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LOG Id: LOG_0015
LOG Titel: A geotectonic paradox: has the earth expanded?
LOG Typ: article

Übergeordnetes Werk

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J. Geophys. 49, 20–25 (1981)

Journal of Geophysics

A Geotectonic Paradox: Has the Earth Expanded?

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Abstract. From the recognition of *common apparent polar-wander* (CAPW) paths for Africa, Australia, Greenland, and North America in the early Proterozoic, we have deduced that these continents today occupy approximately the same relative locations on the globe as they did in the early Proterozoic. However, there is abundant geochemical, geological, geochronological and tectonic evidence for landmasses having been much less dispersed in the Precambrian than they are now. It is shown in this paper that an Earth of about half the present radius accomodates the present continents in such a manner that this paradox can be satisfactorily resolved, and we propose that between about 1,600 Myr and 1,000 Myr ago, the Earth expanded to approximately its present dimensions. A change from Proterozoic to Phanerozoic tectonic styles is supported.

Key words: Tectonics – Earth expansion – Palaeomagnetism.

Introduction

Two types of model have been proposed to characterize the development of foldbelts (mobile belts) during the Proterozoic: those based on horizontal motions (plate tectonics), and those relying more on vertical motions (ensialic orogeny). The applicability of plate tectonic processes has been questioned, on the basis of the geological relationships between the mobile belts and their adjacent Archaean cratons (Clifford 1968; Anheusser et al. 1969; Shackleton 1969; Sutton and Watson 1974). In addition, Briden (1973) gives palaeomagnetic evidence from African cratons which 'flatly eliminates the possibility that hemisphere-sized oceans have been destroyed between these cratons'. Similar palaeomagnetic analyses of data from Africa (Piper et al. 1973), Australia (McElhinny and Embleton 1976; McElhinny and McWilliams 1977) and North America (Irving and Park 1972; Irving and McGlynn 1976; Roy and Lapointe 1976; Irving and McGlynn 1979; Irving 1979) indicate that Proterozoic mobile belts are not a consequence of large-scale horizontal motion, although it has always been accepted that small-scale motion would not be detectable. If small-scale motions were such that ocean basins closed, leaving the juxtaposed landmasses exactly as they were before opening, then obviously the motions would not affect *apparent polar-wander paths* (APWP). However, it has been stressed that this style of tectonics should only be expected under very special circumstances (McElhinny and McWilliams 1977) and, as Briden (1973) emphasizes, instantaneous Euler poles for young ocean basins move substantially, reducing the probability of reversibility.

In the face of the above, Burke et al. (1976) and Cavanough and Seyfert (1977) still propose large-scale horizontal motions and consequent collisions between cratons as the cause of Proterozoic mobile belts on the grounds of uniformitarianism, and have constructed sophisticated APWP for the North American Proterozoic in support of their proposals. However, this approach has been widely criticized by palaeomagnetists (McElhinny and McWilliams 1977; Roy et al. 1978; Irving 1979) because the APWP is needlessly corrupted. While large-scale horizontal motions have been shown to have occurred in recent geological time, it remains conjecture to extrapolate these recent tectonic styles to ancient geological situations. Until two decades ago, the uniformitarian doctrine was that the continents had never moved with respect to each other but, in the light of Palaeozoic and Mesozoic palaeomagnetic data (first obtained by Runcorn 1956; Creer et al. 1957; Graham and Hales 1957; Irving and Green 1958), this view had to be abandoned. Thus uniformitarian arguments can be completely misleading and, in fact, the over-riding opinion among authors is that tectonic styles have changed through geological time.

Comparisons of Proterozoic Apparent Polar-Wander Paths (APWP)

Analyses of Phanerozoic palaeomagnetic, palaeogeographic, biographical and climatological data (Smith et al. 1973; Irving 1977; Morel and Irving 1978; Scotese et al. 1979) all reveal that the continents were clustered in two or three supercontinents, which apparently drifted independently prior to their union to form Pangaea in the middle to late Phanerozoic.

Proterozoic reconstructions of continents are a more speculative topic. Piper et al. (1973) present palaeomagnetic evidence that Africa and South America, which comprise a major part of Gondwanaland, existed as a single continent from as early as 2,200 Myr until 500 Myr ago (i.e., from the beginning of the Proterozoic until its breakup in the late Phanerozoic). They suggest furthermore that North America might have been a part of this supercontinent, at least until 1,000 Myr ago. Subsequently, Piper (1974, 1976) concluded that most of the continental crust formed a Pangaea (in the broad sense) during the Proterozoic. However, Irving and McGlynn (1979) contend that the palaeomagnetic and geochronological evidence is insufficient to argue convincingly for or against the hypothesis of a single supercontinent.

Our approach (Embleton and Schmidt 1979) has been to compare APWP for the few intervals of time for which path sections are fairly well established for more than one continent. These are: (i) 2,300 Myr to 1,900 Myr ago, for which APWP have been constructed for North America (Irving and McGlynn 1976; Roy and Lapointe 1976; Irving and McGlynn 1979; Irving 1979) and

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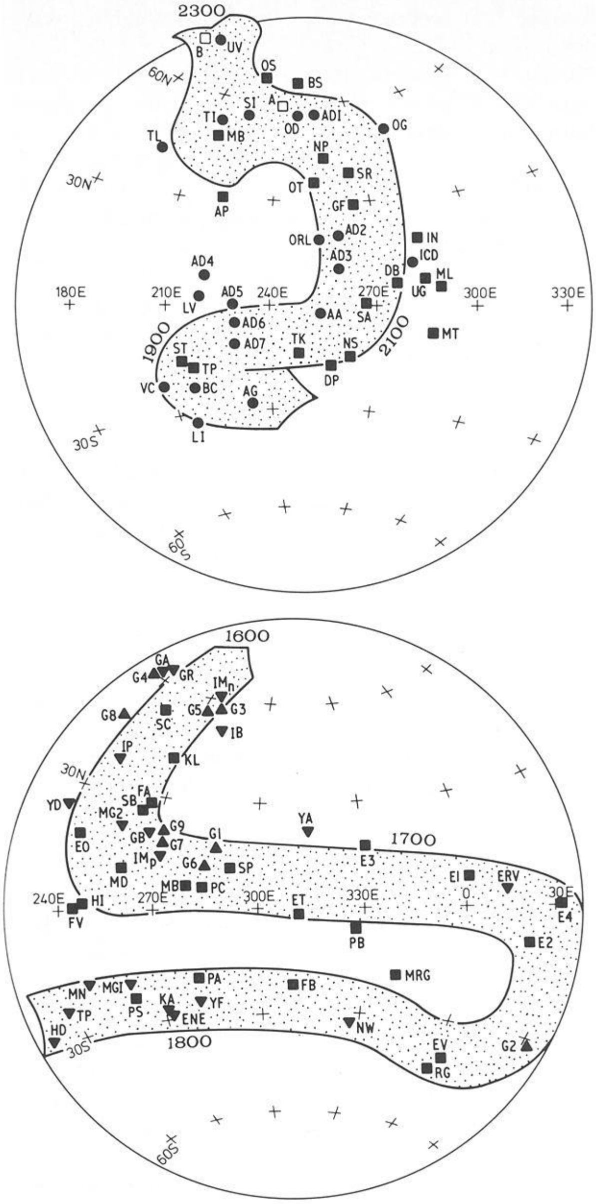

Fig. 1. Common apparent polar-wandering (CAPW) path from 2,300 Myr to 1,600 Myr ago. *Circles* are poles from Africa, *inverted triangles* from Australia, *upright triangles* from Greenland and *squares* from North America (after Embleton and Schmidt 1979). *Open symbols* refer to the obscured hemisphere. No reconstructions have been used

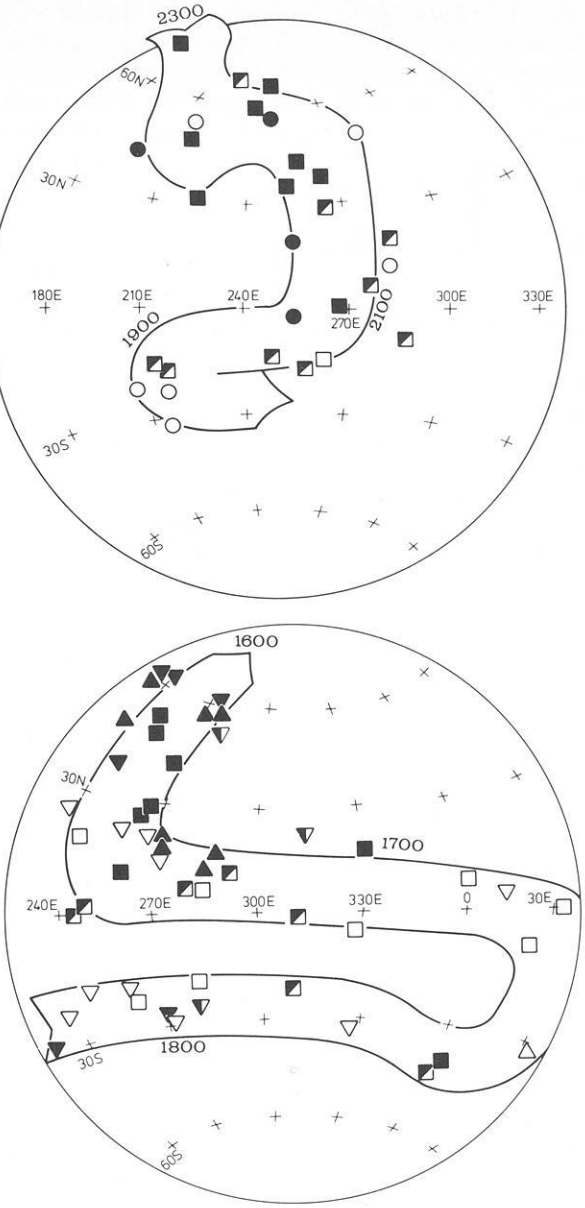

Fig. 2. Polarity patterns for the data plotted in Fig. 1. The polarities of magnetization of rock units have been determined, assuming the paths are north polar tracks. *Closed symbols* represent normal polarities, *open symbols* represent reversed polarities, and *other symbols* represent mixed polarities

for Africa (Piper et al. 1973; Briden 1973); and (ii) 1,800 Myr to less than 1,600 Myr ago, for which APWP have been defined for Australia (McElhinny and Embleton 1976; McElhinny and McWilliams 1977) and for Greenland (Piper and Stearn 1976), and through which the North American data cited above extend.

The agreement between the APWP from the different continents plotted on the present-day globe is striking (Fig. 1) and we find it very surprising that these Proterozoic pole positions should lie along the same path. On the other hand, it would not have been surprising to find this had we first constructed a supercontinent such as Pangaea, which existed in the early and middle Phanerozoic. Common apparent polar wandering (CAPW) would appear to have occurred relative to these three continents in their present-day positions.

Implications for the Arrangement of Precambrian Continents

From a fixed disposition, Africa, Australia, Greenland and North America, in much the same form as we now know them, apparently began to drift with respect to each other sometime after 1,600 m.y. ago. The continents coalesced to form Laurasia and Gondwanaland, which in turn formed Pangaea before the Mesozoic disintegration, returning them to their primaeval locations. This aspect of the data raises some important considerations regarding the early history of the continents. While the possibility of true polar wandering having occurred is interesting in itself, it is the relationships between the various continents, rather than the relationships of the continents and the pole, which are of prime concern here

The simplest interpretation of the data plotted in Fig. 1 is that, in the Proterozoic, the continents were arranged in a similar manner to their present-day configuration. Another possibility is that one (or more) of the pole paths has been assigned the wrong polarity, resulting in a 180° error in plotting the data, which would result in a 180° error in reconstruction of those continents from which the data had been obtained.

We believe we can eliminate this latter possibility on the grounds of the polarities of pole positions plotted in Fig. 2. If the pole paths shown in Fig. 1 are assumed to be north polar paths, then the polarities of rock units can be defined to be normal if greater than 90% of the samples studied have positive magnetic inclinations and the collection sites are closer than 90° to the pole position, or if the inclinations are negative and the sites are greater than 90° from the pole. Reversed polarities are defined if the converse of the above is true, and mixed polarities are defined on the basis of the ratio of polarities falling between 10% and 90%. Some directional data, particularly for African pole positions, are unavailable and consequently it is not yet possible to assign polarities to these poles (Piper et al. 1973). If the pole paths are actually south pole paths, then obviously the opposite of these definitions holds, but this does not affect the following argument.

While necessarily crude, the basic polarity biases revealed in Fig. 2 are fairly clear. Normal polarities predominate from 2,300 Myr to about 2,100 Myr ago, when reversed polarities become more common. Around 1,650 Myr ago normal polarities again prevail. If we had inadvertently assigned the opposite polarity to one of the pole paths, then it is doubtful that any pattern at all would have emerged, rather the paths should appear to be uniformly mixed. Thus we feel confident that the polarity convention assigned is the same for all pole paths – whether the real polarities are normal or reversed is immaterial at this stage.

A Tectonic Paradox

If continents have returned to relative locations similar to those that they occupied during a large part of Proterozoic time, then some fundamental tectonic mechanism must surely be implicated, which should be capable of explaining (i) why continents that were widely separated were not in relative motion and (ii) what became of the intervening crust when the continents eventually drifted to form supercontinents. On the basis of the distribution of Proterozoic foldbelts and their associated cratons, Hurley and Rand (1969), Engel and Kelm (1972), Hargraves (1976), Glikson (1976) and Moorbath (1977) believe that these ancient regions are now much more dispersed on the globe than when they were formed.

The tectonic argument as discussed by Engel and Kelm (1972) and Hargraves (1976) reveals a symmetrical alignment of major Archaean tectonic patterns over 3,000 Myr old within the framework of pre-drift continental clusters. From an analysis of the best preserved of these terrains in North America, Africa, Australia and India, it is apparent that the 'global tectonics between 2.5 and 0.7 b.y. did not involve the large-scale rifting, dispersion, reorientation and reagglomeration of the continental clusters that is typical of the post-Permian' (Engel and Kelm 1972). Evidence based on basement ages complements the tectonic argument and indicates that shield areas, when considered to be clustered in coherent groups, are surrounded by progressively younger continental crust. Such an ordered 'concentric arrangement and the limited degree of scattering of the ancient continental cratons make it difficult to conceive of a series of drift motions prior to the breakup that occurred within the last 200 million years' (Hurley and Rand 1969).

The notion of a coherent sialic regime was clearly favoured by Glikson (1979). However, in response to an explanation regarding the nature of the remaining three-quarters of the Earth's crust, Glikson concluded that 'a tectonically inert simatic regime is difficult to reconcile with the intense tectonic and thermal activity in contemporaneous mobile belts' An alternative model, comprising 'dispersed sial and sima plates', was discounted on geochemical grounds, unless evidence for a Proterozoic simatic regime has been removed (e.g., by subduction) without leaving a geological and geochemical trace. However, it is precisely this configuration of continental dispersion that is clearly favoured from our analysis of the palaeomagnetic data.

There are therefore two contradictory lines of argument. isotope geochemistry, geochronology and tectonics, favouring the in situ growth of mega-continents; and palaeomagnetism, apparently indicating dispersion of continents during the early Proterozoic. We believe that the evidence for both interpretations is cogent enough to warrant an attempt to reconcile this paradox.

A Possible Solution

The simplest interpretation of the palaeomagnetic data alone is to maintain the present Earth dimensions and invoke a modified, non-random form of plate tectonics. In the light of the geological and geochronological evidence for the existence of super-continents in the Precambrian, such an approach would appear to be naive. All aspects must be considered if the paradox is to be resolved.

We have noted previously (Embleton and Schmidt 1979) that the Lower Proterozoic and present locations of the continents are consistent with Carey's (1976) model of radial Earth expansion. However, we are not refuting the palaeomagnetic evidence against expansion according to Carey (Cox and Doell 1961; Ward 1963, 1966; McElhinny et al. 1978), but rather we are drawing attention to the fact that if the Earth expanded such that the continents moved radially apart, then the gross effect on the palaeomagnetic data would be very similar to that actually recorded (Fig. 1). Palaeomagnetic pole positions are invariant under radial expansion. This point has been elaborated recently (Schmidt and Clark 1980) and shown to indicate that an insignificant amount of Earth expansion has occurred since the Palaeozoic. Thus we are in full agreement with McElhinny et al. (1978), who applied Ward's (1963, 1966) method and concluded that Earth expansion is limited to 0.8% in the last 400 Myr. The intriguing point is that Proterozoic expansion of the Earth resolves the above paradox. The effect of expansion on the pole paths is shown in Fig. 3. By comparison with Fig. 1, it is clear that the general form of the pole paths remains the same for an Earth of almost half the present radius as it does for the present-sized Earth.

The method employed to recalculate the pole positions plotted in Fig. 3 is an adaptation of Ward's method (1963, 1966). First the mean palaeomagnetic site geographic coordinates are calculated for each separate continent and these points used as the zero-stress points in Ward's model. The method is not very sensitive to the choice of zero-stress point (Van Hilten 1968) unless it is greater than 90° away from the palaeomagnetic sites, in which case Ward's model fails (Schmidt and Clark 1980). This situation does not arise in the present analysis.

Each palaeomagnetic site and pole subtends the same geocentric angle for different Earth radii, so the effect of reducing the

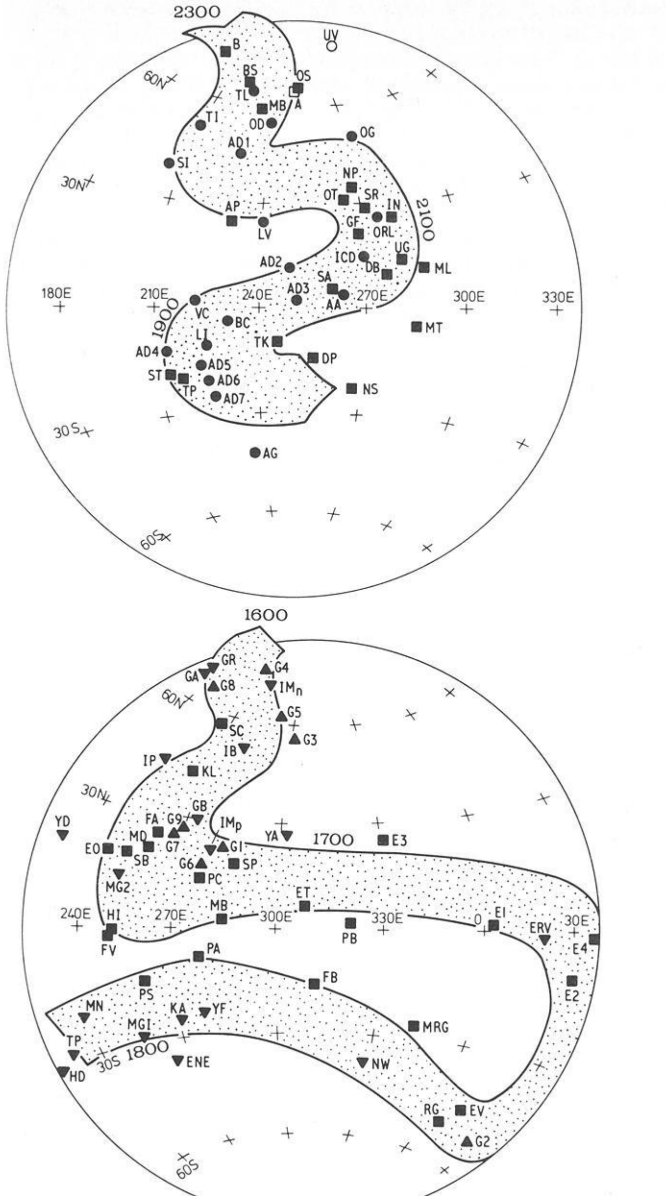

Fig. 3. The pole positions plotted in Fig. 1 have been recalculated following Ward (1963), for a small Earth of a radius equal to 0.55 of the present radius. This demonstrates the general invariance of APWP for different radii

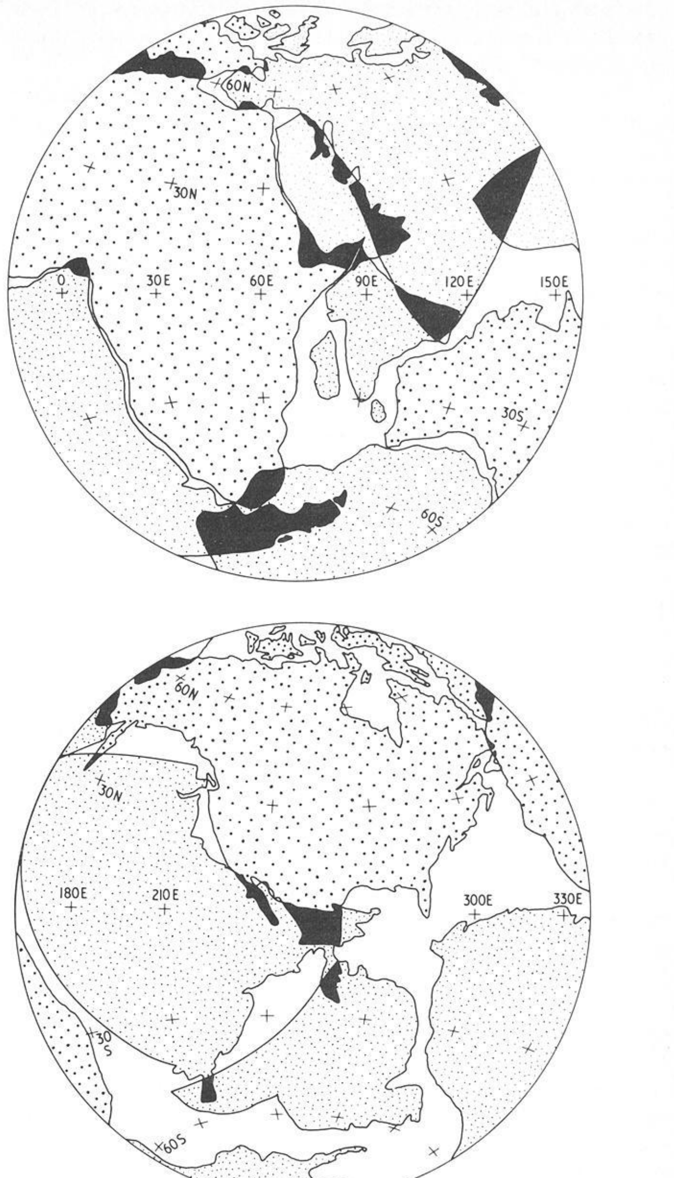

Fig. 4. The continental outlines have been recalculated and fitted for a small Earth of 0.55 present radius by using an adaptation of Ward's (1963) method

radius and recalculating site and pole coordinates is to redistribute the poles, because the geocentric angle between sites and the zero-stress point will increase. This is the basis of Ward's method as applied to Phanerozoic data, and the radius that corresponds to the best grouping of poles (highest k, see Fisher 1953) is assumed to be the most likely radius. This radius estimate is probably biased upwards slightly, due to distortion inherent in the transformation (Schmidt and Clark 1980).

Precambrian palaeomagnetic data are not yet amenable to such treatment because they are relatively scarce and their age estimates are too imprecise. Interestingly enough, though, there appears to be a tendency for poles to group more closely at about 2,100 Myr and 1,900 Myr (and perhaps 2,200 Myr) ago on the small Earth model than they do on the present-sized Earth. It is not possible at this stage to ascertain the significance of this, because there is a possibility of real age differences between some of these poles. Nevertheless, the analogous application of Ward's method to Precambrian data would be to search for the radius that yields the most refined (narrowest and probably least complex) APWP. From this point of view, the small Earth model is seen to have some merit.

The choice of a globe with a radius equal to 0.55 of the present Earth radius stems from the demonstration (Creer 1965) that the present continents can be fitted to it without leaving serious underlap or overlap. The fit 'appears too good to be due to coincidence and hence requires explaining' (Creer 1965). While Creer used perspex shells for model continents, which proved far superior to earlier attempts at sketching continents on small globes, we have digitized the continental outlines (roughly every 10°) and used Ward's method to recalculate the outlines for an Earth model of 0.55 present radius.

The main continents, with the exception of Eurasia, have been treated as individual and indivisible crustal units, in keeping with their supposed primaeval integrity (see above). Smaller islands, isthmuses and peninsulas (many of recent origin) have been dispensed with to simplify the analysis. The continental elements comprising Eurasia existed as a number of distinct regions during much of the Phanerozoic (Morel and Irving 1978; Scotese et al. 1979), and Eurasia has been subdivided accordingly into Baltica, Siberia, India and China (after Scotese et al. 1979).

There is little point in attempting a more rigorous treatment of Eurasia, which has undergone so much post-Proterozoic deformation. Indeed all continental areas have been deformed to some extent relatively recently, and there is obviously a difficulty in recognizing ancient outlines, particularly in the Pacific region. Thus it is unreasonable to expect that an analysis such as this should lead to the perfect fitting of present continents on a smaller globe. For Africa, Australia, Greenland, and North America, the same zero-stress point as that used for the palaeomagnetic analysis was used in calculating the continent outlines on the small globe. For other continental fragments, a point near the centre of each was chosen.

Once continental outlines were transformed to the small globe, Africa, Australia, Greenland, and North America were held fixed, because the pole positions plotted in Fig. 3 were calculated from these locations. South America was reconstructed to its pre-drift location by using an Euler pole equivalent to that defined by Smith and Hallam (1970), and Antarctica and Arabia were likewise reconstructed to Australia and Africa respectively. Siberia was fitted against the west coast of North America according to Sears and Price (1978), then India and China were fitted by inspection. Because of the slight, though unavoidable, distortion of the continental outlines on the small globe, it is not possible to calculate exactly equivalent Euler poles to those used on the present-sized Earth. However, taken in the context of this analysis, the problem is insignificant.

The resulting reconstruction (Fig. 4) reveals considerably more underlap than overlap, probably due to the omission of some small landmasses. Overall, though, the continents appear to interlock remarkably well. By implication, the proto-hydrosphere is present in the form of epicontinental seas. Most areas of overlap are related to Cenozoic or Mesozoic deformation, although those in North Africa and Greenland, and South Africa and Antarctica, appear to be related to Palaeozoic foldbelts. Thus for an Earth of 0.55 present radius, Proterozoic geological, geochronological and palaeomagnetic information can be simultaneously resolved.

While the Earth-expansion hypothesis is at present a controversial topic, it is perhaps appropriate to draw an analogy with the development of the plate tectonic theory. It is barely two decades ago that many eminent geophysicists denounced any suggestion that continents would drift. Now only an insigificant few doubt it. As Creer (1965) concluded, 'It may be fundamentally wrong to attempt to extrapolate the laws of physics as we know them today to times of the order of the age of the Earth and of the Universe'.

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Received February 19, 1980; Revised Version July 22, 1980
Accepted August 15, 1980