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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Discussion

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XII. Discussion

Professor J. L. Worzel (Lamont Geological Observatory, Columbia University, New York) was invited to open the discussion:

We have heard today about the palaeomagnetic evidence which requires the magnetic pole to wander through the body of the Earth and at the same time the continents to wander over the surface of the Earth, since Mesozoic times. We have heard the geological evidence reiterated as evidence of continental drift. Others in the past have equally ably demonstrated that this does not need to be considered evidence of continental drift. We have seen the continents authoritatively reconstructed by a computer. This seems most convincing except of course it seems necessary to discard Central America, Mexico, the Gulf of Mexico, the Caribbean Sea and the West Indies, along with their pre-Mesozoic rocks!

On the other hand we have seen evidence that the ocean crust too breaks into blocks which shift relative to each other by distances up to 1400 km. A series of transcurrent faults occur along the west coast of the United States. Unmentioned is the similar fault along the east coast which extends across 600 km of the continent and out into the sea, continuing, some think, across the Atlantic to the mid-ocean ridge. On land this fault has been dated as pre-Mesozoic. It is at the same latitude as the Mendocino Escarpment off the west coast but shows right lateral movement while the latter shows predominantly left lateral movement.

Along the margins of the Pacific, but predominantly on the continents we have seen abundant evidence of transcurrent motion with the Pacific Ocean basins as a whole rotating relatively counterclockwise to all the continents which border it. In the Indian Ocean we have been told there are micro-continents either small remnants of the larger continents left behind in the drift or small new continents perhaps being formed.

The mid-ocean ridge, believed by some to be the scar of the continental drifting motion, has been shown to be transcurrently faulted at right angles to its axis at many places along its length, with most known displacements in an east–west direction. These ridges were described as located centrally between shield areas rather than between continental margins.

Finally it has been suggested that the mid-ocean ridge central rift zone is a factory which is making new oceanic crust which spreads out in the forming or expanding ocean basins to make the new oceanic crust.

Little has been said about the complicated and significant deep trench-island arc system which occurs at or near the continental margins in the sea area. This system is predominantly a northern hemisphere system while the ridge system is predominantly a southern hemisphere system. Seismic velocities of around 7 km/s beneath the ridges have been attributed to the conversion of mantle material into new crust. These same velocities are commonly found beneath the island ridges of the island arcs associated with the deep trenches and beneath the ridges, which are not attributed to be a part of the mid-ocean ridge system.

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No account has been taken of the uniform structure and velocity of all the ocean crusts. For convenience table 1 lists the most recent summary which has been abstracted from 'The crustal rocks', by R. W. Raitt in *The Sea*, vol. III, p. 85–102 (Interscience), 1963.

TABLE 1. SEISMIC RESULTS FOR THE OCEANS

	layer 2				layer 3				mantle	
area	*t* (km)	s.d. (km)	*V* (km/s)	s.d. (km/s)	*t* (km)	s.d. (km)	*V* (km/s)	s.d. (km/s)	*V* (km/s)	s.d. (km/s)
W.N. Atlantic	2·11	0·70	4·89	0·59	4·76	1·41	6·70	0·27	8·10	0·24
E.N. Atlantic	2·23	0·50	5·14	0·57	4·41	1·03	6·56	0·32	7·85	0·18
W.N. Pacific	2·05	0·50	5·02	0·63	5·08	1·72	6·73	0·25	8·21	0·18
E.N. Pacific	0·89	0·33	5·65	0·61	4·64	0·79	6·75	0·17	8·24	0·15
S. Pacific	1·22	0·45	5·12	0·58	5·43	1·72	6·72	0·20	8·29	0·21
Indian	2·08	0·87	4·62	0·57	—	—	6·69	0·31	—	—
all oceans	1·71	0·75	5·07	0·63	4·86	1·42	6·69	0·26	8·13	0·24

The great uniformity of the crusts of the ocean is obvious. How such uniformity could occur if the crustal matter flows around the continents from the Pacific to form the Atlantic crust is a mystery. Equally mysterious is how a crustal region the size of the Atlantic could be eliminated in the Pacific Basins while a new crust was being formed in the Atlantic Basins. This new crust of course formed since Mesozoic times and still we find almost identical layering both in velocity and thickness to that crust originally formed in the Pacific basin, presumably under vastly different physical conditions and very much longer ago.

The conversion of the mid-ocean ridge type crust into an ocean basin type crust by spreading is equally mysterious. A crust 20 to 25 km thick and of about 7 km/s velocity must 'spread' to become a crust of 5 to 7 km in thickness and with a layer of the order of 2 km in thickness and 5 km/s in velocity overlying a layer of about 5 km in thickness and 6·7 km/s in velocity.

All of these crustal transfers and/or conversions must also be carried out in such a way that almost complete isostatic equilibrium is maintained, or at least has now been achieved, and in such way that the heat flow pattern has stabilized to a standard pattern for all the oceans.

No mention was made of the heat flow data. Several observers have now found normal and even subnormal heat flow values on the mid-ocean ridges as well as the high heat flow values formerly reported. This is now held to be consistent with the volcanism, already a well known feature of the ridge. When near volcanic intrusions or extrusions high heat flow is encountered and when away from such zones low heat flow is encountered.

Oceanic sedimentary volumes also seem difficult to understand. The Atlantic in about 300 My has collected twice the thickness of sediment that the Pacific has collected in 2000 to 4000 My.

So far geophysical measurements have failed to disclose any significant differences between opposite margins of the same ocean or the ocean basins within the ocean. Ridge, crusts, whether mid-oceanic, aseismic, island, or island-arc are different from ocean crusts and from continental crusts.

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Recent reflexion measurements, now coming into print, show that the surface of 'layer 2' has a great large scale roughness in all the oceans of the world. It is difficult to imagine a crust able to spread into uniform thin layers being able to maintain such a surface roughness, both in the newly formed Atlantic and the much more ancient Pacific.

If continental drift is believed, it must be considered that South America is now, or is soon to be, the scene of a gigantic struggle between the westward drifting forces indicated by the Southern Atlantic mid-ocean ridge and the eastward drifting forces indicated by the Easter Island Ridge of the South Pacific.

Dr R. L. Fisher (University of California, San Diego):

My primary intention in entering the discussion is to point out that the median ridge and topographic highs that occur so well developed in the Indian Ocean are by no means the unknown features that several of the speakers thus far obviously assumed. The ridges differ from one another in degree of current seismicity, extent, shape, gravity and magnetic characteristics, age and crustal properties, to list a few types of data already gathered. Before we spend too much time philosophizing and glibly talking about 'micro-continents' for example, we should review what is known about some of the crustal thickness and velocities. To get some micro-insights on these 'micro-continents', I shall draw my information mostly from the results of Russell Raitt, George Shor and colleagues of Scripps Institution, although I must take responsibility for any misquotations or distortions. Raitt presented some of these data at the 1963 meetings of the Geological Society of America in New York. Shor (with Dwight Pollard) published the Seychelles and Saya de Malha results, reviewed below, in *Science*, **142**, 48–49, 1963. Seventy-six seismic refractions stations have been occupied by S.I.O. ships in the Indian Ocean; the following few are chosen to bring out only the similarities and differences in seismic and aseismic, active and possibly inactive ridges so far revealed by preliminary data analysis.

I. '*Micro-continental*' (*in the sense as suggested by Heezen at this meeting*)

(A) Seychelles Bank—Lusiad Expedition (after Shor & Pollard 1963). On a reversed profile 50 km long, three materials, as distinguished by travel-time data, were detected:

1. Upper–Coralline debris (?), with a compressional wave velocity of $2{\cdot}4^-$ km/s, thickens westward, along the section originating near Silhouette Island, from about 0 to 0·75 km. This overlies
2. about 0 to 2 km (again thickening westward) of lava (?) or lithified carbonates (?) with a velocity of 3·97 km/s.
3. Finally, the deepest material detected on this section was characterized by a velocity of 6·22 km/s; it is almost certainly granite such as outcrops nearby. The base of this layer was not found with this 50 km long profile.

(B) Saya de Malha, an extensive old lagoon-bank on the same 'micro-continent' as the Seychelles, lies several hundred km to the southeast and is separated from those islands by passes and shoals. Here again Shor & Pollard report *Lusiad* data, from a reversed profile 110 km long in water 110 to 130 m deep. They detected five velocity layers, but mantle velocities were not observed. The structure deduced was 0·25 to 0·5 km of $1{\cdot}7^+$ km/s coralline mud (?), 0·66 to 1·25 km of $3{\cdot}3^-$ km/s coral rock (?), then three

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layers of rock with velocities typical of volcanic islands: 2·50 to 3·00 km of 4·4 km/s, 4·00 to 4·50 km of 5·6 km/s., and a 6·8 km/s deepest layer.

Here, unlike in the Seychelles, the sequence of velocities is very similar to that observed in the Pacific beneath volcanic islands, atolls and ridges. The typical continental velocity, about 6^+ km/s, is missing under Saya de Malha Bank which, according to S.I.O. workers, appears to be a normal oceanic feature.

(C) The large, currently aseismic, more-or-less east–west-trending ridge of intermediate depth (1500 to 2000 m) lying between 89 and 103° E in the latitudes of southwest Australia, is separated from Naturaliste Bank by steep, northerly-trending scarps, deep water and thin oceanic crust. On this ridge, however, Raitt's group found six velocity segments in the refraction travel-time plots: 2·15 (assumed), 4·7, 5·7, 6·1, 6·6 and 7·3 km/s with respective layer thicknesses (approximate) of 0·5, 2^+, 1·5, 2^+, 6^+ and 7^+ km. (The last thickness, for the 7·3 km/s layer, is based on second arrivals and is somewhat questionable.)

With a crustal thickness of about 20 km, nearly two-thirds of the section has a velocity equal to, or greater than, 6·6 km/s which is encountered at a depth of 8 to 9 km below sea level. The structure is neither clearly oceanic nor clearly continental and is probably intermediate. In some respects, this structure much resembles that found (during the I.G.Y.) for the similarly aseismic Nasca Ridge that lies normal to and just outside the Peru Trench; there, in water depths of around 3000 m, the crust may be up to 15 km thick.

(D) The seismically rather active, strikingly rectilinear Ninetyeast Ridge (Heezen) or East Indian Ocean Ridge (Bezrukov) was investigated near 15° S, where the water depth is 2000± km. Only 3 km of low-velocity crust was found overlying 6·6 km/s material; this structure appears to be typically oceanic, although topographically it is similar to the shoal area 'C' above.

II. *Mid-ocean ridges*

The seismically very active Mid-Indian Ocean Ridge, Eastern Section, was investigated by Raitt in the vicinity of St Paul-Amsterdam. From Lusiad results, it appears that in this region the west flank of the ridge (in water depth of 3 to 3·5 km) has a very thin crust (of the order of 4 to 5 km, including 2·5 km of 6·8 km/s material) overlying mantle displaying an 8·2 km/s velocity. East of Amsterdam Island, along the crest of the ridge in about 2^+ km of water, the crust thickens to 8^+ km, including 6 km of 6·7 km/s material overlying the supposed mantle (with 7·5 km/s velocity, more characteristic of ridge associations in other areas). The west flank here may be atypical, but from Lusiad measurements there is considerably thicker crust in ocean basins east than west of this section of the 'median ridge'.

Mr David Davies (University of Cambridge) added to Professor Fisher's remarks a summary of recent British work in the Western Indian Ocean on R.R.S. *Discovery* and H.M.S. *Owen*.

The structure of the Seychelles Bank has been determined by a two-ship seismic refraction line more than 100 miles long. This shows that material with a granitic velocity extends to a depth of about 13 km and is underlain by a material of seismic velocity 6·8 km/s. The Mohorovičic discontinuity is put at approximately 32 km deep, so there is

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good evidence that Seychelles should be described as a micro-continent from the crustal structure point of view.

It would be as well to warn would-be fitters of the East African Coast that seismically it is impossible to find a distinct boundary between continental and oceanic crust between Seychelles and Kenya. Preliminary results indicate that although the crust is not untypical of a continent near the coast, the crust is by no means oceanic anywhere. The typical oceanic 'layer 3' velocity of 6·8 km/s is absent and seismic arrivals from what is assumed to be the mantle give velocities at least 5% below the normal mantle value of 8·1 km/s.

Dr T. F. Gaskell (British Petroleum Company)

Dr P. E. Kent stressed the importance of a review of the marginal parts of continents in the light of modern deep drilling and seismic information. Part of available information of this type remains unpublished but critical information on deep wells in particular was available in summary form for all the basins around the African coast, and it had considerable bearing on the problems discussed during the day.

The fit of South America into the Bight of Benin, for example, had been under discussion and a minimum clearance assumed before drifting which other speakers had dated as Trias/Jurassic. Deep drilling in Gabon nevertheless proved a Lower Cretaceous salt basin, which must have had a margin west of the present coast. In addition, there were seismic indications of sediments dipping towards the continent as much as 200 miles southwest of the Niger Delta, a feature difficult to reconcile with identification as oceanic crust. Possibly the main split of this part of the Atlantic came later than the Lower Cretaceous (the western side of the salt basin being in Brazil, as stratigraphical evidence has independently suggested), or two salt basins were involved and the fit was very much less close, as might be deduced from the dipping sediments on the deep ocean floor.

In East Africa oil exploration holes near the coast threw considerable light on the early history of that part of the Indian Ocean, and seismic lines seaward from Kenya and Tanganyika showed that Mesozoic sediments dipped continuously without significant faulting from the Continental Shelf into deep water.

Perhaps the time has come when working parties could be set up to compile and analyse information of this kind for the various coastal belts, linking the relatively well known geology of the continental areas with the intensive research currently in progress on the ocean floors.

Professor S. E. Hollingworth (University College London) briefly mentioned three topics:

First, concerning the nature of the Red Sea Rift, he asked Dr Girdler whether the evidence for a broad strongly downfaulted margin of the Rift, as distinct from a 'downwarp', was essential to his interpretation. Recent gravity traverses on its western margin in the Port Sudan region and to the northwest, carried out from the Geology Department of Khartoum University, do not appear to show a major structural break between the Red Sea Hills and the coastal tract. There were sufficient differences between the Central African Rift and the Red Sea to suggest caution in comparisons.

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On Professor Menard's paper he commented that the late negative movements of the Darwin Rise in the North Pacific could be of interest in relation to the world-wide lowering of sea-level relative to the land in the younger Tertiary, which is demonstrated by the great suite of elevated erosion surfaces on the major continents. A eustatic origin tentatively based on a substantial increase in the capacity of the Pacific Ocean had long seemed an attractive hypothesis.

Professor Allen's inclusion of the Atacama Fault of Northern Chile in his discussion of the great transcurrent faults bordering the Pacific, was of particular interest to the speaker, who was acquainted with this fault belt at various points. As Professor Allen's slides had shown, movements are recent in some places. Elsewhere, the fault is older being represented by a strong erosional fault scarp, or, in other areas, by selectively eroded gashes which deeply dissect an uplifted block. The geology has been little studied. Had the author evidence for major lateral movements along this fault?

Dr Girdler replying to Professor Hollingworth said that the seismic refraction work of Dr Drake indicated that the average depth to the shield rocks under the Red Sea shelves was about 2 to 5 km. Such a drop from the Arabian-Nubian Plateau clearly indicates the presence of a fault or a series of faults. These have been recognized by geologists working in the area for a very long time. The seismicity of the area also indicates the presence of faults near the margins in the southern part.

Dr E. R. Oxburgh (University of Oxford) spoke on volcanism and mantle convection:

Present and past oceanic ridges are known to be associated with volcanic activity, and it has been suggested that they are the sites of the ascending limbs of convection currents in the mantle. If this is so, it is plausible to conclude that there is some genetic relation between the volcanic activity and the convection. When this possibility is examined, it appears that one of the advantages of the convection hypothesis is that it provides a simple mechanism for the production of basaltic magma.

Consider a small unit volume of mantle which is carried round in a convective circuit, e.g. path *A*, *B*, or *C* in the left hand side of figure 1 (*a*). The changes in pressure and temperature conditions which this unit volume undergoes as a function of time may be represented on a pressure/temperature diagram such as that shown in figure 1 (*b*).

A small piece of mantle starting (t_1) at the base of an ascending limb will, as it moves upwards, undergo a change in temperature which is small by comparison with the change in pressure, i.e. it will change with time along a path t_1-t_2; during the transport along the upper horizontal limb (t_2-t_3) it will undergo reduction in temperature at constant pressure, while on the descending path (t_3-t_4) the rate of increase of temperature will be slight by comparison with the rate of increase in pressure.

Also plotted on figure 1 (*b*) is the curve for the beginning of mantle fusion. This shows that there may be important differences between material following different paths. Material following path *A* approaches the fusion curve at t_2, but does not cut it, and therefore will not fuse. Material on path *B*, the critical path, almost fuses at the highest point reached, but it just fails to do so. Material on paths outside the critical path, however, e.g. on path *C*, and originating deeper than material on *A* or *B*, will undergo partial fusion. Thus if partial mantle fusion and basalt production does take place during

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mantle convection, this should, if anywhere, happen in the upper part of an ascending limb.

There are three main consequences to this model. First, because mantle material within the critical path, unlike that outside it, does not undergo partial fusion, a compositional layering should develop in the mantle by which an upper layer which has lost its basalt overlies one which has not (figure 1 (*a*), right side). This upper, 'barren', layer

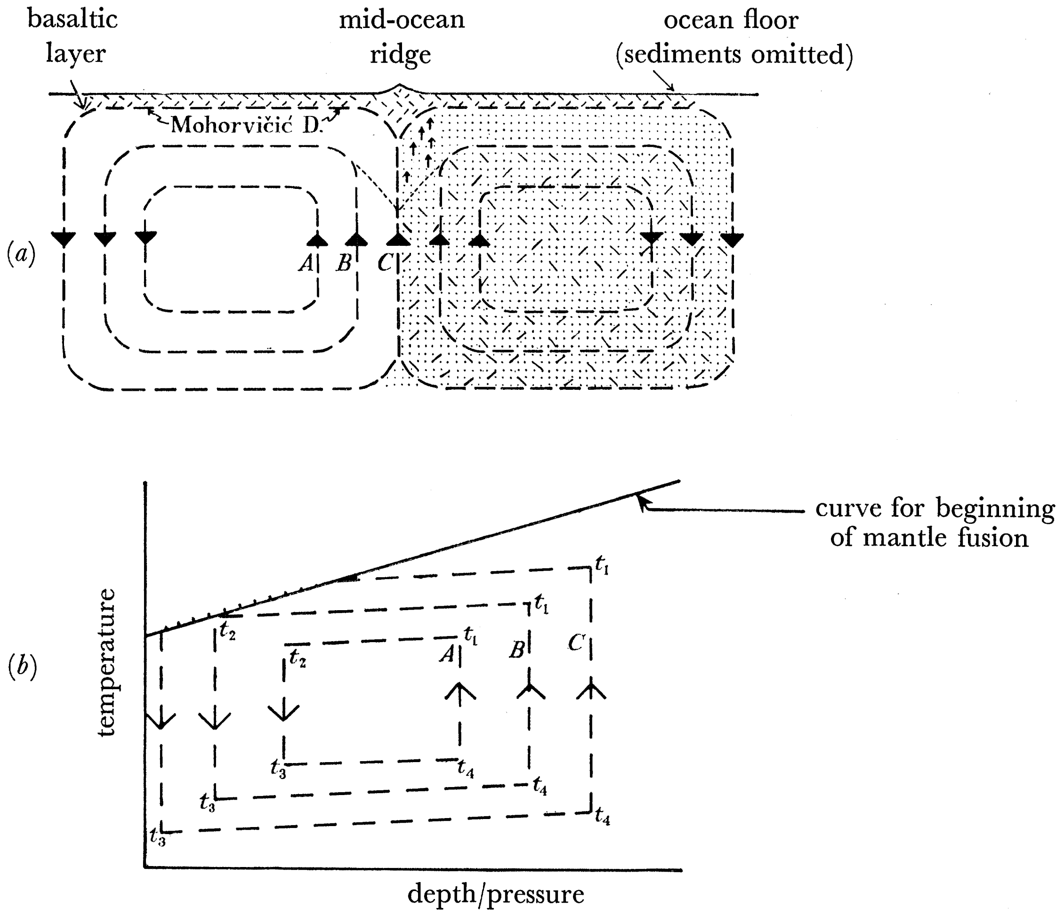

Figure 1. (*a*) Left side: possible convection paths in the upper mantle. Right side: Suggested layered structure of the upper mantle resulting from convection; dashed ornament, basalt; stippled ornament, 'barren' upper mantle; dashed and stippled ornament, undifferentiated upper mantle. Small arrows indicate upward passage of basalt through the 'barren' zone. (*b*) Changes with time in pressure and temperature undergone by small unit volumes of mantle following different flow lines in a convection cell and their relation to the curve for beginning of mantle melting. Capital letters refer to paths shown in (*a*).

through which, however, all basalt had to pass to the surface would be the source of the olivine nodule inclusions in basalts to which Professor H. H. Hess has drawn attention, but which, although widespread and of uniform composition, are too low in potassium and other constituents to be typical of the upper mantle as a whole.

Secondly, in models such as that of Hess involving total crustal drift and generation of new oceanic floor above rising convection limbs, layer 3 of the oceanic crust may be generated by basaltic extrusion at the oceanic ridges and continually transported away

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laterally. On the basis of evidence available it is not possible to discriminate between this and the serpentinization model of Hess except that the present model seems more likely to give a sharper Mohorovičić discontinuity than does a phase change.

Finally the present model provides a means of fusing mantle of the same composition simultaneously under different conditions of temperature and pressure; material just outside the critical path will fuse at relatively lower temperatures and pressures than material following path C. It is just some process such as this which has been invoked in recent years to explain the variety of primary basaltic types.

Professor H. W. Menard in reply to a question by Dr Bruce Heezen said that the evidence for active faulting on fracture zones far out on the flanks of oceanic rises does not depend entirely on old epicenter locations. If epicenter locations by computer, recently published by Sykes, are compared with recent bathymetric maps and physiographic diagrams of the Pacific and Atlantic a close correspondence between epicentres and fracture zones may be seen. Details of the correspondence will shortly be published.

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