Part II

SCIENTIFIC PAPERS

1.1. POSSIBLE RATES OF RELATIVE CONTINENTAL MOTION

G. D. GARLAND
(University of Toronto, Canada)

ABSTRACT

Much of the evidence for continental drift, such as the matching of coastlines, provides only an average rate over a very long time interval. Palaeomagnetic results give average velocities between 0·5 and 3·0 cm/yr, with higher values for some areas such as India. These also represent average rates over long times. Very recent research on the magnetic character of the ocean floors suggest that the present rate of ocean floor spreading can be determined. The continents of South America and Africa may be separating at a rate of 4·0 cm/yr.

RÉSUMÉ

La plupart des témoignages de la dérive des continents donnent seulement une vitesse moyenne correspondant à une période très longue. Les résultats paleomagnétiques donnent des vitesses moyennes entre 0·5 et 3·0 cm/an, avec des valeurs plus grandes pour l'Inde. Les recherches nouvelles sur le caractère magnétique du fond des mers peuvent indiquer la vitesse présente; il est possible que les continents de l'Amérique du Sud et d'Afrique se séparent à 4·0 cm/an.

A great deal has been written during the past five years in support of the hypothesis of continental drift, although objections to it remain. The purpose of the present paper is not to engage in arguments for or against, but simply to review the estimates that are available on the possible rate of continental movement, assuming that it has indeed occurred. These estimates can be deduced from certain of the arguments that have been advanced by authors who have written in favour of the theory.

From the point of view of astronomical tests, however, it is important to distinguish between estimates of average rate over long geological periods, and estimates of present-day velocities. Obviously, it is the latter which are important to any programme of measurements to detect continental displacements within a reasonable number of years, but most of the older estimates give only the former quantity.

The estimates of average rate over a long geological time can be deduced from many of the standard arguments in favour of continental drift. These include:

a. the matching of coastlines, originally by eye and more recently by computer (Bullard *et al.*, 1965);

b. the dispersal of areas of similar climatic history, such as those of Carboniferous glaciation;

c. the displacement of continents as indicated by palaeomagnetic measurements.

All observations of these types give only a displacement, and to determine a rate of

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movement, a time must be associated with the movement. For example, a. and b. suggest the displacement of South America relative to Africa, a distance of 5500 km, in the time since the close of the Carboniferous (280×10^6 years). A minimum rate of movement is therefore 2·0 cm per year, but this evidence by itself does not preclude the possibility that the displacement was accomplished in much more recent time with a correspondingly greater drift rate. In fact, it has been suggested on geological grounds that most of the separation of Africa and America took place in the last 150×10^6 years. Since the rebirth of interest in continental drift owes much to the results of palaeomagnetic measurements, it is desirable to renew the nature of the observations and their role in establishing a rate in some detail.

Measurements of the vector-magnetic intensity of either a sedimentary or an igneous rock are assumed to give the direction of the earth's magnetic field at the time of formation of the rock. Much has been written on the sources of possible complicating factors (see, for example, Runcorn, 1962) but it is now generally accepted that anomalous cases (unstable magnetization, subsequent chemical alteration, etc.) can be recognized, and that reliable determinations of the direction of the field are available at many points for a series of times over at least the past 500 million years. If the dipole nature of the earth's field is assumed, the inclination of the magnetization vector in the sample gives, uniquely, the original magnetic latitude of the site. The original longitude of the site is indeterminate, and the azimuth toward the ancient pole cannot be determined if the rock mass from which the sample was obtained suffered any rotation during its history. If it is assumed that no rotation has occurred, the palaeomagnetic measurements yield an ancient pole position. Measurements from samples of different geological age give a "polar-wandering curve", leading toward the present north magnetic pole for very young samples (Figure 1). A single polar-wandering curve indicates only the possible motion of the poles relative to the earth's surface as a whole. Evidence for continental drift is obtained only when discrete curves are obtained from samples collected from different curves, as shown also in Figure 1. The fact that these curves are displaced from each other is evidence for continental displacement since the date of formation of the rocks on which curves are based. The curves thus converge toward the present pole, and the rate of convergence, in a sense, indicates a rate of drift. The westerly displacement of the Americas from Europe and Africa is indicated in Figure 1, but even more striking are the curves for Australia and Antarctica, which suggest very large displacements for these continents. Since each point on any of the polar-wandering curves is simply the centre of a rather large region of uncertainty, it is difficult at present to use the displacement of the curves to determine a meaningful drift rate. Estimates of drift rate have been made (Deutsch, 1966) from the change in latitude of samples alone, since, as noted above, this is the quantity best determined by palaeomagnetic measurements. Once again, the rate obtained is simply an average over the whole time since the rock was formed, and there is no way of telling if the change in latitude was accomplished in a much shorter time. Considering samples from six land masses, excluding India, Deutsch obtains a range of average drift rates, in latitude only, of 0·5–2·5 cm/year, in the time since Carboniferous. When very young rocks (less than 25×10^6 years old) alone are considered, the indicated rates of drift in latitude range from 0 to 3 cm/year. The case of India is of particular interest, as there is strong evidence for a northward drift of that landmass in the past 60 million years, indicating a rate of 4–12 cm/year.

Most of the estimates of drift rate over shorter periods, which are probably more appropriate to the present day, are related to observations of the ocean floor. There is

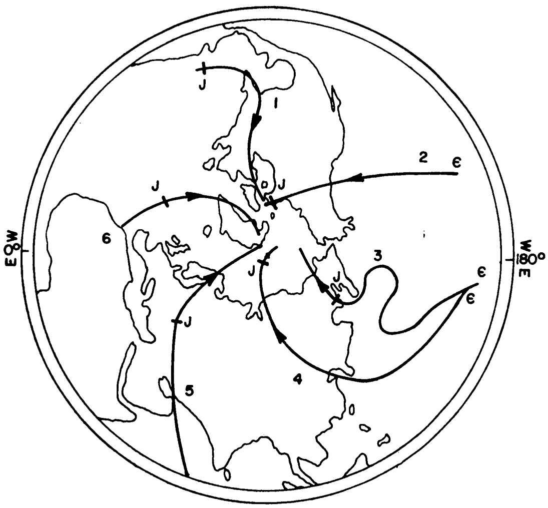

FIG. 1. *Examples of polar-wandering curves (after Deutsch). Curves are numbered according to location of samples; 1. India; 2. Africa; 3. W. Europe; 4. N. America; 5. Antarctica; 6. Australia. The letters* ∈ *and J correspond to Cambrian and Jurassic times respectively.*

considerable evidence (Dietz, 1961) that the floors of oceans are created from basaltic material injected along the oceanic ridges (Figure 2), and then carried to either side. Although it is not the intention here to discuss mechanisms, it may help to visualize the process if one thinks of the oceanic crust subjected to forces provided by mantle-convection cells, with currents rising under the ridges, and dragging the oceanic crust horizontally toward the loci of downward currents. Wilson (1963) has noted that the isotopic ages of oceanic islands increase with distance from the ridges and has proposed that they were all formed at the ridge, and swept aside. He has produced a graph of age versus distance which indicates a horizontal velocity of 3.5 cm/year. There is considerable scatter to the points on the graph, but the rate does appear to be appropriate to within a few million years of the present time.

Wilson (1966) and others have also suggested that rift valleys, such as the Red Sea or the East African rifts represent an earlier stage in the process of oceanic spreading.

If this is the case, The Red Sea represents an opening of 500 km in 25×10^6 years, giving a rate of separation of 2 cm/year. The corresponding figures for the East African Rifts are 50 km in 12×10^6 years or a separation of 0·4 cm/year.

However, it now appears that there is a much more precise method to study the spreading of the ocean floor, and that is by means of the magnetic character of the oceanic crust. Air-borne and ship-borne magnetometer surveys of the oceans have revealed a remarkably linear pattern of anomalies in the magnetic field, with strips of alternately high and low field. The amplitude of these anomalies is such

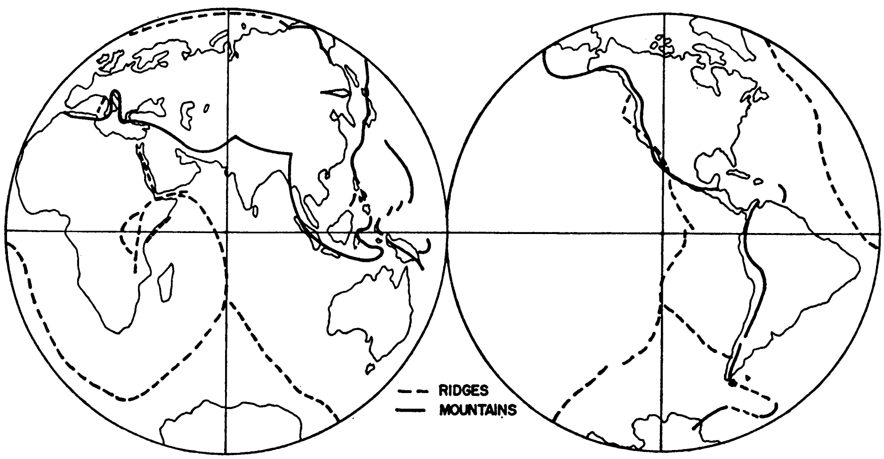

FIG. 2. *The world ridge system.*

that it would be very difficult to explain them in terms of differences in the susceptibility of the oceanic crust. They appear to require the presence of bands of rock, with permanent magnetization alternating between the normal and reversed direction. The fact that the bands are roughly parallel to oceanic ridges led Vine and Matthews (1963) to suggest that they represent rock injected at the ridges, polarized in the direction of the magnetic field at the time of emplacement, and subsequently moved aside. Strong support to this hypothesis is lent by the remarkable symmetry of the pattern on the two sides of a ridge (Figure 3) and by the fact that the widths of bands correlate with the varying lengths of periods of reversals in the earth's main field. The time scale of reversals for the past four million years has been established independently from studies on other rocks, and this indicates four major periods with at least three short-period "events" superimposed on them. The pattern in the vicinity of the ridges is in striking agreement with this timescale.

The power of this method is that it provides a spreading rate up to very recent times – virtually the present rate of spreading, as contrasted with other methods, and that it can be applied to different parts of the oceans in turn. Pitman and Heirtzler (1966) have shown that the spreading rate on either side of the Pacific–Antarctic ridge is 4·5 cm/year, in contrast to a rate of 1 cm/year for the Atlantic Ocean south of Iceland. There is evidence that the spreading rate for the South Atlantic is perhaps twice as great as for the North, as though the Atlantic were opening with a pivotal motion, the pivot being north of Iceland.

There is reason to believe, therefore, that a most powerful method is available for determining the present rate of ocean-floor spreading. However, for our present purpose,

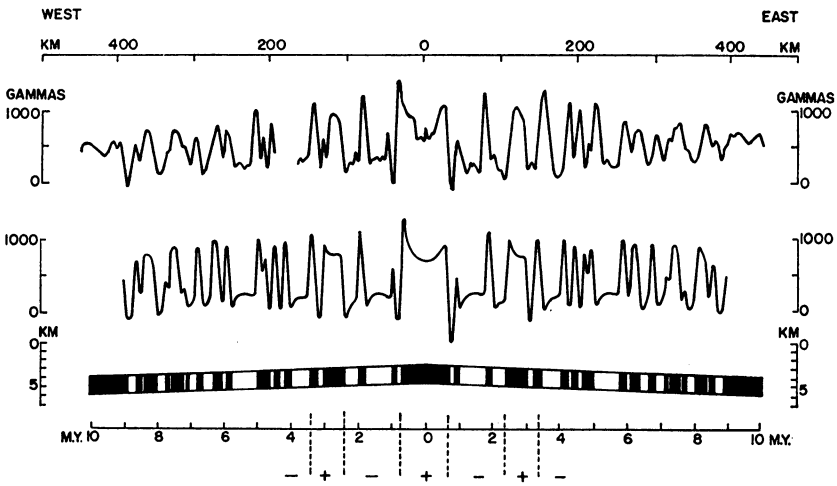

FIG. 3. *Magnetic profile observed (upper) across the Pacific Antarctic Ridge. The lower curve is computed for the assumed ocean-floor structure of normally – and reversely – magnetized blocks shown below it. The time scale for the four most recent epochs of geomagnetic polarity is also shown. (After Pitman and Heirtzler.)*

a careful distinction must be made between ocean-floor spreading and relative motions of the continents. That the two motions are different is obvious when one considers the case of South America: evidently, both the South Atlantic and South-Eastern Pacific Oceans are spreading, but the continent cannot be moving west and east at the same time. The explanation is that the spreading oceanic crust must, in some places, be dragged under the continents, so that continental masses ride over it. It appears that this down-dragging takes place along the line of oceanic trenches, these being assumed to represent the loci of downward convection currents. If this is the case, continents on either side of an ocean with a spreading floor may not move apart if there is such a feature intervening. There is a well-defined trench along the west coast of South America, but there is not in the Atlantic between South America and Africa. It may therefore be assumed that Africa and South America are separating at a rate equal to twice the spreading velocity appropriate to the South Atlantic. This would give a rate of separation of as much as 4 cm/year, assuming that the spreading velocity is twice that found south of Iceland.

Magnetic surveys of the ocean floors are being extended at present by a number of groups, and may be expected to suggest other areas of rapid spreading. On the basis of presently-available evidence the pattern of movement in the Indian Ocean appears to be complicated. For the direct testing of continental drift, therefore, one probably cannot do better at the moment than to take sites on either side of the South Atlantic. Because of the pivotal nature of the motion, mentioned above, a gain of a factor of 2 or 3 is achieved over the rate of separation in the North Atlantic, and this could well make the difference between a detectable or non-detectable displacement in a reasonable number of years.

Measurements in other locations would be useful to test other parts of the hypothesis. For example, precise determination of the position of oceanic islands could be used to test the rate of ocean-floor spreading, and islands on either side of the Pacific-Antarctic ridge could be expected to separate at the very high rate of 9 cm/year. Finally, in some areas, such as across the Red Sea, direct geodetic, as opposed to astronomical, measurements could be used to detect separation.

Measurements of this type have already been made by Danish and Canadian groups to test for relative motion between Greenland and the Canadian Arctic islands.

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