References and Notes

1. C. B. Lipman, *Amer. Mus. Novitates* **589**, 2 (1932).
2. J. D. Buddhue, *Pop. Astron.* **50**, 560 (1942).
3. V. H. König, K. Keil, H. Hintenberger, F. Wlotzka, F. Begemann, *Z. Naturforsch.* **16a**, 1124 (1961).
4. A. P. Vinogradov, K. P. Florenskii, V. F. Volynets, *Geochemistry* (*USSR*) (*English Transl.*) **10**, 905 (1963).
5. H. B. Wiik (unpublished results) reported in B. Mason, *Meteorites* (Wiley, New York, 1962), p. 156.
6. C. B. Moore and C. F. Lewis, *Science* **149**, 317 (1965).
7. J. W. Larimer and E. Anders, *Geochim. Cosmochim. Acta* **31**, 1239 (1967).
8. W. R. Van Schmus and J. A. Wood, *ibid.*, p. 747. We thank C. F. Lewis for preparing the samples for analyses. All of the specimens used in this work are from the Center for Meteorite Studies collection at Arizona State University. Supported by NSF grant GA-909. Contribution No. 33 from Center for Meteorite Studies.

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Gravitational Mechanism for Sea-Floor Spreading

Abstract. *The gravitational attraction of the continents produces a force field at the surface of the earth, similar in geometry to lithospheric displacements deduced from studies of earthquake focal mechanisms.*

Proponents of a mobile, competent lithosphere comprising the surface of the solid earth (*1, 2*) interpret most of the Cenozoic tectonism of the earth as the relative movements of, and interactions between, large plates of lithosphere, with much of the dynamic activity concentrated along the periphery of the plates. The geographical distribution of earthquakes and studies of their focal mechanisms provide perhaps the most detailed picture of these peripheral interactions as thought to be occurring. A summary of tectonic displacements as deduced from focal mechanism studies (*2*) is shown in Fig. 1. Only reliably determined slip vectors are depicted; tectonic displacements no doubt occur elsewhere, but remain undetermined.

Although the assemblage of many geological and geophysical observations points to the existence of a mobile lithosphere, the dynamical cause of the mobility is less clearly defined. Here I reexamine a mechanism, intrinsically simple, which may explain much of the motion of the oceanic lithosphere and its interaction with continental blocks. Directly stated, the continental masses produce a mutual attraction for each other and for the oceanic lithosphere. Jeffreys (*3*) estimated the magnitude of such attraction, but in his computations considered the continental topography to be fully compensated by its subsurface projection. The topography and its compensation taken together were characterized mathematically by a point doublet, the attractive field of which diminishes as the inverse third power of the distance from the doublet. Jeffreys obtained stresses on the order of 10^{-2} dyne/cm^2 acting on the lithospheric surface, a magnitude which he judged insufficient to move continents. The doublet remains in common usage as an isostatic correction in gravity studies.

In reexamining this gravitational mechanism, I postulate that the continental masses are to some degree uncompensated. The attraction of the uncompensated excess mass diminishes only as the inverse square of the distance from the mass, and thus presents the possibility of a stronger field than does the doublet. The distribution of excess mass can be represented by a surface density σ equal to a constant over the continents and zero over the oceans. This representation emphasizes only the fundamental contrast between continents and oceans, while ignoring regional variation within each. The gravitational potential of such a distribution of mass is given by $V = \int_A (G\sigma/r)\, dA$ where G is the universal gravitational constant and r is the distance between a mass element and the field point. The components of attraction can be obtained by forming the gradient of the potential. In this investigation the potential and attraction were obtained by direct numerical integration over a surface divided into segments bounded by successive 15° meridians and parallels.

The horizontal component of the computed attraction vector at the surface of the earth is shown in Fig. 2. This field represents the horizontal forces acting on the lithosphere according to the hypothesis of some uncompensated continental mass. The most prominent feature of this force field is the attraction of the continents for the ocean floor. All convergences of the vector field occur on the continents; all divergences occur in the oceans. At the continental margins the field is everywhere nearly perpendicular. A marked similarity between the slip vectors of Fig. 1 and the force vectors in corresponding localities is apparent. It is the shorter task to call attention to the principal area of disagreement, along the west coast of North America, where the vectors are a quadrant apart. Elsewhere the fields are sufficiently

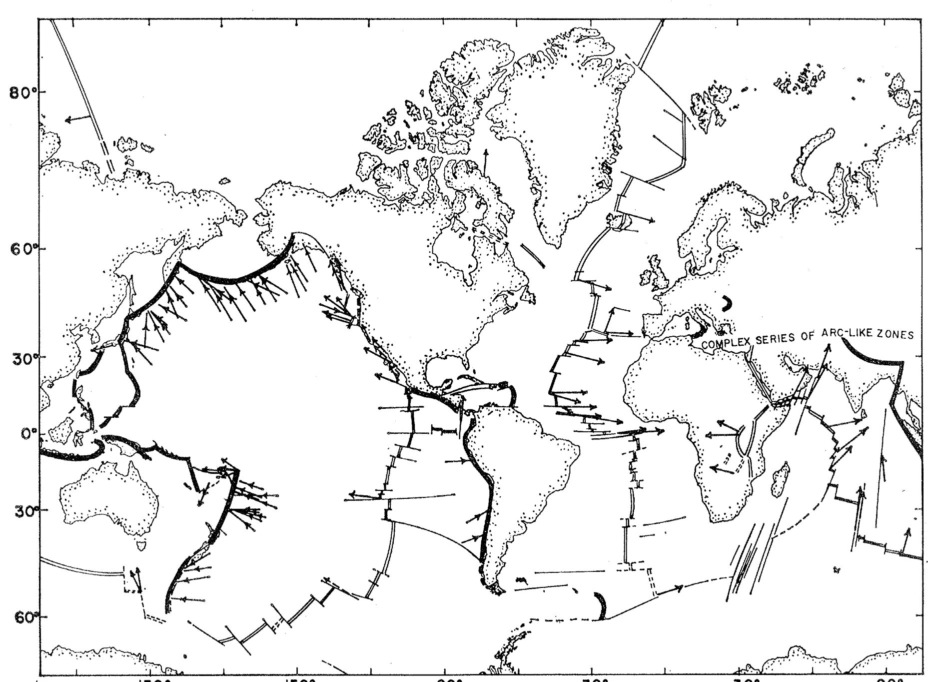

Fig. 1. Slip vectors derived from earthquake-mechanism studies. Symbols: arrows, horizontal component of direction of relative motion of block on which arrow is drawn to adjoining block; double lines, crests of world-rift system; bold single lines, islands arcs and arclike features; single lines, major transform faults [after Isacks and co-workers (*2*)].

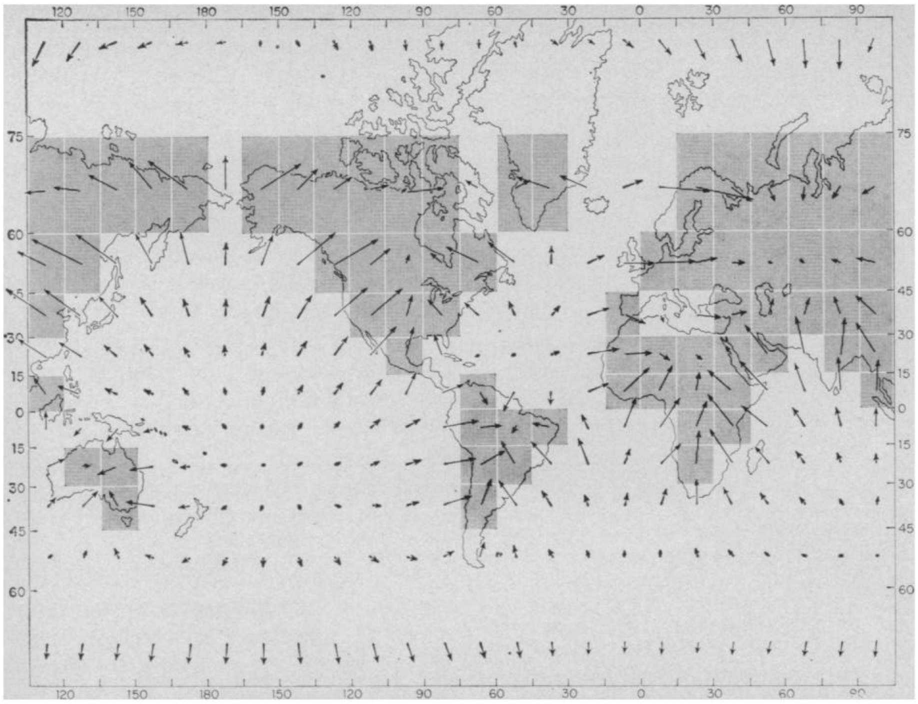

Fig. 2. Horizontal component of gravitational field at surface of the earth due to the attraction of the continents alone. Largest vector shown has magnitude of 1.1 × 10^6 dyne/cm^2; others are scaled accordingly. Approximated distribution of continental mass used in computations shown by shading.

correspondent to suggest a causal relation between the gravitational forces and the observed motions.

That there is not an exact congruence of the force and displacement fields is not surprising, for, if several of the individual mass elements act as a rigid unit, the unit will be acted upon by the resolution of the individual force vectors. In addition, interaction between abutting plates must constrain and modify the motion which a free plate would experience unimpeded. Further, the coarseness of the numerical integration lends a minor distortion to the computed attraction.

The magnitude of the field shown in Fig. 2, computed on the assumption that 10 percent of the continental mass is uncompensated, is generally of the order of 10^5 dyne/cm^2. If such tangential stresses cause sea-floor spreading, then an estimate can be made of the viscosity of the material over which the lithosphere is moving. If the velocity of spreading is 1 cm/yr and the viscous zone is 100 km thick, the viscosity would be 10^{20} g cm^{-1} sec^{-1}. A thicker viscous zone, a greater percentage of uncompensated mass, or a lesser velocity of spreading would imply a higher viscosity. Estimates of the viscosity of the lithosphere itself are in the range of 10^{21} to 10^{22} (*4*), and both solid-state theory (*5*) and observation of elastic-wave attenuation (*4*) suggest a low-viscosity zone beneath the lithosphere.

In summary, the gravitational attraction of the continents offers an interesting mechanism for drawing the ocean floor landward. The question of how the continents assumed their present positions remains open. The gravitational mechanism as hypothesized is to some degree a contradiction of isostasy; the implications of this contradiction invite further study. The chief support for the hypothesis lies in the close correspondence of the predicted force field and the seismically deduced motion of the oceanic lithosphere. It has long been recognized that continents and ocean basins comprise the fundamental contrast within the lithosphere. That this contrast may also impart mobility to the lithosphere is a hypothesis worthy of additional investigation.

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References and Notes

1. J. Oliver and B. Isacks, *J. Geophys. Res.* **72**, 4259 (1967); J. Morgan, *ibid.* **73**, 1959 (1968); X. LePichon, *ibid.*, p. 3661.
2. B. Isacks, J. Oliver, L. Sykes, *ibid.*, p. 5855.
3. H. Jeffreys, *Mon. Not. Roy. Astron. Soc. Geophys. Supp.* 1, 413 (1926).
4. D. L. Anderson and R. O'Connell, *Geophys. J.* **14**, 287 (1967).
5. R. B. Gordon, *J. Geophys. Res.* **70**, 2413 (1965).

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Seismic Waves Reflected from Discontinuities within Earth's Upper Mantle

Abstract. *Precursors to normal seismic waves of the* PKPPKP *type in the distance range of 55° to 75° are ascribed to reflection of this phase from within the earth's upper mantle. The new observations confirm the existence of a sharply defined transition zone, probably worldwide in extent, at a depth of approximately 650 kilometers. These data are shown to be a useful tool for the study of upper mantle structure on a global basis.*

In a study of the earth's core (*1*), an unexplained phase with slope about 2.9 sec/deg was observed nearly 2½ minutes before the arrival of normal *PKPPKP* (*2*) waves. Study of the associated data revealed that these new observations could be explained as reflections of *PKPPKP* from within the earth's upper mantle (a typical ray diagram is shown in the inset of Fig. 1). We now examine the characteristics and important consequences of these new data.

The observations were drawn from short-period vertical seismograms for two large events that were well recorded, with strong onsets, by seismograph stations throughout the world. Observations of *P*, *pP*, and *PKP* were used to relocate these events and the following hypocenter parameters were determined:

3 November 1965
H = 01 39 03.0 (hms, G.M.T.)
9.05 S 71.34 W
h = 590 ± 11 km (depth)
Magnitude 6¾
Peru-Brazil Border

27 October 1966
H = 05 57 57.7
73.40 N 54.87 E
h = 0
Magnitude 6.5
Novaya Zemlya

Signals corresponding to reflected *PKPPKP* waves are clearly recorded only by high-magnification seismographs. An advantage in identification, however, is that the newly identified arrivals always precede the normal *PKPPKP* coda. Shown in Fig. 2 are some examples of reflected and the corresponding normal *PKPPKP* waves. Predicted arrival times of branches for the main phase are noted. Complications are to be expected owing to effects of the crust and subcrustal layers near the zone of surface reflection. Examination of records from other events of comparable magnitude indicates that