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AN EXPLANATION OF THE PYROXENE GEOTHERM BASED ON PLUME CONVECTION IN THE UPPER MANTLE

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Temperatures in the earth's upper mantle have recently been determined by the application of pyroxene geothermometry to ultramafic xenoliths in South African kimberlite pipes. The geotherm predicted by this technique shows a large and unexpected increase in geothermal gradient at a depth of about 170 km. Steady-state transport of heat through the lithosphere seems incapable of explaining this behavior. We suggest that transient heating of a rigid lithosphere moving over a plume in the upper mantle provides a possible explanation for the shape of this geotherm. A solution for the thermal structure of a cylindrical, upper-mantle plume with transient heat conduction into a lithosphere moving over the plume has been obtained numerically. By appropriately locating the kimberlite pipe, good agreement between the pyroxene geotherm and the calculated geotherm is obtained. It is concluded that the pyroxene geotherm is consistent with plume convection in the upper mantle.

Temperatures in the earth's interior have been the subject of much discussion and though many details of the structure of the earth are now known, estimates of temperatures even in the uppermost mantle remain uncertain. However, recent pyroxene geothermometry with rocks from the upper mantle may provide direct measurements of upper mantle temperatures. Boyd [1] derived a pyroxene geotherm by the study of ultramafic xenoliths in the kimberlite pipes of Lesotho in South Africa. Phase equilibria in the systems enstatite–diopside and enstatite–garnet were used to estimate the equilibration pressure and temperature of xenoliths containing the mineral assemblage enstatite + diopside + garnet. The geotherm derived with this techniques has the form shown by the data in Fig. 1 which is replotted from Boyd. To a depth of about 150 km the temperature increases with depth in fair agreement with previous downward extrapolations of the near-surface geothermal gradient. The pyroxene geotherm, however, shows an unexpected increase in geothermal gradient over the depth range 150–200 km.

Assuming that the pyroxene geotherm actually is representative of the temperature in the mantle as a function of depth, at least three possible explanations for such a temperature profile may be given.

(1) Boyd has suggested that shear heating could generate such a transient geotherm. Shear heating in the region of increased geothermal gradient would also explain the contrast in textures observed; xenoliths from depths along the steep part of the geotherm being strongly sheared while those from shallower depths being unsheared. This hypothesis does not explain why the intrusions containing these xenoliths should be fairly localized in occurrence.

(2) The variation in the geothermal gradient could be due to variations in the thermal conductivity. A decrease of thermal conductivity of about a factor of five would be required to explain the data. Current understanding of the composition of the upper mantle and the properties of minerals at these conditions make this explanation unlikely.

(3) A transient change in the mantle convection pattern could lead to such a geothermal gradient. An example would be the interaction between a fixed mantle plume and a moving lithospheric plate. It is this alternative which we wish to consider in this paper.

We suggest that a cold rigid lithosphere moving over a plume of hot rising mantle material will result in a transient geotherm with an abrupt increase in geothermal gradient at the base of the lithosphere.

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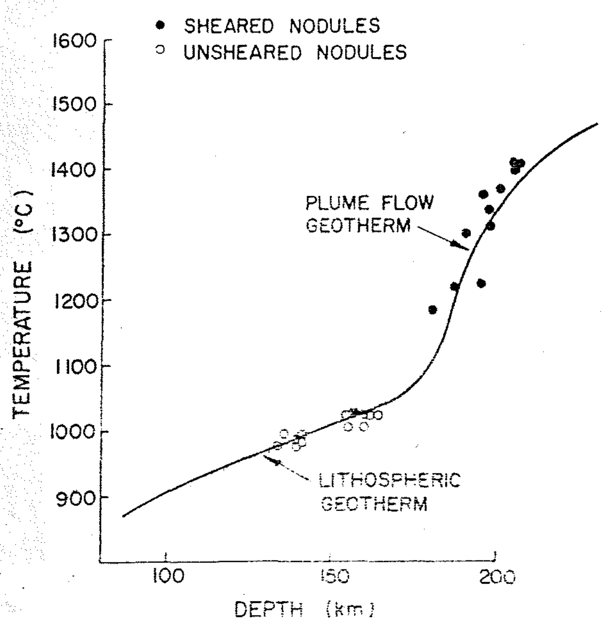

Fig. 1. Data corresponding to the pyroxene geotherm replotted from Boyd [1] compared with the geotherm predicted by the thermal structure of a plume–lithosphere interaction.

As the rigid lithosphere moves over the hot plume, the heat flux to the base of the lithosphere is increased. But this heat must be transported into the lithosphere by conduction, which is a slow process. Consequently, in the time required for the lithosphere to move over the plume, the geotherm in the lithosphere will be modified only near its base. This results in a geotherm composed of essentially two parts, the pre-existing lithospheric geotherm above the base of the lithosphere and the geotherm in hot flowing plume rock at greater depth. Heat conduction insures that the two geotherms merge smoothly at the lithosphere-asthenosphere boundary. In this interpretation the depth of abruptly increased geothermal gradient corresponds to the base of the lithosphere. This is supported by the textures of kimberlite nodules discussed by Boyd [1]. As shown by the data in Fig. 1, the nodules inferred to have come from the greatest depths have highly sheared textures; it is reasonable to infer that these rocks were flowing at the time of their emplacement in the kimberlite magma.

To better understand this interpretation of the pyroxene geotherm, the thermal structure of a plume–lithosphere interaction has been analyzed using numerical techniques. Studies have been made of thermal convection in a cylindrical geometry to identify conditions for which plume-like mantle flows might be expected. Both internal heating and base heating have been considered. Of these two modes of heating, only base heated flows exhibit a plume-like structure. We therefore consider convection confined to the upper mantle above 700 km since it is in this situation that base heating will be most dominant. It should be pointed out that thermal convection is the result of a thermal instability in the mantle. Therefore, it is expected that thermal plumes will be distributed throughout the upper mantle with a spacing of several layer depths. The numerical methods used for the calculation of base heated flows are similar to those used in studies of base heated convection in two dimensions discussed by Torrance and Turcotte [2].

Constant fluid properties were assumed except for the viscosity. A Newtonian viscosity was used with a temperature and pressure dependence appropriate for diffusion creep. The mean viscosity in the absence of a plume was taken to be 10^{22} poise corresponding to the mantle viscosity deduced by Cathles [3] from postglacial rebound studies. The top boundary temperature was taken to be 1075°C corresponding to the temperature at the base of the lithosphere inferred from the pyroxene geotherm. A temperature difference of 700°C between top and bottom boundaries was assumed. Based on this reference viscosity and temperature difference, the Rayleigh number considered was 10^5.

In order to obtain a steepening of the geothermal gradient the rigid lithosphere must move relative to the plume. The required three-dimensional numerical solution is beyond the capabilities of present numerical techniques. We assume that in calculating the plume structure the moving upper boundary can be approximated by a fixed boundary. This is a good approximation since the velocity of the plate (5 cm/yr) is small compared with the maximum velocity in the plume (44 cm/yr). The heat flow from the plume is then used to determine the thermal structure of the moving lithosphere. Although this thermal solution distorts the base of the lithosphere the distortion is small, since heat conduction into the lithosphere is a slow process.

The flow pattern and isotherms for a mantle plume impinging on a rigid lithosphere are shown in Fig. 2. Motion of the lithosphere over the plume is in the direction indicated with a speed of 5 cm/yr. As dis-

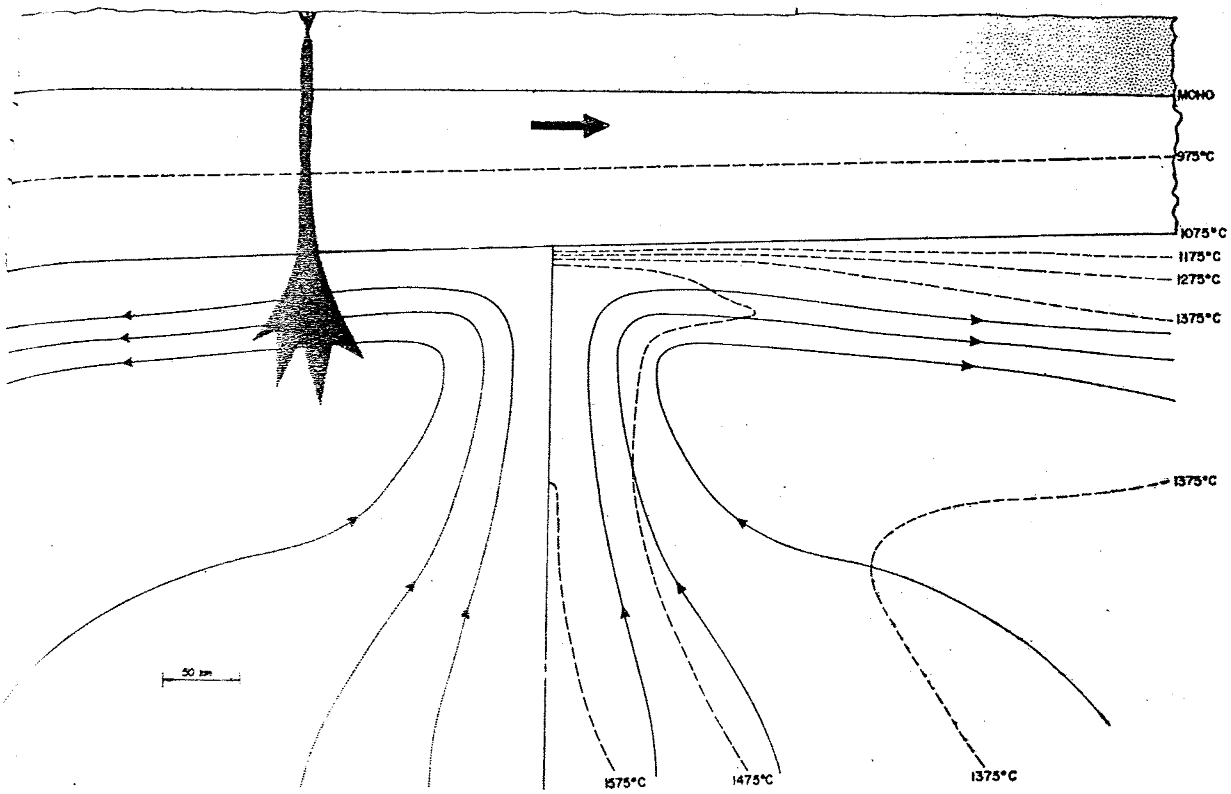

Fig. 2. The thermal structure of the interaction of a moving lithosphere with a mantle plume predicts the geotherm given in Fig. 1. The geotherm is at the location shown by the schematic kimberlite intrusion. Dashed lines are isotherms and solid lines are streamlines with flow direction indicated by arrows. Rigid lithosphere at temperatures below 1075°C is divided into crustal and mantle regions and is moving relative to the plume at a velocity of 5 cm/yr in the direction shown. Note that lithosphere thins slightly in the direction of its motion.

cussed above, the base of the rigid lithosphere is taken to be the 1075°C isotherm. The flow streamlines show a highly concentrated ascending plume. This flow structure results from the strong temperature dependence of the diffusion creep viscosity. Over three-fourths of the volume flow in the cylindrical convection cell passes within a 100-km radius of the plume axis, and the maximum vertical velocity on the axis is 44 cm/yr.

The isotherms show that hot mantle rock rises to shallow depths in the plume and that the highest temperatures remain confined to a region near the axis. A thermal boundary layer with large vertical temperature gradients forms where hot plume material impinges on the colder lithosphere and thickens radially away from the plume axis. As the hot mantle rock cools in the thermal boundary layer its viscosity increases causing streamlines to be deflected away from the base of the lithosphere toward the region of lower viscosity at greater depth. The highly concentrated structure of the plume results in a heat flux to the base of the lithosphere that peaks sharply on the plume axis.

The geothermal gradient in the deeper part of the lithosphere, prior to heating by the plume, depends on its past thermal history and is not determined by the present analysis. We take an undisturbed geothermal gradient of 2°C/km corresponding to that predicted by the shallow section of the pyroxene geotherm. The disturbed lithospheric isotherms plotted in Fig. 2 show the effect of plume heating by their upward deflection in the direction of plate motion. In any vertical section of lithosphere perpendicular to its direction of motion, the upward displacement of the isotherms becomes progressively greater as the time of the interaction with the plume increases. The temperature disturbance at shallow depths in the lithosphere remains small.

A kimberlite intrusion which erupts through the lithosphere is also shown schematically in this figure. This location is chosen because it provides the best fit with the pyroxene geotherm. Although this choice is arbitrary, there is no reason to associate the production of kimberlite magma with a particular location in the plume flow. The lithospheric and plume flow geotherms are identified in the figure. These two sections of the complete geotherm are joined by the geotherm predicted from the temperature distribution in the conduction layer at the base of the lithosphere. The thickness of the conduction layer at this distance from the plume axis is about 20 km. It can be seen that the thermal structure of the plume lithosphere interaction predicts a geotherm that is in good agreement with the pyroxene geotherm.

Pyroxene geothermometry with rocks derived from the mantle under the African continent may provide direct measurements of temperature in the upper mantle. This geotherm predicts reasonable temperatures at shallow depths, but with increasing depth shows an abrupt increase of the geothermal gradient. We suggest mantle plume induced transient heating of a moving lithosphere to account for the shape of the geotherm and as the cause of the magmatic event that emplaced upper mantle materials near the surface of the earth. Numerical studies of plume convection in the upper mantle combined with the calculation of transient heat conduction into the lithosphere leads to a predicted geotherm closely matching that measured. In our interpretation of the pyroxene geotherm, the base of the lithosphere corresponds to the depth of rapidly increasing geothermal gradient. This is in agreement with textural evidence from kimberlite nodules. Nodules from depths greater than the inferred base of the lithosphere have highly sheared textures thought to be indicative of flow while those from depths above the base of the lithosphere have unsheared textures. We feel that the good agreement of this interpretation of the geotherm with observations is consistent with plume convection in the upper mantle.

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