Drift of Continental Rafts with Asymmetric Heating

Abstract. *A laboratory model of a lithospheric raft is propelled through a viscous asthenospheric layer with constant velocity of scaled magnitude appropriate to continental drift. The propulsion is due to differential heat concentration in the model oceanic and continental crusts.*

Most models of the dynamics of continental drift that are based on convection in the upper mantle are unsatisfactory because either (i) the model fails to account for lithospheric plates (relatively rigid blocks of the outer parts of the earth's mantle) being driven to distances of the order of the present separations of the Atlantic continents (*1*), or (ii) the velocities of propulsion that are obtained are not uniform with time (*2*). Self-propulsion at constant velocity was not observed in at least one case (*3*).

A model is needed that can provide reasonable and reasonably constant values for the velocities of continental drift during the last 150 million years or so and account for propulsion to long ranges. Our model is a modification of that of Howard *et al.* (*2*) in which we take into account nonhomogeneous heat production in a single lithospheric plate.

To recapitulate the geophysical basis for the model, we recall that in most models for lithospheric heat production (*4*) it is assumed that the continental surface heat flux can in large part be accounted for by crustal heat production, while little of the heat flux at the ocean bottom, remote from the oceanic ridges, originates in crustal heat sources. If the heat flows in the mantle in continental and oceanic regions are extrapolated to the low-velocity channel, or asthenosphere, it is inferred that there is a reduction in the heat flux in the asthenosphere under the continents relative to the oceans. Since the continental lithosphere is very old relative to the oceanic lithosphere, this asymmetry in the heat flux through the upper surface of the asthenosphere has undoubtedly been present over the last 150 million years and longer.

In this report we consider the effect of asymmetric heat flux through the top of the asthenosphere due to the difference in heat production in oceanic compared with continental regions. This implies a transport of heat laterally through the asthenosphere from the continental toward the oceanic regions (*5*). In the laboratory model, two floating wire heaters were rigidly coupled, as shown in the inset of Fig. 1. The heating elements were constructed of stainless steel wire (0.02 mm) threaded through alumina tubes (1.6 mm) for rigidity. The tubes were rigidly connected at a fixed separation and floated in a layer of silicone oil by means of Styrofoam pontoons immersed either in the oil or in water channels, the latter to see if the pontoons had any drag associated with them. As expected, when the two sources were heated equally no motion was observed, while maximum contrast produced the maximum velocity. In these experiments, the greatest velocity of the raft was produced by letting one heater be inert and heating the other to as high a value as possible. Higher velocities could be obtained, in principle, by refrigerating one wire. The system moves toward the cooler heater at shallow immersions of the wires and toward the hotter element at deeper immersions.

It is convenient to introduce the ratio of the heat intensities of the two wires $Q_2/Q_1 = r$. For $r = 0$, the buried heater with source strength Q_1 causes the fluid to expand near it and to move away toward the surface. The inert wire moves because of the drag of the fluid streaming past it. The cold wire, in turn, drags the hot wire with it because of the rigid coupling. Small floating markers placed near a heater were found to move to distances of 10 to 15 times the depth of the fluid, or more, which is evidence of the elongated flow patterns in the fluid.

Scaled experimental velocities for the two illustrative cases, $r = 0$ and $r = 3/4$, as a function of the scaled heat density of the hotter wire, are shown in Fig. 1. The velocity is scaled by h/κ, the ratio of layer thickness to thermal diffusivity. The linear heat density Q is made dimensionless through

$$R = \alpha g Q h^3/\nu\kappa^2$$

where α is the coefficient of thermal expansion, g the acceleration of gravity,

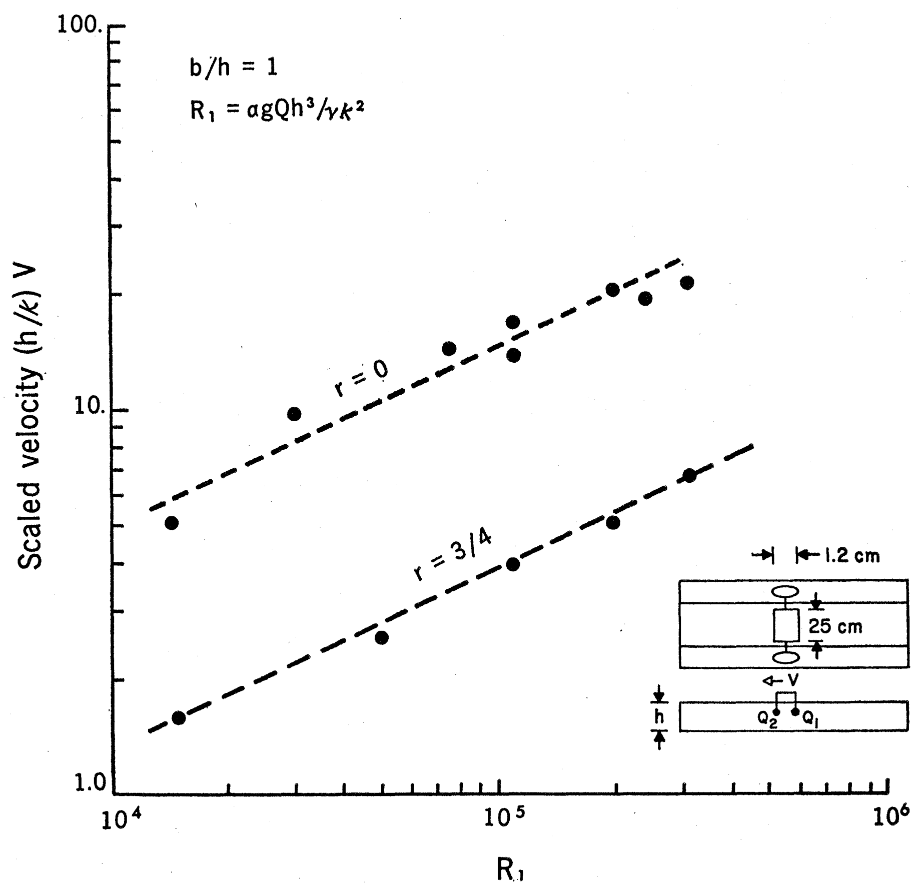

Fig. 1. Scaled velocity as a function of the scaled heater strength of the hotter element in the frame raft for two values of the ratio of heater strengths.

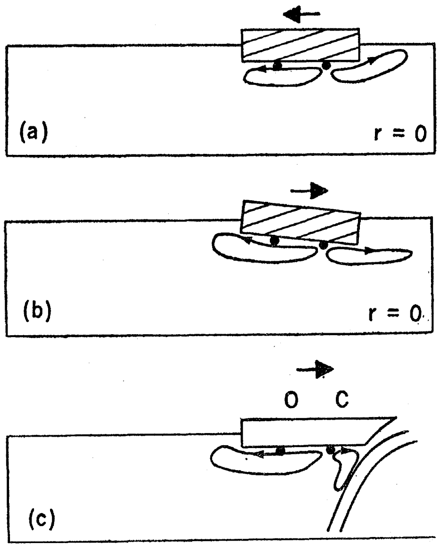

Fig. 2. Schematic diagrams of (a) the flow about a plane raft with the heater at the left inert, propelling the raft to the left; (b) the flow about a slightly inclined plane raft with the heater at the left inert, propelling the raft to the right; (c) the flow about a lithospheric raft with the oceanic heater inert; the raft is propelled to the right because of the downward deflection of the flow pattern at a convergent zone. Symbols are *O*, ocean; *C*, continent.

and ν the kinematic viscosity. The results are not inconsistent with the theoretical result that the velocity should vary as

$$R_1^{1/2}(1-r)/(1+r)^{1/2} = (R_1 - R_2)/(R_1 + R_2)^{1/2}$$

where R_1 and R_2 are the scaled heater strengths of the hotter and cooler elements, respectively. The theory has been developed for isothermal and free upper and lower surfaces, but we believe that the dependence on these variables should not change with a change in the boundary conditions; only the numerical coefficients in the solution should change.

The magnitudes of the velocities for the frame raft are of the order of centimeters per year for suitable values of the parameters. For a heat flux of 1 μcal/cm^2 sec for a continent of width 3000 km, and the values 600 km for h, 3×10^{-2} cm^2/sec for κ, 10^{21} cm^2/sec for ν, and 2×10^{-5} (°C)$^{-1}$ for α, we get velocities of the order of 2 cm/year if $r = 0$ and the heater separation b is set equal to h. Thus, it seems plausible that a lithospheric raft could be self-propelled with appropriate velocities because of the differences in heat production between its continental and oceanic parts.

Plane rafts were also constructed from sheets of hollow plastic, and the two heaters were symmetrically fixed on the lower surfaces. Motion was observed for this model for the case $r = 0$. If the raft were infinite in lateral extent, the symmetry for the case $r = 0$ would require that the raft be stable. Hence, we conclude that an elongated convection pattern, as earlier illustrated by markers, couples to the edge of the finite raft and thus provides an asymmetric drive on the raft (Fig. 2). The experimental results show that the velocity varies as $R^{1/2}$ for large R, as in the case of the frame raft, but falls to lower values at lower R; similar behavior has been observed by Whitehead (*3*) for a line heater suspended beneath a raft. Little dependence on r is found, except close to the singular case $r = 1$.

A lithospheric raft driven by asthenospheric heating under continents, as described here, would move toward the cooler regions, that is, the oceans. This would seem to contradict the behavior near the oceanic ridges. However, we were able to obtain reversal in the direction of motion consistently in experiments with plane rafts (with $r = 0$) inserted at a slightly nonlevel attitude, with the hot side depressed. We infer that the inclination of the raft depressed the circulation pattern near the hot end and allowed the long-range circulation to the cold edge to dominate. The geophysical implication is that the flows may be deflected and depressed by downthrust lithospheric slabs and that propulsion comes from the parts of the earth where the heat is most readily transported to regions near the surface (Fig. 2). In the earth, this is accomplished most effectively at the oceanic rises. There is an additional influence because the boundary conditions at oceanic rises are different from those described here.

This model has the virtue that relatively uniform velocities will be maintained as long as the conditions at oceanic rises remain relatively permanent. A literal result of the model is that plates without continental parts should be stable; two such plates are the Pacific and Nasca plates. These should have rather small relative motions, except as they may be driven through interaction with the other major plates of the world by virtue of closure on an almost spherical earth. Our model has not provided for this interaction.

L. KNOPOFF
K. A. POEHLS, R. C. SMITH
Department of Physics and Institute of Geophysics, University of California, Los Angeles 90024

References and Notes

1. L. Knopoff, *Rev. Geophys.* **2**, 89 (1964).
2. L. N. Howard, W. V. R. Malkus, J. A. Whitehead, *Geophys. Fluid Dyn.* **1**, 123 (1970).
3. J. A. Whitehead, *Phys. Earth Planet. Interiors*, in press.
4. R. P. von Herzen, in *The Earth's Mantle*, T. F. Gaskell, Ed. (Academic Press, New York, 1967), p. 197.
5. L. Knopoff, *Phys. Earth Planet. Interiors* **2**, 386 (1970).
6. Publication No. 1000 of the Institute of Geophysics, University of California, Los Angeles.

10 December 1971; revised 21 March 1972

Genetic and Immunological Complexity of Major Histocompatibility Regions

Abstract. *There are genetic differences within the major histocompatibility complex of the mouse which lead to skin graft rejection but which cannot be detected serologically. When confronted with these differences on allogeneic cells, lymphocytes proliferate in vitro. In other cases, in vitro lymphocyte proliferation but no skin graft rejection is associated with loci that are linked to but genetically separable from the loci controlling the serologically defined antigens.*

There is a single major histocompatibility complex (MHC) in the genomes of mouse (*1*) and of man (*2, 3*). Within that region in each species there are two loci approximately 0.5 recombinational units apart; alleles of these loci control serologically (antiserums) detectable antigens. We refer to these as serologically defined (SD) loci. In the mouse the SD loci are the H-2K and H-2D loci of the H-2 system; in man the LA and four loci of the HL-A system. Each locus is highly polymorphic with at least one antigen associated with each allele.

In addition there are genetic differences in the MHC which are at the very least difficult to detect serologically but which lead to a lymphocyte response in vitro. We refer to such differences as lymphocyte defined (LD) differences. We use the abbreviations