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FLUID CIRCULATION IN THE EARTH'S CRUST

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Abstract. Numerical simulation of thermally driven fluid flow caused by igneous intrusives in the upper crust indicates that fluid circulation is an inevitable consequence of lateral density gradients in pore fluids characteristic of these environments. Thermal perturbations associated with igneous plutons are predicted to be sufficiently large to generate hydrothermal systems in which the magnitude of convective heat transport exceeds that of conductive heat transport for rock permeabilities greater than $10^{-18}$ $m^2$ [Norton and Knight, 1977]. Furthermore, the style of the heat transfer is significantly different from systems in which conduction is the dominant heat transfer mechanism, particularly when the transport and thermodynamic properties of the fluid phase are taken into account. As a consequence of the critical end point which exists in the $H_2O$ and related systems, the region above plutons is predicted to contain extensive vertical zones of nearly constant temperature. These first-order approximations of fluid circulation reveal two points relevant to predicting the thermal regime of the crust: (1) thermal gradients above convection-dominated systems are very nonlinear and cannot uniquely predict subsurface temperatures within our present scope of knowledge and data and (2) since fluid circulation may extend through a considerable portion of the upper crust in tectonically active regions, the thermal regime of these crustal regions is poorly understood.

## Introduction

Temperature conditions in the earth's crust are normally predicted on the basis of extrapolated temperature-gradient data, petrologic arguments, and numerical approximations of conductive heat transfer processes in which various thermal energy sources, as well as rock properties, are considered. Analyses of thermal convection have usually indicated fluid circulation to be an important heat transport process, at least in geothermal areas [Elder, 1965; Ribando et al., 1976; Lister, 1974; Lowell, 1975]. However, the consequences of fluid circulation on the thermal conditions in the crust have only recently been analyzed for situations in which (1) the transport and thermodynamic properties of the fluid phase are allowed to vary with temperature and pressure changes and (2) an igneous intrusive body is present in the upper crust.

The unique characteristics of fluid systems for which $H_2O$ is a principal component suggest that the properties of these types of fluids should contribute significantly to the heat transport process in convection-dominated systems [Norton and Knight, 1977]. Enthalpy, density, and viscosity of phases in the pure $H_2O$ system and in salt-$H_2O$ systems are very dependent on temperature and pressure in a temperature-pressure region which starts at the critical end point and extends to higher pressures. As a consequence of this dependence, natural systems are predicted to have thermal characteristics distinctly different from those predicted on the basis of constant fluid properties or even those predicted on the basis of properties approximated by simplistic equations of state. Most equations of state that have been previously used merely predict fluid properties along the two-phase surface in the $H_2O$ or salt-$H_2O$ systems.

Crustal environments which contain hot igneous bodies inevitably cause fluid circulation, and if the intrinsic host rock permeability is greater than $10^{-18}$ $m^2$, heat transfer by convection accounts for at least 10% of the total heat transfer, and at permeabilities greater than $10^{-18}$ $m^2$, convection greatly predominates over conduction [Norton and Knight, 1977]. Fluid-driving forces are generated as a natural consequence of the near-vertical side contact of intrusives, which cause lateral perturbations in the density of pore fluids. Instability of the fluids and the onset of convection is therefore instantaneous in these systems; the magnitude of the initial fluid flux depends principally on permeability of host intrusive rocks.

The purpose of this communication is to review the nature of fluid circulation related to transient thermal anomalies in the crust and to consider the consequences this fluid circulation might have on our concepts of the thermal environment in the crust.

## Numerical Simulation of Fluid Circulation

Lateral density perturbations in fluids contained in the flow porosity of rocks cause fluid flow. The magnitude of this flow in natural systems can be determined by Darcy's law:

$$\bar{q} = \frac{k}{\nu} (\nabla P + \rho \bar{g}) \tag{1}$$

where the mass flux $\bar{q}$ is a function of intrinsic rock permeability k, fluid viscosity $\nu$, density $\rho$, the gradient in pressure $\nabla P$, and the gravitational vector $\bar{g}$. Density gradients, which may be the result of concentration as well as thermal gradients on the fluid, give rise to $\nabla_x P$ and $\nabla_y P$ terms in the horizontal plane. Although both types of density gradients are ubiquitous in the crust, only those resulting from thermal anomalies are included in the computations.

Thermal anomalies often cause and are coincident with extensive fracture zones and therefore probably represent the most significant contribution to fluid circulation in the crust, except in sedimentary basin environments where large concentration gradients are common. The inferred association of permeable fractured rocks with thermal anomalies in the upper 10-15 km of the crust suggests that fluid circulation is a characteristic feature in these environments.

Fluid flow caused by thermal anomalies related to igneous plutons are effectively scaled and represented in two dimensions by partial differential equations which describe the conservation of mass, momentum, and energy for the fluid-rock system [Norton and Knight, 1977]:

$$\gamma \frac{\partial T}{\partial t} + q\nabla H = \nabla \cdot \kappa \nabla T \tag{2}$$

and

$$\frac{\nu}{k}\nabla\cdot\frac{\nu}{k}\nabla\Psi = R\,\frac{\partial\rho}{\partial y} \tag{3}$$

where T is the temperature; $\Psi$ the stream function; q the fluid flux; t the time; H, $\rho$, and $\nu$ the enthalpy, density, and viscosity of the fluid; k the permeability of the rock; $\kappa$ the thermal conductivity; $\gamma$ the volumetric heat capacity of the fluid saturated media; R the Rayleigh number; t the time; $\nabla$ the gradient operator; and y the horizontal coordinate in the two-dimensional section to which these equations apply.

The physical meaning of (2) and (3) is apparent if one considers that the fluid density gradients on the right-hand side of (3), which result from a thermal anomaly, cause fluid circulation. That is, they define gradient values of the stream function and therefore fluid flux, since $q_z = -\partial\Psi/\partial y$ and $q_y = \partial\Psi/\partial z$. The fluid flux q in turn transports heat away from the thermal anomaly, second term on left of (2); at the same time, thermal energy is conducted away from the thermal anomaly, right-hand side of (2). Both of these processes give rise to a decrease in temperature with respect to time and therefore decrease the horizontal fluid density gradients. And, consequently, the thermal anomaly is decreased by combined convective and conductive heat transfer. Equations (2) and (3) are approximated by finite difference numerical equations which permit computation of the values of the dependent variables at discrete points in the domain from initial and boundary values specified for the system. The numerical analysis provides the option to include variable transport properties of the fluid ($H_2O$ system) and rock, general boundary and initial conditions, and radioactive and volumetric heat sources in a two-dimensional domain. The transport processes related to the transient thermal anomaly are approximated by a time sequence of steady state numerical solutions to (2) and (3), computed at explicitly stable time intervals. An alternating-direction-implicit finite difference method is used to approximate the spatial derivatives at discrete intervals of the order of 0.1 to 0.5 of the system height. Fluid pressure in the system is computed at each steady state step by integration of (2), in which the fluid properties, viscosity and density, are expressed as a function of temperature and pressure. The following discussion relies on computations and analyses using these methods.

## The Nature of Fluid Circulation Related to Thermal Anomalies

The style of fluid circulation in the upper 10 km of crust and the nature of pluton cooling has been simulated [Norton and Knight, 1977] for a variety of host rock permeability values and geometries.

Convection dominates heat transfer in hot igneous pluton environments if rock permeabilities are of the order of $10^{-18}$ $m^2$ or greater, resulting in a spatial redistribution of thermal energy significantly different than that in similar environments in which conductive heat transfer predominates. Although the time duration of convection-dominated thermal anomalies is similar to that of conduction-dominated systems when the pluton itself is impermeable, the cooling time is significantly shortened by increases in permeability such as might accompany extensive fracturing of the pluton. The direct application of these modeling results to actual systems must be made with caution since the in situ values of rock permeability are virtually unknown. However, analogies drawn between permeability values of rocks for which permeability data are available and estimates of permeability suggest that permeability values exceeding the $10^{-18}$ $m^2$ minimum may characterize a substantial portion of the upper crust [Norton and Knapp, 1977].

A numerical model of a system which illustrates the convective transfer of heat around igneous plutons is presented. A basaltic magma at ∿1300°C is presumed to be emplaced relatively rapidly, with respect to the rate of heat transfer away from the magma body, into host rocks whose permeability increases upward from $10^{-16}$ $m^2$ to $10^{-14}$ $m^2$ (Figure 1). The relatively rapid intrusion rate only requires magma flow velocities on the order of a few centimeters per year, a value which seems to be reasonable. Since cooling of magmas is normally accompanied by fracture development resulting from reactions that increase or decrease the pluton volume, the pluton permeability is changed from effectively zero to $10^{-17}$ $m^2$ as the temperature of discrete grid points in the pluton decreases to <700°C, thereby simulating fracture development and permitting fluid circulation through the pluton.

Boundary conditions selected for this system are analogous to natural systems where thermal energy is conducted through all the boundaries. The bottom and top boundary temperatures are set to 220°C and 20°C, respectively. Thermal conductivity of the domain is assumed to be constant, 0.6 cal/ms °C, and since the bottom boundary is conductive, the domain has a constant regional flux of 1.2 μcal/$m^2$ sec (HFU) and the host rocks have an initial background thermal gradient of 20°C/km. The relative permeability values within the domain are set to simulate the decrease in continuous fractures with depth, and the magnitude of the permeability is set to illustrate the effects of fluid circulation. The side and top boundaries are permeable, but the base is impermeable in order to further simulate the decrease in permeability with depth. The permeable top boundary condition does not, however, permit convection of thermal energy out of the system. This latter condition simulates natural systems which do not have hot springs emerging at the top boundary, e.g., the fluids flow through and thermally equilibrate with the rocks at the top boundary. This system was then simulated by using a spatial discretization of 160 points, which results in a 0.1 vertical increment and a 0.06 horizontal increment. The numerical approximations represent the partial differential equations to within a truncation error of the order of 0.05 times the value of the dependent variable. Discrete time increments are computed on the basis of stability criteria, which results in convergence errors of the order of 0.005 times the dependent variable.

The thermal anomaly, introduced by the pluton, causes pore fluids in the host rocks to circulate from the sides and top boundaries of the domain toward the pluton then upward along its side margins and out the top of the domain (Figures 2-4). This circulation pattern significantly increases the heat flux over the pluton top with respect to a purely conductive process. As a consequence of the convective heat transfer, thermal gradients in the domain directly over the pluton are relatively steep near the surface, i.e., 0-0.5 km, decrease sharply and remain constant over several kilometers, then gradually increase toward the pluton top (Figures 5a-5c). The convective heat flux at the surface directly above the pluton varies from 1.2 HFU at the initial time to 15 HFU at $8 \times 10^4$ years, whereas the vertical component of convective flux at 0.5 km depth ranges from 0.5 HFU at $2 \times 10^4$ years to 20 HFU at $8 \times 10^4$ years and then gradually decreases to 10 HFU at $1.5 \times 10^5$ years.

The caveat about these values at the surface is that they are arbitrary to the extent that they are a function of the numerical discretization. However, the relative comparison between the values in the same system at various times is a reasonable approximation of what can be expected in nature. Finer discretization merely results in a nonlinear thermal gradient and predicts it to better precision. Progressive fracturing of the pluton contributes to the persistence of large convective heat fluxes over a long time period. The estimated time duration for which convective fluxes will be greater than the regional heat flux in the upper 2 km of the system is about $5 \times 10^5$ years.

Laterally away from the pluton, thermal gradients in the fluid downflow zone are depressed below the regional gradients as a result of the convective heat flux of -3 HFU. In these regions, at cooling times $\sim 1.2 \times 10^5$ years, the isotherms are depressed downward with respect to their regional position, cf. 200°C isotherm. The portion of the anomaly, at temperatures >100°C, in the upper 3 km is dispersed over an area equivalent to the pluton top.

The several-kilometer vertical extent of relatively constant thermal gradients in the host rocks overlying the pluton and the corresponding temperature values, 100-400°C, are characteristic of convection-dominated systems which we have analyzed [Norton and Knight, 1977]. Transport and thermodynamic properties of supercritical fluid in the $H_2O$ system and salt-$H_2O$ systems are characterized by extremes which contribute to these thermal gradient features (Figure 6). In the region which extends from the critical end point, $\sim$ 375°C and 220 bars for the $H_2O$ system, derivatives of fluid density and enthalpy with respect to temperature at constant pressure are maximums, and fluid viscosity is a minimum. Therefore thermal perturbations at these conditions result in the largest fluid density gradients which together with the minimum in the fluid viscosity tend to maximize the fluid fluxes. The heat capacity of the fluid is also a maximum under these conditions, and hence the convective heat transport is maximized in this temperature-pressure region. As a point of interest these extremes tend to decrease in magnitude from the region near the critical end point to lesser extremes at higher pressures. The critical end point and related extremes in fluid properties are displaced to higher temperatures and pressures for salt-$H_2O$ systems (Figure 6). Fluids which contain dissolved components equivalent to a 3 m NaCl solution have a critical end point at 590°C and 850 bars, and the extremes in fluid properties extend into a region analogous in position to the pure $H_2O$ system (Figure 6).

The nature of the thermal gradients within permeable rocks overlying thermal anomalies in a natural system is clearly predicated on the values of fluid properties and permeability. Since the fluid properties, at least for the $H_2O$ system, are relatively well known, one can reasonably assume that these thermal gradients will at least be characteristic of environments where rock permeabilities are $\geq 10^{-18}$ $m^2$ and anomaly temperatures are $\geq 375$°C at depths where pressures are greater than 220 bars, i.e., ~2.2 km. In natural environments where dissolved components are relatively more concentrated, these effects will be realized at progressively greater depths and slightly higher temperatures.

The example system discussed above contains relatively high values of rock permeabilities with respect to our current best guesses of conditions in the crust. However, fluid circulation effects have been observed in models where the pluton tops are 12-km deep, within low-permeability rocks ($10^{-20}$ $m^2$), but are overlain by higher permeability ($10^{-18}$ $m^2$) zones which simulate vertical fractures. Thermal gradients are more linear in these systems than in the system discussed above, but only a few percent contribution to the heat flux by convection may have a significant effect on our interpretations of the thermal environment in the crust. The most significant feature of the simulated system is that vertical thermal gradients in systems where convective heat transfer occurs do not provide a unique set of data with which subsurface temperatures can be predicted.

## Fluid Circulation in the Crust

Fluid circulation in the upper crust is predicted to be more extensive than was previously thought; its magnitude may be large enough to contribute significantly to the redistribution of thermal energy in this environment. The magnitude of the contribution of fluid circulation to heat transport depends entirely on the magnitude of permeability in crustal rocks and the distribution, with respect to thermal anomalies, of fluid-saturated rocks with permeabilities $\geq 10^{-18}$ $m^2$. The minimum permeability value is realized in rocks which have continuously open-planar fractures spaced 0.1 km apart with an effective aperture of ~20 μm [Norton and Knapp, 1977; Snow, 1970]. This abundance of continuous fractures is easily realized in tectonically active regions and in pluton environments [Villas, 1975; Villas and Norton, 1977], but apertures and continuity of fractures with respect to depth are unknown. In tectonically quiescent regions neither abundance nor aperture of fractures have been documented. However, indirect evidence suggests that permeabilities sufficient to permit significant heat transfer by convection may be realized in the upper crust. First, in tectonically active regions, continuous fractures develop to considerable depths, as is indicated by earthquake hypocenter data. Second, igneous intrusive processes contribute to development of fracture sets in the rocks they intrude. The extent and magnitude of the permeability resulting from combined tectonic and igneous intrusive events is clearly conducive to extensive fluid circulation, as is evidenced by eroded equivalents to these environments which show abundant mineral alteration, as well as by large gains and losses of chemical components in and adjacent to fractures. Transport of thermal energy into the crust by magma or simple conduction also produces fractures due to the differential thermal expansion of pore fluids and rocks [Knapp and Knight, 1977]. In tectonically less active regions, permeability values can be inferred from electrical and, perhaps, seismic properties, empirical relationships between pore continuity, and electrical resistivity [Brace, 1971] or variations in seismic wave velocity [Nur and Simmons, 1969]. These indirect lines of evidence suggest that crustal rocks contain a fluid phase, which may be relatively concentrated in dissolved components, and that they are sufficiently permeable to warrant further efforts toward quantitative determination of bulk rock permeability.

Analyses of transport phenomena in permeable media suggest that fluid circulation through fractured rocks may contribute significantly to heat transfer through the crust, at least to depths of 10-15 km. As a consequence of fluid circulation, several effects may be realized in nature: lower than normal thermal gradients over several-kilometer vertical distances in the upper crust, abnormally low conductive thermal values coincident with fluid downflow zones, and gross errors in predicting subsurface temperatures by downward extrapolation of thermal gradients. These effects are undoubtedly present in active geothermal systems and can be predicted, with reasonable confidence, to occur in the vicinity of virtually all igneous bodies emplaced into the upper crust. The more widespread realization of the effects in more normal crust is mere speculation at this time, and many questions remain that will require more precise numerical models and data acquisition. However, this first approximation suggests that the nature of the upper crustal environment may indeed be the result of dynamic fluid systems, the extent of which is unknown.

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Fig. 1. Two-dimensional cross section of a crust 10 km deep and 24 km wide containing an igneous pluton 4 km high and 6 km wide. Initial value and boundary conditions are for a magma body emplaced instantaneously at 6 km below the surface. Pluton permeability is effectively zero until the temperature of discrete points in the body decreases to 700°C; then permeability at those points is set to $10^{-17}$ $m^2$. Regional heat flux is set at 1.2 HFU for the duration of the system. The initial thermal gradient is 20 C/km, whereas the magma is homogeneous and is connected to a magma reservoir below the base of the pluton at T = 1300°C for the initial 50,000 years. Thermal conductivity is constant at 0.6 cal/m sec °C; the circulating fluid is pure $H_2O$ and does not react with the enclosing rocks.

Fig. 2. Scalar stream function (g/m sec) and temperature (degrees Celsius) distributions after 2 x $10^4$ years elapsed time, illustrating steady state fluid circulation and temperature, respectively. Vertical fluid fluxes of the order of 5 x $10^{-5}$ g/$m^2$ sec are realized 3 km directly above the pluton, which, together with conductive heat transfer, cause the 100°C isotherm to migrate upward at about 0.05 m/yr.

Fig. 3. Scalar stream function and isotherm distributions after 8 x $10^4$ years elapsed time. Vertical fluid fluxes of the order of $10^{-3}$ g/$m^2$ sec are realized 3 km directly above the pluton, and 8 km laterally away from this upflow zone, downward fluid fluxes, $\sim 10^{-7}$, g/$m^2$ sec, occur.

Fig. 4. Scalar stream function and iostherm distributions after $1.5 \times 10^5$ years elapsed time. Vertical fluid fluxes at comparable positions in previous times have decreased to about 50% of the fluxes at $8 \times 10^4$ years. The 100°C and 200°C isotherms have moved to slightly deeper portions in response to the decreasing convective flux. The outer 1.5 km of the upper 2 km of the pluton fractured at $10^5$ years, thereby increasing the cooling rate of the body. The average pluton temperature is 800°C at this time.

Fig. 5a. Vertical thermal gradients from the surface to the base of the system at elapsed time of $2 \times 10^4$ years. Vertical sections are located along the center line, line 1, of the pluton; 1 km away from the side wall of the pluton, line 2; and 5 km away from the side wall of the pluton, line 3 (cf. Figure 1 for positions).

Fig. 5b. Vertical thermal gradients from the surface to the base of the system at elapsed time of $8 \times 10^4$ years. Vertical sections are located along the center line, line 1, of the pluton; 1 km away from the side wall of the pluton, line 2; and 5 km away from the side wall of the pluton, line 3 (cf. Figure 1 for positions).

Fig. 5c. Vertical thermal gradients from the surface to the base of the system at elapsed time of $1.5 \times 10^5$ years. Vertical sections are located along the center line, line 1, of the pluton; 1 km away from the side wall of the pluton, line 2; and 5 km away from the side wall of the pluton, line 3 (cf. Figure 1 for positions).

Fig. 6. Temperature-pressure sections through the NaCl-$H_2O$ systems depicting the two-phase surface, liquid-vapor, and critical end point for 0 m and 3 m NaCl concentrations. The approximate region of anomalous extreme in transport properties of supercritical fluid is depicted for 0 m and 3 m solutions. Note the shift of the critical end point and associated anomalous regions to higher temperatures and pressures as a result of adding NaCl to the system.

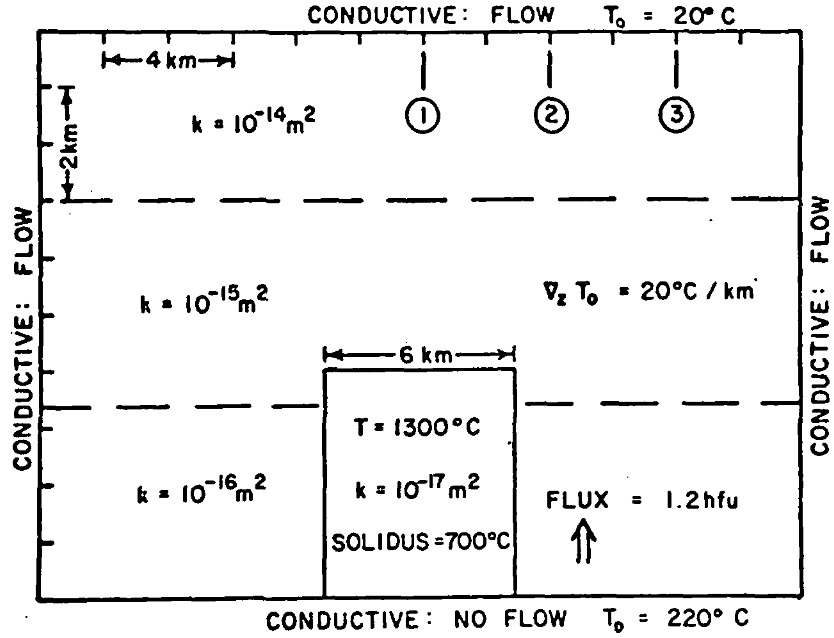


FIGURE 1

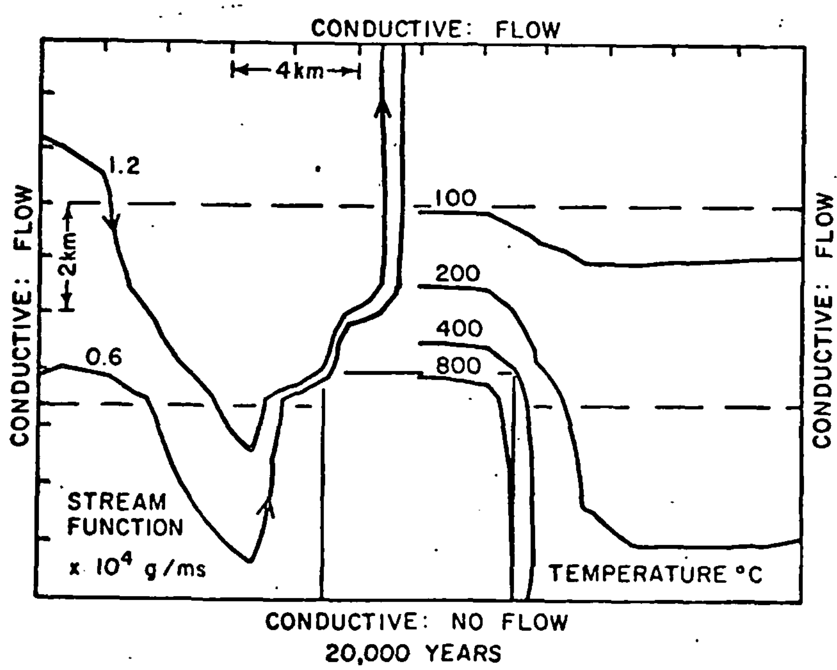


FIGURE 2

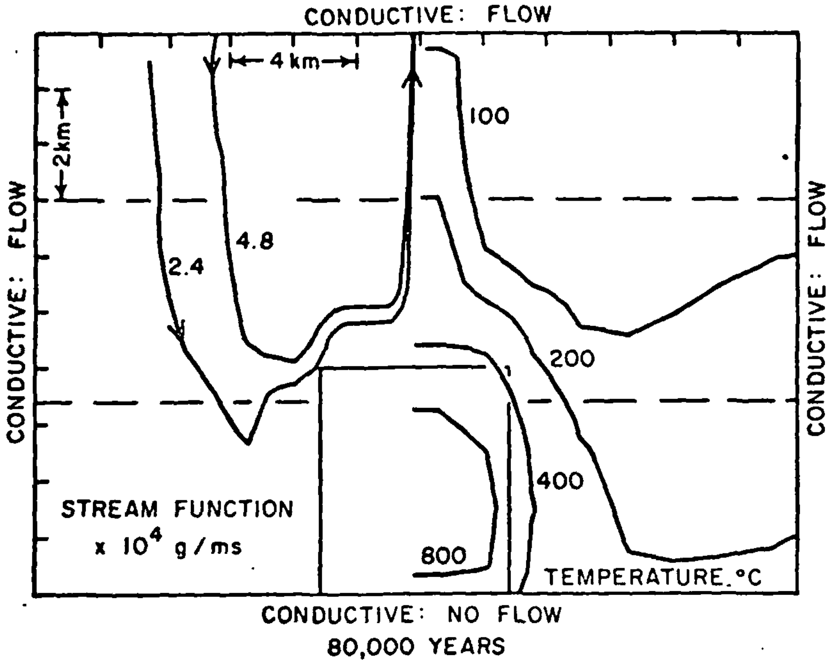


FIGURE 3

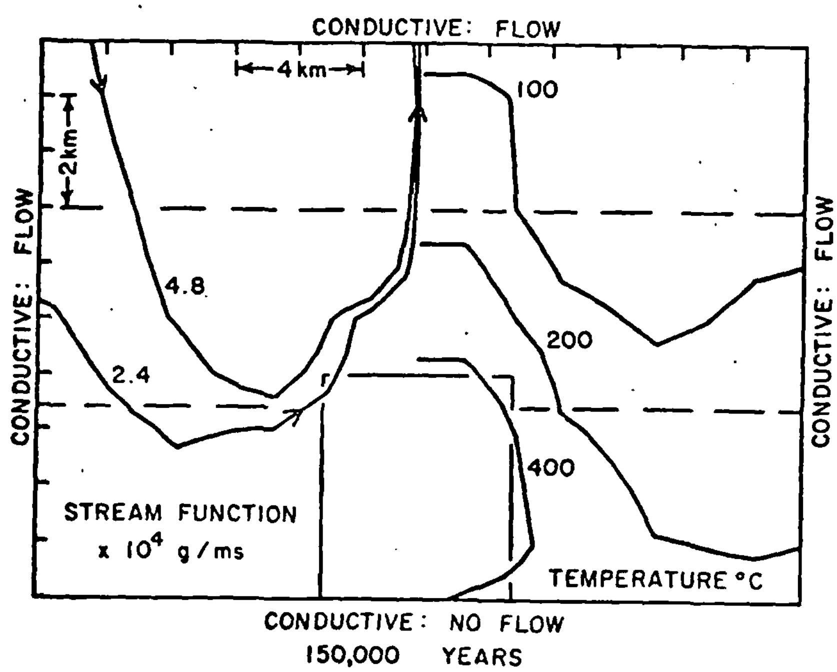


FIGURE 4

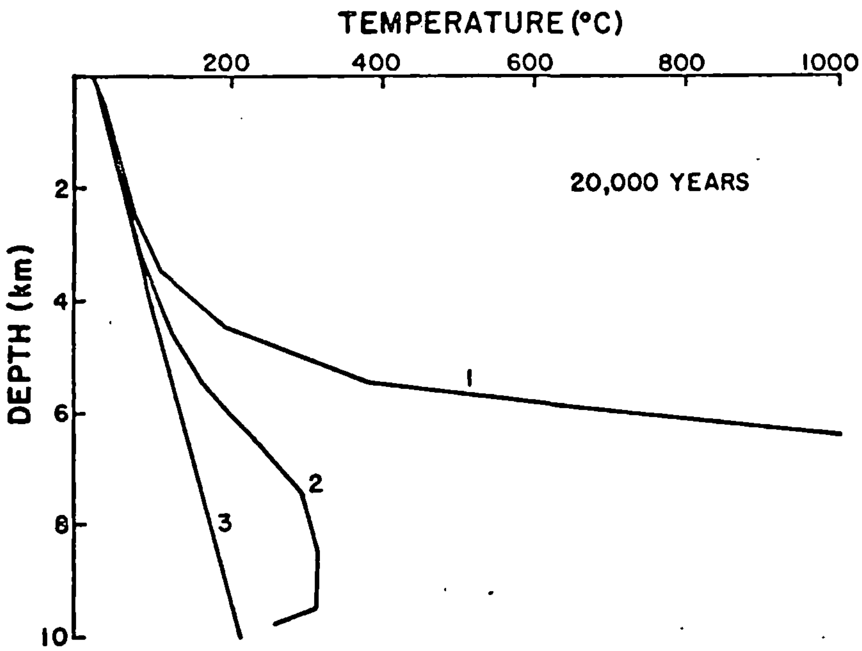


FIGURE 5a

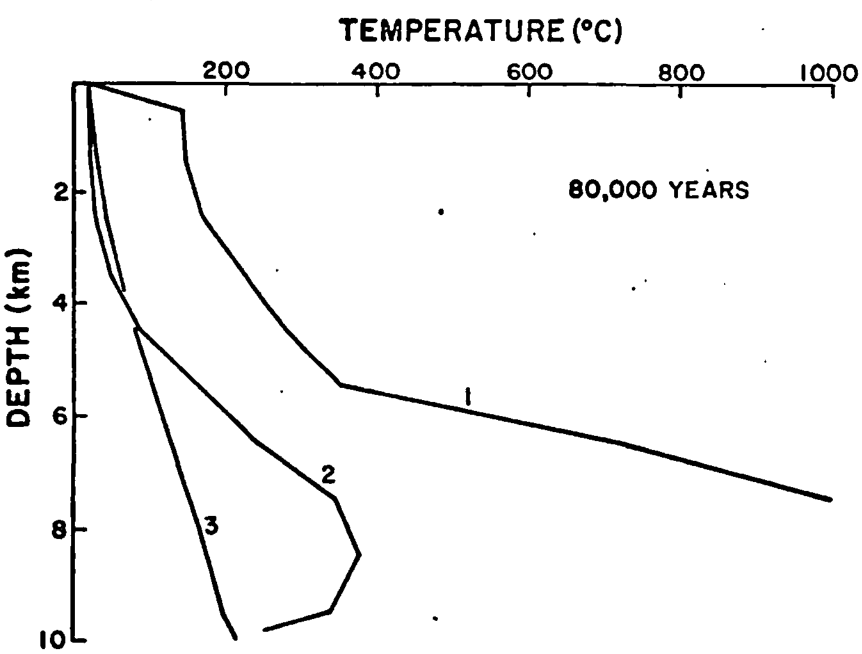


FIGURE 5b

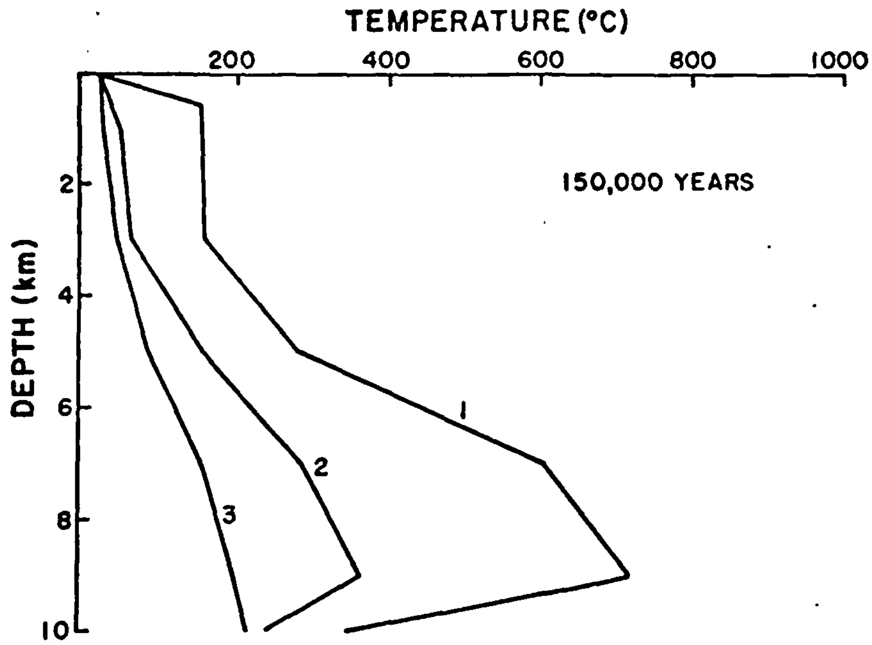


FIGURE 5c

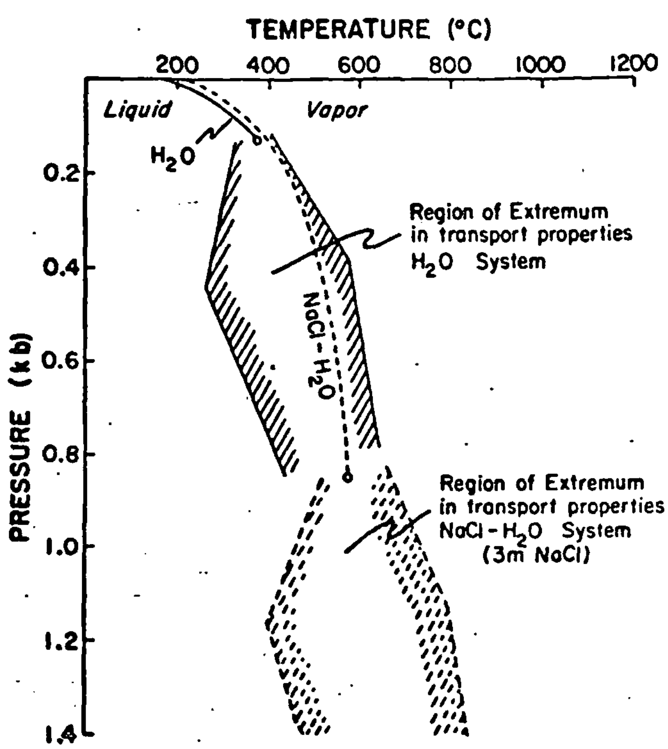


FIGURE 6