PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Proterozoic Magnetostratigraphy and the Tectonic Evolution of Laurentia [and Discussion]

E. Irving, J. C. McGlynn and G. E. Morgan

Phil. Trans. R. Soc. Lond. A 1976 **280**, 433-468
doi: 10.1098/rsta.1976.0006

Phil. Trans. R. Soc. Lond. A. **280**, 433–468 (1976) [433]
Printed in Great Britain

Proterozoic magnetostratigraphy and the tectonic evolution of Laurentia*

By E. Irving and J. C. McGlynn
Department of Energy, Mines, and Resources, Ottawa, Canada

There have been two major orogenic cycles in the Proterozoic of Laurentia which culminated at about −1850 (Hudsonian) and −1000 Ma (Grenvillian). A third event, the so-called Elsonian 'Orogeny' (−1400 Ma) was dominantly a phase of igneous intrusion. The palaeomagnetic poles from Laurentia are reviewed, and an attempt is made to order them into a path of apparent polar wander (a.p.w.). We have constructed this path so as to minimize its length without violating the palaeomagnetic or geological observations. This a.p.w. path defines a magnetic stratigraphy for the Proterozoic of Laurentia which bears on the nature of the above orogenic events and the tectonic evolution that they may signify. If the results from the Grenville Structural Province are excluded, a single polar path for the interval −2200 to −1300 Ma can be constructed, indicating that Laurentia has not been dismembered and that the Hudsonian Orogeny occurred by internal deformation. The geological evidence is consistent with this view, and also indicates that deformation occurred marginally in the Coronation Geosyncline at about −1800 Ma. Poles from the Grenville Province available at present are displaced from the poles from the rest of Laurentia, and may indicate that the southern part of the Grenville Province was displaced 5000 km at about −1150 Ma. The geological evidence is insufficient to determine whether or not such a reconstruction is correct, but it is notable that the Grenville orogenic cycle is preceded by, and is in part contemporaneous with, extensive rift systems, which developed following the Elsonian 'Orogeny'. The Grenville Province may then be a product of marginal tectonics and the first instance of the opening and closing of an ocean basin whose descendant is the present day North Atlantic. It is concluded that during the interval −2200 to −1400 Ma both marginal and internal tectonics occurred in Laurentia, whereas in the later Proterozoic marginal tectonics dominated. The Elsonian 'Orogeny' was apparently the time of changeover from one regime to the other. Nothing can yet be concluded from the palaeomagnetic evidence about the nature of orogenesis in the earliest Proterozoic (−2600 to −2200 Ma). It must be emphasized that these conclusions flow from the basic assumption (that of minimizing polar path length) used in constructing our polar path. The data are also compatible with other more complex reconstructions, requiring greater polar path length, and which do not require this tectonic evolution.

1. Introduction

Laurentia comprises the Precambrian Shields of North America, Greenland, and the Lewisian Platform of northwest Scotland (figure 1). Palaeomagnetic poles from Laurentia are reviewed in this paper; they make up about one-half of all Precambrian results presently available worldwide (Irving & Lapointe 1975; Briden, this volume). Before the palaeomagnetic results can be used for tectonic problems they must first be placed in time sequence, to provide a magnetic stratigraphy. An attempt is made to do this by constructing a path of apparent polar wander (a.p.w.). The a.p.w. path defines a magnetic stratigraphy for Laurentia which at present is only very tentative. Changes in polarity or reversals of the field also provide the basis for a stratigraphy but the record of reversals for the Proterozoic is very incomplete and only a brief mention is made.

* Earth Physics Branch, contribution no. 584.

The first collections of rocks from Laurentia for palaeomagnetic study were made from the Torridon Group of northwest Scotland by S. K. Runcorn & E. Irving (Cambridge University) in June 1951. Later sampling in 1952 and 1953 extended these collections through a stratigraphic thickness of about 3000 m. This was the first palaeomagnetic study of Precambrian rocks and also the first such study of red beds.

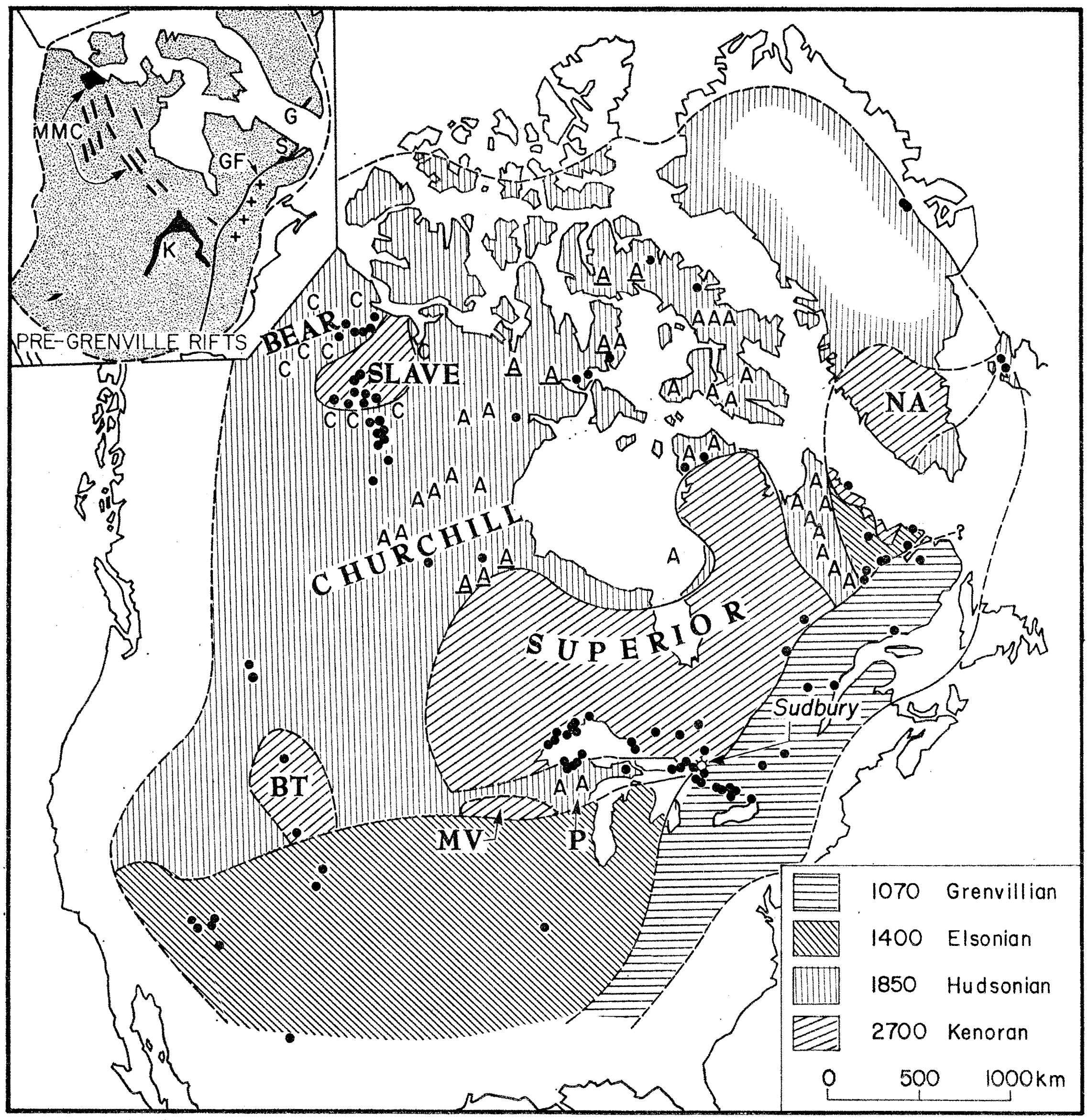


Figure 1. Structural provinces of Laurentia. The chief palaeomagnetic sampling localities are marked by dots and are indexed in the descriptions to figures 4–12. The approximate times at which the four major subdivisions of Precambrian terrain were stabilized are from Stockwell (1972). P is the Penokean fold belt. BT is the Bear-tooth uplift, MV the Archaean terrain of the Minnesota Valley, and NA the North Atlantic Archaean craton. Aphebian sedimentary and volcanic basins are denoted by the letter A. The A's are underlined if extensive ultrabasic pods and lenses are present. Greenland and the Lewisian basement of northwest Scotland are rotated back to their supposed positions at the end of the Precambrian. Base map compiled mainly from Stockwell (1970*b*) and Meulberger, Denison & Lidiak (1967). In the inset the pre-Grenville rifts are shown compiled mainly from Baragar (in Baer *et al.* 1974, p. 56): K, Keweenawan; G, Gardar intrusives; MMC Muskox intrusion, Mackenzie diabase, and Coppermine lavas; S, Seal Group volcanics; crosses are alkaline complexes near to or just south of the Grenville Front (see also figure 19).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The following year, collections were made by the late J. W. Graham (Carnegie Institution, Washington) from two diabase dykes in Baraga County, Michigan. Work on the Precambrian of Laurentia, however, began in earnest when P. M. Du Bois & S. K. Runcorn (Cambridge University) made extensive collections from the Keweenawan, from the Grand Canyon Supergroup and other red beds in Utah and Arizona in the summer of 1954. Du Bois in particular made this the main topic of his research, and in 1955 he returned to North America and continued work at the Geological Survey of Canada, making his more delicate observations at what was then the Dominion Observatory (now the Earth Physics Branch). His work culminated in an important paper (Du Bois 1962) which laid the foundations for the work which is now reviewed. Both E. Irving and P. M. Du Bois were students working under the supervision of S. K. Runcorn, and it was through his stimulus and direction that Precambrian studies began. Runcorn's initial interest was in geomagnetism rather than geology, and he was anxious to discover first, if there actually was a geomagnetic field in the Precambrian, and secondly to measure the magnitude and form of the secular variation. At that time (1951) the secular variation was the longest period variation of the geomagnetic field that was firmly established. Instead of the work progressing as a study of Precambrian secular variation as Runcorn first intended, reversals of polarity and a.p.w. were discovered, and these much larger variations became the main topics of investigations. Systematic studies through the Torridon Group provided the first instance of sequential reversals in a sedimentary sequence (Runcorn 1955*a*), and the Keweenawan yielded the first instance of a.p.w. observed through a sedimentary and igneous sequence (Du Bois 1962).

2. The Laurentian Shield

Laurentia contains five Archaean blocks, namely, the Superior, North Atlantic (including coastal Labrador) and Slave Structural Provinces, the Bear-tooth Uplift in Wyoming and Montana, and the Archaean terrain of the Minnesota River valley (figure 1). These elements are separated by terrain stabilized during the Hudsonian Orogeny which culminated at about −1850 Ma. The Bear Province, which is marginal to Laurentia, was deformed at about the same time as the Hudsonian activity. Terrain stabilized during the Hudsonian Orogeny other than the Bear Province is referred to in Canada as the Churchill Structural Province. Terrain of this type apparently underlies extensive areas of the north-central U.S.A. and occurs in northern Greenland (Nagssugtoquidian). Central Labrador and much of south central U.S.A. is underlain by rocks with ages of about −1400 Ma. In the U.S.A. they are known only from isolated inliers and bore-cores. The geology of these terrains is little understood. To the southeast, the Grenville Structural Province is marginal to the main body of Laurentia, and is separated from it by the Grenville Front. The Grenville Province extends subsurface as far south as Alabama.

In this paper Stockwell's (1972) revised time classification for the Canadian Shield is used (figure 2) where orogenies are regarded as time planes. Stockwell defined these orogenies as the last period of widespread folding and tectonically related metamorphism and intrusion in a type region – for example, the Kenoran Orogeny in the Superior Structural Province. Where possible, ages obtained by the Rb-Sr isochron method from unmetamorphosed late orogenic intrusions were used to define the ages of the orogenies. An orogeny in the sense used by Stockwell is therefore the end of the main deformational phase. The age peaks given by K-Ar mineral ages are now considered by Stockwell to represent post-orogenic uplift ages.

The Archaean supracrustal successions – the typical greenstone belts that occur in the main Archaean blocks – lack the stable shelf elements, miogeosynclinal facies, and other characteristics of the classical Phanerozoic geosynclines, and they occur in a granitic terrain rather than along the margins of cratons. They appear to have been formed on a very mobile crust, at a time when rigid crustal masses as we know them today did not exist. In addition to the five main Archaean blocks, extensive areas of Archaean rocks occur embedded in younger terrain.

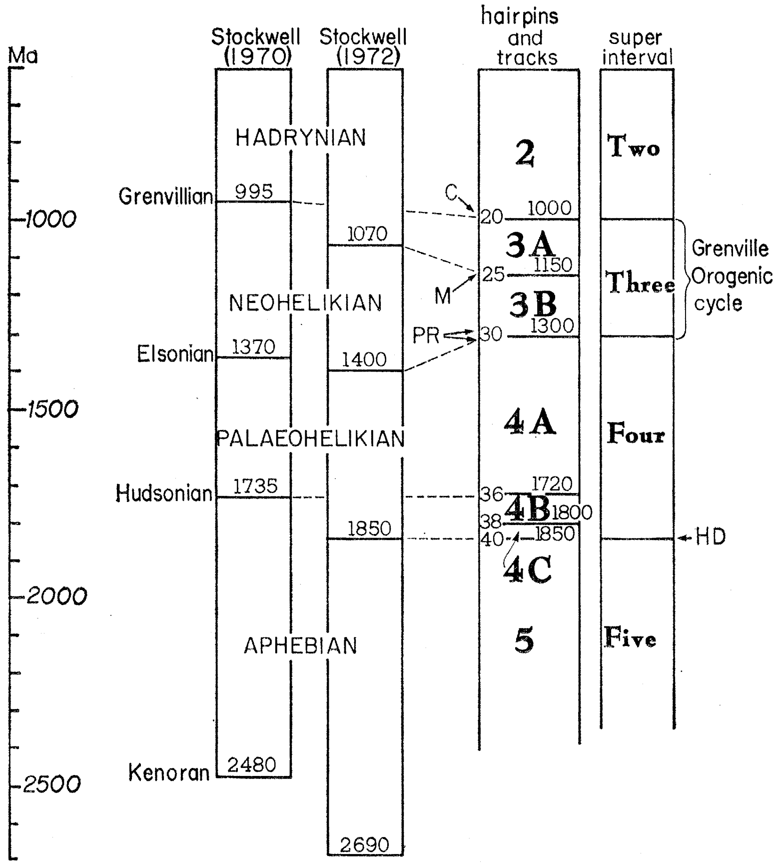


FIGURE 2. The chronologies of Stockwell based on estimated ages of orogenies are given in the first two columns. On the left is an early version based on K-Ar mineral ages. In the centre is the latest version based mainly on Rb-Sr isochron ages. On the right, a tentative a.p.w. stratigraphy for Laurentia is given. The boundaries of four Proterozoic superintervals are defined by hairpins. The superintervals themselves correspond in time to the main polar tracks (figure 13). PR is the time of pre-Grenville rifting, M the probable time of the main Grenvillian high-grade metamorphism, and C the collision based on the interpretation given in §6. HD is the approximate time at which the major change in form of polar curves occurs in the Early Proterozoic, as explained in § 5. Tracks 3A and 3B correspond to superinterval three, the Grenville orogenic cycle, and the Logan Loop as modified in the text. Updated from Irving & Park (1972), and Irving & Lapointe (1975).

In the Bear Province deformed and remobilized Archaean gneisses occur as domes in Aphebian metasediments near to the old Archaean craton of the Slave Province (Frith 1973). In the Churchill Province the extent of Archaean rocks is not well defined, but typical Archaean supracrustal sequences with associated Archaean granitic rocks (Wanless & Eade 1975) have been outlined west of Hudson Bay where they are unconformably overlain by Aphebian sediments (Eade 1975). Rocks of probable Archaean ages also occur in the Melville Peninsula and in Baffin Island (Davidson 1972). Large areas of the remaining parts of the Churchill

Province are probably underlain by reworked Archaean granitic gneisses and highly metamorphosed supracrustal rocks but their precise definition is not yet possible with current levels of mapping (McGlynn 1970; Davidson 1972). Within the Grenville Province many workers have identified deformed Archaean supracrustal rocks and granitic gneisses along the northern margins adjacent to the Superior Province, in a region referred to as zone B (see below).

During the Aphebian extensive deposits were laid down both marginally and internally within Laurentia. The Coronation Geosyncline developed along the western margin of an Archaean continental platform in what is now the Bear Province (Hoffman 1973). Unlike the Archaean basins, the evolution of the Coronation Geosyncline is similar in most respects to Phanerozoic geosynclines, and seems to have been formed by the interaction of oceanic and continental plates, but there is no evidence of continental collision. This activity was terminated by a late Aphebian orogeny at about −1750 to −1850 Ma. This is the oldest documented instance of what might have been true plate interactions in Laurentia.

Within the Churchill Province, at about the time that the marginal Coronation Geosyncline was forming, a second geosyncline (Circum-Ungava) was developing around the sinuous margin of the Superior Province. It also had many of the characteristics of classical Phanerozoic geosynclines, with miogeosynclinal and eugeosynclinal zones occurring progressively away from stable Archaean craton. It remains to be determined whether this was a truly marginal geosyncline, or part of a broader intracratonic basin whose margins are formed by Archaean rocks in Baffin Island and Labrador, as has been suggested by Jackson & Taylor (1972) and by McGlynn (1970).

In the main body of the Churchill Province, west of Hudson Bay, three periods of deposition can be recognized. First, Aphebian sedimentary rocks and associated volcanic rocks occur in a number of rather isolated northeasterly to easterly trending belts. These strata are of essentially shelf or miogeosynclinal facies, and each belt has been deformed, metamorphosed, and intruded by granitic rocks. These events ceased at about −1850 Ma, which corresponds to the Hudsonian of Stockwell (figure 2). In the Aphebian extensive sedimentary deposits (Huronian) accumulated around the southern edge of the Superior Province. The stratigraphic relation of the Huronian to the Aphebian basins of the Churchill Province is uncertain; the Huronian sediments could be older (Eade 1975) or they could be correlative (Young 1973). In late Aphebian or early Helikian time the Churchill Province was broken by large fault systems, many of which trend northeast and northwest. These remained active over a long period of time, probably up to about −1200 Ma. Adjacent to these fault systems, basins were developed, into which thick sequences of clastic red beds and volcanic rocks were deposited, and these are the deposits of the second period. The strata in these basins were only moderately folded and are essentially unmetamorphosed. Finally in Helikian time, extensive deposits of more mature clastic rocks were deposited in broad basins over large area of the western Churchill, Bear, and Slave Provinces. They overlie unconformably the red beds and volcanic rocks of the second period. Only remnants of them are preserved, probably those that were deposited in the deeper parts of the original basins. These Helikian cratonic sequences thicken to the northwest, where they are overlain by stromatolitic carbonate sequences and contain increasing amounts of interbedded shales. They are only slightly folded and are unmetamorphosed.

The presence of numerous extensive areas of Archaean rocks within the Churchill Province indicates that at the end of the Archaean, large areas of Laurentia (North Atlantic, Superior, and Slave cratons, and the Churchill Province) were underlain by Archaean supracrustal rocks and older and younger granitic rocks, and *may* have formed a single coherent continent. The earliest Aphebian sedimentary basins, both marginal (the Coronation Geosyncline and possibly the Circum-Ungava Geosyncline) and internal (basins of the first depositional period), were involved in orogenies that were phases of the Hudsonian Orogeny. The precise temporal relationships of deposition and deformation among the internal basins, and between them and the marginal geosyncline is not known. Davidson (1972) has suggested that the internal basins occurred in unstable zones within more stable Archaean blocks. Therefore, by the end of Aphebian time, there almost certainly existed a large continental mass, comprising several Archaean blocks, and a large area of somewhat deformed Archaean crust with internal belts of deformed Aphebian sediments, and which was partly ringed by marginal geosynclines. The rocks of the second and third periods of deposition are little deformed and are unmetamorphosed. This sequence of events suggests that the Laurentian crust became increasingly stable during the Aphebian and Palaeohelikian (−2500 to −1300 Ma).

The last major tectonic event in Laurentia was the stabilization of the Grenville Structural Province at about −1100 Ma. The Grenville Province differs from the rest of Laurentia in that it consists largely of highly metamorphosed rocks. It is bounded on the north by the Grenville Front. The front cuts across the older, but generally less metamorphosed, Superior Province and the Hudsonian, Elsonian, and Archaean terrain of Labrador (figure 1). In places, south of the front, there is a belt (zone B) up to 100 km in width that consists of metamorphosed equivalents of rocks to the north (figure 19). This distinction is made in order to recognize the fact that the front cannot be a suture. We refer to the Grenville Province without terrain *B* as Grenvillia. Laurentia without Grenvillia is referred to henceforth as Interior Laurentia. Very little is known about the tectonic history of the Grenville Province, but the tectonic cycle which produced Grenville terrain appears to have been initiated by a very extensive rifting phase (see inset to figure 1 and figure 19). This produced the pre-Grenville system of Baragar which was marked by extensive basic intrusions and extensions, and alkalic complexes (Baer, Emslie, Irving & Tanner 1974). The rifting began about −1250 Ma and continued until about −1100 Ma. The pre-Grenville rifts are by far the most extensive to have affected the Laurentian Shield, and for the first time there is evidence of rifting extending across the entire Shield, testifying to the rigidity of the Laurentian crust at that time.

The Elsonian Orogeny at about −1300 to −1400 Ma (figure 2) was dominated by igneous intrusions, particularly the emplacement of anorthosites, but was not accompanied by widespread deformation. It was quite unlike any earlier or later orogeny, and may not really be an orogeny in the commonly accepted meaning of the word. Its significance is obscure.

3. Methods

(*a*) *Principle of a.p.w. stratigraphy*

Precambrian palaeomagnetic results from Laurentia are subject to uncertainties which are roughly an order of magnitude greater than those in Phanerozoic studies, so that the interpretation of results in terms of Precambrian tectonics is necessarily speculative. Traditionally, palaeomagnetic evidence has been obtained from rocks that have been little altered, in the belief that their remanent magnetization reflects the direction of the Earth's field at the time rocks were formed. Lavas that contain pure fine-grained magnetite, and which cool quickly, will acquire their magnetization at about 550 °C. The corresponding blocking temperature for pure haematite, which is the other common carrier of remanent magnetism in rocks, is about 650 °C. However, if cooling (and this may be initial cooling, or cooling following subsequent reheating events) occurs very slowly, then magnetization is acquired at lower temperatures. Estimates of these temperatures are still very uncertain, but Pullaiah, Irving, Buchan & Dunlop (1975) have suggested that over cooling times of 10^5 a the blocking temperatures are about 380 °C for pure magnetite and 450 °C for pure haematite. If substantial impurities

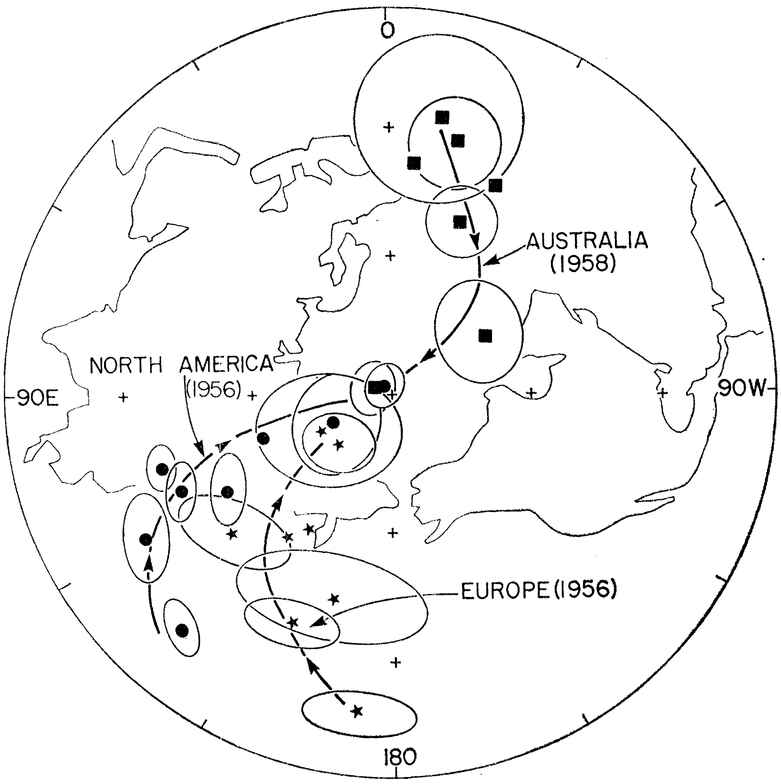


FIGURE 3. Poles from Upper Palaeozoic and younger rocks from Australia (■), North America (●), and western Europe (★) as they were known in the mid-1950s. Compiled from Irving (1956) and Irving & Green (1958). The poles in mid-latitudes are mainly from Upper Palaeozoic rocks, those in high latitudes from Tertiary rocks, so this early evidence suggested that the polar track moves through *about* 70° in 300 Ma, converging on the present pole during the Neogene.

are present (that is the minerals are titanomagnetite or titanohaematite) or if the grain-size is less than the critical size for single domains, these temperatures may be as low as 200 and 300 °C respectively. Most Precambrian rocks have undergone heating to temperatures of a few hundred degrees over long periods, so that their original magnetization may have been partially or entirely replaced by one or more secondary magnetizations or overprints, each marking subsequent thermal events. This is the phenomenon of polyphase magnetization by which a rock unit may contain magnetizations representing the field at several points in time over hundreds of millions of years. Complex techniques are required to properly separate these magnetizations, and in no more than a quarter of palaeomagnetic studies have these techniques been fully applied. It follows therefore that many results may be a mixture of as yet unresolved magnetizations. An example of this is discussed in §4(*d*).

A further uncertainty is in assigning the various magnetic phases present to their correct time basis, and there are four ways in which Precambrian magnetizations and corresponding poles can be placed in a time order. (1) A magnetization can be assumed to have been acquired at the time one or other of the radiometric clocks were set and an age in millions of years assigned. The accuracies of age assignments made on this basis vary from ± 50 to ± 100 Ma or more. (2) The relative order of magnetization observed in a rock sequence can be determined from the superimposition of beds or (3) from cross-cutting relationships. Finally (4) the relative order of polyphase magnetizations can be determined if it is assumed that the magnetizations with higher blocking temperatures are the oldest. In any slowly cooled rock (and most Precambrian rocks, if they did not undergo slow cooling initially, have undergone slow heating and cooling subsequently) the magnetizations with the higher blocking temperatures become magnetized before those with lower blocking temperatures, providing there has been no chemical change. The first three of these methods are based on traditional geological methods. The fourth is a palaeomagnetic method (Irving, Emslie & Ueno 1974; Ueno, Irving & McNutt 1975) which at the present is in the testing stage.

(*b*) *Limits on tectonic resolution*

Precambrian palaeomagnetic poles from Laurentia are subject to statistical uncertainties of 10° or more (that is 1000 km or more) their age uncertainties are between ± 50 and ± 200 Ma, and, as will be shown later (§6, figure 17), the complex geometry of continental motions will cause irregularities in the polar tracks that cannot yet be resolved. In an attempt to circumscribe these potent sources of error we shall follow Stewart & Irving (1974) and represent the tracks as broad zones approximately 20° in width. This gives a reasonable representation of individual polar errors. The magneto-stratigraphy is necessarily crude and the present accuracies of Precambrian results may be usefully compared to those of Phanerozoic results 18 or 20 years ago (figure 3). The very large differences between the later Phanerozoic polar tracks from Australia and the two northern continents reflecting their northward drive in the Mesozoic and Tertiary, would be detectable by the methods available in Precambrian studies, because if the respective paths are regarded as zones 20° in width differences would still be discernible because the poles are as much as 90° apart. However, the differences between the European and North American tracks would be too small to be seen in the Precambrian record so that the opening of small oceans such as the Norwegian and Greenland Seas would therefore go unnoticed.

(*c*) *Procedures*

The palaeomagnetic poles and sampling localities are plotted on a series of maps. Results from Scotland and Greenland are rotated by the amount required to place these land areas in their Palaeozoic positions relative to North America using the Eulerian poles obtained by Bullard, Everitt & Smith (1965). Individual poles are indexed in the figure legends by the Ottawa catalogue number through which the original publication can be traced. Recent results, or results available only in abstract, are not given in the Ottawa catalogue and reference to the original is made in the legends. Errors (95% confidence) are given for most poles. Poles without errors are generally determinations from single sites. Most poles from single sites are individual determinations of 'overprints' and are denoted by open symbols and indexed by letters. Other poles are numbered by their assigned age. In general, results based on fewer than 10 samples have not been included, with the exception of the overprints mentioned above. A

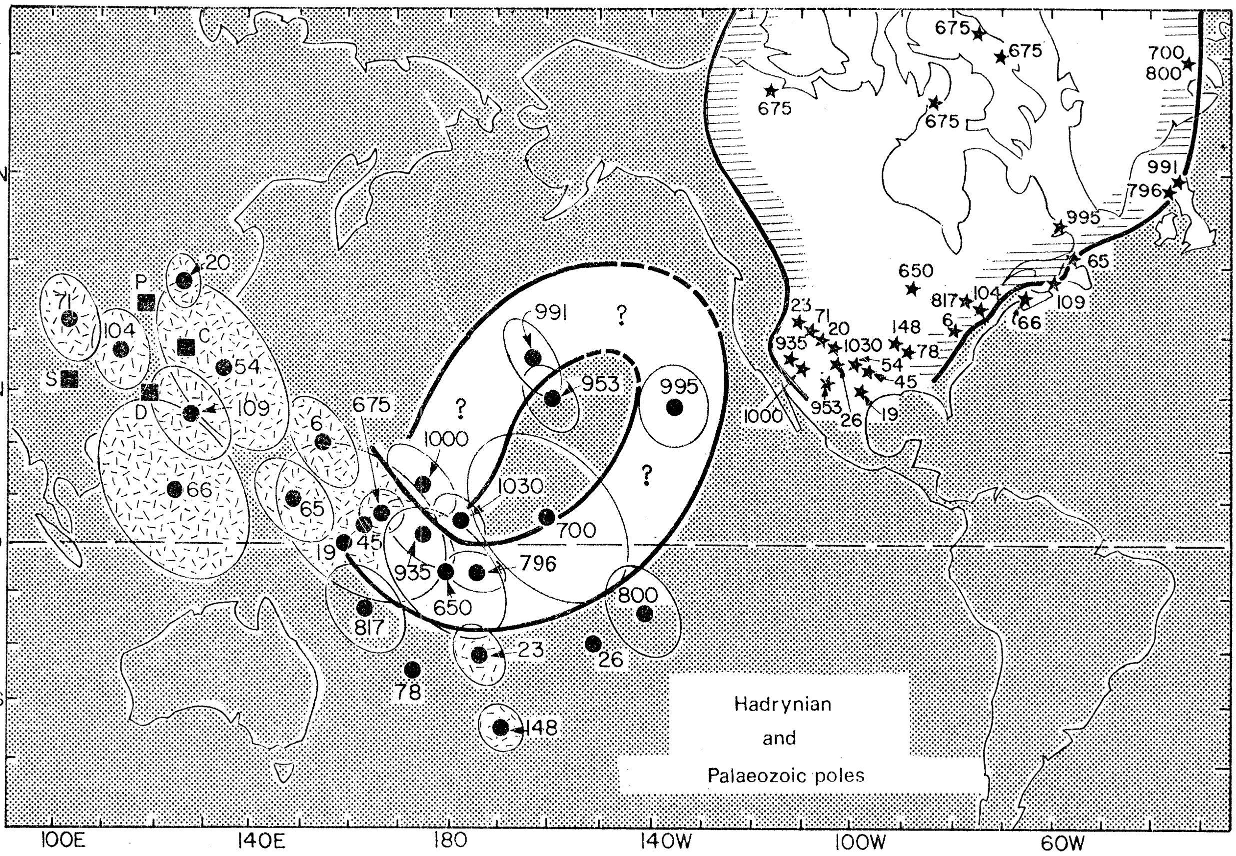


FIGURE 4. Poles for the latest Precambrian (the Hadrynian of Stockwell approximately −600 to −1000 Ma) and Palaeozoic. The first number in the legends to figures 4–12 is the assigned age in millions of years. The letters A, B and C indicate the accuracy of these age assignments (±50, ±100 and ±200 Ma respectively) as explained in the text. The name of the rock unit is then given, and this is followed by the list number in the Ottawa palaeomagnetic catalogues (Hicken, Irving, Law & Hastie 1972; Irving & Hastie 1975). The final letter denotes the basis on which the age assignments are made as follows: K, K-Ar ages; R, Rb-Sr ages decay constant 1.39×10^{-11} a^{-1}; Z, U-Pb zircon ages; S, stratigraphic assignment; U, little age control. In figures 5–12 the relative time order of poles where this is known is indicated by arrows. In figures 5–12 results from 'overprints' are indexed by letters. In figure 4 the squares are means for Permian (P) Carboniferous (C) Devonian (D) and Silurian (S). The early Palaeozoic poles are plotted individually and ornamented.

Precambrian

650 (C) Jacobsville Sandstone (302) S
675 (A) Franklin Diabase (313) K
700 (C) Tillite Formation (056) S
796 (A) Torridon Group (001) R
800 (C) Multicoloured Series (055) A
817 (C) Frontenac Dykes (363) K
935 (B) Rama Diabase (391) K
953 (B) El Paso rocks (953) R
991 (A) Stoer Group (422) R
995 (C) Aillik Dykes (353) K
1000 (B) Nankoweap Formation (396) K
1030 (A) Pike's Peak Granite (153) R

Cambrian

Wilberns Formation, Upper Cambrian (19)
Sawatch sandy dolomite, Upper Cambrian (20)
Ladore Formation (23)
Tapeats Sandstone, Lower Cambrian (26)
Wichita granite, 525 Ma (45)
Wichita basement, 540 Ma (54) R
Bradore Formation (65)
Ratcliffe Formation (66)
Cambro-Ordovician intrusive (71)
Lamotte Formation, Upper Cambrian (78)
Bonneterre sediments (148)

Ordovician

Juniata Formation, Upper Ordovician (6)
Trenton Limestone, Middle Ordovician (104)
St George Group, Lower Ordovician (109)

date is assigned to each result and the results are listed in order of increasing age in the legends to the figures. We regard this sequence as the most reasonable one in the light of present evidence, and it does not conflict, insofar as we are aware, with the geological record. It must be emphasized, however, that the assigned ages are approximate only, and are merely the best we can make of a very incomplete record. The final digit is not significant and is given here only as a means of identification. The methods of determining ages are explained in the legend to figure 4. Following Stewart & Irving (1974) the assigned ages have been slotted into three arbitrary classes and is an attempt to provide 90% confidence limits for the timing of the magnetization process. These time slots are ± 50, ± 100, and ± 200 Ma, and are referred to as categories A, B, and C, respectively. Relative ages where these can be determined are indicated by arrows in the maps. When more than one result is available from a rock unit the averaging procedure used is explained in the Ottawa catalogues.

The palaeomagnetic pole positions are arranged in four time groups (figures 4–11). In each group the poles are connected into a time sequence forming a polar track. The main polar tracks are numbered 2–5; they are constructed so as to minimize their total length and each defines an a.p.w. stratigraphy for the time in question.

4. Polar tracks

(a) *Track* 2

The poles for the interval -600 to about -1000 Ma are plotted in figure 4. This corresponds to the Hadrynian of Stockwell (figure 2). The results are few. There are results from rocks about 1000 Ma old (pole nos 1000 and 1030) and about 700 Ma (796 and 675) old which yield poles in the west-central Pacific near to one another. Between them there appears to have been a polar loop for which there are two pieces of evidence. First, the Stoer Group with pole in the northern Pacific (991) is overlain unconformably by the Torridon Group (796). Both results are keyed to Rb-Sr isochrons (Moorbath 1969), and both magnetizations are known to have originated at the time of deposition (Stewart & Irving 1974). Secondly, there are poles displaced toward Laurentia from the Aillik dykes (995) and El Paso rocks (953) with intermediate ages. These poles can be linked together in a single polar loop (track 2) as was suggested by Stewart & Irving (1974). Obviously track 2 is only poorly defined.

In an attempt to relate the track 2 with the Phanerozoic polar path, the poles from Palaeozoic rocks are also given in figure 4. It is well established that the Late Palaeozoic poles lie in what is nowadays northern China, and that these poles are linked with the present north geographical pole (figure 3). There are, however, no firmly established Early Palaeozoic poles, except that for the Bloomsburg Formation (marked S in figure 6) which is Upper Silurian. The Early Palaeozoic poles all fall in the southwest Pacific, but to what extent this distribution is affected by later overprints is not yet known; none of the magnetizations used to derive these poles has yet been shown to have originated at the time the rocks were formed. No satisfactory Lower Palaeozoic polar path can be drawn, but the evidence, as it is presently known, indicates that the pole moves from the west-central Pacific at the end of the Precambrian, across the southwest Pacific to northern China in the Late Palaeozoic. This argument suggests that track 2 as shown in figure 4 was the trace of the north geographical pole.

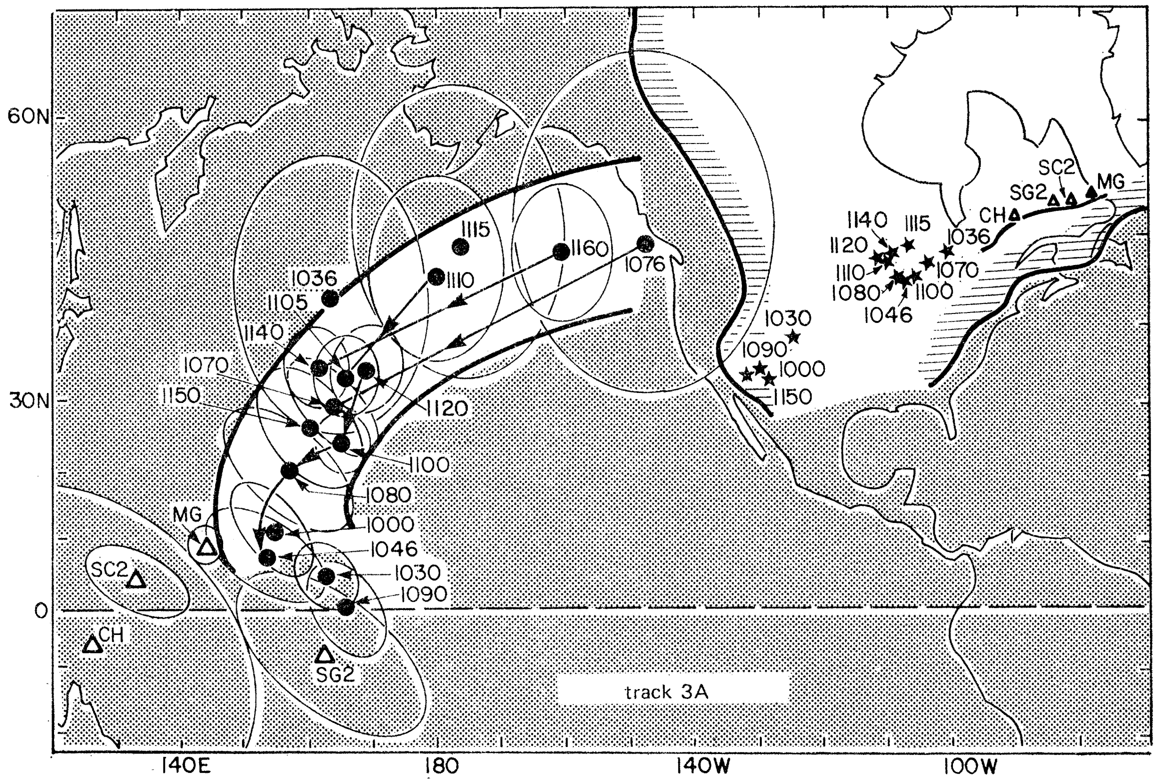


FIGURE 5. Track 3A. Poles for the interval approximately −1000 to −1150 Ma. See description of figure 4 for explanation.

1000 (B) Nankoweap Formation (396) K
1030 (A) Pike's Peak granite (155) R
1036 (B) Nemegosenda carbonatite (412) K
1046 (B) Freda and Nonsuch Sandstone (303) K
1070 (A) Mamainse Lavas, normal (394) R
1076 (A) Mamainse Lavas, reversed (395) R
1080 (B) Copper Harbour Lavas (304) K
1090 (A) Cardenas Lavas (397) R
1100 (B) Portage Lake Lavas (392) K
1105 (A) North Shore Volcanics, normal (393) Z
1110 (A) North Shore Volcanics, reversed (306) Z
1115 (B) Osler Lavas (147) K
1120 (A) Keweenawan intrusive (308) K, Z
1140 (A) Logan Diabase (268) K
1150 (A) Gila Diabase (320)K
1160 (A) Logan Diabase, reversed (309) K

CH Chibougamau
MG Michael Gabbro (322)
SC2 Seal-Croteau igneous rocks (463)
SG2 Shabogamo Gabbro (418)

(b) *Track* 3

Track 3 is dealt with in three parts. Tracks 3A and 3B based mainly on data from the Canadian Shield are described, and then compared with results from the Grand Canyon Supergroup of Arizona. The time interval concerned is from about −1300 to −1000 Ma and corresponds approximately to the Neohelikian of Stockwell (figure 2). Poles from rocks formed between about −1000 and −1150 Ma are shown in figure 5. Most results are from the Keweenawan. The age sequence of several results is known from superimposition and cross-cutting relations as indicated by arrows in figure 5. A polar trend comparable to track 3A was first suggested by Du Bois (1962), and has been subsequently discussed by several authors, among them Robertson & Fahrig (1971) and Spall (1971). Poles from localities within 30 km north of the Grenville Front are indicated by open symbols. They fall in the west Pacific and are regarded here as overprints. They are from rocks ranging in age from Archaean at Chibougamau (pole CH) to about 1300 m.y. in Labrador (pole MG) and in the Naskaupi Fold Belt (poles SC2, SG2). Some authors (Fahrig & Larochelle 1972; Roy & Fahrig 1973; Fahrig, Christie &

Schwarz 1974) consider these magnetizations to be original and indicative of rotation of the northeastern part of the Grenville Structural Province. Recently Ueno & Irving (1975) have shown that rocks from Chibougamau (pole CH) with the same magnetization directions have moderate blocking temperatures distributed between 200–500 °C and therefore are likely to be readily reset (Pullaiah *et al.* 1975). They suggested therefore that these magnetizations within 30 km or so of the Front were produced by heating as the highly metamorphosed Grenville Province to the south was uplifted at about −1000 Ma. This hypothesis explains the polyphase magnetizations observed by Roy & Fahrig in the Naskaupi Fold Belt.

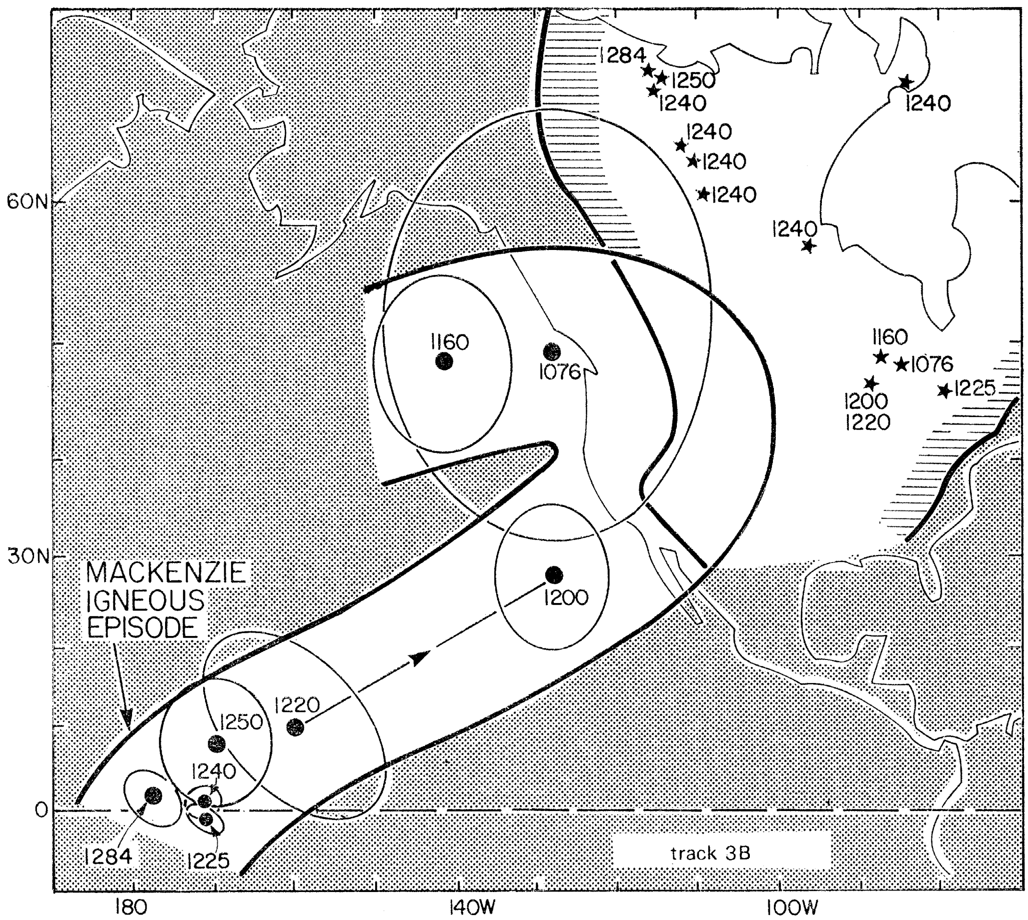


FIGURE 6. Track 3B. Poles from the interval from about −1150 to −1250 Ma. See description of figure 4 for explanation.

1076 (A) Mamainse Lavas, reversed (395) R
1160 (A) Logan Diabase, reversed (309) K
1200 (B) South Trap Range Lavas, reversed (150) S
1220 (B) South Trap Range Lavas, normal (374) S
1225 (A) Sudbury Dikes (120) K, R
1240 (B) Mackenzie Diabase (339) K
1250 (A) Muskox Intrusion (115) K, R
1284 (A) Coppermine Group (472) R, K

Poles for the time interval about −1150 to −1250 Ma are shown in figure 6. There are many results from the rocks of the Mackenzie igneous episode that have been combined into four poles; the Coppermine Group, both lavas and red beds (pole no. 1284), Mackenzie diabase (1240), Sudbury dykes (1225), and the Muskox Intrusion (1250). Two of these are keyed to Rb-Sr isochrons. Some Rb-Sr evidence by Gates & Hurley (1973) indicate an older age for the Sudbury and Mackenzie diabase, but the scattered data points were compared with reference isochrons only. On the basis of present evidence, dates of between −1200 and −1300 Ma seem most reasonable for the Mackenzie igneous episode. There is one pole (1220) from older lavas of Keweenawan which is close to Mackenzie poles. There is one pole (1200) that is stratigraphically above pole 1220, and which approaches the older poles of track 3A (1076) and (1150). Track 3B is, as yet, only poorly documented. It was first tentatively suggested by Du Bois (1962) and has been discussed subsequently by Robertson & Fahrig (1971), Spall (1971), and other workers.

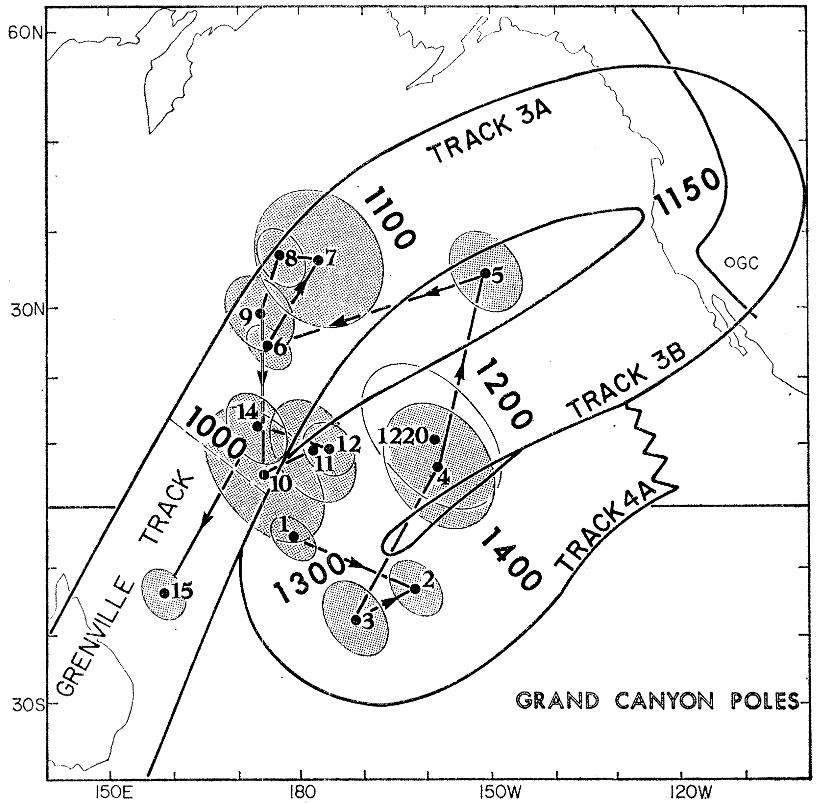


Figure 7. Poles from the Grand Canyon Supergroup (Elston & Grommé 1974) compared with tracks 3A and 3B. The poles are numbered in time sequence oldest first, as follows: 1, Bass limestone (lower); 2, Bass limestone (middle and upper); 3, Hakatai Shale (lower and middle); 4, Hakatai Shale (middle and upper); 5, Shinumo Quartzite (middle); 6, Dox Sandstone (upper lower); 7, Dox Sandstone (lower middle); 8, Dox Sandstone (middle); 9, Dox Sandstone (upper middle); 10, Dox Sandstone (upper); 11, Cardenas Lavas (flows); 12, Cardenas Lavas (intercalated sandstones); 14, Nankoweap Formation (ferruginous member); 15, Nankoweap Formation (upper member). The Shinumo quartzite result is based on only 9 samples and therefore ought not to be plotted according to our selection criteria (section 3) but is included for completeness. Tracks 3A and 3B of figures 5 and 6 are superimposed, and the pole for the oldest Keweenawan lavas (1220) is also added for comparison. Pole 13 from the weathered zone of the Cardenas lavas given by Elston & Grommé (1974) is in error, and has not been plotted (S. C. Grommé, personal communication).

Since compiling the main part of this review a very important set of data has come to hand from the Grand Canyon Supergroup (Elston & Grommé 1974). This work greatly extends the early results from the Grand Canyon Supergroup by Runcorn (1955*b*), Doell (1955), Collinson & Runcorn (1960), Runcorn (1964), and Elston & Scott (1973), which are noted in figures 5 and 6. The new poles are plotted in figure 7, and the polar tracks 3A, 3B and the Grenville

Track (see below) are added for comparison. The Grand Canyon Supergroup has yielded 14 poles in known stratigraphic sequence, spaced through a thickness of 2000 m. One pole (no. 11 Cardenas lavas) is keyed to an Rb-Sr isochron age of 1090 ± 70 Ma. The poles form a loop that agrees approximately with the loop formed by tracks 3A and 3B, although it appears to be less deep. Elston & Grommé (1974) mention preliminary results from rocks

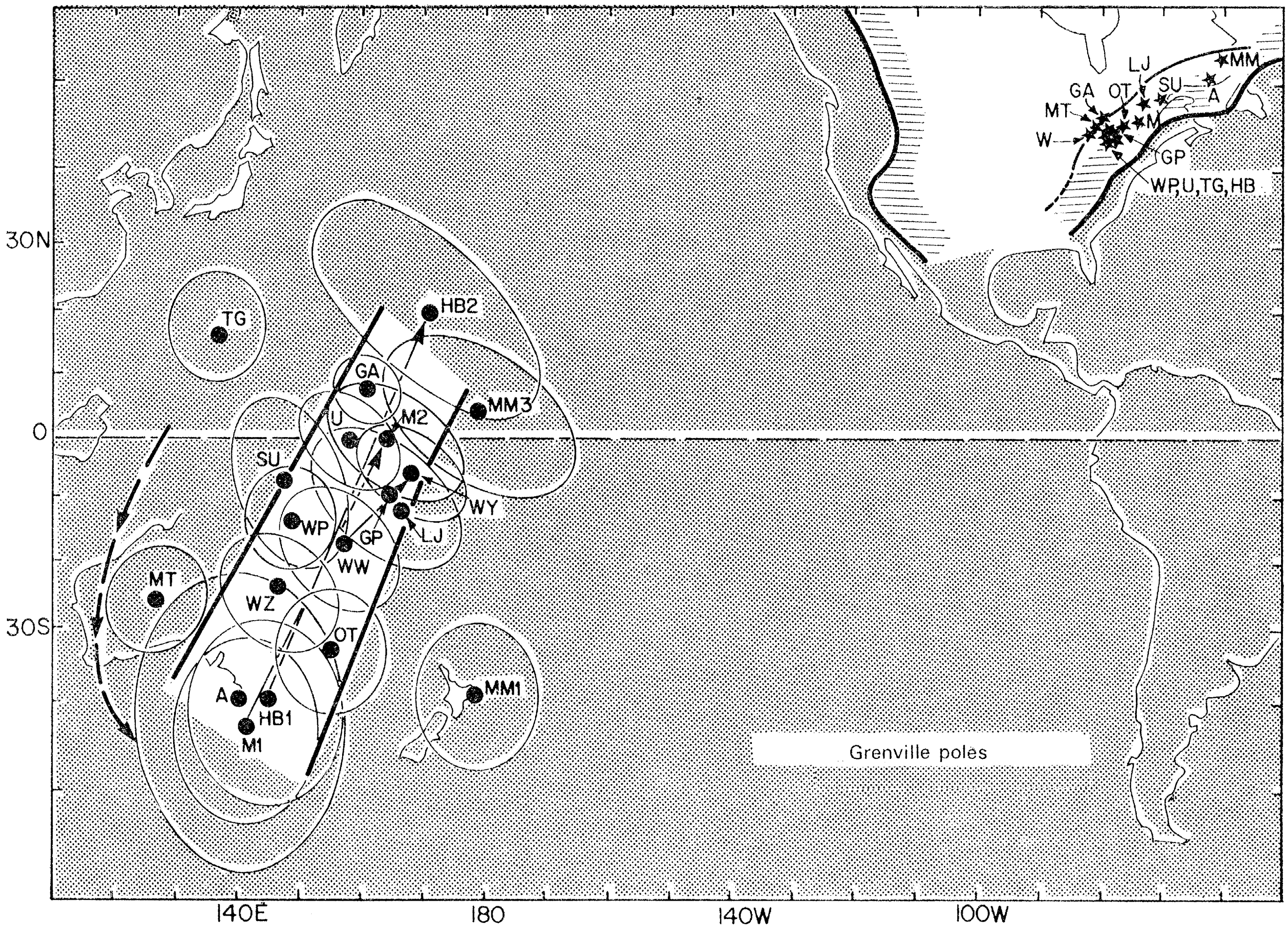


FIGURE 8. Grenville Track. Poles from the Grenville Structural Province. These results are from rocks which are metamorphosed to amphibolite or granulite facies. Ages cannot therefore be assigned in any straightforward way. Polyphase magnetization is ubiquitous in all rock units that have been studied in detail (Buchan & Dunlop 1973; Irving *et al.* 1974; Ueno *et al.* 1975). The formal separation of 'overprints' acquired during late uplift, from magnetization acquired soon after metamorphism, is a hazardous and speculative procedure, and poles that may be such overprints are not indicated separately as in other figures. An argument regarding the general limits to ages of Grenville poles is given in the text. For alternative opinions readers may refer to discussions in Palmer & Carmichael (1973), Fahrig *et al.* (1974), Roy & Fahrig (1973), Irving *et al.* (1974), and Stewart & Irving (1974). Dashed arrows indicates a possible way in which the Tudor Gabbro pole (TG) may be connected to the Grenville Track.

A, Lac Allard Anorthosite (130); GA, Grenville Front anorthosite (086); HB1, Haliburton basic rock (399); HB2, Haliburton basic rock (400); LJ Lac St Jean Anorthosite (Fahrig *et al.* 1974); M1, Morin Complex (haematite magnetization) (482); M2, Morin Complex (probable magnetite magnetization) (483); MM3, Mealy Mts Complex E (415); MM1, Mealy Mts Complex NW (417); MT, Magnetawan metasediments (McWilliams & Dunlop 1974); OT, Grenville metamorphic rocks (322); SU, St-Urbain Anorthosite (409); TG, Tudor Gabbro (458); U, Umfraville intrusive (43); WP, Wilberforce pyroxenite (457); WW, Whitestone Anorthosite, haematite magnetization (500); WY, Whitestone Anorthosite, magnetite magnetization (502); WZ, Whitestone diorite, haematite magnetization (503); GP, Grenville gneisses (86).

stratigraphically immediately beneath the Shinumo Quartzite (pole 5 of figure 7) which gives poles further to the north, but they are uncertain whether their result is valid, or whether it is a result of incomplete separation of primary and secondary magnetizations. If the result is valid it might conform with the upper part of the loop formed by tracks 3A and 3B. Alternatively it may be invalid and the polar sequence as it is known from the Grand Canyon Supergroup may represent the correct depth of the loop. In this connection it is noteworthy that in our reconstruction of tracks 3A and 3B we have accepted the opinion of Du Bois (1962) and Robertson (1973) that the middle Keweenawan poles of reversed polarity (poles 1076, 1115, 1110, 1160) are valid determinations. This is the reason why the loop formed by tracks 3A and 3B is so deep. Spall (1971) on the other hand took the view of Palmer (1970) that the rocks from which these poles were derived were partly remagnetized and therefore did not accept them, and his loop is less deep. Thus the poles from the Grand Canyon Supergroup appear to generally confirm the loop formed by tracks 3A and 3B, although the true depth of the loop remains uncertain. The major feature of the magnetostratigraphy of the Neohelikian appears to be reasonably established, however.

The poles from the Grand Canyon Supergroup are of interest in two other respects. First, the a.p.w. path traced by them has subsidiary loops or kinks. As will be seen later such second-order kinks superimposed on the major loops can be produced in a.p.w. paths by the complexities of continental motions (figure 17). If the polar errors cited by Elston & Grommé (1974) are correct, some of these kinks certainly are real, for example, that observed in the Dox Sandstone (figure 7, poles nos 6–9). However, the polar errors have been calculated giving unit weight to individual oriented samples, a procedure first used by Runcorn (1955) in his work in the Grand Canyon Supergroup and which has been criticized by Irving (1964, p. 64) on the grounds that the estimates of errors obtained in this way may be too small. It is therefore arguable on the basis of present evidence whether or not the kinks are real, although they could be true effects. The second point of interest is the presence of one pole (no. 15, figure 7) that falls in the Grenville track and this matter is discussed in § 6.

(c) *Grenville track*

Most poles from the Grenville Structural Province (figure 8) fall in a roughly meridional array which is referred to as the Grenville track. This is the first polar track observed from metamorphic terrain and the magnetizations were probably acquired during cooling following metamorphism to high amphibolite or granulite facies metamorphism. Three complexes Morin, Haliburton, Whitestone) have polyphase magnetization, in particular, there are haematite and magnetite magnetizations. The haematite magnetizations have higher blocking temperatures and higher remanent coercive forces than the magnetite magnetization, and from the fourth argument of § 3 (*a*) the haematite magnetization is regarded as the older, and the trend is therefore from south to north. Buchan & Dunlop (1973) have shown that the Haliburton basic rocks have two magnetizations, HB1 has blocking temperatures between 550 and 600 °C and is carried by haematite or low-titanium magnetite, and HB2 with a wide range of blocking temperatures is carried largely by titanomagnetite. By the same argument HB2 is younger than HB1 and again the polar trend is from south to north. Thus the simplest explanation of the results is to assume that there is a single north-trending polar track as shown in figure 8. However, the time-order of poles is not at all well-understood, and it is possible that two or more tracks are present, as is discussed later (figure 16, § 6). Clearly no definite conclusions can yet be drawn but all the available evidence is consistent with a single south to north trending track.

Two poles from the Grenville Province do not fall on the Grenville track. First, the pole from the Tudor Gabbro (pole TG) falls to the north and west of the track. The Tudor Gabbro is from the Hastings basin, where the metamorphism is of greenschist facies, much lower than is usual in the Grenville Province. It is possible therefore that its magnetization is premetamorphism and much older than that of the Grenville track, and may record the original emplacement at about −1250 Ma (see discussion by Palmer & Carmichael 1973, p. 171).

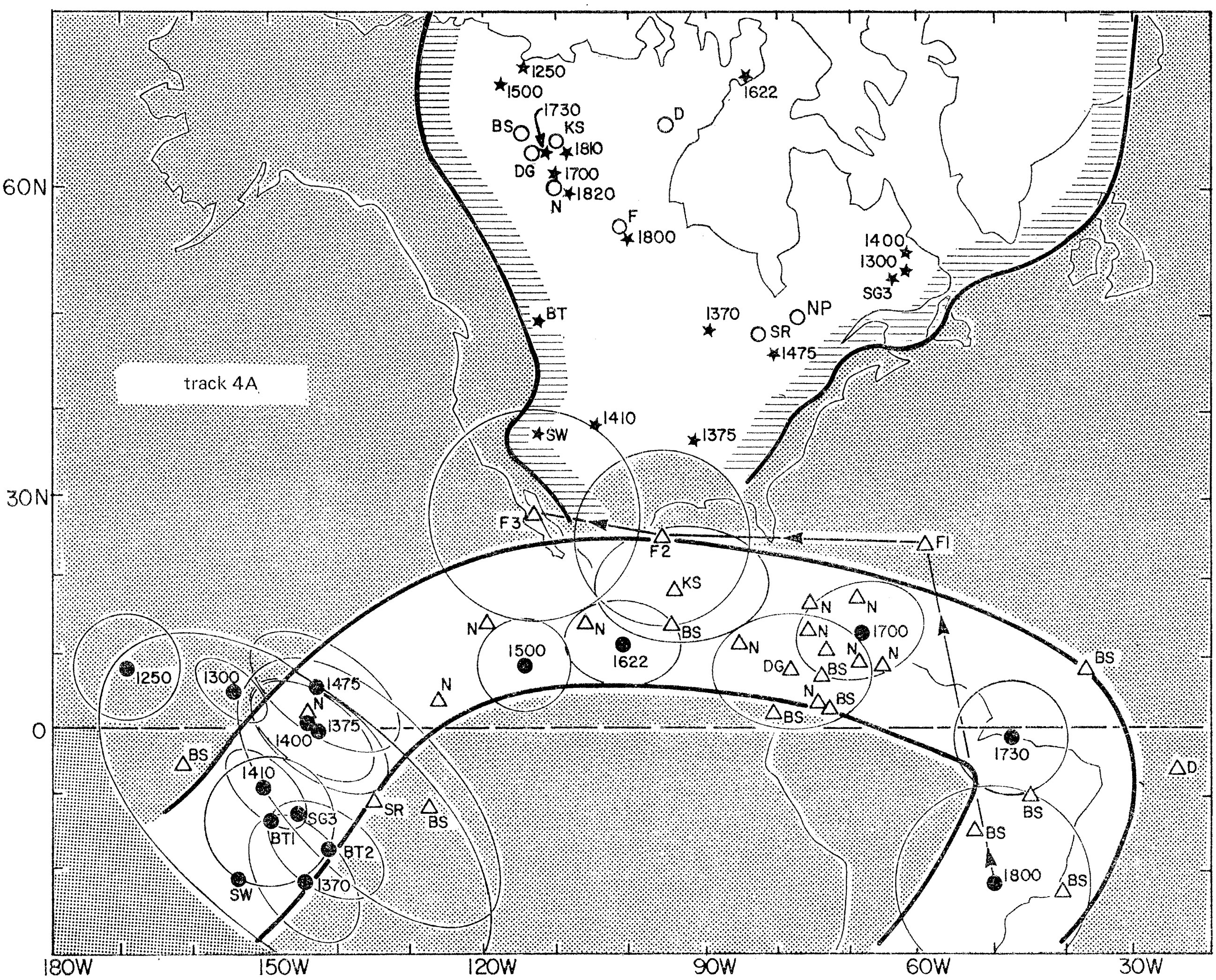
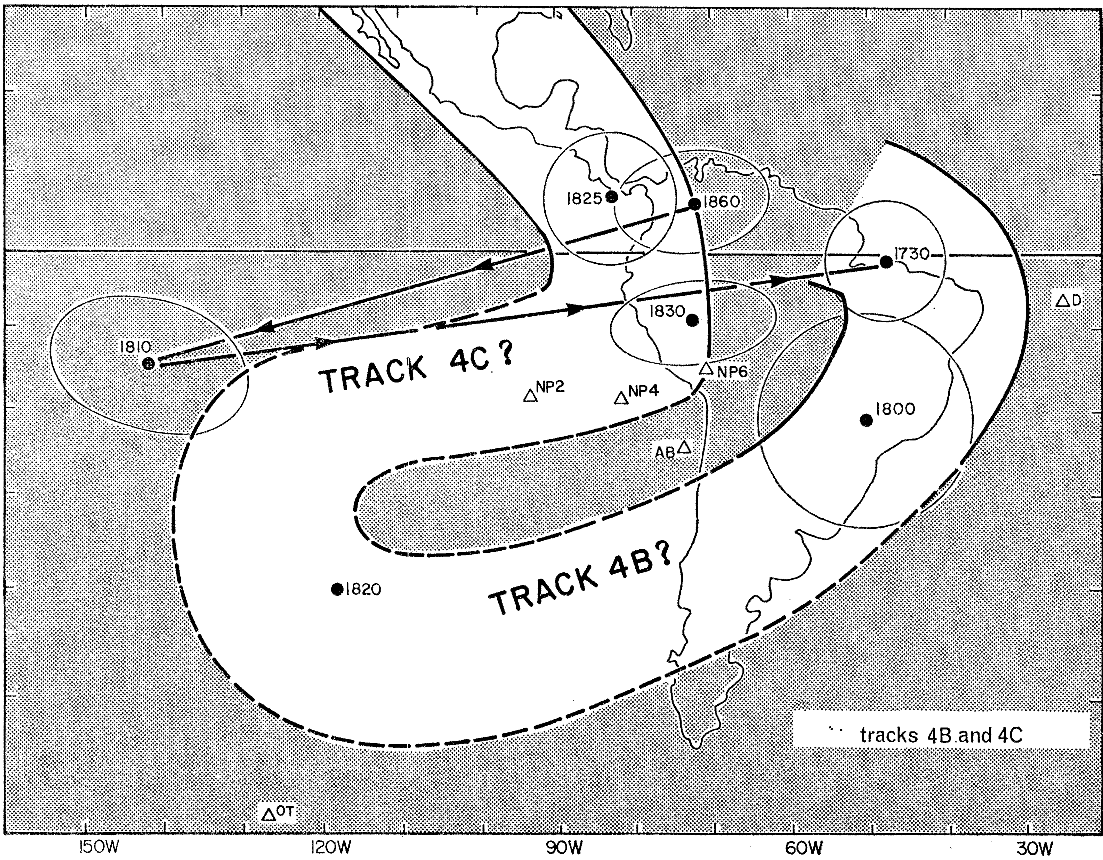


FIGURE 9. For description see opposite.

Second, the pole derived from the east component of Mealy Mountain complex (MM1) falls to the east of the track. This pole has been obtained directly from alternating field cleaning alone without benefit of vector analysis, and it is possible that unresolved polyphase magnetizations are present.



Figures 9 and 10. Track 4. Poles for the interval between approximately −1300 to −1850 Ma. See description of figure 4 for explanation of symbols, and description of figure 11 for indexing of poles related to track 5.

1250 (A) Muskox Intrusion (115) K, R
1300 (B) Seal Group redbeds (464) S
1370 (B) Sibley Group (473) R
1375 (B) St Francois rocks (241) R
1400 (B) Michikamau Anorthosite (205) K
1410 (A) Sherman granite (172) R
1475 (A) Croker Island Complex (129) R
1500 (C) Western Channel Diabase (504) K
1622 (C) Melville-Daly Bay metamorphics K
1700 (B) Sparrow Dykes (410) K
1730 (C) Et-then Group (341) S
1800 (B) Flin Flon B magnetization of Park (1975) R, K
1810 (B) Stark Formation, Christie Bay Group S (Bingham & Evans 1975)
1820 (C) Nonacho Formation S

BT1, 2, Belt Series BT1 is a summary of early results without demagnetization studies (summarized in the Ottawa catalogue no. 300). BT2 is recent work based on demagnetization studies (Evans *et al.* 1975). SW, an average of 9 results from redbeds of Arizona (Pioneer Shale Shinumo Quartzite, and Bass Limestone) and Utah (Uinta Mountain Group, and Big Cottonwood Formation) as detailed in the Ottawa catalogue no. 231. SG3, Shabogamo Gabbro (Fahrig *et al.* 1974). No radiometric age is available, but this pole obtained from rocks at a distance from the Grenville Front of 80 km agrees with poles at 1300–1400 Ma and this agrees with geological relations (R. F. Emslie, personal communication).

Overprints. Overprints in following rock units have been described. BS, Big Spruce Complex (Irving & McGlynn 1975). D, Lapilli tuff of Dubawnt Group (Park *et al.* 1973). DG, Dogrib Dykes (490). F, Flin Flon overprints to which Park (1975) assigns an age based on detailed work of about −1600 to −1700 Ma. KS, Kahochella Formation (McMurry, Reid & Evans 1973). N, Nonacho Group (McGlynn *et al.* 1974). OT, Otto Stock (Pullaiah & Irving 1975). SR, Spanish River Complex.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

(*d*) *Track* 4

Poles for the interval from about −1300 to about −1850 Ma are shown in figures 9 and 10. This interval corresponds to the Palaeohelikian of Stockwell (figure 2). The polar track for this interval is referred to as track 4. Track 4 was first suggested by Irving, Donaldson & Park (1972) and has been revised by Park, Irving & Donaldson (1973) and McGlynn, Hanson, Irving & Park (1974) and is further developed here.

There is a notable group of poles in the central Pacific with assigned ages ranging from −1300 to −1475 Ma. They fall just to the east of poles for the Mackenzie igneous episode (figure 6), and that for the Muskox Intrusion (pole no. 1250) is shown on figure 9 for comparison. There are a number of poles with assigned ages ranging from −1500 to about −1800 Ma (1500, 1622, 1700, 1730, 1800) that fall progressively to the east. Poles with assigned ages greater than 1800, however, are irregularly scattered; the Stark Formation (1810) stratigraphically underlies the Et-then Group (1730) and overlies the Kahochella Formation (1860) as is documented in figure 10. There appears therefore to be a sharp easterly directed loop in the polar track comparable to, but deeper than, that shown by McGlynn *et al.* (1974, figure 7) and this may be preceded by a westerly directed loop (figure 11). It is convenient therefore to divide track 4 provisionally into three parts. Track 4A is the dominant westerly trending limb from about −1300 to −1750 Ma (figure 9) which is reasonably well documented, and there is a much less well documented loop between about −1730 and about −1850 Ma made up of two tracks that are provisionally labelled 4B and 4C (figure 11). Tracks 4B and 4C seem to be needed to accommodate the pole from the Stark Formation, poles 1850 and 1800, and the overprints found in the Otto Stock (OT, figure 11). Pole 1800 is well-defined. Pole 1820 is derived from site 1 of the Nonacho Formation, which has very high blocking temperatures (650 °C) and may therefore represent an original magnetization. Tracks 4B and 4C are obviously very tentative.

Track 4A is characterized by many poles derived from overprints. These are the secondary magnetization (shown to be secondary by a fold test) of the Nonacho Group sediments, the Dogrib Dykes, the Big Spruce Complex, and Flin Flon greenstones (open symbols labelled N, D, BS and F respectively in figure 9). There is some experimental and geological evidence concerning the time order of the overprints at Flin Flon (1800, and the overprints F1 to F3 Park (1975)). Magnetization 1800 has the highest blocking temperatures and is therefore considered by Park to be the oldest. It is obtained typically from the latest intrusions in the area (Boundary Intrusions) and is thought to be a thermoremanent magnetization acquired at the time of their emplacement. The overprints F1 and F2 occur in most rock units at Flin Flon, and F1 has the higher blocking temperature and is therefore believed to be the older. F3 is found only in a group of metasediments that have undergone extensive retrograde metamorphism (haematization close to late faults) and for this reason it is considered to be the youngest component present at Flin Flon. The inferred time order of these magnetizations is indicated in figure 9. The overprints observed in the Big Spruce Complex are complicated and some may belong to the earlier track 5 at the place where it crosses track 4 in the Caribbean region (Irving & McGlynn 1975). The overprints on track 4A, presumably have been acquired during slow cooling and are the palaeomagnetic signature of uplift following the Hudsonian Orogeny.

Several poles of track 4 are of some stratigraphic interest. Studies by Collinson & Runcorn

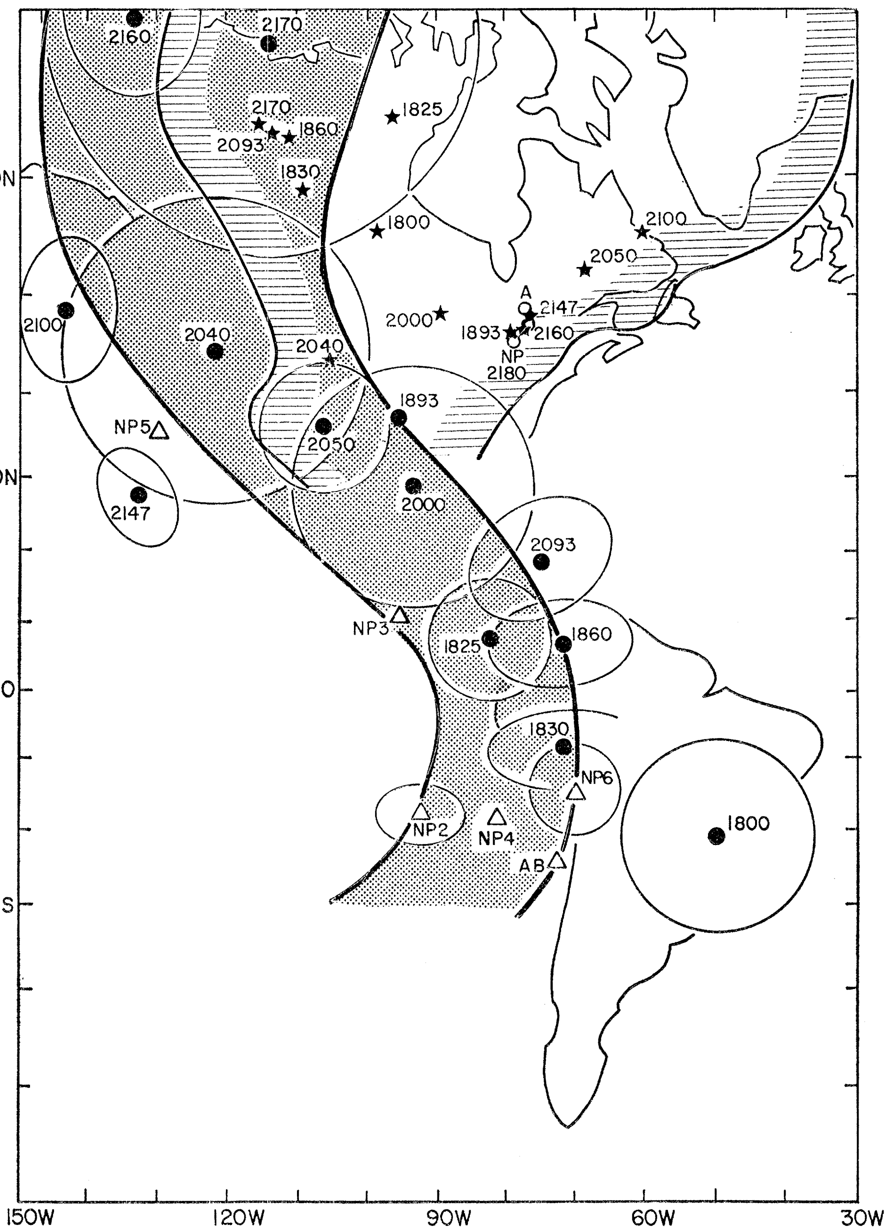


FIGURE 11. Track 5. Results from interval about −1850 to −2200 Ma. See legend to figure 4 for explanations.

1800 (A) Flin Flon B magnetization of Park (1975) R, K
1825 (A) Dubawnt Group (481) R, K
1830 (B) Martin Formation (468) K
1860 (A) Kahochella Formation (McMurry *et al.* 1973)
1893 (A) Spanish River Complex, the error (25°) is large and is not shown to avoid confusion (413) R
2000 (C) Gunflint Formation (191) R
2040 (C) Wind River Dikes (326) K
2050 (C) Otish Gabbro (467) S
2093 (A) Indin Dikes (492) R, K
2100 (C) Mugford Basalt (314) R, K
2160 (A) Otto Stock (Pullaiah & Irving 1975) R
2147 (A) Abitibi Dikes, major magnetization (109) R
2170 (A) Big Spruce Complex (Irving & McGlynn 1975) R

Other magnetizations. Overprints or magnetizations which may be an unresolved mixture of primary magnetizations and overprints. See discussion in § 4 (*d*). AB, Abitibi Dikes, minor magnetization (110). NP2–NP6, Nipissing Diabase (171, 271, 272, 273, 421).

(1960) and Norris & Black (1962, summarized in pole BT1) and by Evans, Bingham & McMurry (1975, pole BT2) have shown that, irrespective of reversals, the Belt Series is uniformly magnetized throughout much of its thickness from the Lower Ravalli to the Upper Missoula Group (figure 8). The earlier work, based mostly on results without demagnetization, is in excellent agreement with later studies. Radiometric age determinations from the Missoula Group range from −1100 to −1300 Ma, and the older levels in the Belt yield values as old as −1400 Ma. In contrast the Beltian palaeomagnetic poles indicate a much smaller age range of −1300 to −1400 Ma, since they agree with other poles in this age range, since there is agreement through much of the thickness of the Belt, and since there is no evidence of the large polar variations found by Elston & Grommé (1974) in the Grand Canyon Supergroup which span a much longer interval comparable to that indicated by the radiometric ages from the Belt (figure 7). Various possible explanations of this paradox have been given by Evans *et al.* (1975) and will not be repeated. The straightforward interpretation, giving full weight to the palaeomagnetic evidence, is that only the maximum radiometric ages provide an estimate of age of the Belt Series which is therefore in the range −1300 to −1400 Ma.

Pole SW is an average of results from a number of rock units in Arizona and Utah (figure 9). The position of these poles indicates that the rocks from which they were derived (which include the Bass Limestone at the base of the Grand Canyon Supergroup, see legends to figures 7 and 9) are about 1300 Ma old.

(*e*) *Track* 5

Poles for the interval about −1850 to about −2200 Ma corresponding to the late Aphebian of Stockwell (figure 3) are plotted in figure 11. They form a meridional array stretching from what is nowadays the Mackenzie delta to Peru, in contrast to poles of track 4 which are distributed in a predominantly east–west belt. The sense of apparent polar motion is considered to be from north to south. The evidence for this is that the Dubawnt Group (pole 1825), the Kahochella Formation (1860), and the Martin Formation (1830) have ages between 1800 and 1900 Ma and are younger than the Indin dikes (pole 2093), the Otto Stock (2140) and the Big Spruce Complex (2170). The dates of the results from the Mugford Basalt, Wind River Dikes and the Otish Gabbro (poles 2100, 2040 and 2050 respectively) are less well known, but ages of about −2000 Ma are probable. There is evidence of overprinting which is also consistent with southerly direction of motion. One apparent inconsistency in this scheme is the position of the commonly accepted pole for the Nipissing Diabase (two Rb-Sr isochrons 2160+60 (Van Schmus 1965) and 2150+50 (Fairbairn, Hurley & Pinson 1969), poles N2, N4 and N6). The Nipissing Diabase, the Otto Stock and (2160 ± 80, Bell & Blenkinsop 1975) the Big Spruce Complex (2170 ± 40, Martineau & Lambert 1974) have radiometric ages that are not significantly different, yet their apparent pole positions are almost 90° apart. However, the time at which the Nipissing Diabase was magnetized is not definitely known. Much of the diabase, especially in the southern exposures, has been regionally metamorphosed to low greenschist facies (Card & Pattison 1973), and the descriptions of Patel & Palmer (1974) indicate that post-cooling alteration of the iron minerals may have been extensive. A successful contact test has never been described; Symons (1967, Table 1, second entry) has given results from the Upper Slate of the Cobalt Group which have *very* roughly the same directions as those in adjacent Nipissing diabase, but this result is based on only 4 samples whose directions have a standard deviation of 40° and their mean has an error of 48°. No conclusions can be drawn from such scattered data. Therefore it is possible that the magnetizations of the Nipissing

Diabase are younger than the age of emplacement. Moreover, the magnetizations observed in Nipissing Diabase are very complex, and directions other than those corresponding to the commonly accepted poles N2, N4, and N6 occur (poles N3 and N5, figure 11). It is also noteworthy that the Abitibi Dykes have one dominant (2147) and one subordinate (AB1) magnetization, although the ages of the rocks from which they were derived are not significantly different (Gates & Hurley 1973). Poles 2147 and N5 are close together, as are poles AB2, N2, N4, and N6. Hence pole AB1 and poles from the Nipissing Diabases may be a complex mixture of as yet unresolved primary magnetizations and overprints. In the absence of successful contact tests and detailed thermal demagnetization studies the positions of the presently available Nipissing Diabase poles must be regarded as uncertain, and all that can be said is that they probably lie near to track 5. This new reconstruction of a north–south polar track in the interval −1800 to −2200 Ma was first made by Irving & Lapointe (1975) and McGlynn *et al.* (1975), and differs very greatly from earlier interpretations (Spall 1971; Irving & Park 1972; Fahrig & Chown 1973; McGlynn & Irving 1975). This major revision is based on very recent data from Aphebian rocks.

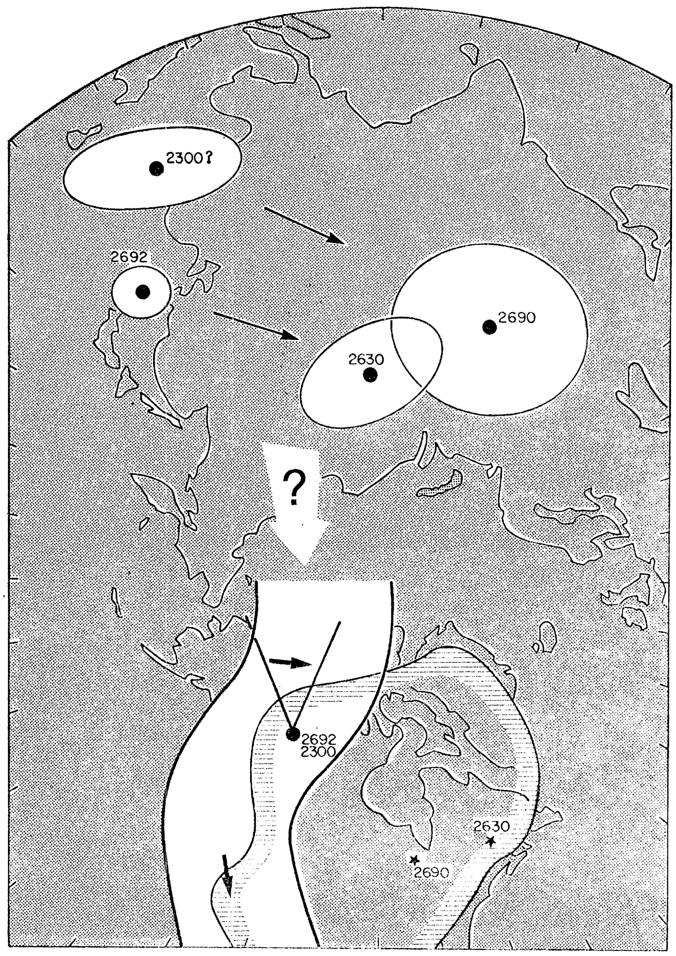


FIGURE 12. Track 5. Results from the interval about −2200 to −2700 Ma are given. The later part of track 5 is documented in figure 11.

2300 (C) X-dikes (493)
2690 (A) Matachewan Dikes (107) R, K
2692 (B) Dogrib Dikes (491) R, K
2630 (B) Chibougamau sills (Ueno & Irving 1975) R

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Only a few poles from lower Aphebian rocks are available and these are plotted in figure 12. The two poles (2630, 2690) available from the Superior Province are in approximate agreement, and probably represent the field at between about −2600 and −2700 Ma, immediately following the Kenoran Orogeny and at the beginning of the Proterozoic. Two poles from the Slave Province fall in more easterly longitude. One of these (2692) is dated by an Rb-Sr isochron (Gates & Hurley 1973) and surveyed in detail palaeomagnetically, the other (2300) is of very uncertain age, and surveyed only in preliminary fashion. The two groups can be reconciled by rotating the Slave Province about a local eulerian pole relative to the Superior Province but without any large displacement. In view of age uncertainties, an equally plausible explanation would be to connect them by a polar path without rotation. Clearly very little can be said about the early Aphebian part of track 5, and no conclusions about tectonics can be drawn.

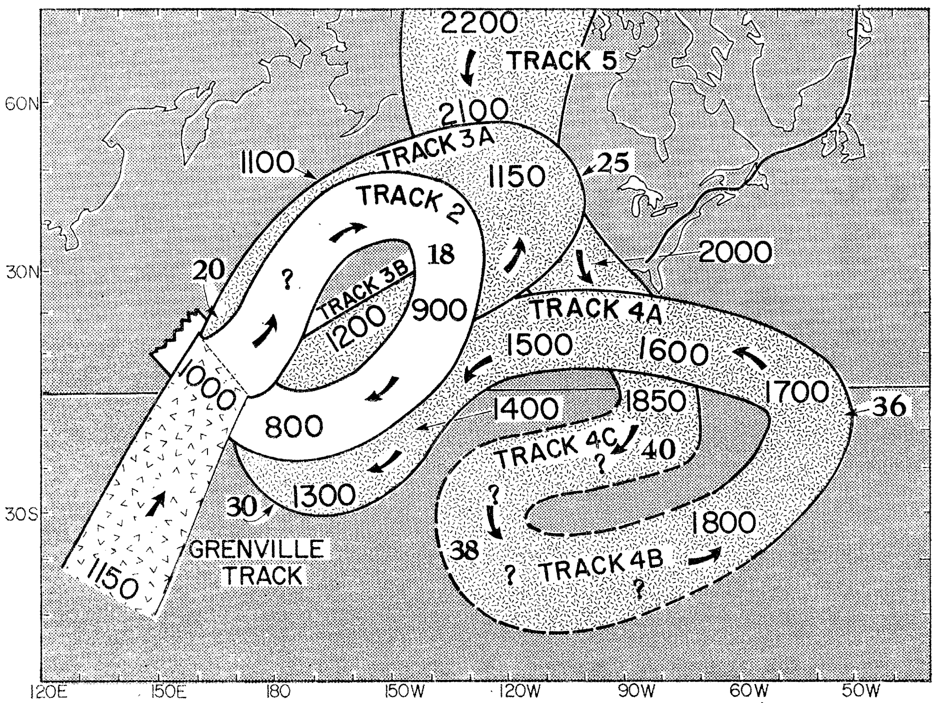


Figure 13. Summary a.p.w. path for the Proterozoic of Laurentia. Please note that the tracks have a substantial degree of uncertainty attached to them and this applies particularly to track 2 and the early part of track 4. The major hairpins in the tracks are indexed by numbers modified from the scheme used initially by Irving & Park (1972).

The concordance of poles from the Kahochella and Dubawnt red beds and volcanics (poles nos 1860 and 1825) whose ages are not significantly different is of some stratigraphic and tectonic interest, since the Dubawnt belongs to the second phase of deposition in the interior of the Churchill Province (§ 2), whereas the Kahochella is situated near the base of the Great Slave Supergroup and is therefore an early deposit of the Great Slave Aulacogen and the Coronation Geosyncline (Hoffman 1973). This indicates that the deposits of the aulacogen are related in time to the second stage of deposition in the interior of the Churchill Province, and are younger than the deposits of the first stage. The latter are pre-orogenic whereas the former are post-orogenic. Therefore much of the deposition and subsequent deformation in the

Coronation Geosyncline may have occurred later than the major deformation of the Churchill Province.

(*f*) *Summary polar paths*

An a.p.w. path for Laurentia between −600 and −2200 Ma is made in figure 13 by combining the polar tracks of figures 4–11. The tracks have been constructed so as to minimize their lengths. Clearly many other reconstructions are possible if other assumptions are made. The application of this assumption implies that the Grenville track is separate from the polar tracks from Interior Laurentia, but the separateness of the Grenville track is by no means an established fact, and some workers prefer an a.p.w. path of greater total length (§6). According to figure 13 the a.p.w. path consists of a number of loops made up of tracks separated by sharp bends or hairpins. The polar signature of early Proterozoic tectonics (prior to −1300 Ma) is very roughly an inverted 'T'; prior to the Hudsonian Orogeny there is a single meridional track (track 5) followed by track 4 with dominantly latitudinal trends. The polar signature of later Proterozoic tectonics has tight, dominantly meridional loops, and a separate Grenville track. The reconstruction of figure 13 implies that the continental motions occurring during the Hudsonian orogenic cycle were of a different type from those in the Grenvillian orogenic cycle.

The a.p.w. curve of figure 13 is obviously subject to revision as new data accumulates, but assuming that it is at least approximately correct, it defines a magnetic stratigraphy for the Proterozoic of Laurentia. In figure 2 a comparison is made with Stockwell's chronology. Hairpins 20, 30 and 36 correspond approximately to the mean ages of the Grenvillian, Elsonian and Hudsonian Orogenies as defined by Stockwell (1970*a*) based on K-Ar ages. Hairpins 25 and 40 correspond approximately to the Grenvillian and Hudsonian Orogenies as defined by Stockwell (1972) mainly on Rb-Sr ages. The comparisons do not differ significantly and perhaps not too much should be read into them because the age uncertainties are large. What is of interest, however, is that the earlier thermal events recorded by the Rb-Sr ages and the later thermal events recorded by the K-Ar ages do appear to have an expression in the a.p.w. path, and they therefore correspond in a general way to changes in motion of Laurentia relative to the pole. Counting hairpin 40 as a convenient demarcation between an earlier dominantly latitudinal a.p.w. regime, and a later dominantly meridional a.p.w. regime, and assuming, as is argued in §6, that tracks 3A and 3B correspond to the Grenville orogenic cycle, then the polar tracks can be arranged into a time sequence corresponding to 4 superintervals. These correspond approximately to the four eras of Stockwell, which means that the magnetic stratigraphy is broadly consistent with Stockwell's classification. This is not to say that other rational schemes for ordering the paleomagnetic data are not possible.

Track 3 (3A and 3B) is comparable to the polar reconstruction for this time given by Du Bois (1962). It is also comparable to the Logan Loop of Robertson & Fahrig (1971), except that the young end of the Logan Loop according to them, was anchored at about −700 Ma by the well-established pole from the Franklin Diabase (pole 675, figure 4). In our reconstruction we terminate track 3 at −1000 Ma, and accept provisionally the proposal of Stewart & Irving (1974) that there is an additional loop between then and −700 Ma. The Mackenzie trend of Spall (1971) corresponds to the early part of track 3B. The Keweenawan trend of Spall corresponds to much of track 3A. The Elsonian trend of Spall corresponds to the later part of track 4A. In figure 13 there is no expression of the Sudbury and Grenville loops of Fahrig & Chown (1973) and Fahrig *et al.* (1974). The use of names, some of them local, may not be a desirable procedure at this early stage in the development of a Laurentian magnetostratigraphy. The polar curves provide a general stratigraphy for large parts of Laurentia which is not made clear by the use of local names. Moreover, as more work is done, the names may become inappropriate, for example, there are now Keweenawan poles in the Mackenzie trend (pole 1220, figure 6). The Mackenzie igneous events (Fahrig & Jones 1969), although they may have an important time connotation locally, are really only a point in time when viewed on a Laurentia-wide scale and their poles are in good agreement (figure 6), so the term Mackenzie 'trend' is hardly appropriate. The names that have been chosen are of varied origins and do not provide the basis for a coherent nomenclature; Logan was the first director of the Geological Survey of Canada, Sudbury is a mining town, Keweenawan is a rock-stratigraphic term, Mackenzie denotes numerous igneous events, and Elsonian and Grenvillian are the names of orogenies. The a.p.w. tracks fall naturally into the classification of Stockwell and the time is not far off when a unified stratigraphy and nomenclature for the Proterozoic, involving magnetostratigraphy and all other methods, will be possible. It is for this reason that we continue to use as an interim measure a numbering system for identifying the polar tracks of Interior Laurentia. However we continue to use the term Grenville track because with one exception (§6) poles which fall in that group are from rocks restricted to the Grenville Province.

5. Hudsonian orogeny

A notable feature of the early Proterozoic a.p.w. path is the meridional trend of track 5. The poles are derived from different parts of Interior Laurentia, including the main Archaean blocks (Superior, Slave and Nain Provinces, and the Bear-tooth uplift, figure 1), indicating that these blocks did not move relative on one another by many thousands of kilometres during the Hudsonian Orogeny, as has already been noted by McGlynn & Irving (1975), Irving & Lapointe (1975), and McGlynn, Irving, Bell & Pullaiah (1975). This is the simplest explanation, but it does not necessarily mean that some relative movements did not occur. The physical basis of many results is insecure; the data are few; the width of the polar track itself is such that the opening of minor oceans of the order of 1000 km would go unnoticed (figure 3); and, relative motion in a purely longitudinal sense cannot be detected. The geometry of track 5 however imposed certain restraints. The poles in the interval -2000 to -2200 Ma are all near to Laurentia, indicating that these Archaean blocks were in latitudes greater than about 60°. Hence *very* large motions are excluded, but small ocean basins may have opened and closed.

The change in latitude required by track 5 (that is the minimum movement required) is about 100° at an average rate of about 3 centimetres per year. From about -1800 to -2200 Ma, Interior Laurentia appears to have moved as a whole relative to the pole at rates comparable to present day plate motions, by amounts (100°) at least several times greater than the relative movements of the Archaean cratons within Laurentia. It is therefore to be expected that marginal deformation akin to Phanerozoic plate-tectonics occurred, and the Coronation Geosyncline and the associated Great Slave Aulacogen is probably of this nature (Hoffman 1973). During this time linear basins were formed within the Laurentian Shield, and they became filled with deposits which were deformed in the Hudsonian Orogeny. The time relations of the deformation in these interior basins and Coronation geosyncline are uncertain but the argument presented in §4 (*e*) indicates that the later, in general, post-dated the former. Thus the Laurentian Shield appears to have undergone intense internal deformation but without loss of general coherence; it does not appear to have been as rigid as the continental parts of modern plates. This discussion is consonant with geological evidence as outlined in § 2, and with the discussion of Sutton & Watson (1974).

A further notable feature of the a.p.w. path for the early Proterozoic is the change from meridional trend of track 5 to dominantly latitudinal trends of track 4. Track 5 implies a movement of Laurentia from near the north pole to equatorial latitudes. Track 4 implies large rotations

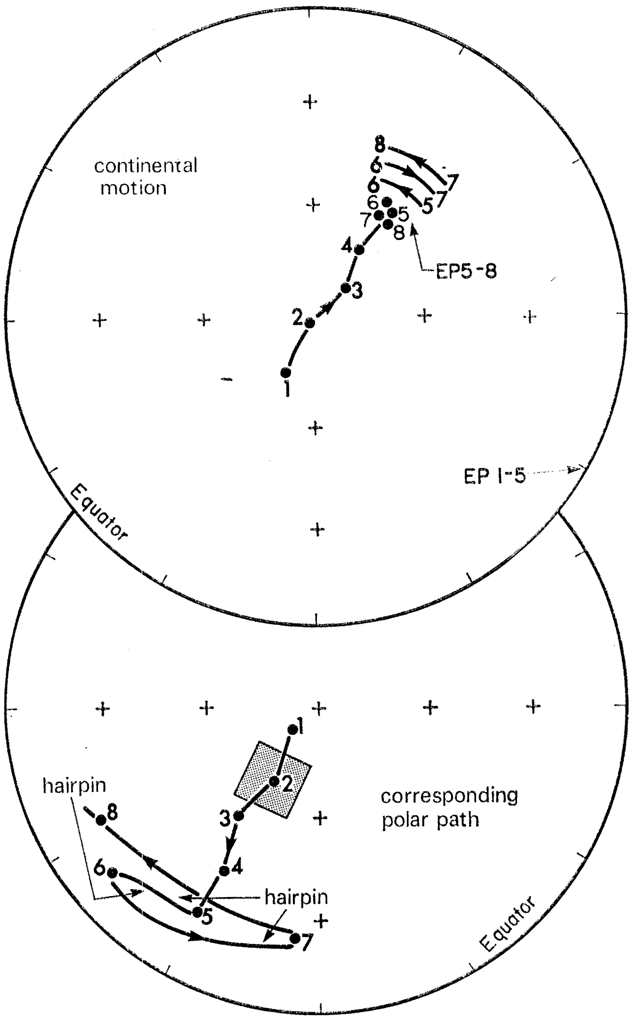


Figure 14. Model a.p.w. curves for two contrasting regimes, rotation about an Eulerian pole (EP 1–5) roughly 90° distant from the continent is followed by rotation about a Eulerian pole near to the continent (EP 5–8). The numbers denote successive time intervals. Above the pole is fixed and the continental motions are shown. Below, the continent, represented by an ornamental square, is fixed and the corresponding palaeomagnetic poles are shown. Equal-area projections are used.

of Laurentia about Eulerian poles close by, first anti-clockwise during track 4C time, then clockwise during track 4B time, and finally anti-clockwise again during track 4A time. Tracks 4C and 4B are poorly documented (figure 10) and the motions inferred from then uncertain, but track 4A is comparatively well established (figure 9) and the corresponding large anti-clockwise rotation of Laurentia probable. In figure 14 an attempt to model these motions is made. It is assumed that no polar wander occurred and that polar signatures are caused entirely by drift. The continent moves over the pole into intermediate latitudes about an Eulerian pole close to the equator. The corresponding polar path passes through the continent and then moves away from it. The Eulerian pole is allowed to move inside a circle of radius about 10° so that the trajectory of the continent and the polar path is not a simple small circle but has a series of kinks (figure 14 positions 1–5). At time 5 the Eulerian pole moves from its equatorial position to a point near to the continent and remains there (within a 10° circle) until time 8. Between times 5 and 8 the continent rotates first anti-clockwise, then clockwise, and finally anti-clockwise. The corresponding polar path has the form of a series of loops, made up of roughly linear tracks separated by hairpins. Hairpins mark large changes either in the position of the Eulerian pole or in rotations about it.

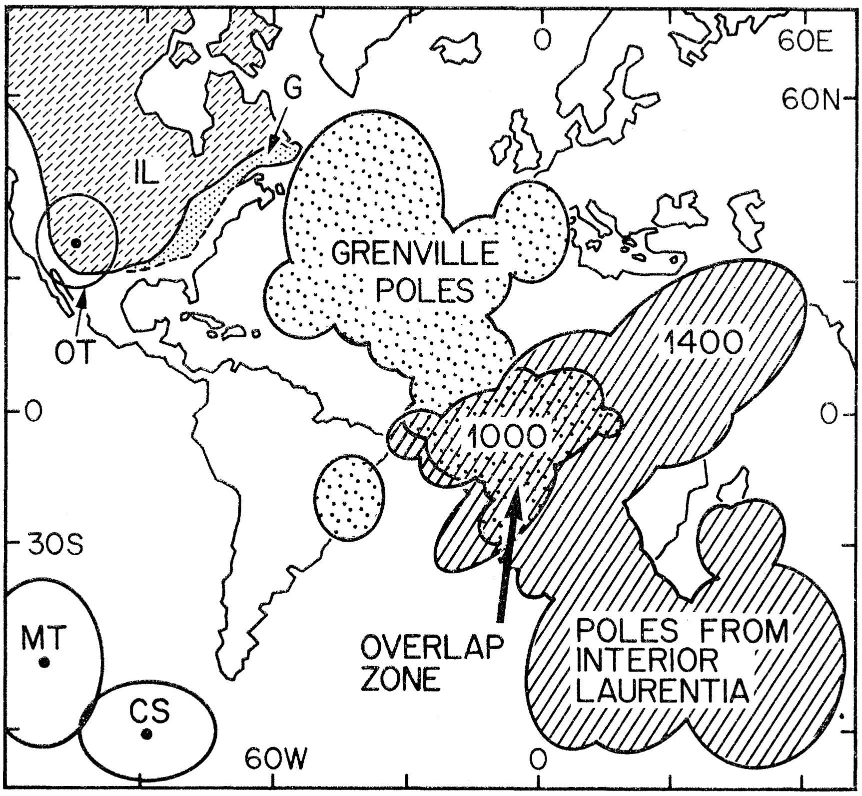


FIGURE 15. General comparison of poles from Grenville Structural Province (G) with those from Interior Laurentia (IL) in the age range −600 to −1400 Ma. The areas of error circles only are shown. The poles from the two regions have different ornament. The poles plotted are the antipoles of those shown in figures 4–8. From Ueno & Irving (1975) with permission.

The hypothetical polar track in the lower part of figure 14 is roughly comparable to tracks 4 and 5 (figure 13) and therefore the upper part of figure 14 is a possible but necessarily very tentative model of the motions of Interior Laurentia before, during, and after the Hudsonian Orogeny. The major change from one regime to the other seems to have occurred at hairpin 40 about −1850 Ma (figure 13). The later Aphebian is characterized by latitudinal drift (rotation about a distant Eulerian pole), and the Hudsonian Orogeny and subsequent Palaeohelikian are marked by rotations about Eulerian poles situated close by. The major deformation phases (1850–1750) are characterized by changes in rotations (tracks 4B and 4C), followed by slow rotation during a long period of slow uplift as signified by track 4A with its abundance of overprints.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

6. Grenvillian Orogeny

The ages of the palaeomagnetic poles from the Grenville Structural Province are not accurately known. It is almost certain that their ages lie between the limits −1400 to −600 Ma. Comparison of figures 5–8 shows that the Grenville poles are in general systematically displaced with respect to those for Interior Laurentia for this interval. The comparison is set out in figure 15, using the convention of plotting antipoles which allows the poles and the Laurentian Shield to be seen close together. The two distributions overlap in the region of the present day equatorial Atlantic (or in east equatorial Pacific, using the more conventional plotting mode) but otherwise there is a large systematic difference between them.

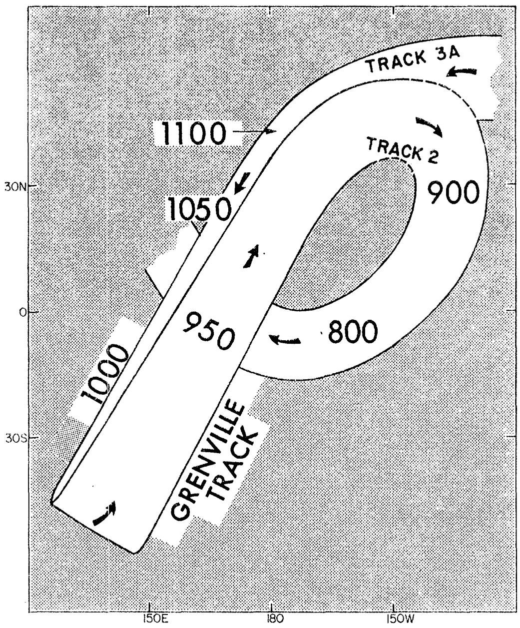


Figure 16. An alternative polar reconstruction for the interval −1100 to −600 Ma. Modified from Stewart & Irving (1974).

The Grenville poles may record the geomagnetic field for an interval of time that is not represented in the existing palaeomagnetic record from Interior Laurentia and form a part of the general path for Laurentia (Du Bois 1962; Irving, Park & Roy 1972; Roy & Fahrig 1973; Stewart & Irving 1974). A possible path is illustrated in figure 16. Alternatively the Grenville poles may correspond in time to some part of the existing polar wander path from Interior Laurentia, the implication being that Grenvillia was once displaced by several thousand kilometres relative to Interior Laurentia (Palmer & Carmichael 1973; Irving, Park & Roy 1972).

The discussion centres about the possible age assignments that can be made and the two most probable assignments are considered here (figures 13 and 16). More general discussions may be found elsewhere (Irving *et al.* 1974; Ueno *et al.* 1975). In figure 13 the Grenville track is assumed to be between about −1150 and −1000 Ma, that is, the magnetizations were acquired after general and widespread regional metamorphism at about −1150 Ma but before final uplift, as recorded in the K-Ar ages at about −1000 Ma. There can be little doubt that high-grade (amphibolite to granulite facies) metamorphism will destroy all earlier magnetizations, and the blocking temperatures of the magnetizations observed in for example the Morin and Whitestone anorthosites (500–675 °C on laboratory time scale) even when one considers cooling over long intervals are almost certainly higher than 200 °C, the temperature at which K-Ar biotite ages are considered to be acquired. An age assignment therefore somewhere between typical dates obtained by Rb-Sr isochrons (−1150 Ma) and K-Ar biotite values (−1000 Ma) is reasonable. On the other hand Grenville magnetizations may be somewhat younger, and in figure 16 another reconstruction is given in which a polar loop is passed through the Grenville track and the calibration of figure 13 has been adjusted within the experimental uncertainties. There is now only a single polar path for all Laurentia and the Grenville poles are assumed to have ages between about −1050 and −950 Ma. The polar changes are first away from and then towards Laurentia, so that Laurentia moved first from near the north pole at about −1150 Ma to near the south pole at about −980 Ma and then back to the north pole about 900 Ma. This represents a minimum average rate of motion of about 15 cm per year relative to the pole. The rate required by the reconstruction of figure 13 is about half this amount.

Obviously, no clear-cut answer can be given on the basis of present evidence. The 'disadvantage' of the reconstruction of figure 16 is that it requires fast drift relative to the pole. Its 'advantage' is that it provides a unified magnetostratigraphy for all Laurentia. The 'disadvantage' of the reconstruction of figure 13 is that it requires the dismemberment of Laurentia. For the remainder of this discussion, we shall accept provisionally the latter reconstruction and consider its consequences. We shall begin by presenting a model which simulates in general fashion the a.p.w. signature of the later Proterozoic.

Model a.p.w. paths for continents bordering an opening and closing ocean (the Wilson cycle) are shown in figure 17. At first there is a single continent in motion (1). The continent splits and an ocean is formed between them (2). The continents move together again and reunite (3). Finally, the reunified continent moves off as a piece again (4). The actual motions are likely to be more complex, comparable perhaps to the zig-zag trajectory shown in the upper part of figure 17. Each of these four regimes produces corresponding polar tracks; phase (1) produces tracks 1–2, phase (2) tracks 2–3B and 2–3A, phase (3) produces tracks 3B–4 and 3A–4, and phase (4) track 4–5. The transition from one regime to the next is generally marked by a change in the positions of the Eulerian poles, and the corresponding transition from one track to another is marked by a hairpin. Since the bordering continents are unlikely to return to exactly the same positions, the pre-rifting a.p.w. paths will look similar but will not coincide. Thus the a.p.w. signature of the Wilson cycle may be a pair of complementary loops joined at one end (4 in figure 17), which is referred to as a polar juncture, and which is the signature of a collision orogeny. Hairpins signify large changes in continental motions, and divide the a.p.w. path into a series of tracks, which spans intervals comparable to the time scale of plate tectonics, namely 10^8 years. Superimposed on the main a.p.w. trends are a series of kinks which correspond to the frequent minor changes in direction of continental motion as already noted in figure 14. The kinks occur more frequently than hairpins, say every 10^7 years, and may be expected to reflect the detailed time-table of plate motions. The kinks may be so extreme as to cause short-term reversals in direction of a.p.w. With present technical uncertainties kinks will not generally be identifiable in Precambrian studies (although they may be present in the Grand Canyon Supergroup, §4(*b*)) but they are likely to be an important source of noise.

According to the reconstruction of figure 13 the Grenville track and track 2A are approximately contemporaneous and form a convergent set with polar juncture. This feature can be expressed in plate tectonic terms. Track 2A and the Grenville track fall on a near-equatorial small circle about 100° in length with a pole at 27° S, 101° W, which can be considered as the common Eulerian pole of Grenvillia and Interior Laurentia. The tracks have been divided into 25 Ma intervals (assuming constant motion), and Grenvillia has been rotated about this pole so as to bring successive contemporaneous poles into coincidence (figure 18). The rate of convergence is 8 cm/a. Although the Grenville Front itself is not a suture (§2), this hypothesis requires a suture within the Grenville Province; it ought to lie south of zone B and north of those localities that have yielded poles of the Grenville track. This zone (zone S) is shown schematically in figure 19. The geology of zone S is exceedingly complex, and at these deep

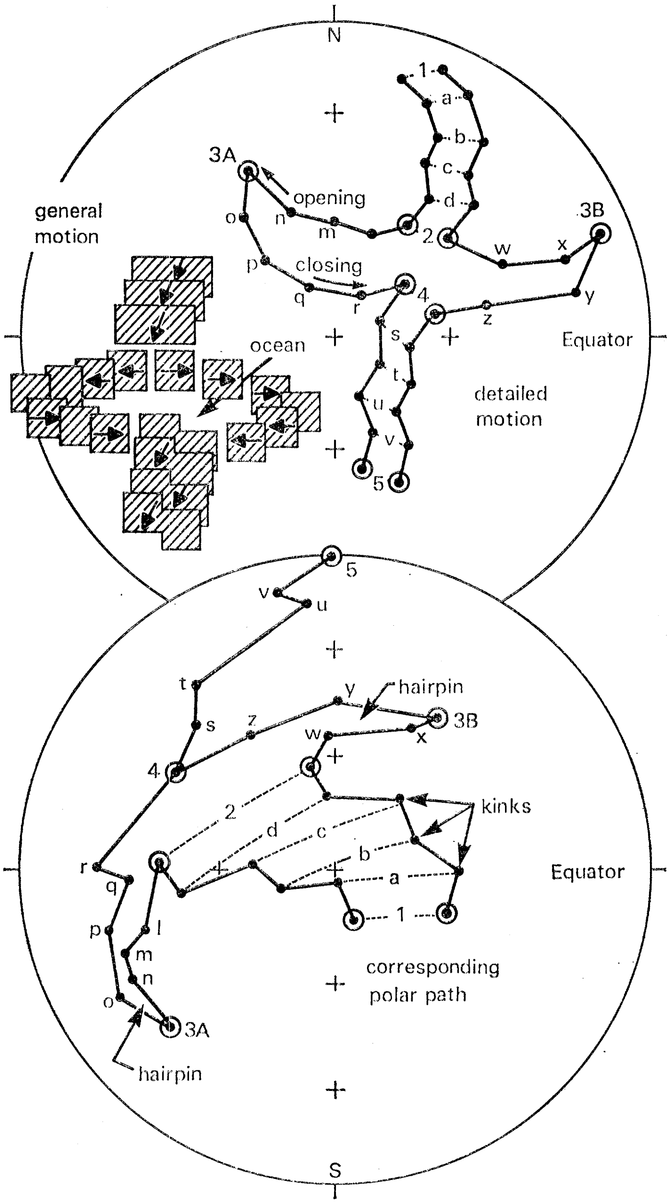


FIGURE 17. Model a.p.w. curves for a Wilson cycle. Continental motions are shown above (pole assumed fixed) and the corresponding a.p.w. paths below (continents assumed fixed). Hairpins are numbered, and kinks are lettered. Equal-area projections are used. The distribution of Eulerian poles is too complex to be given on this simplified illustration.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

crustal levels (formerly 10–20 km) all remnants of intervening oceans may have been obliterated. The area consists mostly of medium- to high-grade gneisses, which except locally have never been mapped in detail. Certain areas of central Ontario inside zone B have, however, been mapped in detail, and it is noteworthy that Chappell, Brown & Moore (1975) have recently suggested that Precambrian oceanic crust is present between Bancroft and Renfrew in Ontario.

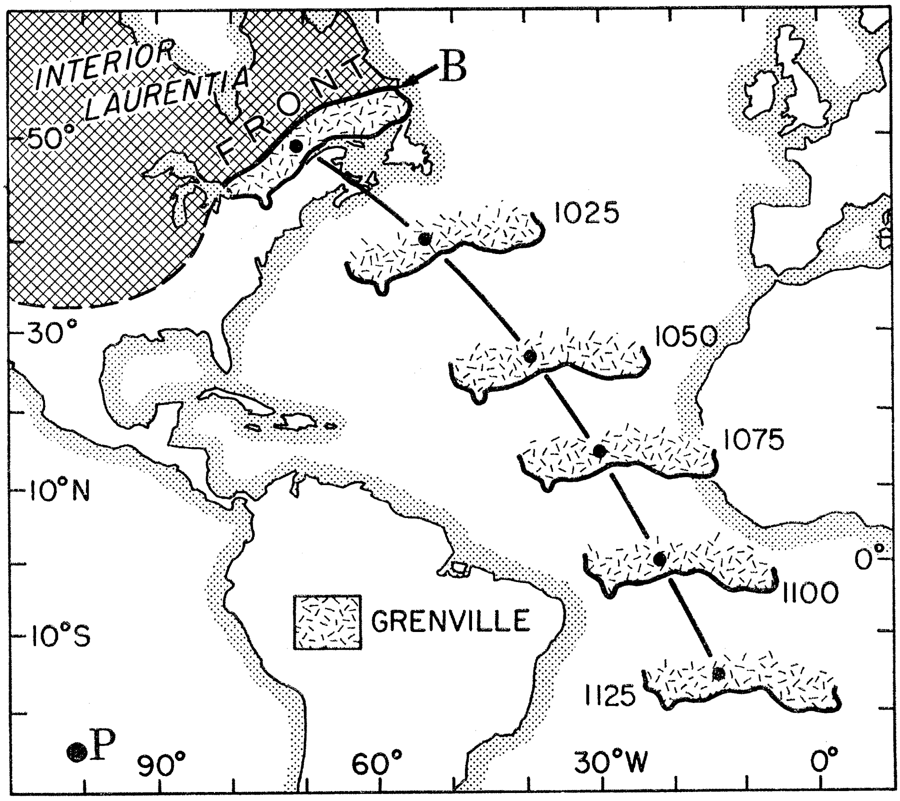


FIGURE 18. Motion of Grenvillia relative to Interior Laurentia derived from the a.p.w. stratigraphy of figure 13. Note that zone B just south of the front does not move in relation to Interior Laurentia. The front is not a suture. P is the Eulerian pole about which Grenvillia is supposed to have rotated relative to Interior Laurentia. Ages are in millions of years. Reproduced from *J. geophys. Res.* (with permission).

There is some evidence for suggesting that the convergence shown in figure 18 was preceded by a rifting phase. According to the above hypothesis the Grenville track and track 3A are the later halves of a pair of complementary loops. Thus track 3B and the conjectural return limb of the Grenville track drawn to accommodate the Tudor Gabbro result may be the earlier halves of these loops and may reflect the divergent phase prior to the convergency just described. This conjectural return limb is shown in figure 8. It is conceivable that in 'sheltered' low-grade metamorphic environment of Hastings Basin in which the Tudor Gabbro is situated, palaeomagnetic evidence of an earlier divergent phase may be preserved. Stronger evidence of an earlier divergent phase is provided by geology. The Grenville Front is approximately parallel to the late Precambrian edge and to the present continental shelf (figure 19). The younger two are thought to be a product of rifting prior to the opening of oceans. The pre-Grenville rift systems of Baragar (figures 1 and 19) are spatially related to the front, and alkaline complexes occur in zones B and S. Therefore it is possible, and consistent with the palaeomagnetic and geological information, that the central feature of the Grenville orogenic cycle is an opening and closing ocean. It is possible that Grenvillia was broken from Interior Laurentia about −1250 Ma at a time of the pre-Grenville rifting, then moved away, and finally returned at about −1000 Ma (Irving *et al.* 1974). This scenario is obviously very speculative, but it does make quantitative and testable predictions about the nature and timing of Grenvillian motions, the position of the suture zone, and the kinematic setting of adjacent igneous events, notably in the Keweenawan and the Seal Group. It would be wrong if poles located on the Grenville track and dated in the interval −1000 to −1140 Ma were found from rocks deep in Interior Laurentia, or if unequivocal geological evidence showed that no suture could possibly exist in zone S. It is therefore noteworthy that a pole derived from the Nankoweap Formation toward the top of the Grand Canyon Supergroup falls in the Grenville track (figure 7) and many more such determinations would constitute a clear disproof of these ideas.

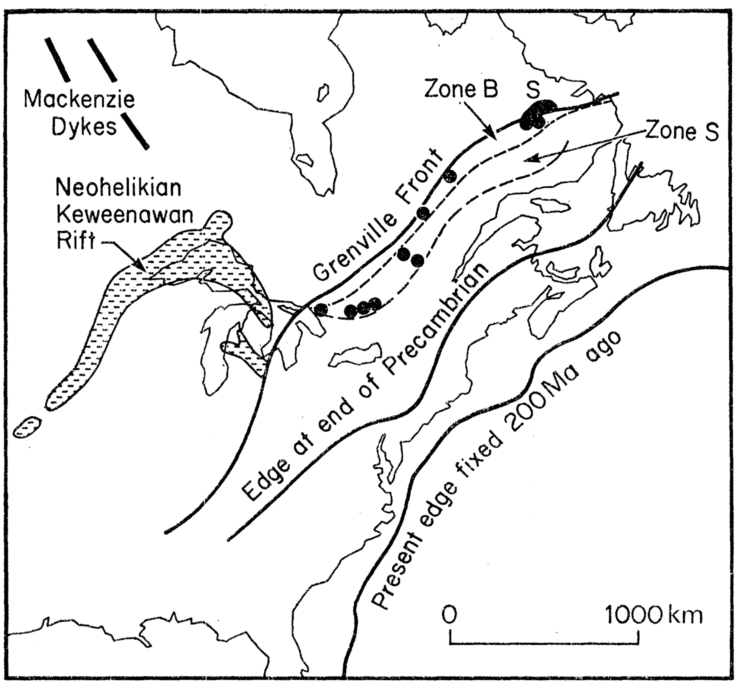


FIGURE 19. Successive southeastern margins of North America. Zones B and S are explained in the text. The present continental shelf edge is marked. The late Precambrian boundary is from Williams & Stevens (1975). The hypothetical Neohelikian edge is between zones B and S. The Seal Lake rift system (S), the Mackenzie Dykes and related Coppermine-Muskox volcanism (−1250 Ma), and the Keweenawan (−1200 to −1100 Ma) are the pre-Grenville rift system of Baragar (see Baer *et al.* 1974). Dots are alkaline complexes in the Grenville Province

7. Tectonic evolution of Laurentia

There are obviously many uncertainties in the magnetostratigraphy of Laurentia as it is presently known, and the uncertainties in the tectonic interpretations derived from it are correspondingly great. The present existing evidence, however, indicates that the tectonics of the early and late Proterozoic were different from one another, the former having some of the characteristics commonly associated with Archaean tectonics, and the latter having characteristics similar to Phanerozoic tectonics. We suggest therefore that there were three major phases in the tectonic evolution of Laurentia.

(1) *Archaean phase* (before −2700 Ma). Archaean deposits appear to have been formed on

a very mobile crust at a time when rigid plates as we know them today did not exist. Deformation seems to have occurred dominantly internally within each Archaean block.

(2) *Early Proterozoic phase* (between about -1300 and -2700 Ma) (Aphebian and Palaeohelikian). Interior Laurentia seems to have been a single entity which underwent strong internal deformation. Evidence for the earliest marginal plate deformation is also found in the Coronation Geosyncline, but there is no evidence of continental collisions (§2). The time relations of these internal and external deformations are not well understood. It is possible that the former were completed before the latter commenced, and there is some evidence for this opinion (§4(*e*)). The uncertainties in the palaeomagnetic determinations are such that small rift oceans (approximately 1000 km) could have opened and closed within Interior Laurentia (§5) in the interval -1300 to -2200 Ma and would have been undetected. The geological evidence indicates increasing crustal stability during this interval (§2). No conclusions can be drawn from the sparse palaeomagnetic data about the nature of orogenesis in the earliest Proterozoic (approximately -2200 to -2700 Ma).

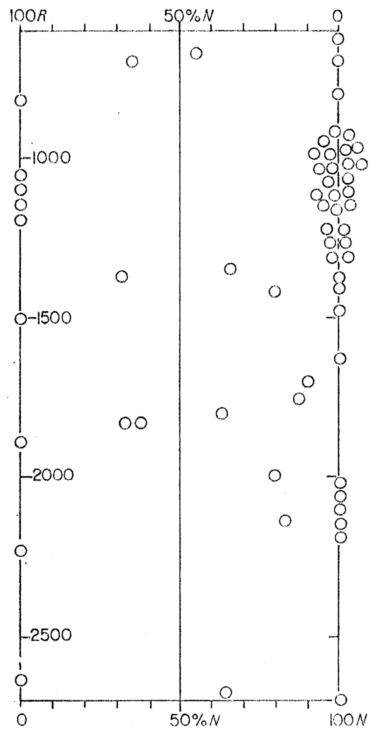


FIGURE 20. The polarity ratios of Proterozoic rocks from Laurentia calculated assuming that the polar path given in figure 13 is the antecedent of the present north pole.

(3) *Later Proterozoic and Phanerozoic phase.* This phase was initiated by an impressive array of pre-Grenville rifts described by Baragar. For the first time dyke swarms extend right across Internal Laurentia, implying a degree of rigidity not hitherto achieved. Major deformation was confined to the margin of Laurentia in what is nowadays the Grenville Structural Province. The data are consistent with the hypothesis that the central feature of the Grenville orogenic cycle was the opening and closing of a major ocean, followed by a collision orogeny. Marginal deformation continued to be dominant for the rest of the Precambrian and for the Phanerozoic.

This evolutionary sequence indicates that the Laurentian continental crust has become increasingly rigid with time, and this could be a result of a progressive increase in thickness of the lithosphere. There appear to have been at least two critical stages in this evolution: first, the change from the Archaean to Proterozoic regime when internal deformation became localized, and the first evidence of marginal deformation is found; secondly, the change from early to late Proterozoic (from Palaeohelikian to Neohelikian) when Laurentia-wide rifting first occurred, internal deformation essentially ceased, and marginal deformation became the dominant mode. The latter stage coincides with the Elsonian Orogeny whose significance is obscure. It may be related to the change from the second to the third tectonic regime.

8. Reversal of polarity

Attempts to draw up reversal sequences have been made for the Torridon Group (Irving & Runcorn 1957) for the Belt Series (Evans *et al.* 1974) and for the Stark Formation (Bingham & Evans 1974) but at present these have only local significance. The frequency of reversals have varied widely. Stewart & Irving (1974) have shown that in the Torridon Group (−796 Ma) the average length of a polarity interval was 1.5 Ma or less. The average length in the underlying Stoer Group (−991 Ma) was greater than 11 Ma. If some way can be found of satisfactorily quantifying reversal frequency, and particularly if long intervals of constant polarity can be recognized, then very useful stratigraphic time markers in the Proterozoic could be identified. For the present discussion we comment only on one surprising feature of the Proterozoic geomagnetic field, namely its persistent bias toward normal polarity. Reversals themselves are easy to detect, but it is less easy to say which observed Precambrian polarity corresponds to that which we now regard as normal and which to reversed. In §4 (figure 4) we attempted to show that the a.p.w. path of figure 13 is probably continuous with the present north pole. This is by no means certain, but it seems the most probable interpretation of the present evidence. Assuming this to be so, the polarity ratios (the percentage of normal or reversed samples found in any rock unit) of Proterozoic rocks from Laurentia are plotted in figure 20. Normal polarities predominate. Altogether, 23 % of observed polarities are reversed and 77 % normal. The mean polarity ratio ($100R\ (N+R^{-1})$ is 23, the standard deviation 36, and the standard error 5, based on the 61 values plotted in figure 20. This means that only 23 ± 5 % of Proterozoic rocks have reversed polarity. If the Grenville poles and overprints are included, the means are 29 % reversed, the standard deviation 41, and the standard error 4. Clearly these values differ significantly from 50 % which means that during the Proterozoic there appears to have been a systematic normal bias to the geomagnetic field. Although in the Phanerozoic there are long intervals of normal or reversed bias, on average the two are evenly balanced (McElhinny 1973, p. 130). Thus, unless the polarity assigned to the a.p.w. path is in error, and unless we have a grossly non-random sample of the Proterozoic, there does appear to be a systematic difference between the reversal behaviour of the geomagnetic field in the Proterozoic from that in the Phanerozoic. Irving & Pullaiah (1975) have argued that the long periodicities (250 Ma) present in the reversed spectrum are a consequence of mantle processes. Therefore, it is possible that there may be a relation between persistent normal bias in the Proterozoic geomagnetic field and the different nature of early Proterozoic tectonics.

It is a great pleasure to acknowledge many helpful discussions with R. F. Emslie, S. C. Grommé, and Jean Roy. We are particularly grateful to S. C. Grommé for sending us a copy of an account of work by D. P. Elston and himself of which we were not previously aware.

References (Irving & McGlynn)

Baer, A. J., Emslie, R. F., Irving, E. & Tanner, J. G. 1974 *Geoscience Canada* **1**, 54–66.
Bell, K. & Blenkinsop, J. 1975 *Can. J. Earth Sci.* (In the Press.)
Bingham, D. K. & Evans, M. E. 1975 *Nature, Lond.* **253**, 332–333.
Buchan, K. L. & Dunlop, D. J. 1973 *Nature, Phys. Sci.* **246**, 28–30.
Bullard, J. E., Everitt, J. E. & Smith, A. G. 1965 *Phil. Trans. R. Soc. Lond.* A **258**, 41–51.
Card, K. D. & Pattison, E. F. 1973 *Geol. Assoc. Canada Sp. Pap.* **12**, 8–30.
Chappell, J. F., Brown, R. L. & Moore, J. M. 1975 *Geol. Soc. Am.* **7**, no. 6, 733.
Collinson, D. W. & Runcorn, S. K. 1960 *Geol. Soc. Am. Bull.* **71**, 915–958.
Davidson, A. 1972 *Geol. Assoc. Can. Sp. Pap.* no. 11, 382–433.
Doell, R. R. 1955 *Nature, Lond.* **176**, 1167.
Du Bois, P. M. 1962 *Geol. Surv. Can., Bull.* **71**, 1–71.
Eade, K. E. 1975 *Geol. Surv. Can. Mem.* 377.
Elston, D. P. & Grommé, C. S. 1974 *Geol. Soc. Am., Rocky Mountain Sec. Meeting.*
Elston, D. P. & Scott, G. R. 1973 *Earth planet. Sci. Lett.* **18**, 253–265.
Evans, M. E., Bingham, D. K. & McMurry, E. W. 1975 *Can. J. Earth Sci.* **12**, 52–61.
Fahrig, W. F. & Chown, E. H. 1973 *Can. J. Earth Sci.* **10**, 1556–1564.
Fahrig, W. F., Christie, K. W. & Schwarz, E. J. 1974 *Can. J. Earth Sci.* **11**, 18–29.
Fahrig, W. F. & Jones, D. L. 1969 *Can. J. Earth Sci.* **6**, 679–688.
Fahrig, W. F. & Larochelle, A. 1972 *Can. J. Earth Sci.* **10**, 1287–1296.
Fairbairn, H. W., Hurley, P. M. & Pinson, W. H. 1969 *Can. J. Earth Sci.* **6**, 489–497.
Frith, R. A. 1973 *Geol. Surv. Can. Pap.* 73–11, Pt. A, 146–148.
Gates, T. M. & Hurley, P. M. 1973 *Can. J. Earth Sci.* **10**, 900–919.
Hicken, A. E., Irving, E., Law, L. K. & Hastie, J. 1972 *Publ. Earth Phys. Br., Energy, Mines and Resour. Ottawa, Can.* **45**, 1–135.
Hoffman, P. F. 1973 *Phil. Trans. R. Soc. Lond.* A **273**, 547–581.
Irving, E. 1956 *Geofis. Pura. Appl.* **33**, 23–41.
Irving, E. 1964 *Paleomagnetism.* New York: Wiley.
Irving, E., Donaldson, J. A. & Park, J. K. 1972 *Can. J. Earth Sci.* **9**, 960–972.
Irving, E., Emslie, R. F. & Ueno, H. 1974 *J. geophys. Res.* **79**, 5491–5502.
Irving, E. & Green, R. 1958 *Geophys. J.* **1**, 64–72.
Irving, E. & Hastie, J. 1975 *Publ. Earth Phys. Br., Energy, Mines and Resour. Ottawa, Can.* (In the Press.)
Irving, E. & Lapointe, P. L. 1975 *Geoscience, Canada.* (In the Press.)
Irving, E. & McGlynn, J. C. 1975 *Can. J. Earth Sci.* (In the Press.)
Irving, E. & Park, J. K. 1972 *Can. J. Earth Sci.* **9**, 1318–1324.
Irving, E., Park, J. K. & Roy, J. L. 1972 *Nature, Lond.* **236**, 344–346.
Irving, E. & Pullaiah, G. 1975 *Earth Sci. Rev.* (In the Press.)
Irving, E. & Runcorn, S. K. 1957 *Phil. Trans. R. Soc. Lond.* A **250**, 83–99.
Jackson, G. D. & Taylor, F. C. 1972 *Can. J. Earth Sci.* **9**, 1650–1669.
Martineau, M. P. & Lambert, R. St J. 1974 *Geol. Assoc. Can.* Annual Meeting Program, p. 59.
McElhinny, M. W. 1973 *Palaeomagnetism and plate tectonics.* Cambridge University Press.
McGlynn, J. C. 1970 *Geol. Surv. Can., Econ. Geol. Rept.* 1, 5th ed. 85–101.
McGlynn, J. C., Hanson, G. N., Irving, E. & Park, J. K. 1974 *Can. J. Earth Sci.* **11**, 30–42.
McGlynn, J. C. & Irving, E. 1975 *Tectonophysics* **26**, 23–38.
McGlynn, J. C., Irving, E., Bell, K. & Pullaiah, G. 1975 *Nature, Lond.* (In the Press.)
McMurry, E. W., Reid, A. B. & Evans, M. E. 1973 *Eos. Trans. A.G.U.* **54**, 248.
McWilliams, M. O. & Dunlop, D. J. 1974 *Eos. Trans. A.G.U.* **55**, 226.
Moorbath, S. 1969 *Scot. J. Geol.* **5**, 154–162.
Muelberger, W. R., Denison, R. E. & Lidiak, E. G. 1967 *Am. Ass. Petrol. Geol. Bull.* **51**, 2351–2380.
Norris, D. K. & Black, R. F. 1961 *Nature, Lond.* **192**, 933–935.
Palmer, H. C. 1970 *Can. J. Earth Sci.* **7**, 1410–1436.
Palmer, H. C. & Carmichael, C. M. 1973 *Can. J. Earth Sci.* **10**, 1175–1190.
Park, J. K. 1975 *Can. J. Earth Sci.* (In the Press.)
Park, J. K., Irving, E. & Donaldson, A. D. 1973 *Geol. Soc. Am. Bull.* **84**, 859–870.
Patel, J. P. & Palmer, H. C. 1974 *Can. J. Earth Sci.* **11**, 353–361.

Pullaiah, G. & Irving, E. 1975 *Can. J. Earth Sci.* (In the Press.)
Pullaiah, G., Irving, E., Buchan, K. & Dunlop, D. J. 1975 *Planet. Sci. Lett.* (In the Press.)
Robertson, W. A. 1973 *Can. J. Earth Sci.* **10**, 1541–1555.
Robertson, W. A. & Fahrig, W. F. 1971 *Can. J. Earth Sci.* **8**, 1355–1372.
Roy, J. L. & Fahrig, W. F. 1973 *Can. J. Earth Sci.* **10**, 1279–1301.
Runcorn, S. K. 1955*a* *Phil. Mag. Suppl. Adv. Phys.* **4**, 244–291.
Runcorn, S. K. 1955*b* *Nature, Lond.* **176**, 505–506.
Runcorn, S. K. 1964 *Geol. Soc. Am. Bull.* **75**, 687–704.
Spall, H. 1971 *Geol. Soc. Am. Bull.* **82**, 2457–2472.
Stewart, A. D. & Irving, E. 1974 *Geophys. J. R. astron. Soc.* **37**, 51–72.
Stockwell, C. H. 1970*a* *Geol. Surv. Can., Econ. Geol. Rept.* **1**, 5th ed., p. 51.
Stockwell, C. H. 1970*b* *Geol. Surv. Can. Map* 1251A.
Stockwell, C. H. 1972 *Geol. Surv. Can. Pap.* 72–52, 1–4.
Sutton, J. & Watson, J. V. 1974 *Nature, Lond.* **247**, 433–435.
Symons, D. T. A. 1967 *Can. J. Earth Sci.* **4**, 1161–1164.
Ueno, H. & Irving, E. 1975 *Precambrian Research.* (In the Press.)
Ueno, H., Irving, E. & McNutt, R. H. 1975 *Can. J. Earth Sci.* **12**, 209–226.
Van Schmus, W. R. 1965 *J. Geol.* **73**, 775–780.
Wanless, R. K. & Eade, K. E. 1975 *Can. J. Earth Sci.* **12**, 95–114.
Williams, M. & Stevens, R. K. 1975 *Early Paleozoic continental margin of Eastern North America* (ed. C. A. Burk & C. L. Drake), 781–796. Berlin: Springer-Verlag.
Young, G. M. 1973 *Geol. Assoc. Can. Spec. Pap.* no. 12.

Discussion

G. E. Morgan (*Geophysics Department, Imperial College, London, S.W.*7). I would like to draw attention to the value of palaeomagnetic studies in regionally metamorphosed terrains, an aspect of Precambrian palaeomagnetism that has received relatively little attention until recently, but one which can potentially make unusually detailed contributions to our knowledge of Precambrian apparent polar wander paths. From the palaeomagnetic point of view the most important characteristic of these areas is that they almost certainly cooled extremely slowly. At least the later stages of cooling were probably caused by unroofing due to erosion, and a few simple calculations show that for typical rates of erosion at the present day it could take many millions of years for rocks to cool a few tens of degrees. This very slow cooling has several important implications

(1) Most rocks contain magnetic minerals with a range of blocking temperatures, so that with very slow cooling the magnetization process could have taken several tens of millions of years. Many cycles of secular variation would have occurred during this period, and so secular variation will have been effectively averaged out. Both within-site and between-site dispersion due to secular variation should be very small, and so palaeomagnetic results of very high precision should be obtained.

(2) Due to slow cooling, sampling sites that are at different levels compared to the ancient horizontal would have been magnetized at different times. Rocks at lower levels would have been magnetized millions of years after rocks say one kilometre higher. Now if apparent polar wander was occurring during this period of time the site mean poles should be affected by this, and so should be strung out in a linear trend corresponding to that particular section of the apparent polar wander path. It is not always necessary to have considerable vertical relief in the sampling area, as many regions have probably been tilted a few degrees from the original horizontal. Thus sampling over a horizontal distance of 20–30 km should correspond to a vertical distance of about 1 km.

(3) Sampling sites which are fairly close together, say within a few hundred metres, should

all give site mean poles which are very close together, because they would all have cooled at more or less the same time. However, if, because of differences in magnetic mineralogy, the mean blocking temperatures varied from one site to another, then the mean poles would be strung out along the linear trend according to their mean blocking temperatures, those with high blocking temperatures at the older part of the trend, and those with lower blocking temperatures at the younger part of the trend. As it should be possible by thermal experiments in the laboratory to determine the blocking temperatures of rocks from each site, it should be possible to distinguish between younger and older parts of the linear trend of poles.

(4) If the magnetization process took several tens of millions of years, then at each site the rocks contain the magnetic record of that interval of time, and if apparent polar wandering was occurring during that period, then progressive demagnetization, if it demagnetizes grains with successively higher blocking temperatures, should take the site mean pole back along the apparent polar wander path.

Thus, in a terrain which has experienced slow regional cooling, one should be able to define a whole section of the apparent polar wander path with considerable accuracy, and also to determine the sense of movement along the path.

I am currently investigating the palaeomagnetism of some Proterozoic rocks from a high grade metamorphic terrain on the west coast of Greenland, and to a greater or lesser extent all the phenomena described above are apparent in the palaeomagnetic results. It is not to be expected that every slowly-cooled terrain will show results of this sort, because there are at least two constraints. First there must of course be rocks of suitable palaeomagnetic stability present, and secondly the area must have been magnetized during an interval of constant magnetic polarity. If rocks cooled through their critical range of blocking temperatures over several tens of millions of years, and reversals occurred at a rate of 3–4 per million years, then clearly the rocks would have been effectively demagnetized.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES