ards should contribute to our knowledge of the nature and magnitude of the systematic errors in this field.

L. A. W. Kemp
A. R. S. Marsh
M. J. Baker

Division of Radiation Science,
National Physical Laboratory,
Teddington, Middlesex

Received August 24, 1970.

[1] *ICRU Report 14*, Intern. Commission on Radiat. Units and Measurements, Washington DC (1969).
[2] Laughlin, J. S., and Genna, S., in *Radiation Dosimetry*, **2** (edit. by Attix, Roesch, and Tochilin), 389 (Academic Press, New York, 1966).
[3] Petree, B., and Lamperti, P., *J. Res. US Nat. Bureau Stand.*, **71C**, 19 (1966).
[4] Domen, S. R., *J. Res. US Nat. Bureau Stand.*, **73C**, 17 (1969).
[5] Klein, C., *Rev. Mod. Phys.* (January 1962).
[6] Blackman, L. C., Saunders, G., and Ubbelohde, A. R., *Proc. Roy. Soc.*, A, **264**, 19 (1961).
[7] Spain, I. L., Ubbelohde, A. R., and Young, D. A., *Phil. Trans. Roy. Soc.*, A, **262**, 345 (1967).
[8] Moore, A. W., *Ned. T. Natuurk.*, **32**, 221 (1966).

Convection Plumes in the Lower Mantle

THE concept of crustal plate motion over mantle hotspots has been advanced[1] to explain the origin of the Hawaiian and other island chains and the origin of the Walvis, Iceland–Farroe and other aseismic ridges. More recently the pattern of the aseismic ridges has been used in formulating continental reconstructions[2]. I have shown[3] that the Hawaiian–Emperor, Tuamotu–Line and Austral–Gilbert–Marshall island chains can be generated by the motion of a rigid Pacific plate rotating over three fixed hotspots. The motion deduced for the Pacific plate agrees with the palaeomagnetic studies of seamounts[4]. It has also been found that the relative plate motions deduced from fault strikes and spreading rates agree with the concept of rigid plates moving over fixed hotspots. Fig. 1 shows the absolute motion of the plates over the mantle, a synthesis which satisfies the relative motion data and quite accurately predicts the trends of the island chains and aseismic ridges away from hotspots.

I now propose that these hotspots are manifestations of convection in the lower mantle which provides the motive force for continental drift. In my model there are about twenty deep mantle plumes bringing heat and relatively primordial material up to the asthenosphere and horizontal currents in the asthenosphere flow radially away from each of these plumes. The points of upwelling will have unique petrological and kinematic properties but I assume that there are no corresponding unique points of downwelling, the return flow being uniformly distributed throughout the mantle. Elsasser has argued privately that highly unstable fluids would yield a thunderhead pattern of flow rather than the roll or convection cell pattern calculated from linear viscous equations. The currents in the asthenosphere spreading radially away from each upwelling will produce stresses on the bottoms of the lithospheric plates which, together with the stresses generated by the plate to plate interactions at rises, faults and trenches, will determine the direction in which each plate moves.

Evidently the interactions between plates are important in determining the net force on a plate, for the existing rises, faults and trenches have a self-perpetuating tendency. The plates are apparently quite tough and resistant to major changes, because rise crests do not commonly die out and jump to new locations and points of deep upwelling do not always coincide with ridge crests. (For example, the Galapagos and Réunion upwellings are near triple junctions in the Pacific and Indian Oceans. Asthenosphere motion radially away from these hotspots would help to drive the plates from the triple junctions, but there is considerable displacement between the "pipes to the deep mantle" and the lines of weakness in the lithosphere which enable the plates to move apart.) Also, a large isolated hotspot such as Hawaii can exist without splitting a plate in two. I believe it is possible to construct a simple dynamic model of plate motion by making assumptions about the magnitude of the flow away from each hotspot and assumptions about the stress/strain rate relations at rises, faults and trenches. Such a model has many possibilities to account for past plate motions; hotspots may come and go and plate migration may radically change the plate to plate interactions. But the hotspots would leave visible markers of their past activity on the seafloor and on continents.

This model is compatible with the observation that there is a difference between oceanic island and oceanic ridge basalts[5,6]. It suggests a definite chain of events to form the island type basalt found on Hawaii and parts of Iceland. Relatively primordial material from deep in the mantle rises adiabatically up to asthenosphere depths. This partially fractionates into a liquid and solid residual, the liquid rising through vents to form the tholeiitic part of the island. The latter alkaline "cap rocks" would be generated in the lithosphere vent after plate motion had displaced the vent from the "pipe to the deep

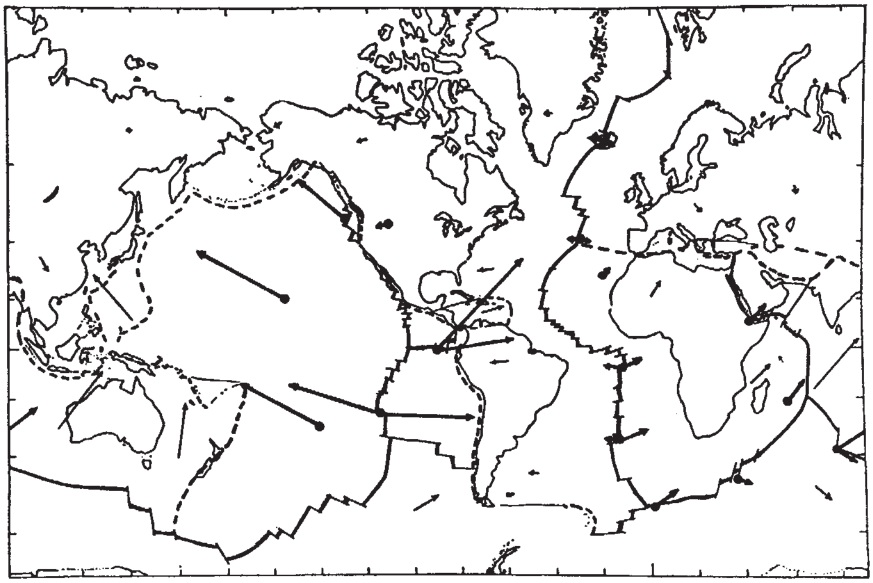

Fig. 1 The arrows show the direction and speed of the plates over the mantle; the heavier arrows show the plate motion at hotspots. This synthesis was based on relative plate motion data (fault strikes and spreading rates) and predicts the directions of the aseismic ridges/island chains emanating from the hotspots.

mantle". In contrast, the ridge basalts would come entirely from the asthenosphere, passively rising to fill the void created as plates are pulled apart by the stresses acting on them. The differences in potassium and in rare earth pattern for island type and ridge type basalts may be explained by this model. Moreover, the 2 billion year "holding age" advocated by Gast[7] to explain lead isotope data of Gough, Tristan da Cunha, St Helena and Ascension Islands may reflect how long the material was stored in the lower mantle without change prior to the hotspot activity.

My claim that the hotspots provide the driving force for plate motions is based on the following observations to be discussed below. (1) Almost all of the hotspots are near rise crests and there is a hotspot near each of the ridge triple junctions, agreeing with the notion that asthenosphere currents are pushing the plates away from the rises. (2) There is evidence that hotspots become active before continents split apart. (3) The gravity pattern and regionally high topography around each hotspot suggest that more than just surface volcanism is involved at each hotspot. (4) Neither rises nor trenches seem capable of driving the plates.

The symmetric magnetic pattern and the "mid-ocean" position of the rises indicate that the rises are passive. If two plates are pulled apart, they split along some line of weakness and in response asthenosphere rises to fill the void. With further pulling of the plates, the laws of heat conduction and the temperature dependence of strength dictate that future cracks appear down the centre of the previous "dike" injection. If the two plates are displaced equally in opposite directions or if only one plate is moved and the other held fixed, perfect symmetry of the magnetic pattern will be generated. The axis of the ridge must be free to migrate (as shown by the near closure of rises around Africa and Antarctica). If the "dikes" on the ridge axis are required to push the plates apart, it is not clear how the symmetric character of the rises could be maintained. The best argument against the sinking lithospheric plates providing the main motive force is that small trench-bounded plates such as the Cocos plate do not move faster than the large Pacific plate[8]. Also, the slow compressive systems would not appear to have the ability to pull other plates away from other units. The pull of the sinking plate is needed to explain the gravity minimum and topographic deep locally associated with the trench system[9], but I do not wish to invoke this pull as the principal tectonic stress. This leaves sub-lithospheric currents in the mantle and the question now is: are these currents great rolls (mirrors of the rise and trench systems), or are they localized upwellings (that is, hotspots)?

A recent world gravity map[10] computed for spherical harmonics up to order 16 shows isolated gravity highs over Iceland, Hawaii, and most of the other hotspots. Such gravity highs are symptomatic of rising currents in the mantle. Even if the gravity measurements are inaccurate (different authors have very different gravity maps), the fact remains that the hotspots are associated with abnormally shallow parts of the oceans. For example, note the depth of the million square kilometres surrounding the Iceland, Juan de Fua, Galapagos, and Prince Edward hotspots. The magnitude of the gravity and topographic effect should measure the size of the mantle flow at each hotspot.

There is evidence of continental expression of hotspot activity in the lands bordering the Atlantic: the Jurassic volcanics in Patagonia (formed by the present day Bouvet Island plume), the ring dike complex of South-west Africa and flood basalts in the Parana Basin (Tristan da Cunha plume), the White Mountain Magma series in New Hampshire (the same hotspot that made the New England Seamount Chain (Azores plume?)), the Skaegaard and the Scottish Tertiary Volcanic Province (Iceland plume) and perhaps others. I claim this line-up of hotspots produced currents in the asthenosphere which caused the continental break-up leading to the formation of the Atlantic. Likewise the Deccan Traps (Reunion plume) were symptomatic of the forthcoming Indian Ocean rifting. A search should be made for such continental activity, particularly in East Africa and the western United States (the Snake River basalts?) as an explanation for the rift features found there. There is a paucity of continental hotspots in Fig. 1; perhaps this is a bias due to continental complexity versus oceanic simplicity, but the model presented here predicts that most hotspots will be near a spreading rise.

I thank Kenneth Deffeyes and Fred Vine for their contributions to the ideas in this letter. This work was partially supported by the US National Science Foundation and the Office of Naval Research.

W. J. Morgan

Department of Geological and Geophysical Sciences,
Princeton University,
Princeton, New Jersey

Received December 21, 1970.

[1] Wilson, J. T., *Phil. Trans. Roy. Soc.*, A, **258**, 145 (1965).
[2] Dietz, R. S., and Holden, J. C., *J. Geophys. Res.*, **75**, 4939 (1970).
[3] Morgan, W. J., Hess Memorial Volume (edit. by Shagam, R.), *Mem. Geol. Soc. Amer.* (in the press).
[4] Francheteau, J., Harrison, C. G. A., Sclater, J. G., and Richards, M. L., *J. Geophys. Res.*, **75**, 2035 (1970).
[5] Engel, A. E. J., Engel, C. G., and Havens, R. G., *Geol. Soc. Amer. Bull.*, **76**, 719 (1965).
[6] Gast, P. W., *Geochim. Cosmochim. Acta*, **32**, 1057 (1968).
[7] Oversby, V. M., and Gast, P. W., *J. Geophys. Res.*, **75**, 2097 (1970).
[8] McKenzie, D. P., *Geophys. J.*, **18**, 1 (1969).
[9] Morgan, W. J., *J. Geophys. Res.*, **70**, 6189 (1965).
[10] Kaula, W. M., *Science*, **169**, 982 (1970).

Fossil Pingos in the South of Ireland

REMAINS of former pingos or ice-lens mounds are known in the Low Countries, Scandinavia, East Anglia[1] and Wales[2]. They are also widely distributed in the south of Ireland.

Fine examples occur near Camaross, on the road from Wexford to New Ross, 9 km west-north-west of Wexford town. A cluster of at least twenty fossil pingos north-east of Camaross Cross Roads (S891249) have been specially photographed by Dr J. K. St Joseph, Director in Aerial Photography, University of Cambridge (obliques 23/890245 and 7; verticals K17/W25–30). Part of K17/W26 is reproduced here by kind permission (Fig. 1*a*).

Three fossil pingos are seen. Pingo A (top right) has a basin about 60 m in diameter; the enclosing rim, which is almost complete, rises in a grassy ridge 1.5 m above the surrounding badly drained rushy ground (well seen on the south-east side). The elongated basin of pingo B does not contain open water, but the rushy vegetation inside the rim and outside it on the south-east is in contrast with the grass cover of the rim. Pingo C (bottom left) has an elongated basin which contains a wet swamp. In this vicinity, ridges of rock at about 75 m OD (ordinance datum) separate small valleys whose lower slopes (falling from north-west to south-east) are covered by soliflucted till with very poor natural drainage. The pingos formed near the base of the slopes.

Fine examples also occur at 60 m OD in Carrigeenhill Townland (W945953) on the road from Fermoy to Tallow, 14 km east-south-east of Fermoy. Here there is a rock-ridge to the north of the road, and a small valley partly filled with badly drained soliflucted till to the south. A large field abutting against the south side of the road showed at least three pingo basins and several curved ridges. When seen, the field was in the course of being drained and the lay-out of the drainage ditches had been imposed by the distribution of the pingo basins and ridges, which had disturbed the solifluction slope.

About 5 km west-north-west of Castleisland, the road from Castleisland to Tralee runs through a series of groups of fossil