CONVECTION CURRENTS IN THE EARTH'S MANTLE: A MECHANISM FOR CONTINENTAL DRIFT?

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The first to postulate the existence of convection currents underneath the earth's crust — and hence to formulate some of the basic ideas still used to explain the mechanism of continental drift — was the Austrian geologist Otto Ampferer. He saw convection currents mainly as a mechanism for mountain building. The first to formulate continental drift in terms of convection currents was Arthur Holmes. The concept was later expanded into the sea-floor-spreading hypothesis by Hess, Dietz, Wilson and others, and still the most widely used model to explain continental drift.

What is Convection?

Convection is quite easily observable in a pot of boiling water. Density differences within a fluid cause the heavier portion to sink and the lighter portion to rise. This phenomenon is thermal convection because it is caused by a density difference in the water which is created by a temperature difference. If water is heated from below, the heated portion expands, becomes light and thus rises to the surface, where it is cooled and sinks down again. This circulation of water has the effect of heating the water throughout and convection is well known as one of the classical methods of heat transfer.

The phenomenon of convection was first investigated in depth by H. Bénard. In his famous experiment (1906) he placed a thin film of paraffin on top of an iron cylinder and heated the cylinder from below. Bénard found that convection did not occur until the cylinder had reached a certain temperature. After convection had set in for a while, a regular hexagonal pattern appeared on the surface. The explanation is that heated fluid rises to the surface at the centre of each hexagon, and cooled liquid on the top descends at the sides. The interesting fact about this phenomenon is that stirring cannot disturb this pattern for long, i.e. the convection cells form a *stable* pattern. These cells are known as Bénard cells. Another interesting fact is that the ratio between the thickness of the layer and the horizontal size of the hexagonal cells is close to one. Bénard's findings were theoretically analyzed by Lord Rayleigh in 1916, who developed the necessary conditions for convection to occur. These conditions are a relationship between the depth of the liquid layer, the coefficient of thermal expansion, the temperature gradient, the force of gravity, the thermal diffusivity and the viscosity. If the viscosity is large compared to the other factors, convection is inhibited. These numbers are combined in a ratio to form a dimensionless number called R (Rayleigh's number), and if R reaches 1000, convection begins to occur.

Convection Currents in the Earth's Mantle

Arthur Holmes[1] ventured the idea that such convection currents occur in the earth's mantle. This appears at first sight to be a peculiar idea because the mantle is a solid body. However, geophysicists argue that no matter how solid, no substance can permanently withstand the prolonged action of forces. Thus, a tall iron pillar will ultimately bend under the force of gravity and collapse after a long time. Even a crystalline substance like ice will eventually flow, even if very slowly. One interesting indication of the earth's fluidity is its shape—it has an ellipsoid shape. It is not completely spherical because its rotations cause it to bulge at the equator. This simple fact seems to show that the earth can act as a fluid body.

Arthur Holmes developed the following concept of convection currents in the earth's mantle: basaltic magma rises with the ascending convection currents at the mid-ocean ridges and forms the ocean crust. The convection currents descend back into the mantle at the deep ocean trenches. Convection currents rising up underneath the continents (without penetrating the crust necessarily) would transport the continents conveyor belt-like and hence produce continental drift. Different variations of Holmes' scheme are still current among geophysicists today.

A number of objections have been voiced about such models. First of all I want to describe briefly some of the objections to the theoretical model of the mechanism, and then review some of the empirical evidence quoted against the convection current hypothesis.

The Earth's Mantle as a Fluid, and the Convection Current Theory

There are a number of factors which complicate the model of convection in the earth's mantle very considerably. The most obvious one from a physical point of view is that it is very hard to know what kind of fluid the mantle is. 'Ordinary fluid dynamics' deals with fluids known as Newtonian fluids. If the mantle behaves as a non-Newtonian fluid, it may be difficult even to define such important variables as the viscosity, and to solve the equations of motion of non-Newtonian fluids around a spherical shell is a formidable task indeed. (Geophysicists are working on it!) Another complication has already been mentioned in passing: we are dealing with a viscous fluid layer which exists in the form of a spherical shell, and not a horizontal layer heated from below. The famous astrophysicist S. Chandrasekhar extended Rayleigh's theory of thermal convection to spherical bodies and he also studied spheres like the earth which contain another spherical body (the core) inside.[2, 3] The results of his research indicates that large-scale convection with a flow that encircles the entire earth can occur only if the core is small. With the core increasing, the pattern of convection is disrupted and the cells decrease considerably in size.

At this point we might consider another controversy: how deep do the convection currents reach into the mantle? Geophysicists have long argued about the

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question whether convection currents are confined to the upper seismically 'soft' layer of the mantle (i.e. the upper 250 km) or reach deep down into the mantle. One could argue against the latter model on the grounds that the pressures of the mantle are so high in these regions that the rocks are four times harder than steel and harder in fact than diamond, and that it seems implausible that the currents can be maintained in these regions. If the objections against convection in the deep regions of the mantle prove to be justified, then Chandrasekhar's theory might be used to question the whole feasibility of the convection current model. This is an interesting area of research to be pursued.

S. K. Runcorn[4] tried to use Chandrasekhar's arguments to explain the break-up of continents due to the instability of convection currents caused by a growing core. This elegant hypothesis was not very widely accepted. Physically it can be argued: (a) The actual state of the earth's interior is remote from the model to which the Rayleigh-Chandrasekhar theory was applied, and since the Rayleigh number in the mantle may be far greater than the critical Rayleigh number, such a simple convection pattern cannot exist. (b) Such a simple model is not applicable to the actual mantle in which the viscosity varies. Other complications arise out of the fact that the heating of the liquid is not only from below, but there are radioactive heat sources within the mantle. Moreover, various properties, which in the Rayleigh theory were considered constant, are actually functions of temperature and pressure, such as the viscosity.

It is an interesting fact which was discovered by Myron Block[5] in 1956 that Bénard convection is not actually a thermal effect, as Bénard himself thought and is still widely believed. The motion is not induced by changes in density due to heating, but rather through differences in surface tension. Bénard's experiment in the end has little bearing on thermal convection. Some scientists have argued that Block's discovery effectively destroys the convection cell theory of continental drift. The light sima and sial crust on top of the mantle will counteract the surface tension effects of convection cell formation. Egon Orowan[6] argued in the *Scientific American* that no geophysicist would have accepted the convection current hypothesis of Holmes and Hess if Block's results had been known before 1956. Other geophysicists have replied, however, that Rayleigh's thermal convection theory remains valid provided the layers are thick enough. It ought to be said that it is by no means certain that thermal convection can occur in the earth's mantle on the scale envisaged.

Another problem that arises if we accept that the convection currents are limited to the soft asthenosphere in the upper mantle is that the cells are too small. It is a conclusion of the theory of Rayleigh convection, and of all more complicated versions, that the ratio of the horizontal size of the cells to the vertical depth should be close to one. Consequently, this limits the horizontal scale of convection cells to a few hundred kilometers. The kind of movements this mechanism is supposed to explain, however, are on a scale of several thousand kilometers. Some respected researchers see this as a grave problem for the theory.

Many geologists have assumed that given enough time the earth can act as an ideal or Newtonian fluid. Nobody knows for certain, however, that this is actually the case. We do not even know exactly what the mantle consists of, and so we have little idea about the fiuid dynamics of the mantle. Newtonian fluids obey equations of motion in which the rate of strain of a substance is proportional to the stress. The limited experimental evidence that exists seems to indicate that the mantle does not behave like a Newtonian fluid at all; the rate of strain seems to increase exponentially by many powers proportionate to the stress. The conclusion that some geophysicists have drawn from these experiments is that flow in the mantle may be localized like a jet current. In most areas the flow will be very slow, but in some local areas it will be largely accelerated. Again, here is a very fruitful area for more research.

Empirical Objections to the Convection Current Theory

A devastating argument against mantle convection was published by the Soviet geophysicist E. Artyushkov[7] in 1973. Previously, geophysicists had been greatly influenced by estimates of the mantle viscosity calculated by "postglacial rebound" in Scandinavia. This method was based on the principle of isostacy: the great mountain ranges are floating on the mantle and are subject to the principle of buoyancy. Scandinavia is believed to have been covered by a glacier; and after the ice melted at the end of the Ice Age the Scandinavian peninsula was relieved of a great weight. This in turn caused the Scandinavian peninsula to rise in order to regain isostatic equilibrium. The rate at which it is still rising was used to calculate the viscosity.

The result thus obtained was thought to be compatible with mantle convection, but Artyushkov argued convincingly that particularly under oceanic areas the viscosity of the asthenosphere should be one or two orders of magnitude smaller. The consequence would be that the force exerted at the bottom of the lithosphere due to flows in the asthenosphere would be too insignificant to drive the motion of the plates.

The interpretation of the mid-ocean ridges as the points where the convection current rises to the surface is in conflict with a number of empirical data. Peter Kaiser[8] observes that the convection current model implies that the rate of transport of the continents should depend on the size of the continents. Since North America is considerably smaller than Eurasia, the Mid-Atlantic Ridge ought to be much closer to Europe. In fact, however, it is fairly close to the centre, especially at places where the width of the continents is larger and these effects would be more noticeable. Another interesting observation is that on the west side of the Mid-Atlantic Ridge, close to America, the sea floor was dated at 160 million years old, whereas on the east side, close to Africa, it was dated at only 110 million years. This is difficult to explain if the sea floor spreads from the ridge.

More devastating to the theory are the so-called "fracture zones" at the mid-ocean ridges. J. T. Wilson[9]

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