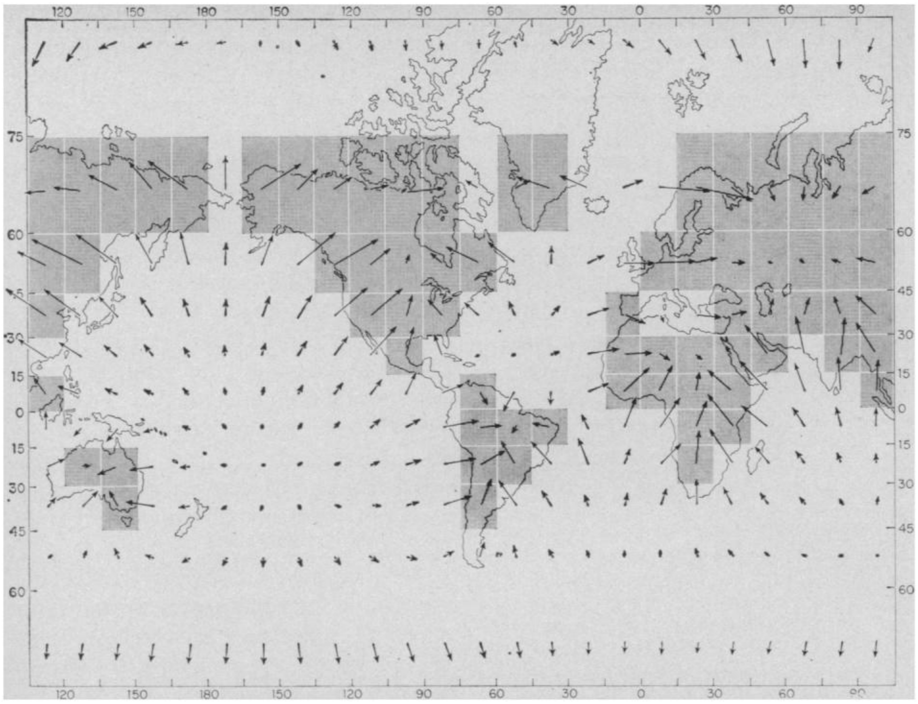

Fig. 2. Horizontal component of gravitational field at surface of the earth due to the attraction of the continents alone. Largest vector shown has magnitude of 1.1×10^6 dyne/cm^2; others are scaled accordingly. Approximated distribution of continental mass used in computations shown by shading.

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.

HENRY N. POLLACK

Department of Geology and Mineralogy, University of Michigan, Ann Arbor 48104

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25 September 1968; revised 4 October 1968

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
$h = 590 \pm 11$ km (depth)
Magnitude 6¾
Peru-Brazil Border

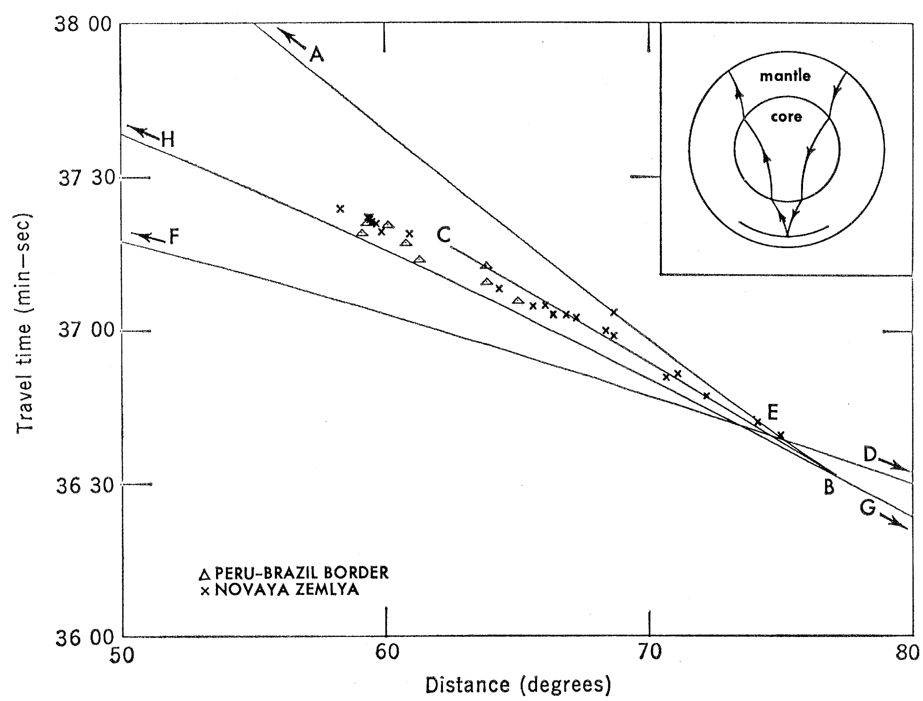
27 October 1966
$H = 05\ 57\ 57.7$
73.40 N 54.87 E
$h = 0$
Magnitude 6.5
Novaya Zemlya

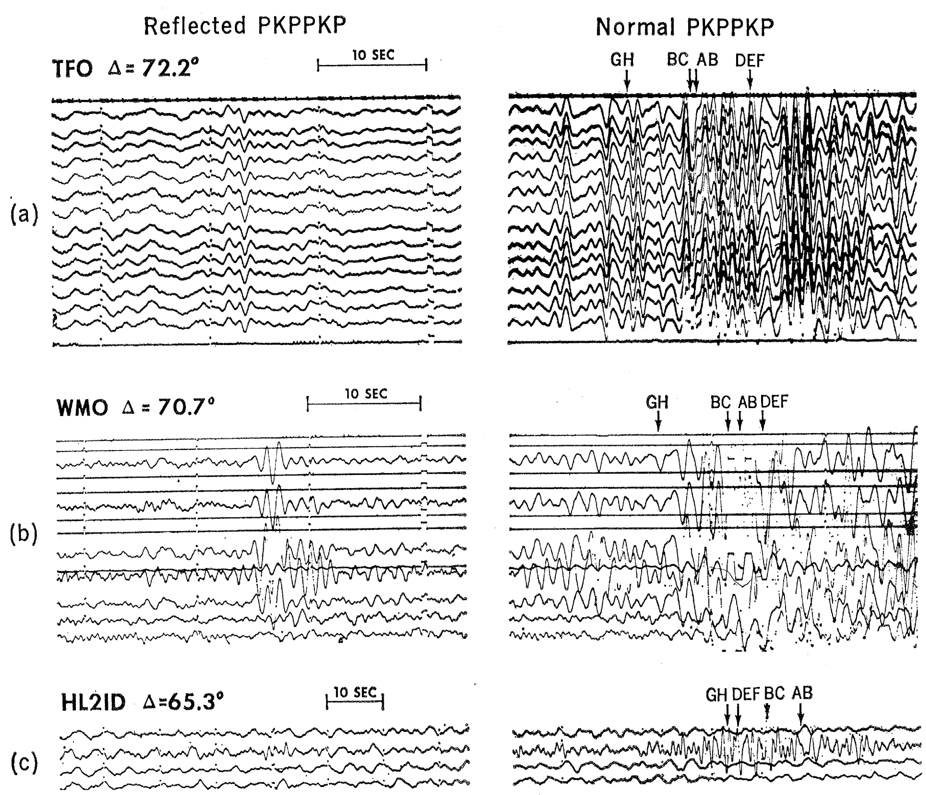
Signals corresponding to reflected *PKPPKP* waves are clearly recorded only by high-magnification seismographs. An advantage in identification, however, is that the newly identified arrivals always precede the normal *PKPPKP* coda. Shown in Fig. 2 are some examples of reflected and the corresponding 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

PKPPKP is not always as well observed, possibly due to peculiarities of the radiation pattern at the source.

Travel times for reflection of *PKPPKP* at a depth of 650 km are plotted with the observed data in Fig. 1. These theoretical curves were constructed by adjusting surface-focus *PKPPKP* travel times and distances by the two-way transit from the surface to a depth of 650 km. Since core waves are steeply incident ($i < 13°$) in this part of the mantle, the adjustments are practically independent of the differences in present models of the region.

Examination of Fig. 1 reveals that, although most of the data are probably associated with the caustic curve *ABC*, there are some observations near 60° not explained by present core models. To interpret this phenomenon new information derived from a recent study of *PKP* must be considered. Engdahl (*1*) showed that an unusually large-amplitude *PKP* arrival, occurring intermediate in time to the *AB* and *DEF* branches, is commonly recorded near 150°. This arrival can either be associated with an extension of the *BC* branch or with the Bolt *GH* branch (*3*), which is several seconds too early in this distance range. More important, this newly identified large-amplitude *PKP* phase follows the same ray path as observations of reflected *PKPPKP* near 60°. As further support, a $dT/d\Delta$ of approximately 2.9 sec/deg was measured from a reflected *PKPPKP* arrival at Tonto Forest Observatory ($\Delta = 72.2°$) (Fig. 2).

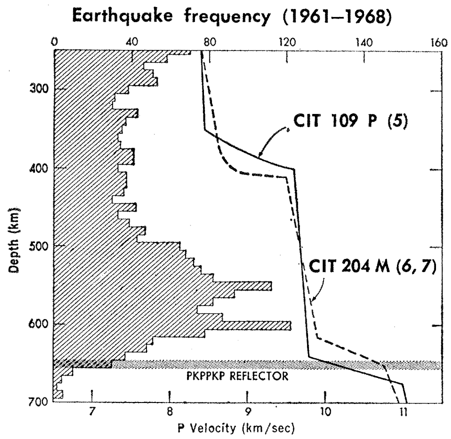




To determine the depth of reflection, travel-time curves were constructed for *PKPPKP* reflected at intervals of 5 km in depth in the upper mantle. By inspection, a reflection depth of 650 km represented the best fit to the observed travel times.

The existence of two transition zones in the upper mantle has been proposed by many investigators (*4–7*). Anderson (*8*) attributed these transition zones to phase changes from olivine to spinel and from spinel to a postspinel phase. Details of the transition zones for two well-determined structures are shown in Fig. 3. The deep reflector and transition zone also coincide with the limit of earthquake activity with focal depth. The model of Archambeau, Flinn, and Lambert was derived from observations of *P*-wave travel times and amplitudes, and is appropriate for the midcontinent region of the United States. Johnson's model was originally based only on $dT/d\Delta$ observations in western North America; this structure was modified by Julian and Anderson to fit observations of travel times. The details of the low-velocity zone and the overall mean

Fig. 1 (above left). Surface-focus travel-time curve for *PKPPKP* reflected at a depth of 650 km within the upper mantle. Cusps and other points are identified according to common usage. All data have been corrected for elevation and ellipticity, and adjusted to a surface focus. Fig. 2 (left). Representative seismograms of reflected and the corresponding normal *PKPPKP* waves. The normal waves follow the reflected waves by about 2½ minutes. Expected arrival times of predicted branches are indicated. (a) Tonto Forest Observatory (TFO); $\Delta = 72.2°$ from Novaya Zemlya; (b) Wichita Mountains Observatory (WMO); $\Delta = 70.7°$ from Novaya Zemlya; (c) Hailey, Idaho (HL2ID); $\Delta = 65.3°$ from Peru-Brazil border.



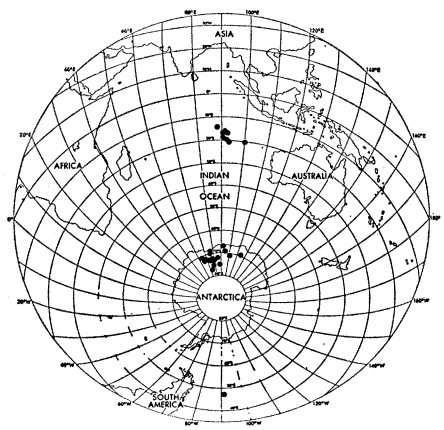


Fig. 3 (left). Earthquake frequency and *P* velocity as a function of depth below the earth's surface. The *PKPPKP* reflector is centered at 650 km. Fig. 4 (right). Reflection points for observations of *PKPPKP* waves reflected within the upper mantle.

travel time can be adjusted to bring the two structures into good agreement.

The data on the reflected *PKPPKP* that are presented here appear related to either the top or the bottom of the lower transition region, and hence may be considered as further evidence for the existence of such a transition region. The two-way travel time through the transition region is about 8 seconds for both structure models. The total absence on all records of another reflected *PKPPKP* phase both preceding and following by 8 seconds the single observed phase suggests that the top and bottom of the lower transition zone do not consist of the same order of discontinuity.

The fact that reflections from the upper transition region were not observed suggests that the transition zone may be defined by third-order rather than second-order discontinuities. The alternative explanation, that this zone may not be global in extent, can be rejected on the ground that one would hardly expect to find the transition from the spinel to the postspinel phase without the transition from olivine to spinel.

Reflection points for *PKPPKP* from the deep transition zone are plotted in Fig. 4. They form two groups: one in the Indian Ocean for Peru-Brazil data and the other at the edge of the Antarctic continent for observations from Novaya Zemlya. At least for these regions, it appears that the deep transition zone is independent of major differences in the earth's surface features.

The partition of energy on reflection from the proposed transition zones of the upper mantle is difficult to assess, since details concerning changes in density and precise thicknesses have not been completely resolved. For a simple model of steeply incident waves on a plane boundary, which has a 7.5 percent increase in density and 9.5 percent increase in compressional velocity, the reflection coefficient is approximately 0.15. If the major portion of the density jump in the upper mantle were evenly distributed between the two transition zones, as Anderson (*8*) suggests, one would expect to observe reflections from the shallow transition zone. The observed data suggest that the physical parameters of the deeper region are more sharply defined.

It is evident from the foregoing presentation that these new data have important consequences for future studies of the upper mantle. A thorough search of seismograms from high-magnification stations for well-recorded *PKPPKP* phases is now being made to assist in accurately describing zones of reflection in the upper mantle and their global extent (*9*).

ERIC R. ENGDAHL
Environmental Science Services Administration, Coast and Geodetic Survey, Rockville, Maryland 20852

EDWARD A. FLINN
Geotech (a Teledyne Company), Alexandria, Virginia 22313

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9. Since this paper was submitted for publication we have learned of a paper (R. D. Adams, *Bull. Seismol Soc. Amer.*, in press). Adams studied precursors arriving 10 to 70 seconds before normal *PKPPKP* waves, and interpreted them as reflections from discontinuities or inhomogeneities in the upper mantle. One of the events used by Adams was the deep-focus earthquake we analyze in the present paper. We find that an alternative explanation of Adams' data is the unreported phase *SKKKP*. This phase is conspicuous on the records we studied, but we did not comment on it because it is apparent from the $dT/d\Delta$ of 4.4 sec/deg that this phase is not a reflection of *PKPPKP* from a discontinuity within the upper mantle (E. R. Engdahl and E. A. Flinn, *Bull. Seismol. Soc. Amer.*, in press.
10. We thank R. D. Adams for making a copy of his paper available to us in advance of publication. We also thank D. L. Anderson and Miss I. Lehmann for discussions. Supported in part by the Advanced Research Projects Agency, Nuclear Test Detection Office, under project VELA UNIFORM, and accomplished under the technical direction of the Air Force Technical Applications Center under contract F-33657-68-C-0945.

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Potassium-Sodium Ratios in Aqueous Solutions and Coexisting Silicate Melts

Abstract. *Silicate melts were equilibrated with aqueous chloride solutions at temperatures between 770° and 880°C and a total pressure of 1.4 to 2.4 kilobars. The ratio of potassium to sodium in the aqueous phase was (0.74 ± 0.06) times the corresponding ratio in the coexisting melt over the entire range of temperature and pressure for all chloride concentrations between 0.2 and 4.2 moles per kilogram.*

During the course of a series of experiments designed to clarify the distribution of cations between silicate melts and aqueous solutions, we have determined the concentration of sodium and potassium in granitic melts and in coexisting chloride solutions at temperatures between 770° and 880°C and pressures between 1.4 and 2.4 kb. A starting glass was prepared by mixing 37 percent (by weight) clear vein quartz with 30 percent (by weight) albite from Amelia Court House, 6 percent (by weight) anorthite from Naxos, Greece, and 27 percent (by weight) adularia (63 percent orthoclase and 37 percent