no extensive linearity) | massive anorthosites + rapakivi granites | Africa; India; Australia; North America; Baltic-Ukrainian Shield; Siberia (Angara) Shield |
| 1500 | development of Proterozoic magmatic-tectonic lineament | silicic + basic volcanic suites; clastic sedimentation (often in grabens) | |
| 1000 | development of marginal and ophiolitic suites Arabia, Anti-Atlas, Urals Caledonides | long linear mobile belts + extensive thermal overprint 1150 ± 200 Ma; break-up of super-continent | India 750; Australia 750; North America 800; Gondwanaland |
| 500 | Pan-African mobile belts Caledonian, Uralian Herynian orogenic belts | | |

Essentially the supercontinent was dismembered along three zones identified in figure 6*b* as the Hercynian, the Caledonian and the Uralian sutures named after orogenic belts which subsequently formed by plate collision along the zones. These dislocations resulted in four major plates comprising the Gondwanaland, North American, Baltic–Ukrainian and Siberian segments which moved independently of one another for at least part of the Late Precambrian to Palaeozoic interval.

The Proterozoic super-continent is not greatly different in form from the super-continent Pangaea resulting from the rewelding of these plates and although we do not yet know how much relative movement took place in the intervening period, from this evidence alone it seems unlikely to have been extreme. Thus motions required to bring the Baltic–Ukrainian and North American plates into confluence along the Caledonian orogenic belt, and the Siberian and Baltic–Ukrainian plates into confluence along the Uralian orogenic belt involve mainly sinistral strike-slip in both cases (indicated diagramatically in figure 6). Palaeomagnetic data show that the first motion was complete by at least Middle Silurian times while the second motion was underway in Ordovician times and completed in Permian times (Hamilton 1970). The motion required to bring the Gondwanaland plate into confluence with the North American plate is larger, but is again principally a sinistral strike-slip. As is the case with the Archean–Proterozoic transition, the change from mobile belt tectonics characteristic of Proterozoic times and plate tectonics characteristic of Phanerozoic time was essentially transitional, since formation of the ensialic Pan-African mobile belts (figure 6*b*, 750–450 Ma) overlaps in time with these relative plate movements.

### (*c*) *Implications to Proterozoic mantle processes*

The change of metamorphic facies through time from a preponderance of low P–high T assemblages in the early Precambrian to high P–low T assemblages formed in present subduction environments is concise evidence for a changing temperature gradient within the Earth's crust and is widely related to a fall in radiogenic heat production and a thickening of the crust. Metamorphic assemblages may imply crustal thicknesses of 25 km over 3000 Ma age (Saggerson & Owen 1969), although attempts to relate chemistry of volcanic rocks to temperature gradients yield estimates of 15 km (Hart *et al.* 1972) and 10–25 km (Condie & Potts 1969) at 2700 Ma; these may involve circular arguments (Shackleton 1973) since chemistry is predominantly a function of depth of origin and hence thermal gradient. The crust may then already have reached at least 50 and probably 70 % of its present thickness by the beginning of Proterozoic times, and during the interval for which evidence for the Proterozoic super-continent is compelling 2200–1000 Ma) radiogenic heat production dropped from between about 2.0 to 1.5 or 1.25 times its present values (Dickenson & Luth 1971) compared with values between 2.5 and 5 times present values during formation of the early high grade gneiss-migmatite crust at *ca.* 4000 Ma.

The two diachronous changes in tectonic behaviour of the lithosphere are defined by the Archaean–Proterozoic and Proterozoic–Phanerozoic (plate tectonic) transitions. The first, representing increasing rigidity of the crust, may be explained as a consequence of the fall off in radiogenic heat production. The second expresses a change in the mode of heat loss from the Earth's interior: dispersal of the greater amount of radiogenic heat in Proterozoic times (presumably as large scale convection currents) did not achieve disruption of a more plastic (and probably thinner) lithosphere. The alignment of magmatic activity between *ca.* 2300 and 1000 Ma and 1150 ± 200 Ma mobile belts along a great circle occupying about 220° of arc is only consistent with a simple system of heat accession from the mantle. Also, a single large landmass could only result initially from a simple mantle convection system with two or three cells only to concentrate sialic material at down-going currents (Runcorn 1962). Whether or not the great circle alignment of magmatic and tectonic activity in Proterozoic times is a consequence of up or down welling convection beneath the sial is unclear: downgoing currents would account for preservation of the crust as a coherent unit, although Shackleton (1973) attributes Proterozoic mobile belts to upwelling currents from which the silicic material intruded into them could be differentiated (see also Bridgwater & Windley 1973).

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## Appendix 1

Precambrian and Lower Palaeozoic palaeomagnetic poles from Africa listed in order of age. Also given in this table are the radii of the circles of 95% confidence ($A_{95}$) and the number of sites and samples from which the poles are derived. The pole falling in the northern hemisphere is quoted and wherever possible poles are referenced according to their listing in tables compiled by Irving or McElhinny in the *Geophysical Journal of the Royal Astronomical Society*, the first number referring to the list and the second to the number of the pole within that list. Where poles have not yet been listed in these tables they are numerated according to sources listed in the footnote. Only poles for which at least a general idea of the age is available are included in these tables.

| pole no. | rock unit–source area | age/Ma | mean palaeomagnetic pole | $A_{95}$ | no. of sites | no. of samples | reference or pole number† |
|---|---|---|---|---|---|---|---|
| 1 | Modipe Gabbro, Botswana | 2630 ± 470‡ | 33° N, 221° E | 10½ | 10 | 36 | 8/157 |
| 2 | Great Dyke, Rhodesia | 2520 ± 30‡ | 21½° N, 61½° E | 9 | 9 | — | 7/62–63 |
| 3 | Jeppestown Amygdaloidal Lava, South Africa | *ca.* 2500 | 10° N, 99° E | — | 1 | 5 | 1 |
| 4 | Gaberones Granite, Botswana | 2340 ± 50‡ | 34½° N, 103½° E | 16 | 7 | 43 | 9/158 |
| 5 | Tonalites, NW Sahara | *ca.* 2160‡ | 4° N, 5° E | 23 | 3 | 23 | 2 |
| 6 | Lower Ventersdorp Lavas, South Africa | *ca.* 2500 | 4° N, 220° E | 11 | 25 | — | 1 |
| 7 | Upper Ventersdorp Lavas, South Africa | 2300 ± 100 | 71° N, 173° E | 9 | 10 | — | 1 |

APPENDIX 1 (*cont.*)

| pole no. | rock unit–source area | age/Ma | mean palaeomagnetic pole | $A_{95}$ | no. of sites | no. of samples | reference or pole number† |
|---|---|---|---|---|---|---|---|
| 8 | Lavas, Transvaal System, South Africa | *ca.* 2250‡ | 42° N, 194° E | — | — | — | 3 |
| 9 | Syntetonic Igneous rocks, NW Sahara | *ca.* 2160‡ | 55° N, 226° E | 25 | 5 | 23 | 2 |
| 10 | Tarkwaian intrusions, Ghana | *ca.* 2200 | 53° N, 216° E | 13.5 | 5 | 29 | 4 |
| 11 | Obuasi greenstone body Ghana | *ca.* 2200 | 50° N, 282° E | 14 | 5 | 74 | 4 |
| 12 | Dolerite dyke, Obuasi, Ghana | *ca.* 2200 | 56° N, 248° E | — | 1 | 10 | 4 |
| 13 | Dolerite intrusion, Ivory Coast | 1730 ± 170 | 11° N, 282° E | — | 1 | 10 | 4 |
| 14 | Cunene Anorthosite Complex, Angola | 2070‡ | 3° N, 75° E | 21 | 12 | 75 | 5 |
| 15 | Orange River Lavas, South Africa | > 1850‡ | 19° N, 254° E | 20 | 3 | 11 | 6 |
| 16 | Aftout Gabbro, Algeria | *ca.* 1950‡ | 29° N, 55° E | — | — | — | 7 |
| 17 | Basic granophyre, Vredefort Ring Complex, South Africa | *ca.* 1970 | 22° N, 27° E | 12 | — | 12 | 12/163 |
| 18 | Bushveld Complex, South Africa | 1950 ± 50‡ | 23° N, 36° E | 12 | 5 | — | 1/142 |
| 19 | Losberg intrusion, South Africa | *ca.* 1950‡ | 33° N, 36° E | — | — | — | |
| 20 | Diorite intrusions, NW Sahara | *ca.* 1950‡ | 7 poles from 7 sites given in figure 1*a* | | | | |
| 21 | Waterberg Sandstones, South Africa | < 1950, > 1780‡ | 5 poles from 9 sites (88 samples) given in figure 1*a* | | | | 9/148–52 |
| 22 | Mashonaland dolerites, Rhodesia | 1880‡ | 7° N, 340° E | 7½ | 14 | 116 | 8/151 |
| 23 | Premier Mine, Kimberlite, South Africa | 1750 ± 100 | 51° N, 37½° E | — | 1 | 32 | 10/197 |
| 24 | Kanango Kimberlite, Ivory Coast | — | 62½° N, 66½° E | — | 1 | 7 | 8 |
| 25 | Van Dyke Mine, dolerite dyke, South Africa | 1650 | 12½° N, 14° E | — | 1 | 16 | 8/156 |
| 26 | Dolerite dykes, NW Sahara | < 1920‡ | 35° N, 30° E | 33 | 8 | 39 | 2 |
| 27 | Pilansberg dykes, South Africa | 1310 ± 60‡ | 7½° N, 42½° E | 10½ | 5 | — | 1/141 |
| 28 | Lavas, Kisii Series, Kenya | *ca.* 1210 | 6° N, 348° E | 14 | 9 | 63 | 9 |
| 29 | O'okiep intrusions, South Africa | 1040 | 15° N, 335½° E | 16 | 5 | 22 | 6 |
| 30 | Waterberg dolerites, Botswana | — | 65° N, 50½° E | 4½ | 13 | 90 | 8/155 |
| 31 | Umkondo dolerites, Rhodesia | 1140 | 65½° N, 40° E | 7 | 9 | 76 | 8/154 |
| 32 | Barby Formation Lavas, South West Africa | < 1200‡ > 1020 ± 70‡ | 67½° N, 28° E | 13 | 19 | 98 | 6 |
| 33 | Umkondo Lavas, Rhodesia | 1115‡ | 61½° N, 15° E | 12 | 9 | 21 | 8/154 |
| 34 | Guperas Formation Lavas, South West Africa | < 1020 ± 70‡ | 63° N, 317° E | 2 | 4 | 16 | 6 |
| 35 | Auborus Formation, South West Africa | < 1020 ± 70‡ | 43° N, 354° E | 10 | 8 | 37 | 6 |
| 36 | Bukoba Sandstone, Tanzania | > 990–1000 | 40° N, 317° E | — | 1 | 20 | 10 |
| 37 | Abercorn Sandstone, Zambia | — | 49° N, 300° E | — | 1 | 5 | 11 |
| 38 | Plateau Series (i) Zambia | — | 54° N, 278° E | — | 1 | 12 | 11 |
| 39 | Ikorongo Group, Tanzania | — | 35° N, 264° E | 23 | 6 | 31 | 11 |
| 40 | Dykes, Klein Karas, South West Africa | 878 ± 41 | 20° N, 294° E | 35 | 4 | 12 | 6 |
| 41 | Kigonero Flags, Tanzania | > 890 | 12° N, 273° E | 28 | 4 | 20 | 10 |
| 42 | Malagarasi Sandstone, Tanzania | — | 7° N, 112° E | — | 1 | 10 | 10 |
| 43 | Mbala Dolerites, Zambia | — | 9° N, 100° E | 17 | 2 | 16 | 11 |
| 44 | Bukoban Dolerites, Tanzania | 806 ± 30 | 11° N, 101° E | 16 | 16 | 67 | 10 |
| 45 | Gagwe Amygdaloidal Lavas, Tanzania | 813 ± 30 | 29° N, 103° E | 11 | 28 | 129 | 10 |
| 46 | Manyovu Red Beds, Tanzania | < 813 ± 30 | 24° N, 118° E | 30 | 5 | 44 | 10 |
| 47 | Mbozi Complex, Tanzania | 743 ± 30 | 72° N, 68° E | 14 | 5 | 19 | 11 |
| 48 | Lower Buanji Series, Tanzania | — | 87° N, 263° E | 7 | 6 | 25 | 11 |

APPENDIX 1 (*cont.*)

| pole no. | rock unit–source area | age/Ma | mean palaeomagnetic pole | $A_{95}$ | no. of sites | no. of samples | reference or pole number† |
|---|---|---|---|---|---|---|---|
| 49 | Pre-Nama dykes, South Africa | 653 ± 70 | 85° N, 228° E | 25 | 5 | 28 | 6 |
| 50 | Ntonya Ring Structures, Malawi | 630 ± 24‡ | 27½° N, 345° E | 2 | 7 | 27 | 9/137 |
| 51 | Sijarira Group, Rhodesia | — | 2° N, 352° E | 18 | 9 | 40 | 12/149 |
| 52 | Klipheuval Formation, South Africa | Lower Cambrian(?) | 16° N, 316° E | — | — | — | 14 |
| 53 | Sabaloka Ring Structure, Sudan | 540 | 83° N, 339° E | 10 | 3 | 17 | 12 |
| 54 | Plateau Series, Zambia | four poles of Lower Palaeozoic age from 13 sites (67 samples) shown in figure 2*a* | | | | | 11 |
| 55 | Fish River Group, South West Africa | L. Cambrian poles from 12 sites shown in figure 2*a* | | 30 | 9 | 44 | 6 |
| 56 | Lavas, Morocco | Middle Cambrian | 53° N, 34° E | — | — | — | 13 |
| 57 | Doornpoort Formation, South West Africa | 500–550 | 22° N, 45° E | 9 | 6 | 28 | 6 |
| 58 | Hook Intrusives, Zambia | 500 ± 17 | 14° N, 336½° E | 36 | 3 | — | 9/132 |
| 59 | Table Mountain Formation, South Africa | Ordovician | 50° N, 349° E | — | 1 | 101 | 4/32 |
| 60 | Tassili sediments, Algeria | Cambrian-Ordovician | 53° N, 26° E | — | — | — | 15 |

† References to poles not yet included in *Geophysical Journal* listings are: 1, Henthorn (1973); 2, unpublished results of K. Lomax and author; 3, Briden, unpublished result; 4, Piper & Lomax (1973); 5, Piper (1975*a*); 6, Piper (1975*b*); 7, Lomax, unpublished result; 8, Strangway (1970); 9, Brock, Raja & Vise (1972); 10, Piper (1972); 11, Piper (1975*c*); 12, Briden (1973); 13, Helsley (1965); 14, Creer (1973); 15, Ileana (1971).

‡ Ages marked with an asterisk are Rb-Sr determinations. Other ages are based on K-Ar determinations except for pole 28 where the quoted age is the maximum of several plateau ages determined by the $Ar^{39}$-$Ar^{40}$ technique, K-Ar determinations give a maximum age of 960M a for this pole. Age of poles 10–12 is based on a U-Pd determination; K-Ar dates suggest an age of *ca.* 2150 Ma for these poles.

APPENDIX 2

(A compilation of Precambrian to Ordovician palaeomagnetic poles from Australia, Antarctica, India, and South America.)

| pole no. | rock unit | pole position (°N, °E) | | age/Ma | reference or pole number† |
|---|---|---|---|---|---|
| (i) Australia | | | | | |
| 1 | Widgiemooltha dykes | 8 | 337 | 2420 ± 20 | 10/200 |
| 2 | Nullagine lavas | 51 | 342 | *c.* 2100 | 1/144 |
| 3 | Hart dolerite | 29 | 46 | 1800 ± 25 | 12/162 |
| 4 | Edith River Volcanics | 6 | 346 | 1760 | 1/145 |
| 5 | Mt Goldsworthy G3 | 30 | 330 | Archean (?) | 10/170 |
| 6 | Iron Monarch −ve | 64 | 267 | — | 9/146 |
| 7 | Iron Prince | 39 | 247 | — | 9/147 |
| 8 | Iron Monarch +ve | 15 | 272 | — | 9/145 |
| 9 | Mt Goldsworthy G2 | 22 | 259 | Archean (?) | 10/171 |
| 10 | Mt Goldsworthy Banded iron formation | 0 | 86 | Archean (?) | 10/172 |
| 11 | Mt Goldsworthy G1 | 20 | 84 | — | 10/169 |
| 12 | Dowd's Hill | 43 | 356 | Archean (?) | 10/173 |
| 13 | Mt Tom Price | 22 | 57 | — | 10/174 |
| 14 | Mt Newman | 17 | 66 | — | 10/175 |
| 15 | Giles Complex | 34 | 311 | 1100 | 13/87 |
| 16 | Precambrian dykes, B Group | 24 | 102 | 750 | 1 |
| 17 | Pound Quartzite | 60 | 186 | Late Precambrian | 2 |
| 18 | Antrim Plateau Volcanics | 9 | 160 | < 663 | 12/148 |
| 19 | Arumbera Sandstone | 9 | 325 | Late Precambrian | 3 |



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Appendix 2 (*cont.*)

| pole no. | rock unit | pole position (°N, °E) | age/Ma | reference or pole number† |
|---|---|---|---|---|
| 20 | Aroona Dam Sediments | 36 213 | Late Precambrian | 2 |
| 21 | Hugh River Shale | 11 37 | L.-M. Cambrian | 3 |
| 22 | Hudson Formation | 18 19 | M. Cambrian | 4 |
| 23 | Lower Lake Frome Group | 8 205 | M. Cambrian | 2 |
| 24 | Upper Lake Frome Group | 38 206 | U. Cambrian | 2 |
| 25 | Jinduckin Formation | 13 205 | L. Ordovician | 4 |
| 26 | Stairway Sandstone | 2 $230\frac{1}{2}$ | M. Ordovician | 5 |
| (ii) Antarctica | | | | |
| A1 | Dykes, Vestfold Hills | 17 193 | $1030 \pm 220$ | 6 |
| A2 | Charnockites, Mienyy Station | 2 208 | 502 | 1 |
| A3 | Sr Røndane intrusives | 28 190 | 480 | 10/140 |
| (iii) India | | | | |
| 1 | Visakhaptnam Charnockites II | 48 152 | 1800–1650 | 10/189 |
| 2 | Visakhaptnam Charnockites I | 15 9 | 1800–1650 | 10/188 |
| 3 | Gwalior Traps | 19 176 | 1815 | 7/60 |
| 4 | Haematite, Parkhuri | 15 335 | *ca.* 1815 | 7 |
| 5 | Quartzites, Pokhra | 2 357 | *ca.* 1815 | 7 |
| 6 | Cuddapah Sandstone | 22 340 | 1160 | 8 |
| 7 | Cuddapah Shales | 23 337 | 1160 | 8 |
| 8 | Chifloor dyke | 15 329 | 1100–1200 | 8 |
| 9 | Veldurthi haematites | 45 333 | 1200–900 | 8/158 |
| 10 | Malani rhyolites | 78 45 | 745 | 7/61 |
| 11 | Mundwara Complex | 42 295 | 850–650 | 7/58 |
| 12 | Kaimur sandstones | 82 286 | 1140 | 8/150 |
| 13 | Bhander Sandstone | 49 213 | Pc-Cambrian | 1 |
| 14 | Upper Rewa Sandstone | 35 222 | Pc-Cambrian | 7 |
| 15 | Upper Bhander Sandstone | 32 199 | Pc-Cambrian | 7 |
| 16 | Purple Sandstone, Salt Range | 28 212 | Lower Cambrian | 11/85 |
| 17 | Salt Pseudomorph Beds | 27 233 | Middle Cambrian | 1 |
| (iv) South America | | | | |
| 1 | Roraima dolerites (i) | 63 231 | 2070–2090 | 10/160 |
| 2 | Roraima dolerites (ii) | 45 167 | 2070–2090 | 10/161 |
| 3 | Blackawatra Dykes | 8 233 | 2070–2090 (?) | 13/73 |
| 4 | Kabaledo dolerites | 44 210 | 2070–2090 (?) | 13/74 |
| 5 | Purmanarca Village sediments | 61 293 | Cambrian | 9 |
| 6 | South Tilcara sediments | 52 27 | Cambrian | 9 |
| 7 | North Tilcara sediments | 49 24 | Cambrian | 9 |
| 8 | Purmamarca sediments | 5 39 | Cambrian | 9 |
| 9 | Abra de Cajas sediments | 2 28 | Cambrian | 9 |
| 10 | Salta and Jujuy sediments | 12 239 | Cambro-Ordovician | 12/146 |
| 11 | Salta sediments | 31 13 | Ordovician | 9 |
| 12 | Sediments, Bolivia | 4 302 | Ordovician | 12/140 |
| 13 | Urucum Formation | 17 347 | Ordovician-Silurian | 12/140 |

† References to poles not yet included in *Geophysical Journal* listings are: 1, quoted by McElhinny (1973); 2, Embleton & Giddings (1974); 3, Embleton (1972*a*); 4, Luck (1972); 5, Embleton (1972*b*); 6, Embleton & Arriens (1973); 7, Mishra, unpublished result quoted by Athavale, Verma, Bhalla & Pullaiah (1970); 8, Prasad, unpublished results, quoted by Athavale *et al.* (1970); 9, Thompson (1973).

## Appendix 3

Precambrian poles from North America from the interval 2600–1000 Ma. This compilation is based on the listings of McElhinny (1973) with additional poles published since. The pole falling in the northern hemisphere is given and ages quoted are those favoured by the original authors, or accepted by McElhinny (1973).

| no. | rock unit | pole position (°N, °E) | age/Ma | reference or pole number† |
|---|---|---|---|---|
| 1 | Stillwater complex | 62 112 | 2500 | 12/166 |
| 2 | Soudan iron formation | 39 117 | 2600 | 9/153 |
| 3 | Metachewan dykes | 37 59 | 2690 ± 93 | 8/174 |
| 4 | Matachewan dykes | 63 61 | 2690 ± 93 | 8/175 |
| 5 | Matachewan dykes | 45 81 | 2690 ± 93 | 8/181 |
| 6 | Abana dykes | 54 71 | 2690 ± 93 | 8/182 |
| 7 | Older Abitibi dykes | 24 107 | 2147 ± 68 | 8/172 |
| 8 | Nipissing diabase | 19 92 | 2160 ± 60 | 12/164 |
| 9 | Older Abitibi dykes | 21 58 | 2147 ± 68 | 8/173 |
| 10 | India Harbour dykes | 6 63 | 2080 | 1 |
| 11 | Cobalt Group sediments | 22 263 | 2180–2650 | 9/159 |
| 12 | Wind River dykes | 43 239 | 1880–2060 | 2 |
| 13 | Otish Gabbro | 35 253 | 1790 ± 100 | 3 |
| 14 | Marathon dykes | 29 213 | 1810 | 8/176 |
| 15 | Spanish River, Alkalic rocks | 37 264 | 1790 ± 100 | 4 |
| 16 | Gunflint iron formation | 28 266 | 1850–1600 | 10/152 |
| 17 | Dubawnt Group | 7 277 | 1835 | 5 |
| 18 | Churchill Province, Metamorphic rocks | 12 259 | 1622 | 6 |
| 19 | Sparrow dykes | 12 291 | *ca.* 1700 | 7 |
| 20 | Et-Then Group | 1 228 | 1250–1845 | 8 |
| 21 | Nonacho sediments | 13 274 | 1400–1700 | 7 |
| 22 | Sudbury irruptive | 39 261 | *ca.* 2000 | 5/92 |
| 23 | Sudbury irruptive | 53 245 | *ca.* 2000 | 5/92 |
| 24 | Molson dykes | 36 251 | 1445 | 8/177 |
| 25 | Western Channel Diabase | 9 245 | 1325–1785 | 8 |
| 26, 27, 28 | Younger Abitibi dykes | 32 228<br>27 226<br>17 228 | 1230 | 8/170, 171, 180 |
| 29 | Arbuckle granites | 17 210 | 1320–1400 | 10/166 |
| 30 | Croker Island complex | 5 217 | 1475 | 11/90 |
| 31 | Michikamau anorthosite | 1 34 | 1400 | 10/191 |
| 32, 33 | St Francois igneous rocks | 1 38<br>1 37 | 1400–1300 | 8/159, 160 |
| 34 | Sherman granite | 8 29 | 1410 | 9/144 |
| 35 | Grand Canyon Series | 9 29 | 1400–1100 | 1/137–138<br>3/83–84 |
| 36 | Belt Series (combined pole) | 10 27 | 1325–1100 | 3/77–82, 5/89–91<br>8/161–162<br>combined |
| 37 | Seal Group sediments | 5 205 | — | 9 |
| 38 | Seal and Croteau Lavas | 22 17 | 1200–1500 | 9 |
| 39 | Sibley Group sediments | 20 34 | 1370 | 10 |
| 40 | MacKenzie dykes | 4 183 | 1315‡ | 8/179 |
| 41 | MacKenzie dykes | 4 193 | 1315‡ | 11/89 |
| 42 | MacKenzie diabases | 3 190 | 1315‡ | 11 |
| 43, 44 | Sudbury dykes | 8 17<br>4 9 | 1285 | 7/78, 8/178, 9/143 |
| 45 | Muskox gabbro | 4 185 | 1150 | 8/183 |
| 46 | Coppermine lavas | 1 184 | 1150 | 8/184 |
| 47 | Coppermine lavas and sediments | 3 182 | *ca.* 1150 | 12 |
| 48 | Mungford basalt | 49 217 | 948 | 15 |
| 49 | Purcell System | 18 33 | 1150–1000 | 7/79 |
| 50, 51 | Nonesuch shale and Freda sandstone | 9 169<br>7 186 | 1046 | 1/32, 10/184 |

Appendix 3 (*cont.*)

| no. | rock unit | pole position (°N, °E) | age/Ma | reference or pole number† |
|---|---|---|---|---|
| 52 | Boulter intrusive | 42 203 | 1150–1000 | 5/93 |
| 53 | Thanet and Umfraville intrusives | 1 338 | 1150–1000 | 5/94 |
| 54 | Tudor intrusive | 42 149 | — | 5/95 |
| 55 | §Tudor gabbro | 17 137 | — | 13 |
| 56 | §Wilberforce pyroxenite | 15 328 | — | 13 |
| 57 | §Fall Lake anorthosite | 8 161 | — | 13 |
| 58 | §River Valley anorthosite | 8 164 | — | 13 |
| 59 | §Frontenac axis dykes | 12 343 | > 817 | 14 |
| 60 | §Ottawa area basic intrusions | 32 335 | — | 14 |
| 61 | §Allard Lake anorthosite | 39 320 | 1000 | 9/142 |
| 62 | Central Arizona diabase | 27 179 | 1150 | 15 |
| 63, 64 | Copper Harbour lavas and sediments | 30 176 | 1200 | 1/133 |
| | | 13 176 | 1046 | |
| 65, 66 | Portage Lake lavas | 24 183 | 1200 | 10/168, |
| | | 27 181 | | 12/158 |
| 67 | Grant Portage lavas | 44 197 | 1150–1000 | 12/159 |
| 68 | Ironwood flows | 29 232 | 1150–1000 | 12/160 |
| 69 | Beaver Bay complex | 28 190 | 1000 | 11/87 |
| 70, 71 | Keweenawan gabbro | 48 183 | 1150–1000 | 11/88, 12/156 |
| | | 36 185 | | |
| 72, 73, 74 | Duluth anorthosite, layered series and gabbro | 42 191 | 1115 | 12/150–152 |
| | | 36 190 | | |
| | | 32 200 | | |
| 75 | Duluth gabbro/Logan diabase | 42 204 | 1115 | 12/153 |
| 76 | Logan diabase | 26 194 | 1115 | 12/154 |
| 77 | Eudion sill | 32 191 | 1115 | 12/155 |
| 78 | Lester River sill | 35 199 | 1115 | 12/157 |
| 79 | Pikes Peak granite | 6 181 | 1040 | 12/161 |
| 80 | Logan sills | 48 218 | 1060 | 12/167 |
| 81 | Osler Group Volcanics | 49 203 | 1100 | 12/168 |
| 82 | Alona Bay volcanics | 47 233 | 1100 | 12/160 |
| | Mamainse Point volcanics, | | | |
| 83 | (i) Reversed Group | 49 232 | 1076 | 10 |
| 84 | (ii) Normal Group | 30 183 | 1076 | 10 |
| 85 | Michipicoten Island volcanics | 29 179 | 1100 | 12/172 |
| 86, 87 | Cape Gargantua volcanics | 34 180 | 1100 | 12/173–4 |
| | | 72 223 | | |
| 88, 89 | North Shore volcanics | 47 200 | 1115 | 12/175–6 |
| | | 32 188 | | |

† References to poles not included in *Geophysical Journal* listings are: 1, Murthy & Deutsch (1972); 2, Spall (1971*b*); 3, Fahrig & Chown (1973); 4, Robertson & Watkinson (1974); 5, Irving *et al.* (1973); 6, Park (1973); 7, McGlynn, Hanson, Irving & Park (1974); 8, Irving, Park & McGlynn (1972*b*); 9, Roy & Fahrig (1973); 10, Robertson (1973*a*, *b*); 11, Park (1974); 12, Barager & Robertson (1973); 13, Palmer & Carmichael (1973); 14, Irving *et al.* (1972*a*); 15, McElhinny (1973).

‡ See also Gates & Hurley (1972).

§ Grenville Province poles (see also figure 4*a*).

## *Discussion*

Dr G. E. J. Beckmann (*School of Physics, The University, Newcastle upon Tyne NE*1 7*RU*). Palaeomagnetic work carried out at Imperial College on the Scourie dykes of NW Scotland is relevant to the polar wander paths for North America put forward by Dr Irving and Dr Piper. The common directions of magnetization of the dykes and country rock suggest simultaneous magnetization while all the rocks were hot. It seems likely that this related either to the time of intrusion of the dykes at 2200 Ma (Evans & Tarney 1964) or to the Late Laxfordian metamorphism at 1800 Ma (Lambert & Holland 1972). I have favoured the latter alternative

(Beckmann, in press); moreover work with Dr R. Dearnley has established the same direction of magnetization from the tonalite body of the South Harris igneous complex, which was metamorphosed in the Late Laxfordian episode (Dearnley 1963). If the Atlantic Ocean is closed in accordance with the reconstruction of Sir Edward Bullard & others (1965), the mean pole for the Scourie dykes falls on Piper's path at *ca.* 1800 Ma, corresponding to Late Laxfordian magnetization. It also falls on Irving's curve at *ca.* 2050 Ma; this might represent some point in the cooling history following intrusion or to Early Laxfordian magnetization.

## References


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Dearnley, R. 1963 The Lewisian Complex of South Harris. *Q. Jl. geol. Soc. Lond.* **119**, 243–312.

Evans, C. R. & Tarney, J. 1964 Isotopic ages of Assynt dykes. *Nature, Lond.* **204**, 638–641.

Lambert, R. St J. & Holland, J. G. 1972 A geochronological study of the Lewisian from Loch Laxford to Durness, Sutherland. *J. geol. Soc. Lond.* **128**, 3–19.


Dr J. P. N. Badham (*University of Southampton*). The first four speakers showed us convincing evidence that Precambrian polar wander paths from the major continents are real and meaningful. They all concluded that the broadness of these paths at any one time (about 1000 km) reflected in part the quality of the data, and in part 'jostling' events between the cratons. They further concluded that the data indicate that the individual cratons that now form parts of the major shield areas were in their present juxtaposition in the early Precambrian. This last conclusion rests on the comparative absence of data that might indicate relative movements between cratonic nucleii. While accepting these conclusions, I have some reservations in doing so, because of the possibility that the data are selective.

The vast preponderance of igneous rocks are today generated at divergent or convergent margins, and by their very nature are selectively destroyed by continent–continent collision. Furthermore, erosion of collision orogens removes any remnant igneous rocks that were generated between diverging cratons, and will leave a complex of two cratons separated by a gneissic 'mobile' belt. The igneous rocks preserved in this complex will be

(1) basic dykes in the cratons, and marginal to the 'mobile' belt, these being remnants of the rocks produced during initial rifting.

(2) Granitic rocks in the 'mobile' belt produced during collision.

Palaeomagnetic sampling of the two cratons and the intervening mobile belt may have been concentrated on these two rock types (especially the first). The results therefore can only indicate 'closed' situations.

Relatively few igneous rocks are formed on the cratons during 'open' situations and fewer still may be preserved. Results from these rocks may therefore be swamped by those from 'closed' situations and consequently be regarded as anomalous. I repeat therefore, that, while I personally do accept the palaeomagnetic interpretations, it should be borne in mind that the results may be selective.