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PRECAMBRIAN PALAEOMAGNETIC RESULTS COMPATIBLE WITH CONTEMPORARY OPERATION OF THE WILSON CYCLE

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ABSTRACT

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Sutures marking zones along which continental blocks have collided can be recognized on geological evidence in rocks with ages from Archaean onward. The existence of these sutures leads to the conclusion that the Wilson cycle of ocean opening and closing has been in operation since early Precambrian times. We have used published palaeomagnetic pole positions to test the validity of this conclusion by plotting APW (apparent polar wander) paths for suture-bounded blocks. We find that APW paths produced in this way fit the palaeomagnetic data better than APW paths for present-day continents or Pangea. Previous suggestions based on the interpretation of palaeomagnetic data that plate tectonics did not operate between about 2500 and 600 m.y. ago therefore appear invalid.

INTRODUCTION

There are few who now dispute that plate tectonics has operated since the beginning of the Mesozoic and there is fairly general agreement that the existence of a plate tectonic regime can be recognized from the rock record since about 600 m.y. ago but, as the report on the recent Penrose conference on pre-Mesozoic plate tectonics shows (Dewey and Spall, 1975), there is less agreement about global tectonic regimes during the Precambrian.

METHOD

We first compiled a map of the world showing sutures — that is, places at which we concluded from structural, stratigraphic, sedimentological, palaeoclimatic, petrological, geophysical, geochemical, radiometric and (for the Phanerozoic) fossil age evidence that we could see strong evidence of operation of the Wilson cycle of ocean opening and shutting (Wilson, 1968; Dewey

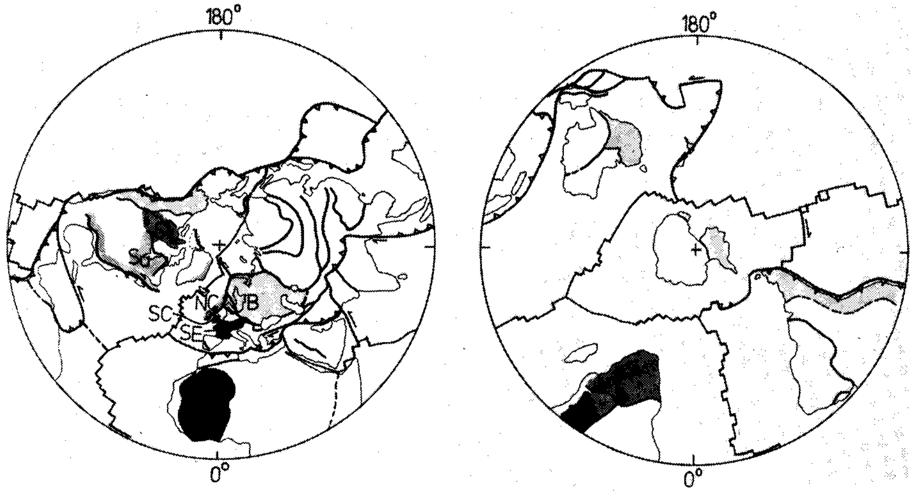

Fig. 1. Stereographic equal-angle (Wulff) projections of the world showing active plate boundaries and sutures — that is zones along which continental blocks have collided. SL = Slave and Wyoming province; SU = Superior province; NC = Northern Caledonides; SC = Southern Caledonides; SE = Southern Europe; B = Baltic Shield and Ukraine; WA = West African craton; EA = East African craton; SA = South African craton.

and Burke, 1974; Dewey and Spall, 1975). An equal-angle polar stereographic projection of this map forms Fig. 1.

The main respect in which our procedure for determining APW paths differed from that of most earlier authors who have plotted Precambrian APW paths was that instead of plotting paths for areas of continental dimensions, such as Africa, North America, Pangea, Gondwana or Laurasia, we treated suture-bounded blocks as separate. Since we knew, from radiometric and, in the Phanerozoic, fossil dating, when particular oceans had closed to form particular sutures we could predict independently of paleomagnetic evidence when APW paths that had been separate would unite. In general, these predictions have stood the test well. Our procedure for determining APW paths was as follows. We plotted, on polar Wulff nets, all category A poles from Hicken et al. (1972) and later results (list of references, poles and copies of Wulff net pole plots available on request) and then, treating suture-bounded blocks individually, constructed best fit APW paths. Our suggested APW paths are shown in Figs. 2, 3 and 5.

RESULTS

Africa and South America (Fig. 2)

Burke and Dewey (1972, 1973) interpreted the Precambrian structural development of Africa in plate tectonic terms seeing much of the boundary

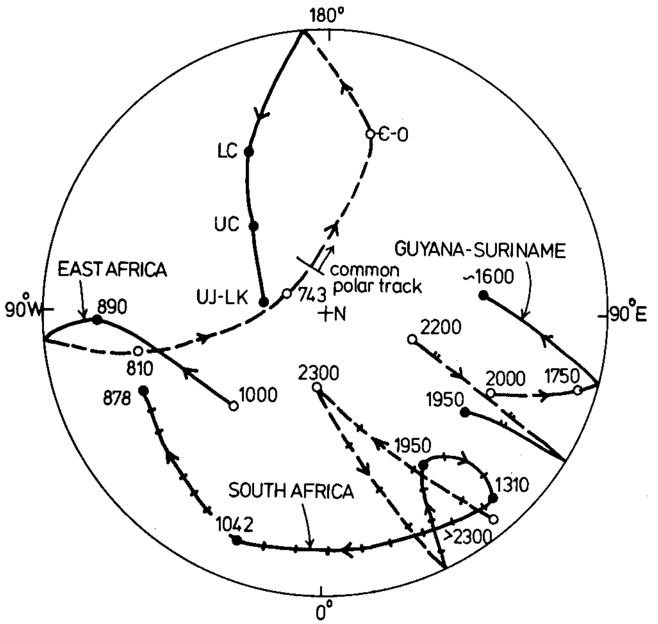

Fig. 2. Separate APW paths for the South African, East African and West African cratons join as a result of Pan-African suturing at about 600 m.y. In these figures continuous lines represent North pole paths in Northern hemisphere and dashed lines North pole paths in the Southern hemisphere. APW path from 2200 to 1950 m.y. represents West Africa.

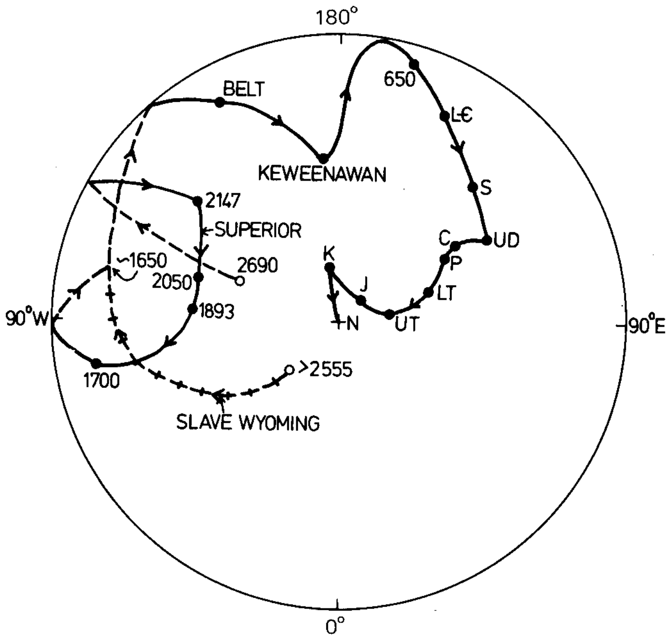

Fig. 3. The APW path for the Slave province and Wyoming joins that of the Superior at the time of Hudsonian suturing at Thompson.

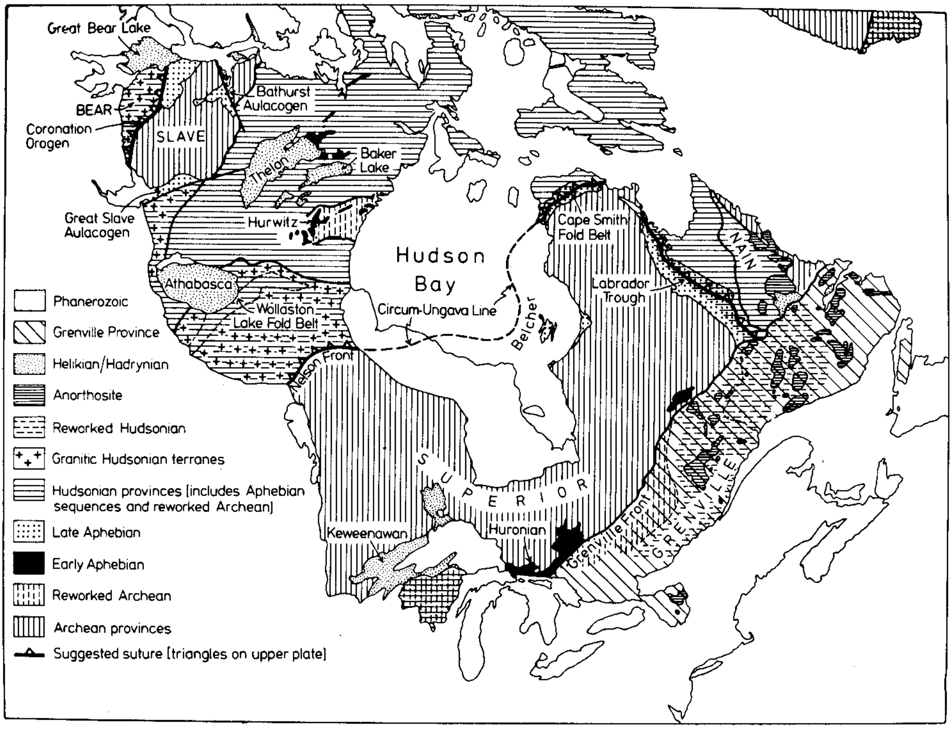

Fig. 4. Sketch map of the Precambrian of Canada to show how the great suturing event of Hudsonian times made North America one continent. The sutures of the Coronation orogen, Nelson-Thompson front, Cape Smith belt and the Labrador trough are all about 1700 m.y. old. The Wopmay fault lies on the site of the Coronation orogen suture.

between the reactivated Pan-African terrains and the older cratons as the sites of cryptic sutures and the reactivated terrains as products of Tibetan developments consequent on continental collision. On this interpretation, APW paths for Africa would combine in Pan-African times (about 600 m.y. ago) but would be expected to pursue different paths earlier.

Figure 2 shows a pole path for the West African craton between 2200 and 1950 m.y. ago which differs from a South African craton path of similar age. Between 1950 and 1042 m.y. all data come from South Africa and there is nothing to compare with it elsewhere on the continent except for a short period from 2000 to ~1600 for South America (Guyana and Suriname). From 1000 to 900 m.y. ago South and East Africa have different APW paths although they approach at 900 m.y. From 900 m.y. to 700 m.y. all data come from East Africa and from about 600 m.y. on Africa has a single pole path. Our conclusion is that although palaeomagnetic data from the Precambrian of Africa are rather sparse (cf. Irving and Lapointe, 1975), results currently available are compatible with our earlier interpretations based on geologic evidence alone and require that relative motion was taking place between continental blocks at least between 2200 and 1700 m.y. ago and again between 1000 and 900 m.y. ago. Thus, both geologic and palaeomagnetic evidence from Africa is compatible with operation of the Wilson cycle during the Proterozoic. Piper et al. (1973) reached a different conclusion regarding Africa as one continental block from at least 2400 m.y. ago, but they achieved this result only by rejecting published dates for some poles and by plotting their APW as a very wide swath. Their conclusions are no more consistent with the palaeomagnetic data than ours and entirely inconsistent with the geological evidence of Pan-African and earlier suturing.

North America (Fig. 3)

Wilson suggested in 1968 that there had been an episode of suturing around Ungava about 1700 m.y. ago; Gibb and Walcott (1971) modified this idea by extending the western side of the circum-Ungava suture to join the Nelson-Thompson front in Manitoba (Fig. 4). Dewey and Burke (1973) attributed the Hudsonian reactivation events broadly contemporaneous with the suturing to Tibetan phenomena accompanying the continental collisions. The end of a Wilson cycle with collision of an arc or continent appears to us to be represented by the development of the intrusive and volcanic rocks of the Bear batholith (Hoffman and Cecile, 1974) abutting against the deformed rocks of the Cornation geosyncline and Hepburn batholith (Hoffman, 1973) across the Wopmay fault which we would like to suggest marks a suture. Later suturing of arcs and continents to North America is recorded only in peripheral areas of the continent, such as the Cordillera; the Innuitian belt and the Appalachians although indistinct evidence of an Elsonian collision exists a little farther inland. The geological evidence thus indicates that APW paths for suture-bounded blocks in North America will be separate in the earlier Proterozoic and, except close to the edges of the continent, will come together at the time of the Hudsonian orogeny about 1700 m.y. ago.

Figure 3 shows the common APW path that was predicted for the Late Proterozoic from the geological evidence. For the interval from $\simeq$2700 m.y. (about the end of the Archaean) to 1600 m.y. ago, Fig. 3 shows that the Slave and Wyoming provinces appear to have moved together recording a short pole track in the Southern Hemisphere while the Superior province moved independently, the pole path rising into the Northern Hemisphere and then dropping back into the Southern. McGlynn et al. (1975) concluded that the Superior and Slave shared a common APW between 2200 and 1700 m.y., but this is inconsistent with the strong geologic evidence of suturing along the Labrador trough, the Cape Smith belt and the Nelson front and accords with the palaeomagnetic data only if Otish, Spanish River and most Abitibi dike poles are rejected for the Superior. McGlynn and Irving (1975) concluded that the Superior and Slave record separate though close APW paths during this interval and argued that the data are consistent with opening of an ocean and later suturing in roughly though not precisely the same place.

Much has been written about the palaeomagnetism of the Grenville and it has been argued that Grenville rocks yield poles indicating convergence on the North American polar wander curve at about 1 b.y. (see, for example, Irving et al., 1974; Palmer and Carmichael, 1973), but there is no geologic evidence of suturing between the Grenville and the rest of North America 1 b.y. ago and for this reason we reject this hypothesis. The geologic evidence accords better with the suggestion (Dewey and Burke, 1973) that the 1 b.y. old events in the Grenville represent Tibetan phenomena associated with a continental collison whose suture is perhaps exposed in southern Sweden (see Fig. 1) but is obscured elsewhere. It is becoming clear that Tibetan phenomena associated with collision include tremendous strike-slip faulting (Molnar and Tapponier, 1975) which has the effect of rotating pieces of continental lithosphere up to 1m km^2 in area about vertical and inclined axes through angles of tens of degrees.

Because of the high temperatures involved in basement reactivation and the long period (probably in excess of 10 m.y.) during which Tibetan environments remain hot, it seems improbable that palaeomagnetic vectors measurable in Grenville rocks record anything earlier than the $\simeq$1 b.y. collision event and the complex distribution of poles reported from the Grenville

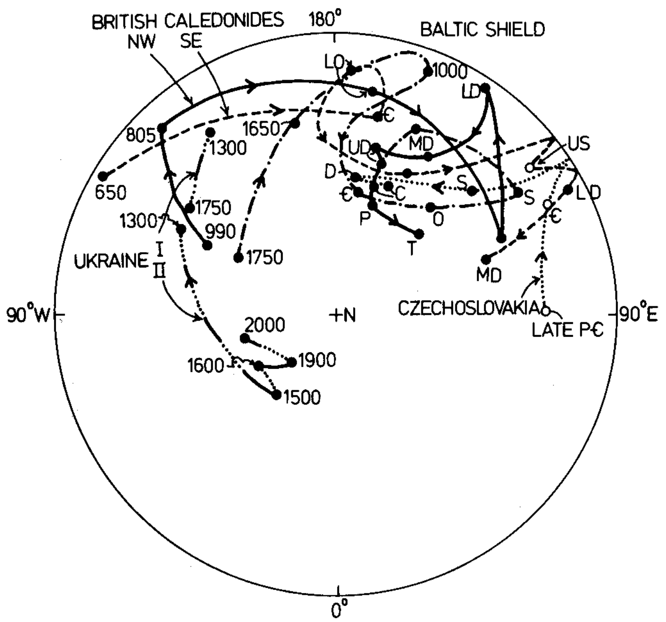

Fig. 5. APW paths for northeastern British Caledonides, for the Baltic shield and two paths for the Ukraine came together in Late Devonian times when Caledonian oceans have closed. The Czechoslovakian APW path joins in Late Carboniferous time.

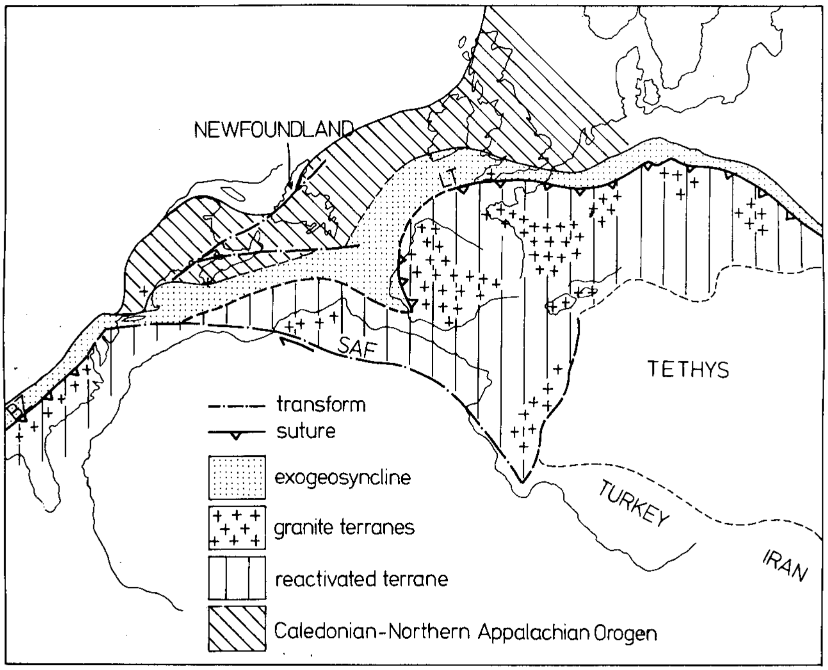

Fig. 6. Southern Europe and Africa joining northern Europe and North America along a suture in a Tibetan style collision to form Pangea in Late Carboniferous times. This event brought the APW paths of these continental blocks together and they remained together until the Central Atlantic opened in Early Jurassic times. The position of the suture in the United States has not yet been well defined but it probably lies southeast of where it is shown on this sketch.

seems readily explicable if the province contains areas which have undergone rotations about vertical and inclined axes (roller-bearing tectonics) of the kinds that Molnar and Tapponier (1975) have shown are happening in much of Asia today.

Europe (Fig. 5)

Dewey (1969) showed that, by Late Devonian times, the various Caledonian oceans had closed and Europe north of the Hercynian suture was in one piece. Separate APW paths are illustrated in Fig. 5 for the northwestern Caledonides; the southeastern Caledonides (on either side of Iapetus) and the Baltic shield. These paths join in Late Devonian time confirming Dewey's conclusion and that of McKerrow and Ziegler (1972). APW paths confirm that the three areas were separate in Precambrian time and whilst we recognize sutures on geologic evidence within the Baltic shield no palaeomagnetic data are available across these boundaries for significant time intervals. The

Czechoslovakian APW path is different from other European paths until Carboniferous times. Here, again, the paleaomagnetic results are consistent with the conclusions reached on geological evidence by McKerrow and Ziegler in 1972 and Dewey and Burke (1973). They located a suture marking the closure of a Rheic ocean in from the Lizard ophiolite complex to Bohemia (Fig. 6).

Ukraine (Fig. 5)

In general, recognition of continental displacement from palaeomagnetic evidence has followed recognition from more general geologic evidence. For example: Wegener (1912) and Du Toit (1937) preceded Runcorn (1956) in recognizing the opening of the Atlantic; Gibb and Walcott (1971) demonstrated the existence of the Nelson-Thompson suture before it was recog-

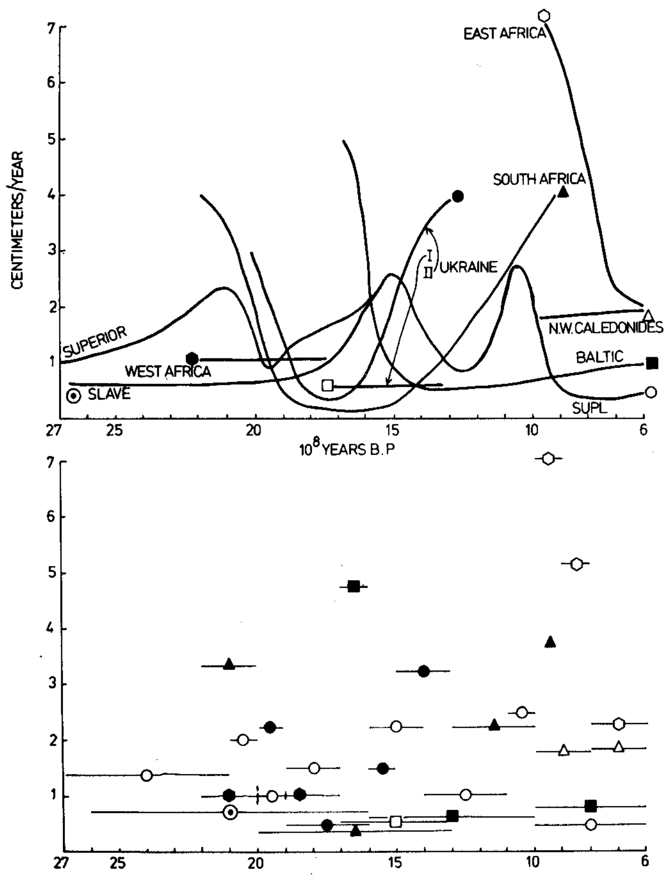

Fig. 7. Polar shift rates in cm/y plotted against time in years × 10^8 for individual continental blocks at specific times (below) and to show tentative variation in rate (above).

nized on palaeomagnetic evidence (this paper) and Burke and Dewey (1972) argued the widespread distribution of sutures in Africa from geological evidence before this was recognized from palaeomagnetism (this paper). We know of no geologic studies in the Ukraine indicating that the Precambrian rocks there contain a suture but it appears from Fig. 4 that two Ukrainian APW paths are separate at the latest date for which information is available (1300 m.y.). Both paths are distinct from the Baltic shield APW path so it looks as though palaeomagnetic evidence requires that there is a post-1300 m.y. suture within the Ukraine as well as one between the Ukraine and the Baltic shield although the magnetic data are not of the highest quality (Spall, 1972).

There are very few results for Europe before Ordovician times making all these observations highly speculative.

RATES OF POLAR SHIFT

Another approach we have tried is the highly speculative comparison of polar shift rates among the blocks we distinguish. For intervals when blocks lie on the same plate they will record the same rate of polar shift because the angular rate of polar shift for all parts of the plate will be the same. In Fig. 7 we plot the results of this approach. We see little resemblance between the rates for different blocks at the same time. However, features of interest do emerge: (1) The Grenville orogeny (~1000 m.y.b.p.) occurred at a time of rapid polar shift of North America with slow polar shifts both before and after; (2) a general low rate appears for the 1850—1650 m.y. interval; and (3) there is a general congruence of polar shift rates for the Superior, South Africa and part of the Ukraine during the interval 2000—1900 m.y. This congruence could be the result of the three blocks all lying on one plate at this time — although not necessarily forming one continental body on that plate.

DISCUSSION

The existence of APW paths shows that there was a mobile earth during the Precambrian — a static earth would yield a constant single pole from all blocks and this apparently never existed. If all continental blocks could be fitted to a single APW path, as Piper (1974) argued for the 2200—1730 m.y. interval, we would have had one large plate bearing all the continental blocks (perhaps a huge continent) moving with respect to the spin axis. Something approaching this happened during the nearly 100 m.y. long life of Pangea although there were quite large continental blocks, now forming much of Asia, moving in different ways with respect to the spin axis during that time. In general, during the Phanerozoic we have had between three and ten continents lying on different plates, moving in different ways with respect to the spin axis and producing different APW paths. The results described in this paper indicate that conditions were much th[illegible]hout the Proterozoic (too few results exist to permit statements about the Archaean).

Since it is widely accepted that a plate tectonic regime has operated throughout the Panerozoic, the general similarity of Proterozoic and Phanerozoic styles of apparent polar wander is compatible with the idea that a plate tectonic regime existed throughout the Proterozoic.

We have argued elsewhere (Burke et al., in press) for a Proterozoic plate regime because plate tectonics appears to provide a dominant mechanism in dissipating the heat generated within the earth. Sclater and Francheteau (1970) showed that about half of the earth's heat is used up in making lithosphere at mid-ocean ridges and in cooling this lithosphere as it ages. Later studies suggest that this estimate may be on the low side. Since in the Precambrian heat generation, mainly from uranium and potassium decay, was much greater than today (perhaps two or three times as large at the end of the Archaean) it seems reasonable to suggest that much of this additional energy was dissipated by a plate system running faster than that active now, either by having a greater total length of ridge or by faster spreading or, more probably, by a mixture of both processes. It seems unnecessary to consider a non-mobile Precambrian earth from which much of the heat was removed by conduction and in which steep thermal gradients persisted since, at present, heat dissipation is dominated by the convective processes of plate tectonics; it is clear that these processes are capable of coping with the need for greater heat dissipation in the past.

GEOLOGY AND PALAEOMAGNETICS COMPLEMENTARY

The complementary nature of geological and palaeomagnetic interpretations becomes clear from the results of our study. Geological evidence allows sutures to be identified and thus permits demarcation of blocks of continental lithosphere formerly bounded by ocean which can be expected to yield distinct APW paths. Although geological evidence is required to identify the sites of former oceans palaeomagnetic evidence complements it by permitting some estimates to be made of the sizes of the oceans that have closed. The extent and intensity of tectonism at a suture is so great (Molnar and Tapponier, 1975) that it makes estimation of the size of an ocean that has closed from geological evidence impossible. Most of the rocks that are preserved when an ocean has closed form at one or the other of two times: (1) just as the ocean opens when large volumes of graben facies and miogeoclinal wedges deposited; and (2) just before the ocean closes when arcs, especially Andean arcs and large volume flysch fans (Graham et al., 1975) arc active. Because of this the rocks preserved at a suture are very similar whether the ocean that has closed is 500 or 5000 km wide. All oceans are small twice — once when they first form and once just before they close — and it is at these times that most of the rocks preserved after collision form.

CONCLUSIONS: SUTURES OR HALLUCINO-SUTURES?

Most geologists agree that the Indus suture north of the Himalaya (Dewey, 1969; Dewey and Burke, 1973; Molnar and Tapponier, 1975) marks the site of closing of a substantial ocean and there is similar agreement that the Urals mark the site of suturing of Europe and Asia in Permian time (Hamilton, 1969) but no such consensus exists regarding the character of many of the older lines marked as sutures on Fig. 1. This is partly because at the levels of exposure general in these old terrains the sutures may be represented by no more than a sliver of serpentinite, a few flakes of fuchsite or merely a mylonite zone. We have called these zones cryptic sutures (Burke and Dewey, 1972) although Shackleton has suggested (in Dewey and Spall, 1975) that hallucino-sutures might be a more appropriate name.

The alternative views of old sutures may be summarized thus: either (1) in these places the association of some or all of graben facies rocks, miogeoclinal wedges, arc-rocks and dismembered ophiolites with exogeosynclinal rocks on one side and reactivated ensialic (Tibetan style) terrains on the other has the same implication that it has today: namely the sutures are the sites of ocean closure; or (2) these facies could be made and brought into association by some other processes which are no longer active. That is to say some other tectonic regime capable of simulating the results of plate tectonic obtained in the Proterozoic. In our view, as the rock associations can be adequately explained by the plate-tectonics in operation today, it is inappropriate to invoke some necessarily less well-defined mechanism that operated in the past and no longer operates today.

To palaeomagneticians who wish to help resolve this issue without getting involved in geological controversy, we would suggest that APW paths be constructed separately for (1) suture-bounded blocks, as the plate-tectonic interpretation requires and (2) continent-sized blocks as those who see Proterozoic tectonics as ensialic require.

Our presentation in this paper indicates that palaeomagnetic data accord as well with the plate tectonic interpretation as with the ensialic regime interpretation. We have made no attempt to discuss possible sources and magnitudes of error in Precambrian palaeomagnetic studies as Irving and Lapointe (1975) have recently discussed this question. However, it would be a mistake to underestimate these errors since differences in pole positions smaller than 10° can rarely be measured, Precambrian radiometric dates are rarely accurate to better than 50 m.y., there is often doubt as to whether measured ages and magnetizations were acquired simultaneously and since the source of much studied material is from within collision orogenic belts where late large-scale rotations about vertical and inclined axes are the rule rather than the exception. For these reasons there must be a question as to how much palaeomagnetic studies can as yet add to the analysis of Precambrian tectonics. We suggested, in an earlier section, that palaeomagnetic studies might be complementary to geological studies since the latter could show where an ocean lay but not how wide it was, and palaeomagnetism could ideally allow an estimate of the width of this ocean. Although inferences can be made about relative longitudinal positions of localities on the same continental block, no such inferences are possible for localities which were on different plates when they acquired their magnetization. For this reason it might be argued that since estimates of ocean widths are likely to have errors $>10°$ in latitude and of unknown longitudinal amount, palaeomagnetic studies of the Precambrian are not at present able to add much useful information to conventional geologic studies. In this paper we have not adopted that extreme view.

REFERENCES

Burke, K. and Dewey, J.F., 1972. Orogeny in Africa. In: T.F.J. Dessauvagie and A.J. Whiteman (editors), African Geology, Ibadan, 1970. Geol. Dept., Univ. Ibadan, Nigeria, pp. 583—608.

Burke, K. and Dewey, J.F., 1973. An outline of Precambrian plate development. In: D.M. Tarling and S.K. Runcorn (editors), Implications of Continental Drift to the Earth Sciences, 2. Academic Press, pp. 1035—1046.

Burke, K., Dewey, J.F. and Kidd, W.S.F., in press. In: B.F. Windley (editor), NATO Conference on Oldest Rocks.

Dewey, J.F., 1969. Continental margins: A model for the transition from Atlantic-type to Pacific-type. Earth Planet. Sci. Lett., 6: 187—197.

Dewey, J.F. and Burke, K., 1973. Tibetan, Variscan and Precambrian basement reactivation: products of continental collison. J. Geol., 81: 683—692.

Dewey, J.F. and Burke, K., 1974. Hot spots and continental break-up: Implications for collisional orogeny. Geology, 2: 57—60.

Dewey, J.F. and Spall, H., 1975. Pre-Mesozoic plate tectonics: How far back in earth history can the Wilson cycle be extended? Geology, 3: 422—424.

Du Toit, A.L., 1937. Our Wandering Continents. Oliver and Boyd, 366 pp.

Gibb, R.A. and Walcott, R.I., 1971. A Precambrian suture in the Canadian Shield. Earth Planet. Sci. Lett., 10: 417—422.

Graham, S.A., Dickinson, W.R. and Ingersoll, R.V., 1975. Himalayan—Benegal model for flysch dispersal in Appalachian—Ouachita system. Geol. Soc. Am. Bull., 86: 273—286.

Hamilton, W., 1969. The Uralides and the motion of the Russian and Siberian platforms. Bull. Geol. Soc. Am., 81: 2553—2576.

Hicken, A., Irving, E., Law, L.K. and Hastie, J., 1972. Catalogue of palaeomagnetic directions and poles. Publ. Earth Phys. Branch EMR, Ottawa, 45 (1).

Hoffman, P.F., 1973. Evolution of an early Proterozoic continental margin; In: I. Sutton and B.F. Windley (editors), Evolution of the Precambrian Crust. Philos. Trans. R. Soc. London, Ser. A, 273: 547—581.

Hoffman, P.F. and Cecile, M.P., 1974. Volcanism and plutonism, Sloan River map-area, Great Bear Lake, District of Mackenzie. Geol. Surv. Can. Pap., 74-1A: 173—176.

Irving, E., Emslie, R.F. and Ueno, H., 1974. Upper Proterozoic palaeomagnetic poles from Laurentia and the History of the Grenville Structural Province. J. Geophys. Res., 79: 5491—5502.

Irving, E. and Lapointe, P., 1975. Palaeomagnetism of Precambrian rocks of Laurentia. Geosci. Can., 2: 90—98.

McGlynn, J.C. and Irving, E., 1975. Palaeomagnetism of Early Aphebian diabase dykes from the Slave Structural Province, Canada. Tectonophysics, 26: 23—38.

McGlynn, J.C., Irving, E., Bell, K. and Pullaiah, G., 1975. Palaeomagnetic poles and a Proterozoic supercontinent. Nature, 255: 318—319.

McKerrow, W.S. and Ziegler, A.M., 1972. Palaeozoic oceans. Nature, 240: 92—94.
Molnar, P. and Tapponier, P., 1975. Cenozoic tectonics of Asia: Effects of a continental collison. Science, 189: 419—426.
Palmer, H.C. and Carmichael, C.M., 1973. Palaeomagnetism of some Grenville Province rocks. Can. J. Earth Sci., 10: 1175—1189.
Piper, J.D.A., 1974. Proterozoic crustal distribution, mobile belts and apparent polar movements. Nature, 251: 381—384.
Piper, J.D.A., Briden, J.C. and Lomax, K., 1973. Precambrian Africa and South America as a single continent. Nature, 245: 244—248.
Runcorn, S.K., 1956. Palaeomagnetic comparisons between Europe and North America. Proc. Geol. Assoc. Can., 3: 301.
Sclater, J.G. and Francheteau, J., 1970. The implications of terrestrial heat flow observations on current tectonic and geochemical models of the crust and upper mantle of the earth. Geophys. J., 20: 509—542.
Wegener, A., 1912. Die Entstehung der Kontinente. Geol. Rundsch, 3: 276—292.
Wilson, J.T., 1968. Origin of Hudson Bay. In: J.F. Beals (editor), Science, History, and Hudson Bay. Dept. Energy, Mines and Resources, Ottawa. p. 1015—1027.