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5. These techniques and data will be published extensively in the near future.
6. Blue's sixth track was a flock release from Fitchburg and is not shown. It covered the same ground as the first five tracks shown in Fig. 1.
7. Supported in part by contracts Nonr 1866(12), 1866(46), and 3225(00) between the Office of Naval Research and Harvard University and by NSF grant GB 3403.

12 August 1966

Age of the Ocean Floor

According to Wilson (*1*), the ages of islands increase with distance from an oceanic ridge; recent potassium-argon dating of sea-floor basalts also suggests ages roughly proportional to this distance, which might be interpreted as the consequence of movement of the ocean floor with constant velocity away from the crest of a ridge. On the basis of this assumption, a velocity of 1 cm/yr would lead to an age of 1 million years for a point on the ocean floor 10 km from the axis of the ridge. Accordingly, when Saito, Ewing, and Burckle (*2*) recently discovered Lower Miocene microfossils in two boulders dredged from points 10 and 130 km from the crest of the Mid-Atlantic Ridge, they concluded that, unless patches of old rock were left behind near the crest, "expansion or crustal movement, if any, ceased at least 20 million years ago," and that "The data rule out the possibility of large-scale continental drifting or spreading of the ocean floor since the Lower Miocene."

The implications of this conclusion may be appreciated if one remembers that the mean annual displacement along the major seismic faults currently amounts to several centimeters per year (the maximum rate along the San Andreas fault is assumed to be 5 or 6 m/100 yr). Since earthquakes are caused by relative movement of continental or oceanic blocks adjacent to the seismic fault, the velocity of drift of these blocks also must amount to several centimeters per year. Evidently, neither contraction nor expansion of the earth can be responsible for the movement. Oceanic ridges would demand expansion; the Gutenberg-Richter seismic shear bands, on the other hand, require contraction if they are essentially thrust faults complicated by later strike-slip movements. If the belief of most geologists in the existence of genuine orogenic compression (different from mere folding of surface veneers by gravity sliding) is well founded, there can be no global expansion of tectonic significance. Finally, the observed (seismic plus aseismic) fault displacements around the Pacific add up to relative movements of diametrically opposite continents, probably by some 5 or 10 cm/yr; if these were due to expansion or contraction, the radius of the earth would increase or decrease at a rate no less than about 1 cm/yr—that is, by 1000 km in 100 million years.

Naturally, the currently observed drift velocity of crustal blocks, although of the magnitude assumed by Wegener, does not mean evidence for his scheme of continental movements. However, the results of the recent International Indian Ocean Expedition (*3*) constitute overwhelming support for what seemed the riskiest element in Wegener's theory—the long-range drift of India [see, in particular, Heezen and Tharp's fig. 2 (*3*)].

How then can the findings of Saito, Ewing, and Burckle be fitted into this framework of seismologic and oceanographic facts? Their conclusions are based, as I have mentioned, on the assumption of constant horizontal velocity of the ocean floor, with a discontinuous jump from positive to negative value at the axial line of the ridge. The flow pattern adopted to obtain this velocity distribution is shown in Fig. 1 (*4*). The upwelling beneath the ridge is assumed to consist in vertical rise of a rigid block between rigid walls; the direction of the velocity changes discontinuously from vertical to horizontal in two 45° planes (dashed lines), and the horizontal flow also is represented by the sliding of rigid blocks on a rigid base, *A–A*.

In general this flow pattern is not mechanically possible for several reasons: The discontinuity of velocity at the 45° planes amounts to a shear strain of 200 percent occurring in an infinitesimally short time if the velocity of flow is finite. With Newtonian viscosity this would imply an infinitely high shear stress; with the Andradean viscosity of crystalline materials in the hot-creep range (*5*), the shear stress would be very high at the 45° planes and very low (below the creep limit) at an infinitesimally small distance from them. Velocity discontinuities of this kind are possible only in the hypothetical "ideally plastic" material, which has a sharp yield point, no strain hardening, and no velocity dependence of the deformation (no viscosity); moreover, the deformation must be a matter of plane strain (discontinuities caused by the yield phenomenon, as in steel, can be disregarded here).

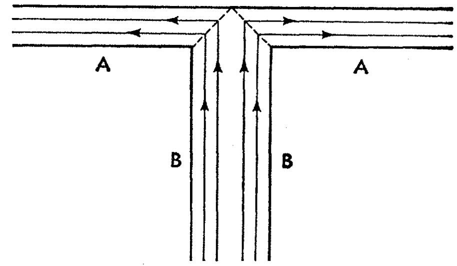

Fig. 1. Discontinuous-flow pattern of upwelling, giving constant velocity at the surface.

Furthermore, if any shear stress is transmitted in the horizontal planes *A–A*, it produces compressive stresses in the horizontally sliding slabs, increasing with distance from the crest. Onward from a certain distance, thrust faulting would occur, of which no indication has been observed.

Finally, the flow pattern of Fig. 1 requires that the width of the rising vertical slab be exactly twice the thickness of the horizontally sliding slabs, which thickness is presumably determined by a soft layer in the upper mantle [the thickness of the horizontal slabs is supposed to be of the order of 100 km (*4*)]. If the vertically rising slab is thicker, as is suggested by the width of the oceanic ridges, which have to be floated by lighter material below, use of the 45° shear plane would lead to the flow pattern of Fig. 2. A plateau would rise in the center of the vertical slab; it would gradually flow apart, but no major rift would arise in its center because of no horizontal spreading below the ridge to produce the tensile stress needed for rifting at the surface.

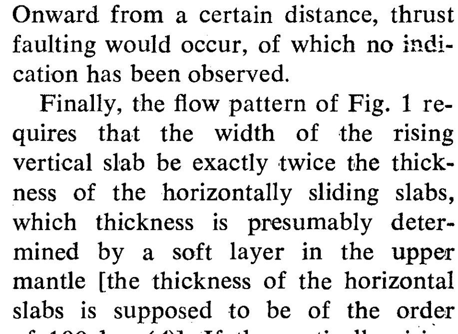

Fig. 2. Discontinuous-flow pattern corresponding to Fig. 1 but for a thicker vertical column.

For the ideally plastic material, the solution of a problem similar to that of ridge flow is known: it is the problem of two-dimensional "side extrusion," in which the extruded sheet emerges from the side of the extrusion vessel rather than from the top [(*6*); discussed and generalized in (*7*)]. If the (vertical) extrusion vessel has two diametrically opposite slit dies, the billet represents the ascending slab under the ridge; the two sheets extruded in opposite directions, the horizontally diverging layers. Unless the thickness ratio of the billet to the extruded sheets is 2:1, the flow picture is very different from Fig. 1: plastic deformation is distributed over finite volumes, and the horizontal component of the velocity increases with distance from the symmetry axis, although there is still a discontinuity at the axis. This, however, is no longer observable in side-extrusion experiments with billets of plasticine provided with square grids (*7*, fig. 115*d*); the relatively small difference between the properties of plasticine and of the ideally plastic material is sufficient to make the discontinuity disappear.

The mantle below the Coulomb layer is still-farther removed from ideal plasticity: where it is not liquid, it is Andradean viscous. Figure 3 shows qualitatively the pattern of divergent flow to be expected in such a material at a convective upwelling [this pattern is essentially identical with that proposed by Menard (*8*)]. The horizontal velocity vanishes at the point of stagnation (*S*) and increases with distance from it. Figure 4 shows three possible ways in which the velocity may vary with the distance: Curve *1* rises vertically; it does not have the extreme discontinuity of Fig. 1, but it is still unrealistic. Curve *2* rises linearly near the axis and levels at the constant value of the velocity of the ocean floor far from the ridge; this behavior at the axis of upwelling was assumed by Lord Rayleigh in his classic paper on thermal instability and convection in a horizontal layer of a liquid. Curve *3* has a horizontal tangent at the axis and points of inflexion between the crest and the constant-velocity plateau.

Because the Coulomb layer covering the viscous part of the mantle is practically incapable of plastic or viscous deformation, and because it fractures by faulting if it is stretched by the increase in velocity of the mantle beneath as this accelerates away from the point of stagnation, faulting begins where the strain rate underneath—that is, the gradient of horizontal velocity—is highest. In the case of curve *2* the maximum of the gradient of velocity occurs at the axis; with curve *3*, at the points of inflexion. According to Menard (*8*), the crest of the East Pacific Rise is smooth, but there are two fault belts at its flanks; if the faults were tensile, this fact would indicate that the velocity increases according to curve *3*.

The thickness of the Coulomb layer is probably between 10 and 20 km: at a depth of 20 km the temperature is close to 500°C and creep should be fast enough to prevent Coulomb fracture; the width of the vertical upwelling should be comparable with the width of the ridge itself for the reason I have mentioned. Since the width of the ridge is of the order of 1000 km, the thickness of the Coulomb layer is only about 1 percent of this; thus the layer plays a role similar to that of Stresscoat lacquer in mechanical testing: its cracking indicates the amount and direction of the strain in the body it covers without significantly influencing its deformation. It is appropriate, therefore, to consider first the deformation and age distribution of the ocean floor in the hypothetical case of absence of the Coulomb layer.

Since the curves in Fig. 4 level at distances of 700 or 800 km from the axis, and the boulders studied by Saito, Ewing, and Burckle were found 10 and 130 km from it, it is sufficient to approximate curve *2* by its initial tangent *OA*. If *a* is the abscissa of *A*, the horizontal velocity (v) of the ocean floor near the axis is

$$v = v_0 \frac{x}{a} \qquad (\text{if } x < a) \qquad (1)$$

and it is v_0 for $x > a$. The time required for a particle on the ocean floor to travel from a distance x_1 to a distance x_2 from the axis is

$$\Delta t = \int_{x_1}^{x_2} \mathrm{d}t = \int_{x_1}^{x_2} \frac{\mathrm{d}x}{v} = \frac{a}{v_0} \ln (x_2/x_1) \qquad (\text{if } x_1 < x_2 < a) \qquad (2)$$

Outside the belt of upwelling, the travel time is simply

$$\Delta t = (x_2 - x_1)/v_0 \qquad (\text{if } x_2 > x_1 > a) \quad (3)$$

If the Atlantic is about 5000 km wide, the round figure $v_0 = 1$ cm/yr would correspond to an age of about 250 million years. As mentioned, a boulder would require 1 million years to travel 10 km at this velocity; for the region near the axis, however, the approximation Eq. 2 must be applied instead of Eq. 3. For a travel time $\Delta t = 20$ million years, a terminal distance of 10 km, and the above values for a and v_0, Eq. 2 gives $x_1 = 7.7$ km. If, therefore, the boulder was dredged 10 km from the axis, its distance from the axis during the Lower Miocene was about 7.7 km; in other words, its mean velocity was little more than 0.01 cm/yr. Similarly, the boulder dredged 130 km from the axis was about 30 km closer 20 million years ago, and its mean velocity was about 0.15 cm/yr if the terminal velocity outside the ridge has remained constant at 1 cm/yr to this day.

If the Coulomb layer consisted of the same material as the mantle, nothing would have to be added to these considerations: the layer would stretch by faulting, and its velocity at any point would approximate that of the viscous-plastic mantle underneath. Apart from the discontinuities resulting from disintegration of the Coulomb layer into fault blocks, the age of a particle placed on the ocean floor would be given by Eqs. 2 and 3. However, the upper half or uppermost quarter of the Coulomb layer is oceanic crust that, outside the ridge, consists of three layers: Layer 1 is of unconsolidated sediments, a few hundred meters or less in thickness. Below is layer 2, assumed (*9*) to consist of volcanics such as basalt and characterized by a compression-wave velocity of about 5 km/sec; its thickness is usually 1 to 1.7 km. It lies over layer 3, which is 4.5 to 5 km in thickness, with a wave velocity of 6.2 to 6.8 km/sec. According to Hess (*10*), layer 3 is mainly highly serpentinized peridotite interleaved with sheets of basaltic outpourings.

Seismic reflection and refraction measurements (*11*) have shown that crust and mantle are quite different in a wide inner belt of the oceanic ridges. The volcanic layer 2 seems thicker than normal, perhaps 2 to 3 km thick; the main oceanic crustal layer 3 is missing under an inner belt of perhaps 700 or 800 km in width, and gradually thickens to its normal thickness over marginal belts of perhaps 100 or 200 km in width. Moreover, underneath the ridge the mantle does not have its normal compression-wave velocity of 8.1 km/sec; velocity is reduced in the "ridge mantle" to 7.3 or 7.5 km/sec. The ridge mantle changes into normal mantle where layer 3 appears.

The main oceanic crustal layer 3 seems to arise from the ridge mantle as this flows away from the crest and segregates into normal mantle and layer 3; the main process of the segregation, according to Hess, is probably formation of serpentine from peridotite and water dissolved in the mantle at higher temperature and pressure. But where does the volcanic layer 2 arise? At present it is tacitly but widely, if not generally, assumed that it originates mainly from the rift and its immediate surroundings, where volcanic outpourings would "paint" the surface of the crust; with the flow pattern of Fig. 1, the crust would move away from the crest as a rigid plate, and the age of its basaltic paint would be proportional to the distance from the crest.

However, if the flow below the Coulomb layer is a continuous divergence, with velocity increasing away from the crest, the Coulomb layer cannot move as a rigid plate. Its tensile strength is very low, between 300 and 600 bar, and so it must break into small fault blocks if the flow pattern is of the type of Fig. 3. If this is so (as seems unavoidable), how can the age of the ocean floor be proportional to the axial distance instead of being given by the radically different Eq. 2?

If the oceanic crust were "created" at the rift, the floor of the rift would be raised intermittently by isostatic forces, and the raised fault-block would be rifted subsequently. Such a process would explain the shallow-focus earthquakes along the axial zone of the rift, but it would also raise difficulties. If the rift were a highly active and mobile feature, it could hardly be cut into short staggered segments by swarms of faults—as along the equatorial Mid-Atlantic Ridge, or the Indian Ocean Ridge which is cut into sharply staggered segments by the Mozambique, Prince Edward, Malagasy, Amsterdam, and other fracture zones.

A large-scale upwelling cannot have the sharp steps of the rift, and it would change them into a continuously curved line if the rift were constantly widened and changed by the upwelling. Moreover, there seems to be no indication of a progressive and sufficiently rapid uplift of the rift floor. The isostatic-compensatory uplift faulting would be opposite in sign to the rift

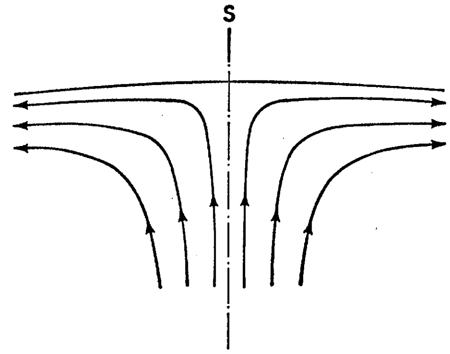

Fig. 3. Continuously diverging flow at upwelling.

faulting; it would have the sign of rift faulting in the Wayland (compressive) theory of rifting, whereas in the Rhinegraben and African rifts Cloos and Gregory have found only the opposite ("tensile") faulting.

It is unavoidable, therefore, that one consider seriously the possibility that the walls of the rift do not move apart with a velocity comparable with that of the ocean floor outside the ridge; and that, according to Menard's assumption, much or most of the "creation" of crust takes place by stretching of the ridge flanks by the divergent flow underneath. If, as I have mentioned, layer 2 is about twice as thick in the axial belt as in the normal oceanic crust, this assumption would account for 2:1 stretching; but this is not enough. Additional stretching would require the injection of volcanics along the slope; how could this occur without producing far more young volcanics along the slope than have been discovered?

There is a simple answer to this. Where the horizontal gradient of the velocity is small, rifts are narrow and widen slowly; lava flowing into them is likely to freeze before gravity slumping of one of the walls of the rift, by faulting, could squeeze it to the surface, particularly because the height of the walls—and thus the frequency of faulting—decreases with distance from the axis. The intrusions needed to stretch

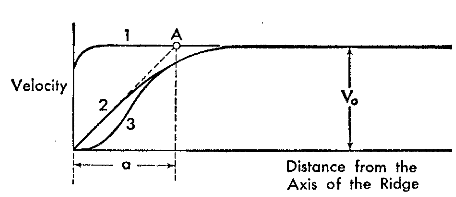

Fig. 4. Different types of increase in horizontal velocity with distance from the axis of a ridge.

layer 2, therefore, may well occur without bringing fresh volcanics to the surface. The "basalt-paint age" of the ocean floor, therefore, may be quite different from the age of the crust at the same point, and also from the age of objects found on the floor.

It is notable that slumping by gravity faulting of the walls of the lava container probably accounts for a large class of volcanic phenomena and for outpourings of basaltic flows. Wherever it is, it should be possible to estimate the depth of the magma reservoir. If it is below the Coulomb layer, fracture and faulting cannot occur and the volcanic activity is quiet and steady (unless water or gases under high pressure are present). Within the Coulomb layer, however, collapse by faulting is rapid and volcanic activity can be paroxysmal.

A great, and perhaps decisive, advantage of the mechanism of crust creation by stretching of the ridge flanks is that it gives a simple answer to the question of why the normal oceanic crust—in particular the main layer 3—is of remarkably constant thickness everywhere outside the crestal belt of ridges. Layer 3 arises by segregation of ridge mantle, including the hydration of peridotite. Since the mantle is unlikely to contain sufficient water to give, say, 70 percent serpentinized peridotite, water must migrate upward to make its apparent contribution to layer 3. Migration by diffusion in a solid at a relatively low temperature is a very slow process; however, it is speeded by orders of magnitude if the solid is crushed and free surfaces and voids of various dimensions are created. This condition is satisfied if the Coulomb layer is stretched along a substantial part of the slope of the ridge. The thickness of layer 3 is then directly determined by the thickness of the Coulomb layer, which of course is the same everywhere: it is the thickness that can be produced by the water and other necessary ingredients contained within the Coulomb layer. Because at the incidental temperatures basalt cannot melt without water, the thickness of layer 2 may also be directly determined by the amounts of water and basalt-producing components contained in the Coulomb layer.

In summation I may say that the flow model of Fig. 1, which led to the conclusion that continental drifting and sea-floor movements must have ceased at least since the Lower Miocene, is in-compatible with the mechanical properties of real materials and with the conditions at an upwelling. Continuously diverging flow, on the other hand, seems compatible both with the increase in basalt-veneer age with distance from the crest, and with the presence of old rocks near the crest; moreover, it explains the globally constant thickness of the oceanic crust outside the axial belts of ridges. Continuously diverging upwelling, in contrast with the discontinuous pattern of Fig. 1, does not bring hot mantle material to the crest, and therefore does not demand a high heat flow there. Consequently, with a mechanically permissible flow pattern, the presence of old fossils and the absence of great heat flow at points near the crest do not indicate absence or slowing of the movement of the oceanic floor away from the ridge examined. But, even if a ridge were found inactive, the vigorous seismic and aseismic faulting going on at present would give evidence of movements of continental and oceanic blocks with velocities of the order assumed in the theory of continental drift.

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23 June 1966

Much of Orowan's discussion appears to apply to a paper by Langseth, Le Pichon, and Ewing (*1*) that he read before its publication.

Saito, Ewing, and Burckle's statement (*2*) regarding the impossibility of significant drift during the late Cenozoic obviously applied to the Atlantic Ocean, not to any ocean as Orowan apparently understood. This conclusion was based on the mechanism of drift that is currently most favored in the literature; the "spreading floor" mechanism (*3*). In this model, sediment distribution, seismic activity, and magnetic pattern are attributed to the flow of the crust away from the axis of the ridge, with a discontinuity of flow at the axis and no horizontal acceleration of flow away from the axis.

It was to determine whether measured heat flows are consistent with the spreading-floor hypothesis that Langseth, Le Pichon, and Ewing used the schematic model of convection shown in Orowan's Fig. 1. This crude model was used only to enable a numerical estimate of the pattern of heat flow created by a convecting mantle in which the vertical velocity in the rising column equals the horizontal velocity in the spreading layer. Further computations, with a more refined mesh allowing a gradual transition of flow direction, have confirmed that the only important factor is the ratio of vertical to horizontal velocity. The thickness of 100 km was chosen only because it was felt that the distribution of temperature has to be nearly adiabatic below this depth; no special geologic significance was attached to it. Consequently, the only important point indicated by this figure is the absence of any acceleration of flow away from the axis; this absence results from the equality of velocities of flow in the rising hot column and in the spreading horizontal layer.

Orowan believes that this pattern of flow, which is advocated by Hess and others, is mechanically impossible and proffers an alternative comprehensive hypothesis that would account for what he considers "overwhelming evidence" of continental drift. Clearly we cannot now extensively discuss such a hypothesis, which should be tested against all geologic and geophysical data obtained from the oceans. Papers now in preparation in this laboratory will review the recent data in the light of current geologic hypotheses.

However, we should point out that Orowan's hypothesis conflicts with published data on several points; for example, he uses physiographic evidence obtained over the East Pacific Rise indicating that the roughness is maximum over the flanks, without mentioning that over the Mid-Atlantic Ridge maximum roughness occurs near the axis. On the other hand, he uses seismic data obtained over the Mid-Atlantic Ridge indicating the absence of layer 3 in the axial zone and the thickening of layer 2 over the ridge, without mentioning that layer 3 is continuous over the East Pacific Rise and that there layer 2 is of its normal thickness from the basins to the crest.

Also, the pattern of convection he advocates would produce a broad heat-flow anomaly over the ridge; the amplitude of this great heat flow depends on the ratio of vertical to horizontal velocity, which in Orowan's Fig. 3 seems to be of the order of ½ to ⅓. For a horizontal velocity of several centimeters per year away from the ridge, the anomaly produced would reach several microcalories per square centimeter per second and could easily be measured. This pattern of heat flow does not fit the measured heat flows over the East Pacific Rise or the Mid-Atlantic Ridge; in any case it does not account for the great difference between these two heat-flow patterns if the same process is now at work on both ridges.

While we agree with Orowan that the pattern of flow supposed by Hess and others seems hardly possible physically, their hypothesis is considered by many geologists to account for the distribution of many of the geologic and geophysical parameters measured in the ocean better than any mechanism of drift yet advocated. This is why in seeking to determine whether continental drift has left any decipherable record in the oceanic crust we have used the spreading-floor hypothesis as a working tool.

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