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The Relative Motion of 'Hot Spots' in the Atlantic and Indian Oceans During the Cenozoic*

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Summary

Reconstructions of the Greenland, Eurasia, North America, Africa, South America and India plates to their relative position at the times of anomalies 13 (38 My) and 24 (60 My) imply relative motion of about 10–20 mm/yr among the principal 'hot-spots' in the Atlantic and Indian Oceans during the Cenozoic.

Introduction

Among the more prominent, poorly-understood features of the ocean floor are the linear island chains and aseismic ridges. The topographic expression of these features is usually interpreted as the result of an unusually large amount of volcanism. In general, dating of the oldest rocks found at any point along the chains or ridges points to a monotonic increase in age with increasing distance from an active volcano ('hot-spot') marking the younger end (Wilson 1965). The volcanic chains, which are imbedded in the lithosphere, are often inferred to result from the motion of the plates over sources beneath the lithosphere (Morgan 1971; Wilson 1965). The cause of the origin of these sources, however, is a hotly-debated subject, and unfortunately critical tests of most of the theories do not exist.

If these chains and ridges result from sources beneath the lithosphere, then the velocities at which the spots move with respect to each other provide important constraints on the convection process in the mantle beneath the plates. For instance, if the inferred 'hot-spots' were found to be fixed with respect to each other, then such a result would imply a very stable pattern of convection and could be used as strong support for Morgan's (1971) contention that narrow plumes rise from the lower mantle to form these volcanoes and their associated traces. Alternatively, if the 'hot-spots' moved rapidly with respect to each other, then the origin of at least some of the linear volcanic chains and ridges might better be ascribed to another phenomenon, such as a crack propagating through the plates (Betz & Hess 1940; Jackson & Wright 1970; Menard 1964; Turcotte & Oxburgh 1973), and localized volcanic sources (or spots) beneath the plates might not exist at all. The use of the global set of 'hot-spots' as a reference frame in which the motions of the plates can be measured is useful only in so far as the set is rigid or the motion of its components is fully known.

Thus far, three published studies have directly attacked the problem of how much the 'hot-spots' move with respect to each other. Minster *et al.* (1974) concluded that

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there had been no measurable relative motion among them during the last 10 My. Molnar & Atwater (1973) concluded that during the last 38 My the principal ' hot-spots ' in the Atlantic and Indian Oceans moved at 8–20 mm/yr with respect to the Hawaiian spot. Burke, Kidd & Wilson (1973) concluded that since the Mid-Cretaceous the Central and South Atlantic ' hot-spots ' moved at an average of about 20 mm/yr (and up to 60 mm/yr) with respect to each other. Because of the problem of defining ' hot-spots ' and their traces, difficulties in sampling and dating the rocks along the traces, and inaccuracies of plate reconstructions, aspects of each of these studies are vulnerable to criticism. Consequently we present another test of the fixity of ' hot-spots ' by considering traces in the Atlantic and Indian Oceans that formed during the Tertiary. We did not consider the Azores or Colorado Seamount, as did Burke *et al.* (1973), because of the ambiguity in determining the linear volcanic chain that lies on sea-floor of early Tertiary age and that is associated with these spots.

Reconstructions

To examine the relative motion of the ' hot-spots ' we reconstructed the positions of the surrounding plates at the times of anomalies 13 and 24, which are respectively 38 and 60 My old, according to the magnetic reversal chronology of Heirtzler *et al.* (1968). These anomalies were chosen because they are among the best defined. The uncertainties in the ages of these anomalies is probably not much more than 10 per cent and has a negligible effect on the results discussed below. Parameters for the reconstructions are given in Table 1. The differences between the parameters for the North Atlantic used here and by Pitman & Talwani (1972) are not important for the present study. To check the rotation parameters, we rotated anomalies 13 and 24 from maps given by Herron & Talwani (1972), Pitman & Talwani (1972), and Vogt & Avery (1974) in the North Atlantic, Ladd, Dickson & Pitman (1973) in the South Atlantic, and McKenzie & Sclater (1971) in the Indian Ocean, and from the fit of these anomalies we confirmed that the parameters used were accurate. Because most of the angular rotations are small and the poles for finite rotations are well determined, except for the Indian plate, the relative positions of the plates are probably uncertain by less than 100 km. The position of India, and therefore the Ninety-East Ridge, with respect to Africa is less well determined than the Atlantic reconstructions. With respect to the other plates the position of the India plate is probably uncertain by 200 km.

To test whether the ' hot-spots ' remained fixed with respect to each other, we considered various possible positions of the reconstructed plates with respect to the Iceland spot. Assuming the ' hot-spots ' have not moved with respect to each other, we then compared the relative positions of the various other spots and their respective traces. If the ' hot-spots ' had not moved with respect to each other, then each would have underlain its respective trace. Because we did not observe this, by exploring a number of possible positions of the plates with respect to Iceland we determined lower bounds for the maximum possible displacements, or rates of motion, among the ' hot-spots '. Without more reliable dating of the islands and volcanic chains, we cannot determine the component of relative motions of the spots parallel to their respective traces.

Whereas the reconstructions of the relative positions of the plates may be determined objectively and easily from the position of magnetic anomalies and fracture zones, determination of the positions of the plates with respect to the ' hot-spots ' is less simple. We assumed that the Iceland spot has always been close to the Greenland–Eurasia accreting plate boundary, but this assumption does not yield unique reconstructions. For either time considered, one is free both to rotate the reconstructed plates about a pole through the Iceland spot, and to choose the position of the Iceland spot along the Greenland–Eurasia plate boundary. To examine the first condition, all

Table 1

Rotation Parameters*

		Lat. (°N)	Long. (°E)	Angle†	Ref.
Eurasia					
To Iceland (anom. 13–38 My)	(1)	41·5	107·5	−1·4‡	(1)
	(2)	69·3	128·0	−2·0	(2)
	Equivalent	58·4	115·4	−3·3	
To Iceland (anom. 24–60 My)	(1)	41·5	107·5	−3·3‡	(1)
	(2)	69·3	128·0	−2·0	(2)
	Equivalent	52·3	111·5	−5·1	
Greenland					
To Iceland (anom. 13–38 My)	(1)	69·3	128·0	4·0	(2)
	(2)	41·5	107·5	2·8‡	(1)
	(3)	41·5	107·5	−1·4‡	(1)
	(4)	69·3	128·0	−2·0	(2)
	Equivalent	58·5	114·6	3·3	
To Iceland (anom. 24–60 My)	(1)	69·3	128·0	4·0	(2)
	(2)	41·5	107·5	6·6‡	(1)
	(3)	41·5	107·5	−3·3‡	(1)
	(4)	69·3	128·0	−2·0	(2)
	Equivalent	52·5	110·5	5·1	
North America					
To Europe (anom. 13–38 My)		62·8	137·0	7·2‡	(3)
To Europe (anom. 24–60 My)		62·8	137·0	13·0‡	(3)
To Iceland (anom. 13–38 My)		62·8	157·5	4·0	
To Iceland (anom. 24–60 My)		64·5	160·6	8·2	
Africa					
To North America (anom. 13–38 My)		70·5	−18·7	−10·4	(4)
To North America (anom. 24–60 My)	(1)	70·5	−18·7	−10·4	(4)
	(2)	70·6	− 3·3	− 8·8	(4)
	Equivalent	70·9	−11·7	−19·2	
To Iceland (anom. 13–38 My)		50·8	7·5	− 8·0	
To Iceland (anom. 24–60 My)		−47·5	171·2	14·5	
South America					
To Africa (anom. 13–38 My)		67·3	−39·5	14·0‡	(5)
To Africa (anom. 24–60 My)		67·3	−39·5	21·4‡	(5)
To Iceland (anom. 13–38 My)		−60·6	74·0	− 7·9	
To Iceland (anom. 24–60 My)		−65·1	37·4	−10·3	
India					
To Africa (Somalia) (anom. 13–38 My)		16·0	48·3	−22·4	(6)
To Africa (Somalia) (anom. 24–60 My)	(1)	16·0	48·3	−22·4	(6)
	(2)	11·1	19·1	−11·8‡	
	Equivalent	12·8	38·5	−33·2	
To Iceland (anom. 13–38 My)		24·3	38·9	−28·4	
To Iceland (anom. 24–60 My)		21·3	24·7	−43·6	

Notes to Table 1

* All rotations are with respect to a reference frame attached to the Greenland–Eurasia accreting plate boundary and the presumed ' hot-spots ' in their present position.

† Angles give motion of named plate in a right-handed sense.

‡ Angle of rotation from this paper.

References

(1) Le Pichon *et al.* (1974)

(2) Minster *et al.* (1974)

(3) Le Pichon *et al.* (1971).

(4) Francheteau (1973).

(5) Le Pichon & Hayes (1971).

(6) McKenzie & Sclater (1971).

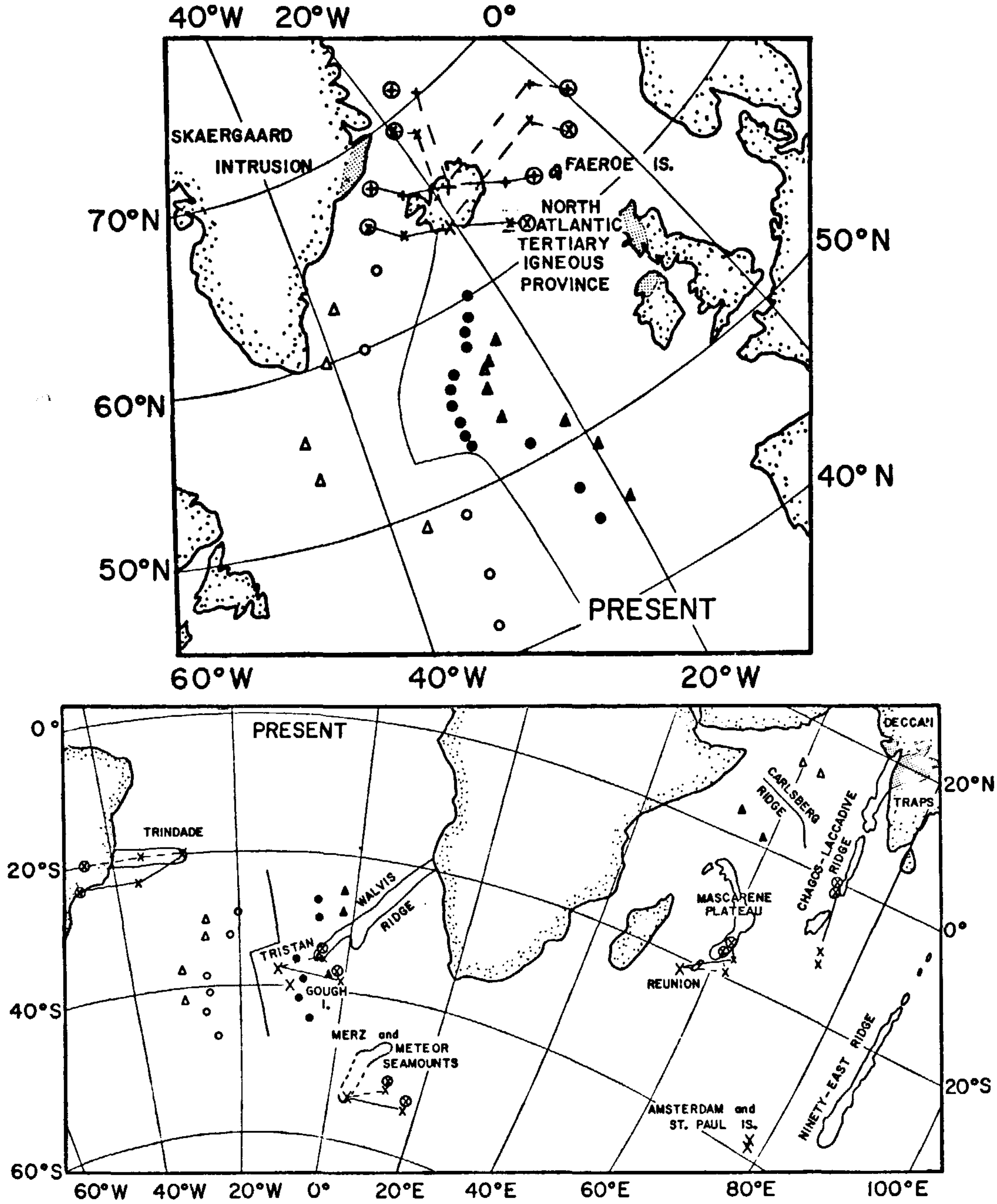


FIG. 1. Land boundaries, magnetic anomalies, 'hot-spots' (crosses), and their traces (crudely sketched) for (a) the North Atlantic, and (b) South Atlantic and Indian Oceans. Circles and triangles show magnetic anomalies 13 and 24 respectively. Closed symbols for Africa and Eurasia plates, open symbols for North and South America and India plates. Large (present) and small crosses and plus signs with circles surrounding them (anomaly 24) and without circles (anomaly 13) show positions of 'hot-spots' with respect to plates, assuming 'hot-spots' are fixed with respect to one another. Continuous and dashed lines connecting these symbols show motions (flow lines) of plates with respect to 'hot-spots' for two models discussed in text. For solid line model (Figs 2 and 4 below), with respect to Greenland and North America, the positions of proposed 'hot-spots' beneath Myvatn or Surtsey are assumed to be close to the Tertiary volcanic rocks on each plate. Note that possible 'hot-spots' beneath Tristan da Cunha or Trindade would have been south of their respective traces. Conversely for dashed line model (Figs 3 and 5 below) the proposed 'hot-spots' at Tristan da Cunha and Trindade underlie the Walvis Ridge and the trace west of Trindade, but proposed Iceland spots would be far north of Iceland (Figs 3 and 5).

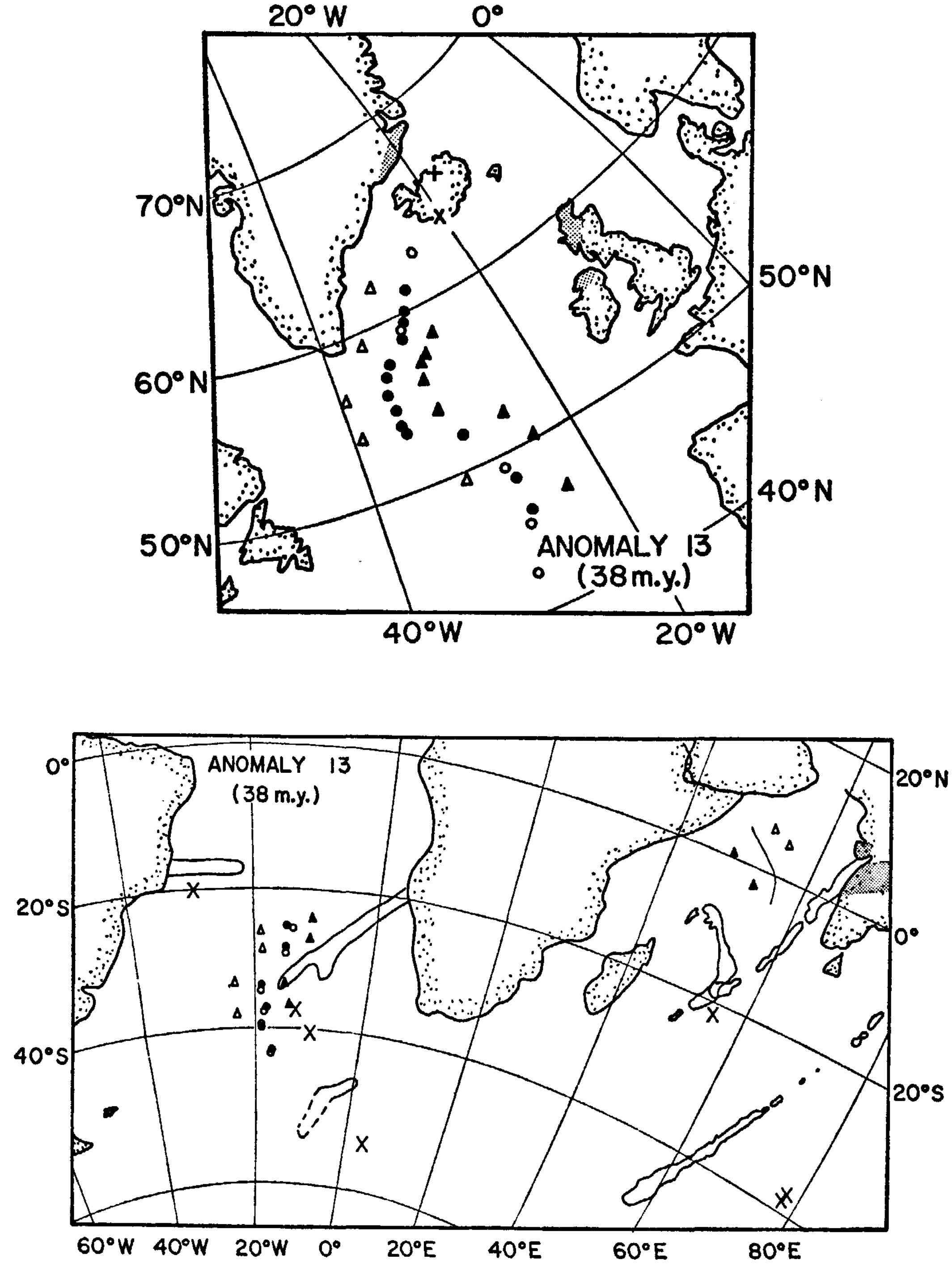


FIG. 2. Reconstruction for the time of anomaly 13 (about 38 My) for (a) the North Atlantic, and (b) South Atlantic and Indian Oceans, assuming no component of motion of a ' hot-spot ' beneath Iceland along the Mid-Atlantic Ridge. Symbols same as in Fig. 1. In this and all subsequent maps ' hot-spots ' are held fixed with respect to the co-ordinate system, and the plates with their ' hot-spot ' traces and magnetic anomalies are moved. If ' hot-spots ' generated their respective traces and remained fixed with respect to one another, at all times they would underlie their respective traces. Note that except for Iceland which is assumed to underlie its trace, all others do not underlie their respective traces. The worst case is the Ninety-East Ridge which is 1000 km from either Amsterdam and St Paul's Islands or Kerguelen (at about 50° S, 70° E, off the map).

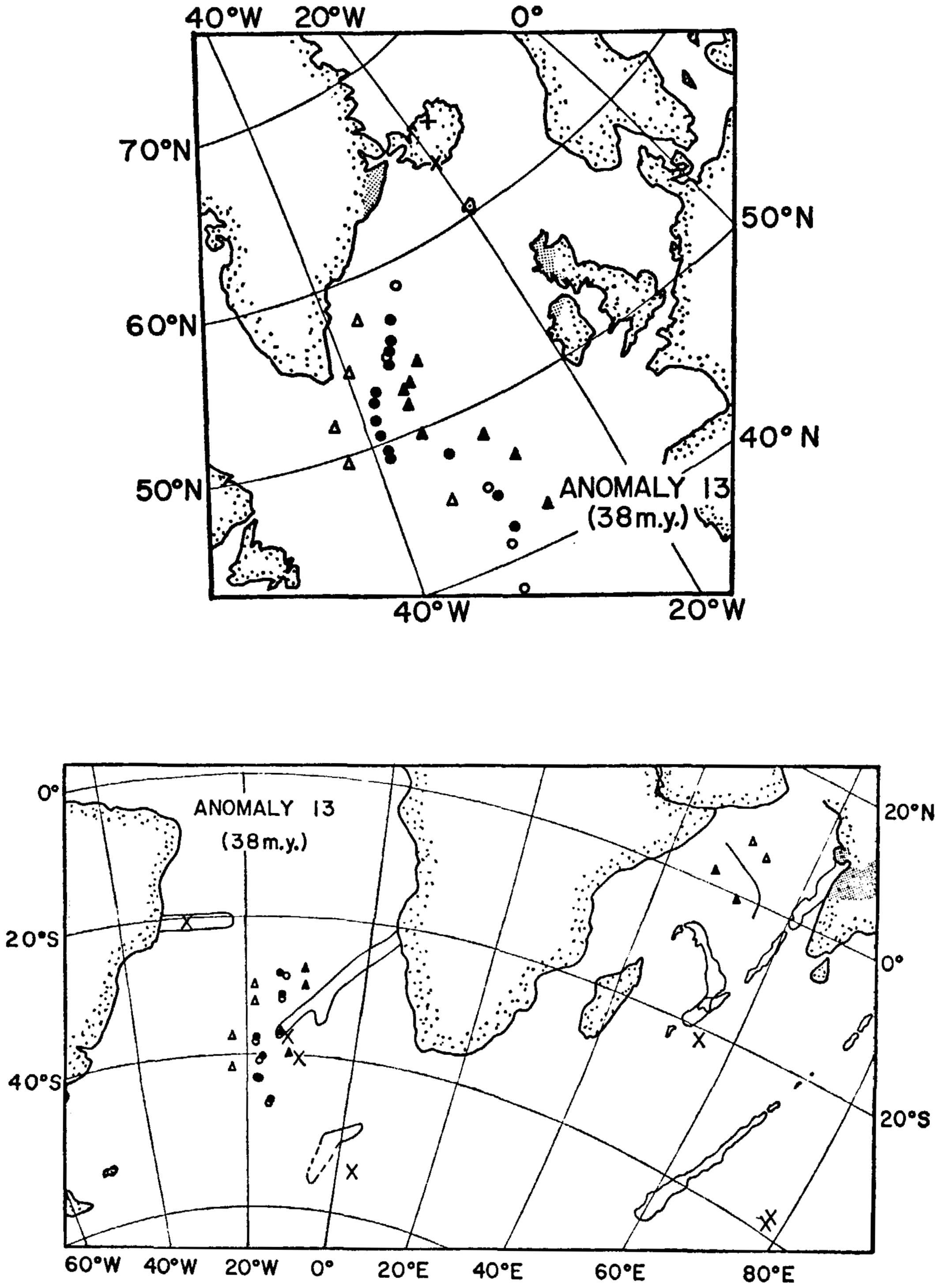
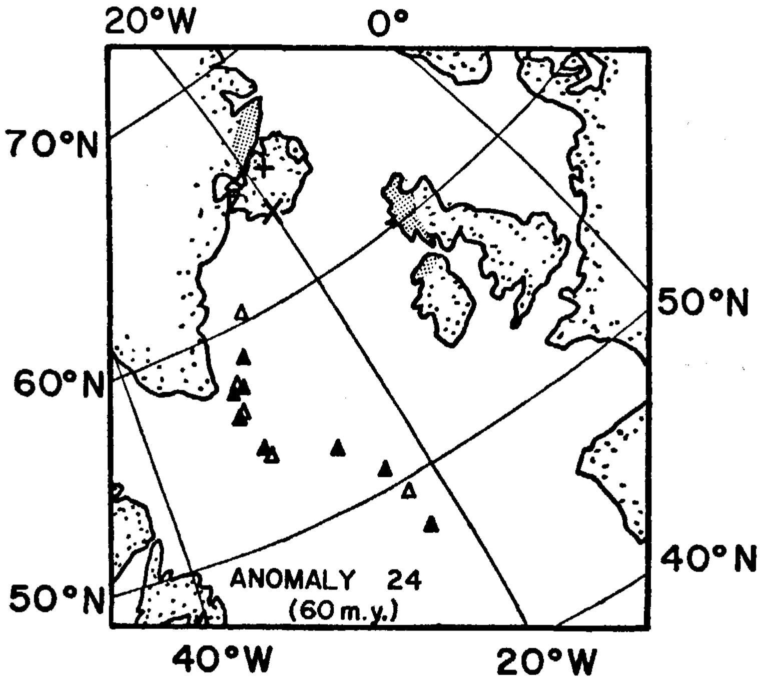


FIG. 3. Reconstruction for the time of anomaly 13 for (a) the North Atlantic, and (b) South Atlantic and Indian Oceans, assuming enough motion of a 'hot-spot' beneath Iceland along the axis of the Mid-Atlantic Ridge to allow the spot beneath Tristan da Cunha to underlie the Walvis Ridge. Symbols same as for Fig. 1; logic same as for Fig. 2.



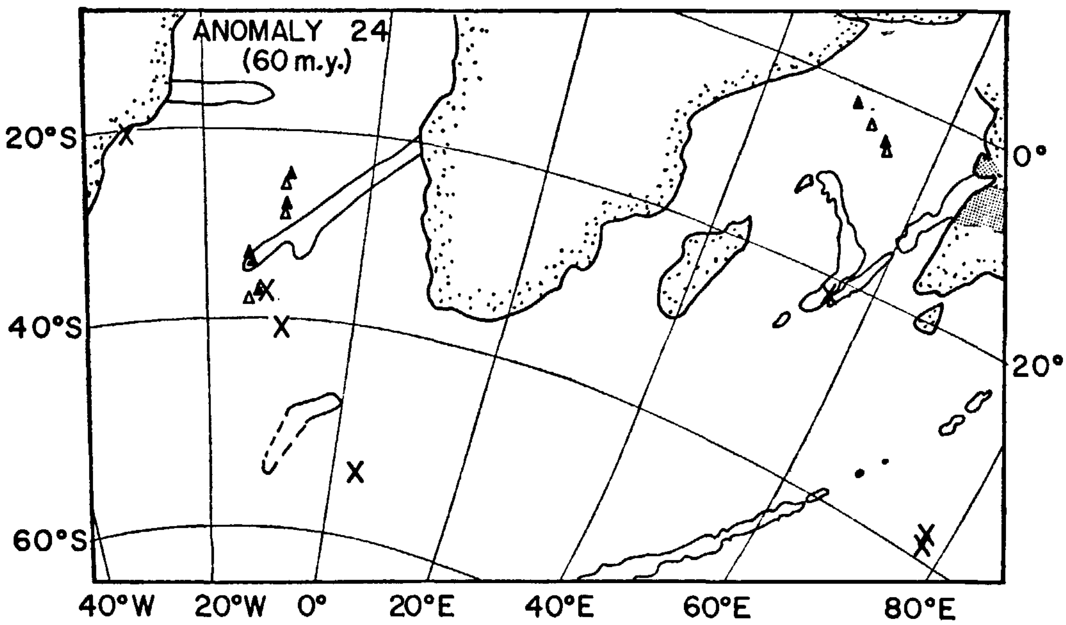


FIG. 4. Reconstruction for the time of anomaly 24 (about 60 My) for (a) the North Atlantic, and (b) South Atlantic and Indian Oceans, with the same assumptions and logic as for Fig. 2 and symbols as for Fig. 1.

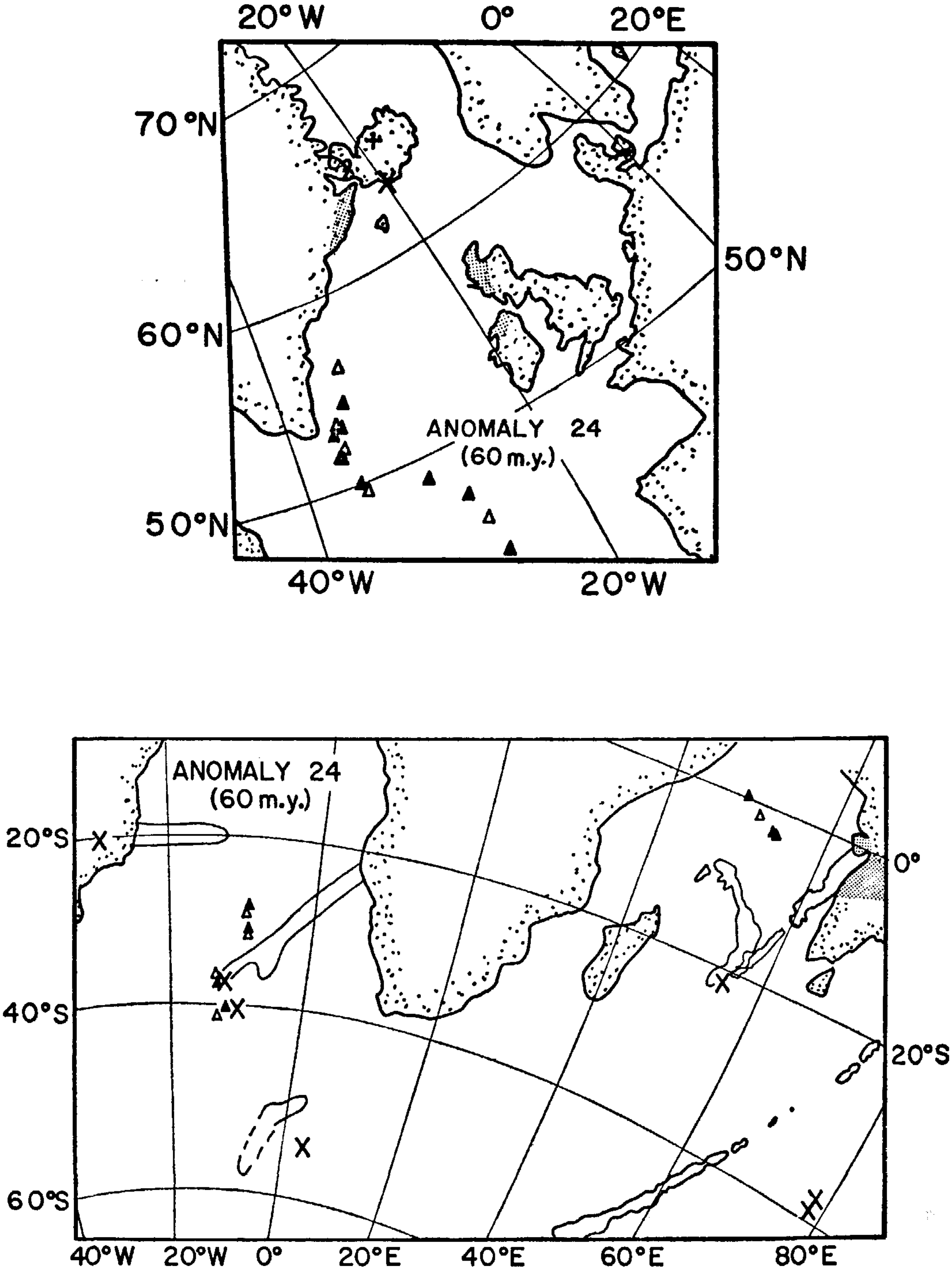


FIG. 5. Reconstruction for the time of anomaly 24 for (a) the North Atlantic, and (b) South Atlantic and Indian Oceans, with the same assumptions as for Fig. 3, logic as for Fig. 2, and symbols as for Fig. 1.

maps of the South Atlantic and Indian Ocean are oblique Mercator projections with their pole through Iceland. Thus the relative positions of the ' hot-spots ' and their traces can be modified easily by translating the plates with respect to the ' hot-spots ' in a direction parallel to the top and bottom of the maps. The second condition is equivalent to adding an extra rotation about a pole located in present-day Africa, for which the Reykjanes Ridge falls approximately along a line of latitude. We examined a family of such reconstructions and present two extremes that minimized the distance between most of the ' hot-spots ' and their associated traces (Figs 1–5). In one case the position of Iceland was chosen midway between the Skaergaard intrusion in Greenland and the North Atlantic Tertiary Igneous Province in Scotland and the Faeroe Islands. In the other case, the position of the Iceland spot with respect to Greenland and Europe was chosen to allow a spot beneath Tristan da Cunha to underlie the Walvis Ridge.

Results

As the reconstructions in Figs 2–5 are based on several assumptions, we can consider the relative motion of ' hot-spots ' from two opposite points of view: (a) If the reconstructions are correct, how far and how fast do the ' hot-spots ' move with respect to each other? (b) If we assume that the ' hot-spots ' do not move with respect to each other, what does this imply for the assumptions made in making the reconstructions? For each of the following points we tried to make clear which assumptions were critical.

(1) In all models, if a ' hot-spot ' beneath Bouvet generated a trace north-east of it to the Merz and Meteor Seamounts (Johnson, Hey & Lowrie, 1973), this spot must have moved at a rate of about 10 mm/yr with respect to spots beneath Tristan da Cunha and Gough Island or Iceland (Figs 2–5). Note, however, that Bouvet is at present on the Antarctic plate and that the predicted trace is not parallel to the proposed trace between Bouvet and Merz and Meteor Seamounts (Johnson *et al.* 1973). Thus, the origin of Merz and Meteor Seamounts may be unrelated to that of Bouvet with no trace connecting them.

(2) If the Iceland ' hot-spot ' is presently beneath Central Iceland (e.g. near Myvatn) and did not move along the plate boundary during the last 60 My (Figs 2(a) and 4(a)), then spots beneath Tristan da Cunha or Gough must have moved about 500 km or 800 km respectively with respect to the Iceland spot (Figs 2(b) and 4(b)).

(3) In order to generate the Walvis Ridge and the Martim Vaz Chain above ' hot-spots ' under Tristan da Cunha and Trindade that are fixed with respect to another spot beneath Iceland, both Greenland and Eurasia must have had a north-east component of displacement of approximately 550 km (14 mm/yr for the last 38 My) (Fig. 1(a) and 1(b)). Minster *et al.* (1974) speculated that the active volcanism on Surtsey and Vestmannaeyjar Island may imply a recent NE movement of Iceland with respect to the Iceland spot. Thirty-eight or sixty million years ago, this spot must have been near the north end of the Tertiary volcanic province in Greenland and some 200 km north of the Faeroe Islands (Figs 1(a), 3(a) and 5(a)). For a ' hot-spot ' beneath Gough Island to have generated the Walvis Ridge and be fixed with respect to the spot beneath Iceland, this Icelandic spot must have been yet 300 km farther north-east with respect to Greenland and Europe. Fig. 1(a) shows the predicted volcanic chains on the Greenland and Eurasia plates that arise from the Tristan spot generating the Walvis Ridge and the Trindade spot generating the Martim Vaz Chain with the Iceland spot either near the south coast of Iceland or near Myvatn. Bathymetric data do not show such predicted features.

(4) If the ' hot-spots ' did not move, or moved very slowly, with respect to each other, the spot that generated the Walvis Ridge more likely underlies Tristan da Cunha and not Gough Island at present.

(5) If a ' hot-spot ' now beneath Réunion underlay the Mascarene Plateau 38 My ago, the reconstructions between Africa and Eurasia must be in error by at least 200 km in the sense required to reduce the calculated distance between the Réunion spot and the Mascarene Plateau (Figs 1(b), 2(b) and 3(b)).

(6) If the Réunion spot generated the Chagos–Laccadive Ridge and the Deccan Traps, and if it were fixed with respect to the Iceland spot, at the time of anomaly 24 the Deccan Traps would have been about 2000 km north-east of the present position of the Réunion spot (Figs 1(b), 4(b) and 5(b)). A revised age of anomaly 24 is given as 56 My by Sclater *et al.* (1974). The Deccan Traps are dated as 60 to 65 My old (Wellman & McElhinny 1970), but palaeomagnetic data from the Deccan Traps and the North Atlantic Tertiary Volcanic Province agree well with each other if the Deccan Traps are slightly older than the measured age (67–68 My) and if Sclater *et al.*'s revised age of anomaly 24 is used (Molnar & Francheteau 1975). Given the uncertainties in the estimates of the ages, the difference in age between the Deccan Traps and anomaly 24 is about 10 My. For fixed ' hot-spots ', the rate of motion of the India plate over the spot would have been approximately 200 mm/yr. This is approximately the rate between India and Africa (McKenzie & Sclater 1971), and therefore, immediately after the Deccan Traps were extruded, the India–Africa spreading centre would have migrated north leaving the Réunion spot beneath the Africa plate. If India moved away from the Réunion spot at a lower rate, then at the time the Deccan Traps were erupted, the spot would have been under the Africa plate and not beneath India. Moreover, because the Africa–India spreading centre would have migrated away from the Africa plate and the Réunion spot at 100 mm/yr, this spot would have underlain the India plate for only a short time. Yet magnetic anomalies and fracture zones in this region (Schlich 1974) imply that the Chagos-Laccadive Ridge formed on the India plate. Thus, a great deal of asymmetric spreading or a large jump of the spreading centre ($\sim$ 600 km) would be required to form the Chagos Ridge above a ' hot-spot ' fixed with respect to others in the Atlantic and be on the India plate now. Because a ridge jump appears to have isolated the Seychelles in the late Cretaceous, a similar ridge jump could easily have separated the Chagos Ridge from the Africa plate and joined it to the India plate. Alternatively, if the Réunion spot moved at a velocity of about 20 mm/yr with respect to the Iceland spot in the late Cretaceous and early Tertiary, spreading at the India–Africa plate boundary could have occurred symmetrically as Schlich's (1974) data imply.

(7) The formation of the Chagos–Laccadive Ridge over a ' hot-spot ' fixed with respect to other ' hot-spots ' can be examined in another way. The Chagos–Laccadive Ridge is approximately parallel to a fracture zone created by motion of India away from Africa between about 75 and 45 My ago (Fisher, Sclater & McKenzie 1971; McKenzie & Sclater 1971). As the Chagos–Laccadive Ridge and Mascarene Plateau are often presumed to have been generated by a ' hot-spot ', the pole of rotation of India and Africa with respect to each other is the same as that between either of the two plates and this spot. At the same time, the Walvis Ridge is presumed to record the motion of the Africa plate over a ' hot-spot ' at Tristan da Cunha or Gough Island. If the ' hot-spots ' that generated the Indian Ocean and South Atlantic aseismic ridges were fixed with respect to each other, at the time these ridges formed they would have fallen on small circles about the same pole of rotation, the pole for relative motion of India and Africa, between 45 and 75 My ago. This pole can be calculated easily from parameters given by McKenzie & Sclater (1971) or by determining it directly from the trends of this ancient transform fault (the Chagos Trench and the Mauritius Trench). For our purposes, the two determinations agree well and show that the pole is in central Africa. The Walvis Ridge is not parallel to a line of latitude about this pole, but in fact is close to a meridian for this pole. Thus there is no way for the ' hot-spots ' in the North-west Indian Ocean and beneath the Walvis Ridge to remain fixed with respect to each other unless Africa moved very little with respect

to the Walvis Ridge spot so that very little of the Walvis Ridge was generated during this interval.

(8) The reconstructions (Figs 2(b), 3(b), 4(b) and 5(b)) show that a ' hot-spot ' beneath either St Paul and Amsterdam Islands or beneath Kerguelen (near 50° S, 70° E) cannot have produced the Ninety-East Ridge if they have remained fixed to the Atlantic spots. Either of these postulated ' hot-spots ' must have moved at rates of at least 20 mm/yr with respect to the Atlantic ' hot-spots ' if it generated the Ninety-East Ridge. Alternatively, the Ninety-East Ridge was formed by another process, or another ' hot-spot ' produced the Ninety-East Ridge but no longer is active.

Discussion

For the inferred localized sources beneath these active volcanic areas to have remained fixed with respect to one another, several possible, but in our opinion implausible, circumstances must have fortuitously occurred simultaneously. A more likely explanation for the genesis of many of the volcanic chains is either that these sources move with respect to each other at rates *at least* as great as 10 mm/yr or that the sources are not localized but extend over distances larger than 600 km or both. Rates of 10 mm/yr are typical for separation rates of continents and the dimension required for ' hot-spots ' is of the order of the thickness of the asthenosphere. Both of these are consistent with at least some ' hot-spots ' being the results of convective flow in the upper 700 km of the mantle. The association of many linear volcanic chains with fracture zones may be of a consequence of fracture zones being zones of weakness in the lithosphere, along which material from the asthenosphere migrates to the surface.

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References

Betz, F. & Hess, H. H., 1942. The floor of the North Pacific Ocean, *Geog. Rev.*, **32,** 99–116.

Burke, K., Kidd, W. S. F. & Wilson, J. T., 1973. Relative and latitudinal motion of Atlantic hotspots, *Nature*, **245,** 133–137.

Fisher, R. L., Sclater, J. & McKenzie, D. P., 1971. The evolution of the Central Indian Ridge, Western Indian Ocean, *Bull. geol. Soc. Am.*, **82,** 553–562.

Francheteau, J., 1973. Plate tectonic model of the opening of the Atlantic Ocean south of the Azores, eds D. H. Tarling and S. K. Runcorn, *Implications of Continental Drift to the Earth Sciences*, 191–196. Academic Press, London.

Heirtzler, J. R., Dickson, G. O., Herron, E. M., Pitman, W. C., & Le Pichon, X., 1968. Marine magnetic anomalies, geomagnetic field reversals, and motions of the ocean floor, *J. geophys. Res.*, **73**, 2119–2136.

Herron, E. M. & Talwani, M., 1972. Magnetic anomalies on the Reykjanes Ridge, *Nature*, **238**, 390–392.

Jackson, E. D. & Wright, T. L., 1970. Xenoliths in the Honolulu Volcanic Series, Hawaii, *J. Petrology*, **11**, 405–430.

Johnson, G. L., Hey, R. N. & Lowrie, A., 1973. Marine geology in the environs of Bouvet Island and the South Atlantic triple junction, *Mar. Geophys. Res.*, **2**, 23–36.

Ladd, J. W., Dickson, G. O. & Pitman, W. C., 1973. The age of the South Atlantic: eds A. E. M. Nairn and F. G. Stehli, *The Ocean Basins*, 555–573. Vol. 1, Plenum Press, New York.

Le Pichon, X., Francheteau, J. & Bonnin, J., 1974. *Plate tectonics*, Elsevier Scientific Publishing Co., Amsterdam, 300 pp.

Le Pichon, X., Francheteau, J. & Sibuet, J. C., 1974, The fit of the continents around the Eurasian and Norwegian-Greenland Sea, *unpublished manuscript*.

Le Pichon, X. & Hayes, D. E., 1971. Marginal offsets, fracture zones, and the early opening of the South Atlantic, *J. geophys. Res.*, **76**, 6283–6293.

Le Pichon, X., Hyndman, R. D. & Pautot, G., 1971. Geophysical study of the opening of the Labrador Sea, *J. geophys. Res.*, **76**, 4724–4743.

McKenzie, D. & Sclater, J. G., 1971. The evolution of the Indian Ocean since the late Cretaceous: *Geophys. J. R. astr. Soc.*, **25**, 437–528.

Menard, H. W., 1964. *Marine geology of the Pacific*, McGraw–Hill Co., New York, 271 pp.

Minster, J. B., Jordan, T. H., Molnar, P. & Haines, E., 1974. Numerical modelling of instantaneous plate tectonics, *Geophys. J. R. astr. Soc.*, **36**, 541–576.

Molnar, P. & Atwater, T., 1973. The relative motion of hot-spots in the mantle, *Nature*, **246**, 288–291.

Molnar, P. & Francheteau, J., 1975. Plate tectonic and paleomagnetic implications for the age of the Deccan Traps and the magnetic anomaly time scale, *Nature*, **255**, 128–130.

Morgan, W. J., 1971. Convection plumes in the lower mantle, *Nature*, **230**, 42–43.

Pitman, W. C. & Talwani, M., 1972. Sea-floor spreading in the North Atlantic, *Bull. Geol. Soc. Am.*, **83**, 619–646.

Schlich, R., 1974. Sea-floor spreading history and deep sea drilling results in the Madagascar and Mascarene Basins, Western Indian Ocean, *Initial Reports of the Deep Sea Drilling Project*, **XXV**, 663–678.

Sclater, J. G., Jarrard, R. D., McGowran, B. & Gartner, S., 1974. Comparison of the magnetic and biostratigraphic time scales since the late Cretaceous, *Initial Reports of the Deep Sea Drilling Project*, **XXII**, 381–386.

Turcotte, D. L. & Oxburgh, E. R., 1973. Mid-plate tectonics, *Nature* **244**, 337–339.

Vogt, P. R. & Avery, O. E., 1974. Detailed magnetic surveys in the Northeast Atlantic and Labrador Sea, *J. geophys. Res.*, **79**, 363–389.

Wellman, P. & McElhinny, M. W., 1970. K-Ar age of the Deccan Traps, India, *Nature*, **227**, 595–596.

Wilson, J. T., 1965. Evidence from oceanic islands suggesting movement in the earth, *Phil. Trans. R. Soc. Lond. Ser. A.*, **258**, 145–167.