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Hydrothermal Convection and Uranium Deposits in Abnormally Radioactive Plutons *

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Abstract

Hydrothermal uranium deposits are often closely associated with granites of abnormally high uranium content. We have studied the question as to whether the heat generated within such granites can cause fluid convection of sufficient magnitude to develop hydrothermal uranium deposits. Numerical models of flow through porous media were used to calculate temperatures and fluid flow in and around plutons similar to the Conway Granite, New Hampshire, i.e., with a half-width of 17 km, a thickness of 6.25 km, and a uniform internal heat generation rate of 20×10^{-13} cal/cm^3-sec. Fluid convection was computed for plutons with permeabilities between 0.01 and 5 millidarcies (1×10^{-13}cm^2 to 5×10^{-11}cm^2).

Flow rates and the size and location of convection cells in and around radioactive plutons like the Conway Granite were found to depend critically on the permeability distribution within the pluton and in adjacent country rocks. The depth of burial, the distribution of heat sources within the pluton, and the small rates of heat generation in the country rock are only of minor importance. Topographic relief is unlikely to affect flow rates significantly but can have a major influence on the distribution of recharge and discharge areas.

Within a few million years, the mass of water transported by steady state convection through such radioactive plutons can equal the mass of water which can convect through them during initial cooling from magmatic temperatures. If the permeability in a Conway-type pluton is on the order of 0.5 millidarcies, then the rate of fluid convection is probably sufficient to develop a hydrothermal ore deposit containing 10,000 tons of uranium in a period of two million years. Such a uranium deposit is most likely to develop in an area of strong upwelling or strong downwelling flow.

Introduction

HYDROTHERMAL uranium deposits are often found in close association with granites containing more than 10 ppm uranium (e.g., Bräuer, 1970; Gangloff, 1970). This close association and the high percentage of leachable uranium in many granites suggest that granitic rocks may well have been the source of uranium in such deposits (Rich et al., 1977). In general, the driving force for the hydrothermal redistribution of metals within granitic plutons is either the initial heat content of the plutons or the later addition of heat from nearby thermal disturbances. Plutons with a high content of radioactive elements are subject to a third driving force: the thermal anomalies within and near such plutons produced by the radioactive decay of potassium, uranium, thorium, and their daughter products. We have investigated the question whether this driving force can generate hydrothermal flow regimes of sufficient magnitude to transport the quantities of uranium found in hydrothermal uranium deposits associated with abnormally radioactive plutons.

We chose as our standard pluton an intrusive of dimensions and composition similar to those of the Conway Granite in New Hampshire. The Conway Granite covers an area of approximately 30×50 km^2. Birch et al. (1968) found a conductive heat flow between 1.95 and 2.21 HFU (1 HFU = 10^{-6}cal/cm^2-sec) associated with radioactive heat generation between 17.5 and 20.9 HGU (1 HGU = 10^{-13}cal/cm^3-sec) generated by approximately 15 ppm U, 57 ppm Th, and 4 percent K. Heat flow not produced by radioactivity within the pluton was estimated to be 0.9 HFU. A linear correlation between heat generation in near-surface rocks and heat flow at the surface was observed, and a thickness of 6 km was inferred for the pluton, assuming that the radioelements have a uniform distribution within the pluton.

The Computational Method

The computations of the temperature distribution and convective flow patterns in and near abnormally radioactive plutons were based on the equations for fluid flow through porous media:

$$-\nabla p + \rho g - \frac{\nu}{k} q = 0 \quad \text{(Darcy's law)} \qquad (1)$$

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* To Professor Hans Fehn on the occasion of his seventy-fifth birthday.

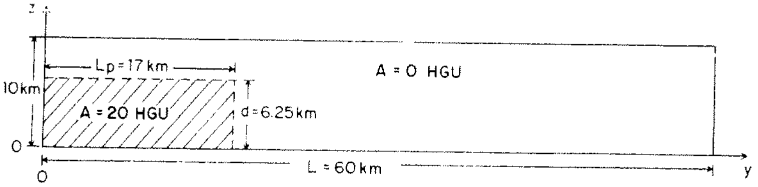

FIG. 1. The computational domain; the point $y = 0$, $z = 0$ is located at the center of the base of the pluton.

$$\nabla \cdot q = 0 \qquad \text{(mass balance)} \tag{2}$$

$$\rho_m c_m \frac{\partial T}{\partial t} = A - \nabla \cdot q c_f T - K_m \nabla^2 T \qquad \text{(heat balance)} \tag{3}$$

where A = radioactive heat generation (cal/cm^3-sec), c_f = heat capacity of fluid (cal/g-°C), c_m = heat capacity of fluid-saturated rock (0.2 cal/g-°C), g = gravitational acceleration (980 cm/sec^2), H = enthalpy of water (cal/g) ($c_f = H/T$), k = permeability (cm^2), K_m = thermal conductivity of fluid-saturated rock (6×10^{-3}cal/cm-°C), p = pressure (dynes/cm^2), q = fluid mass flux (g/cm^2-sec), ν = kinematic viscosity of water (cm^2/sec), ρ = fluid density (g/cm^3), and ρ_m = density of fluid-saturated rock (2.7 g/cm^3).

Cathles' (1977) program was used to solve this system of equations by means of finite difference methods. Solutions were calculated for two-dimensional models such as that shown in Figure 1. The computational grid contained 20 points in the vertical direction and 30 points in the horizontal direction. Values for the kinematic viscosity, density, and enthalpy of the convecting fluid were assumed to be those of pure water at the appropriate temperatures and pressures of each time step and grid point. The following boundary conditions were used: $q = 0$ (no flow) for $z = 0$, $y = 0$, $y = L$; $q = 0$ (no flow) or $\partial q/\partial z = 0$ (free flow) for $z = h$; $j = K_m\, \partial T/\partial y = 0$ (insulating) for $y = 0$ and $y = L$; $j = -K_m\, \partial T/\partial z = 1$ HFU for $z = 0$; and $T = 20°C$ for $z = h$. Most of our solutions were obtained for hypothetical plutons of dimensions similar to those of the Conway Granite, i.e., a half-width of 17 km and a thickness of 6.25 km; the burial depth was generally taken to be 3.75 km; zero heat generation in the country rock was assumed, and the heat flow from below the computational domain of 10 km × 60 km was taken to be 1.0 HFU.

In most of our calculations we assumed that the radioelements were uniformly distributed within the pluton and that they generated heat at a rate of 20 HGU. Lachenbruch (1970) and Albarede (1975) have suggested that the linear relationship between radioactive heat generation in near-surface rocks and surface heat flow which has been observed in the region of the Conway Granite and in several other areas (e.g., Lachenbruch, 1968; Jaeger, 1970) is better explained if the concentration of heat sources is assumed to decrease exponentially with depth within the crust. However, differences between the temperature distribution produced by an exponentially decreasing heat source and the temperature distribution produced by a uniform heat source within a Conway-sized pluton were found to be small compared to the magnitude of the temperature anomalies themselves and to produce only second order effects on the patterns and intensity of convective flow. Our results can thus be applied to cases where a linear relationship between heat generation in near-surface rocks and surface heat flow is observed.

Temperatures in and around Impermeable Plutons

The distribution of heat flow and the location of isotherms in and near an impermeable, Conway-type pluton at steady state are shown in Figure 2. At the center of the base of the intrusion, the steady state temperature is 326°C. This temperature is about 140°C higher than the temperature at the same depth beyond the influence of the pluton. The surface heat flow is 2.2 HFU above the center and 1.7 HFU above the edge of the pluton. Temperature and heat-flow anomalies disappear approximately 35 km from the center of the pluton.

The gradual decrease of the heat flow above this pluton outward from its center indicates that heat losses through the sides of the pluton are significant. In a one-dimensional model, i.e., if heat flow through the sides of the pluton is neglected, the surface heat flow j at steady state is the sum of the heat generation in the pluton, Ad (d = thickness of pluton), and the heat flow from below, j_0:

$$j = \mathrm{Ad} + j_0 \tag{4}$$

We have calculated the heat flow above two-dimensional plutons of various sizes and heat generation rates and have compared our results with the results obtained with (4). The steady state heat flow above the center of a pluton was found to be given by the expression

$$j = b_e \mathrm{Ad} + j_0 \tag{5}$$

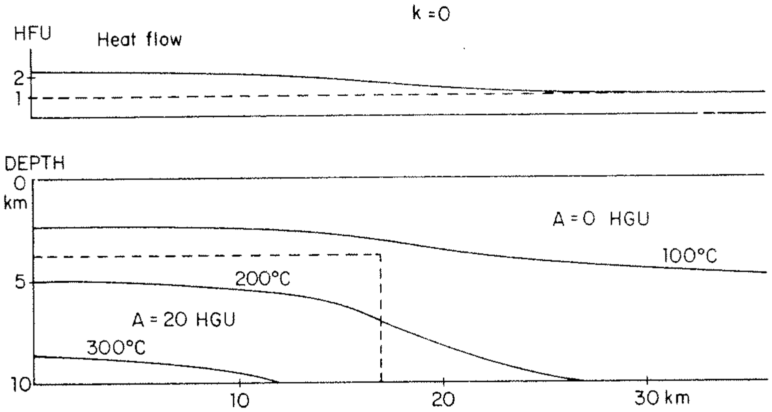

FIG. 2. Steady state distribution of temperatures and surface heat flow in a Conway-type pluton without convection; the broken line indicates the limits of the pluton.

where the coefficient b_c is smaller than unity. The value of b_c depends largely on the ratio of the half-width, L_p, to the thickness, d, of a pluton and is independent of A and nearly independent of the depth of burial. In Figure 3, calculated values of b_c are plotted as a function of the aspect ratio, L_p/d. The heat flow above the center of a Conway-type pluton ($L_p/d = 2.7$) is reduced by only 3 percent by the flow of heat through the sides of the pluton. The values of b_c for plutons with aspect ratios smaller than 1 are less than 0.5; more than half of the heat generated within such plutons is therefore lost through their sides. Consequently, temperatures within, as well as conductive heat flow above, plutons with low aspect ratios or above vertical uranium veins are significantly lower than would be expected on the basis of one-dimensional calculation.

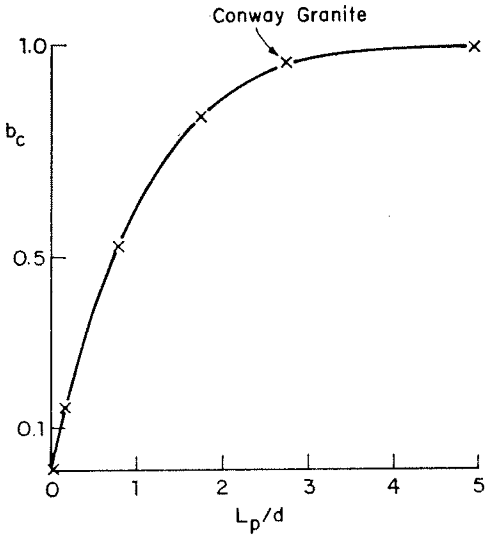

FIG. 3. Values of the coefficient b_c in equation (5) as a function of the aspect ratio L_p/d of the plutons.

Temperatures and Convective Flow in and around Permeable Plutons

Unfractured granites have very low permeabilities, on the order of 10^{-3} millidarcies (1 md = 10^{-11}cm^2) (Davis, 1969) at surface conditions. Measurements on Westerly Granite (Brace et al., 1968) show that the permeability decreases by two orders of magnitude over the depth range we are considering here. These bulk permeabilities are too low to allow any significant convection through the granite. In order to generate hydrothermal convection the presence of fractures in the granite has to be postulated. Fractured granites can have permeabilities several orders of magnitude greater than unfractured granites even under increased pressure (Pratt et al., 1977). In our calculations of convective flow through Conway-type plutons, we have used permeabilities between 0.01 md and 5 md.

The distribution of temperature in such plutons depends on the temperature distribution at the time of fracturing, on the permeability, and on the openness of flow through the surface. The curves in Figure 4 illustrate the effects of these variables on the time variation of the temperature at the center of the base of a Conway-type pluton after the onset of convective flow. The temperature-time curves (a) through (e) were computed for the initial temperature distribution (conductive steady state) shown in Figure 2. Curve (f) was computed for a domain with an initial temperature distribution corresponding to a heat flow of 1 HFU from below and no heat generation in the domain before the onset of convection. The broken curves (a) and (c) show the variation of the temperature at the base of intrusions of permeability 0.1 md and 0.5 md, respectively, if no flow takes place through the surface. If the formation lies slightly below sea level or if a strong interaction between surface water and ground water occurs, as in some geothermal fields (e.g., Elder, 1965), boundary conditions permitting free flow through the surface are more realistic. The solid curves (b), (c), and (e) show how the temperature at the center of the base of the intrusion varies with time if free flow takes place through the surface.

Steady state is reached more rapidly in plutons of high than in plutons of low permeability, but in all cases a new near-steady state temperature is reached 1.5 m.y. after the onset of fluid flow. The temperature at the center of the base of the pluton increases slightly along curve (a) when the permeability of the pluton is only 0.1 md and no flow through the surface is permitted. In cases (b) through (e), the temperature decreases with time, more so at higher permeabilities and if free flow takes place through the surface. Along curve (f) the temperature first increases, then declines, and finally becomes indistinguishable from the temperature along curve (d) after about 0.8 m.y.

Steady state isotherms, streamlines, and heat-flow distributions are shown in Figures 5a through e for five different permeability distributions. All these cases were calculated to a time of 1.7 m.y. after the onset of convection. If the permeability is uniformly 0.5 md, and if no flow takes place through the surface (Fig. 5a), then two convection cells develop within the pluton. The center of the larger cell is close to the center of the pluton, and upwelling flow is most intense at the center of the pluton. A second, smaller cell is located near the edge of the pluton. The surface heat flow distribution is related to the flow pattern. A maximum heat flow of 4.6 HFU is reached over the center of the pluton; a second maximum of 2.1 HFU is located above the edge of the pluton.

If free flow through the surface takes place above a pluton of the same uniform permeability of 0.5 md, the flow pattern is drastically different (Fig. 5b) There is a single, large convection cell covering the entire area of the pluton; the intake area is broad and the discharge area over the center of the pluton is narrow. At a distance of 30 km from the center of the pluton, a weak counter cell develops. Heat flow reaches a maximum of 17 HFU in the discharge area of the main convection cell but is sharply depressed below 1 HFU due to downward convection in the area between 4 and 30 km from the center of the pluton.

It is rather unlikely that the permeability of a Conway-type pluton is independent of depth below the surface, and we have determined the effects of an exponential decrease in the permeability with depth on the pattern of convective flow through plutons. We have set the permeability, k, equal to

$$k = k_0 \exp[-f(h - z)/h] \qquad (6)$$

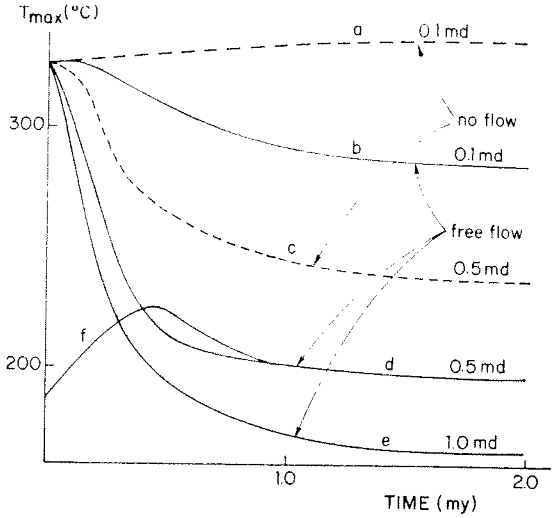

FIG. 4. The temperature at the center of the base of a Conway-type pluton as a function of time after the onset of convective flow; see text for explanation of the individual curves.

where k_0 is the permeability at the surface ($z = h$), and where the permeability k_b at the base of the pluton ($z = 0$) is

$$k_b = k_0 e^{-f}. \qquad (7)$$

If $k_0 = 0.5$ md and $f = 2.3$ in a domain without flow through the surface (Fig. 5c), a single convection cell develops at the center of the pluton with a weak extension to the edge of the pluton. Heat flow is affected above the center of the pluton only, where a maximum of 4.5 HFU is reached. In the rest of the domain, heat flow is similar to that in the absence of fluid flow.

If the surface permeability is taken to be 5.0 md, and if it decreases by two orders of magnitude within the domain ($f = 4.6$), a rather different flow pattern is generated (Fig. 5d). Three quite strong convective cells develop, whose centers are located just above the intrusion at a depth of 3 km. These cells give rise to a second upwelling zone 12 km from the center of the pluton, and there are two maxima in the heat flow distribution with values of 4.5 and 4 HFU, respectively.

The permeability of many plutons is smaller than that of the surrounding country rock. The flow pattern and heat flow distribution in Figure 5e show that large differences between the permeability of the country rock and the pluton affect the pattern of fluid flow considerably. The permeability of the pluton has been taken to be uniformly 0.05 md, the permeability of the country rock ten times greater. Free flow through the surface has been assumed. Two circulation cells develop, a rather shallow one above the pluton and a deeper one just outside the pluton.

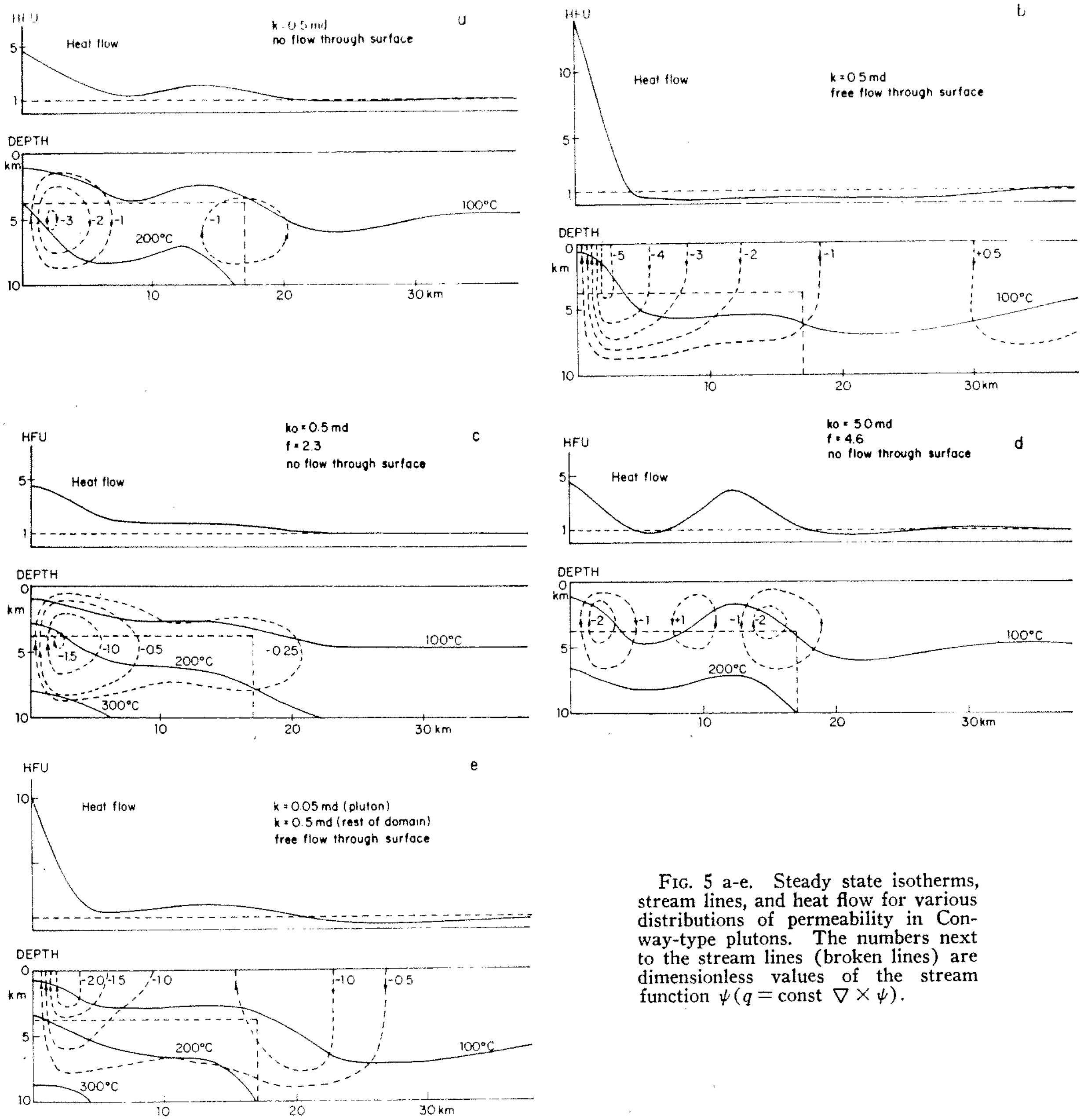

FIG. 5 a-e. Steady state isotherms, stream lines, and heat flow for various distributions of permeability in Conway-type plutons. The numbers next to the stream lines (broken lines) are dimensionless values of the stream function $\psi (q = \text{const } \nabla \times \psi)$.

The heat flow maxima are considerably smaller, and the shape and position of the cells are somewhat different from those in Figure 5b, where a uniform permeability of 0.5 md was taken for both the pluton and the country rock.

Convective Mass Fluxes

Figures 5a through e show that the steady state rate of fluid flow through the top of the pluton varies considerably from place to place. In Figure 6 the maximum steady state rate of fluid flow through the top of the pluton is plotted against the permeability of the pluton. When the permeability in the domain is uniform, the maximum flow rate is always found over the center of the pluton. Fluid flow increases rapidly with increasing permeability and is higher in a pluton of a given permeability if free flow is permitted through the surface than if no flow takes place through the surface. In both cases, maximum flow rates are between 1 and 5 gm/cm^2-yr in the upper part of the permeability range investigated.

A useful measure of the efficiency of steady state convective flow driven by radioactive heat generation is the time, t_p, required to convect through the surface of the pluton a mass of solution equal to the mass of the pluton itself. Since upward flow prevails only in part of the pluton, t_p is considerably longer than the time computed using the maximum flux rates of Figure 6. In Figure 7, values of t_p are shown for all cases calculated in this study; the closed symbols represent cases where free flow through the surface of the domain was permitted, the open symbols represent cases with a closed surface. Cases calculated for permeabilities exponentially decreasing with depth are plotted at their respective surface permeability.

For permeabilities between 0.5 and 1.0 md, values of t_p fall between 3 and 5 m.y. In plutons of lower permeabilities, the flux time t_p can exceed 100 m.y. Because the major part of the convection in domains of exponentially decreasing permeabilities (triangles in Fig. 7) takes place in the upper part of the domain, the flux times t_p are usually longer for these cases than for comparable cases with uniform permeabilities. Higher permeability in the surrounding country rock than in the pluton (closed square in Fig. 7) causes faster convection not only in the country rock but also within the pluton, so that the flux time t_p is shorter by 3.7 m.y. than t_p when the permeability is 0.05 md in the entire domain.

The flux time t_p is not particularly sensitive to the value of heat generation in the country rock. If heat generation in the country rock is raised from 0 to 3 HGU, then t_p is reduced by less than 5 percent. It is also little influenced by the thickness of cover above the pluton. Complete elimination of the 3.75 km cover increases t_p by 2 percent. One case was calculated for a pluton of a uniform permeability of 0.5 md, without flow through the surface, in which the concentration of radioelements decreased exponentially with depth (Lachenbruch, 1970). If such a pluton has the same heat generation in near-surface rocks and the same surface heat flow as a pluton in which the radioelements are uniformly distributed (Birch pluton), then the Lachenbruch pluton has to be thicker than the Birch pluton. Although this increased thickness of the pluton was entered into our calculations, fluid flow was restricted for the sake of consistency to the same 10 km depth as in the comparable Birch pluton. The time t_p obtained for the Lachenbruch pluton was 4.0 m.y., which differed by only 0.2 m.y. from the value of t_p calculated for the comparable Birch pluton.

Discussion

A comparison of the values of t_p calculated for various plutons shows that permeability dominates the development of convection cells in a pluton of a given size and heat generation rate. Depth of burial, heat generation in the surrounding country rock, and the distribution of radioelements in the pluton exert only a minor influence on the speed and geometry of fluid convection driven by radioactive heat generation. All the flux times were computed using steady state flow rates. During the transient phase after the onset of convection, flow rates are considerably higher than steady state rates; the integrated mass of fluid convected through the pluton during the transient phase can be up to 20 percent larger than the mass calculated using steady state rates. However, since the flux times t_p are at least twice as long as the time required to reach steady state, errors in t_p incurred by neglecting transient flow are probably no greater than 10 percent.

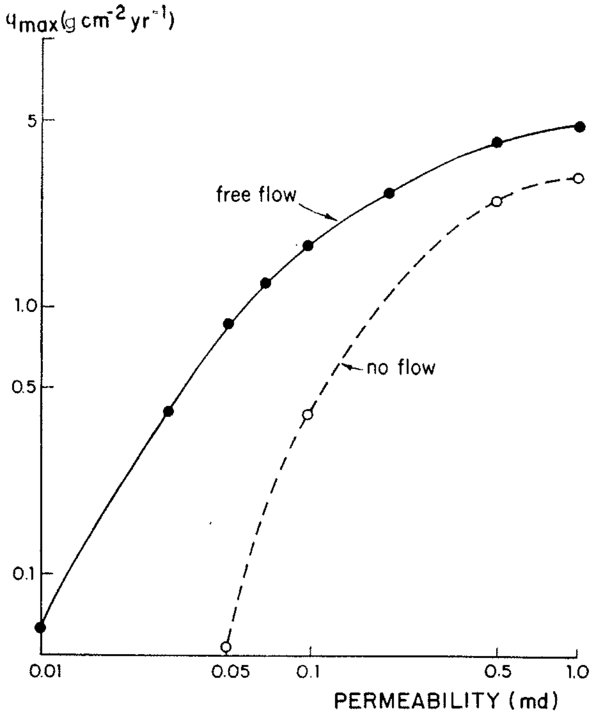

FIG. 6. Maximum steady state flow rates through the tops of Conway-type plutons as a function of uniform permeability in the domain.

In the calculations described above, temperatures and fluid flow were determined for two-dimensional models where heat losses in the third direction are neglected. Horizontal heat losses through a vertical cylinder are twice as large as horizontal heat losses through a vertical plate (Carslaw and Jaeger, 1959); the temperature and fluid flow distribution in and around plutons of equal x- and y-dimensions are therefore somewhat different from those in and around the plutons discussed above. If heat losses in the x-direction are taken into account in a cylindrical Conway-sized pluton, heat flow above the center of the pluton is reduced by an additional 3 percent of the heat flow produced within the pluton, by 15 percent at a distance of 12 km from the center of the

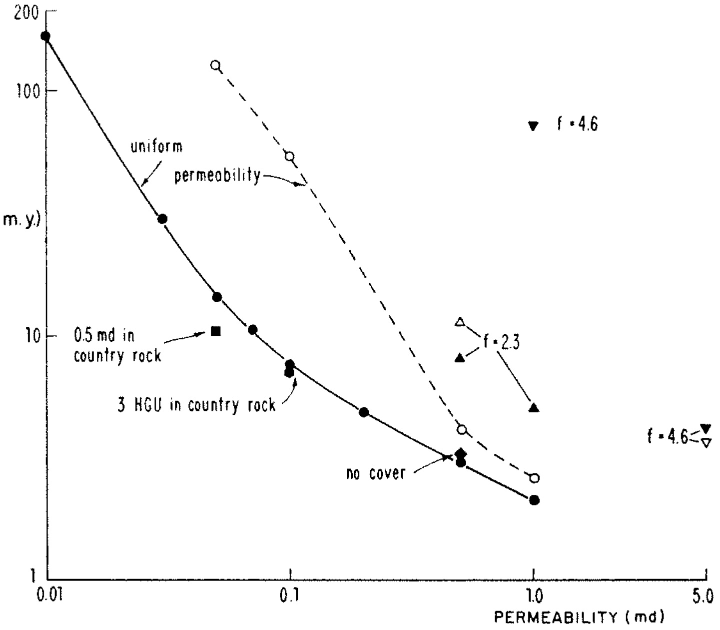

FIG. 7. Flux times t_p for various permeability distributions in Conway-type plutons; t_p is the time required to convect through the surface of the pluton a mass of solution equal to the mass of the pluton itself. Closed symbols = free flow through the surface; open symbols = no flow through the surface; circles = uniform permeability; triangles = permeability exponentially decreasing with depth, plotted at surface permeability.

pluton, and by 35 percent at the edge of the pluton. Since more than 80 percent of the fluid circulation takes place within the inner 11 km of the pluton considered in this paper, heat losses in the x-direction are unlikely to reduce the calculated flow rates by more than 10 percent.

The principal flow direction in our two-dimensional models is toward the center of the pluton. Since the highest temperatures in any pluton with a horizontally uniform distribution of heat sources are necessarily in the center of the pluton, the principal flow direction in plutons with a finite third dimension is also toward the center of the pluton, as long as no cross rolls or other, more complicated, three-dimensional flow patterns develop. Such complications are unlikely at the low Rayleigh numbers (Ra < 60) of our models (Holst and Aziz, 1972; Combarnous and Bories, 1975). The results for two-dimensional flow are therefore probably applicable to plutons with a finite third dimension.

Equations (1) through (3) are specifically applicable to domains in which water convects through a uniformly permeable medium, but they are also applicable to domains in which water moves through a system of fractures, provided the fracture spacing is small enough so that temperatures within matrix blocks between fractures are close to those of a homogeneous porous medium. Relaxation times of matrix blocks with diameters smaller than a few hundred meters are short enough so that this assumption is valid even during the transient phase after the onset of convection.

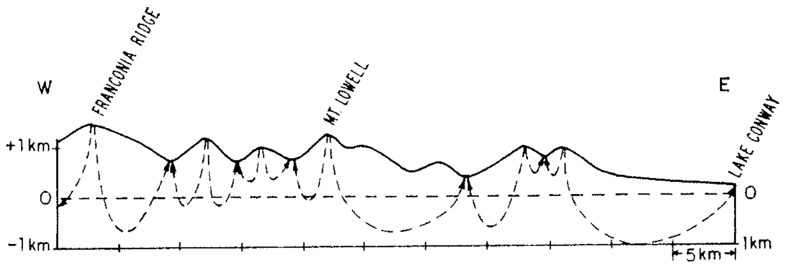

FIG. 8. East-west profile through the Conway area, New Hampshire after Billings (1956); vertical exaggeration 4 : 1. Broken lines indicate depth below which ground-water flux is smaller than 0.4 g/cm^2-yr; $k = 0.5$ md in equation (8); $d = 6$ km in equations (9) and (10), see Appendix.

If distances between fractures are larger than a few hundred meters, the convective system should be modeled in terms of zones of high permeability embedded in a matrix of low or intermediate permeability. Examples of convective flow through domains of this kind have been calculated in a similar investigation of hydrothermal convection at mid-ocean ridges (Fehn and Cathles, in press). There it was shown that a fracture which attracts the fluid flow of an area 3 km wide carries a mass flux which is not significantly different from the mass flux through a similar domain with the same average, but uniform, permeability. The uniform permeabilities used in the present paper can therefore represent the average of high and low permeability zones; flux times and flow rates are likely to remain reasonably unchanged, even if a major part of the fluid flow occurs in fractures spaced as much as several kilometers apart.

A flat surface and a horizontal water table were assumed in all of the calculations. In areas with nonzero topographic relief, the water table is likely to follow the topography. Ground-water movement normally occurs in response to differences in water table elevation. It can be shown, however, that a topographic relief such as that of the Conway area (Fig. 8) does not cause ground-water movement at depths below 1,500 m of a magnitude comparable to that driven by radioactive heat generation (see appendix). Thus, topographic relief of this magnitude does not change the calculated flux times significantly, but it could well influence the geographic distribution of discharge and recharge areas.

Application to the Development of Uranium Deposits

The purpose of our study was to determine whether convection caused by radioactive heat generation in plutons similar to the Conway Granite is of sufficient magnitude to produce ore deposits of uranium. Typical hydrothermal uranium deposits contain on the order of 10^{10}g (10,000 tons) of uranium (Rich et al., 1977), an amount of uranium which is small compared to the 10^{14}g of uranium present in a Conway-type pluton. The uranium in these deposits is typically concentrated in veins with a surface area of around 1 m × 1 km. If 10^{10}g U are contained in a vein 1 m wide in the y-direction and 1 km long in the x-direction, 10^5 g of uranium have been deposited per cm in the x-direction. For a uniform permeability of 0.5 md (no flow through the surface, see Fig. 5a), a steady state flow of 5×10^5 g/cm-yr was found through the top of the pluton. If we assume a content of 0.1 ppm U in the convecting solution—a concentration which is probably common in hydrothermal solutions associated with highly radioactive granites (Rich et al., 1977)—then 5×10^{-2} g U/cm-yr can be precipitated from the fluid in the convection cell. At this rate of uranium precipitation, 2 m.y. are necessary to deposit 10^5 g U/cm. Radioactive heat generation can thus cause convection of sufficient magnitude to develop typical hydrothermal uranium deposits in a reasonably short period of time.

This statement gains strength when one observes that the integrated mass of water convected by radioactive heat generation becomes comparable within a few million years to the mass of water convected during the cooling of a hot intrusive. The cooling of a pluton from 700° to 100°C sets free an energy of approximately 120 cal/g; the heat released by exothermic chemical reactions between fluids and the cooling pluton can increase this amount to approximately 150 cal/g (Norton and Cathles, in press). During the cooling of a pluton of permeability of 0.25 md, a half-width of 1.8 km, and a thickness of 2.25 km from 700° to 100°C, a mass of water equal to about half the mass of the pluton is circulated through the pluton (Cathles, 1977). A radioactive pluton generating 20 HGU needs 4.5 m.y. to attain the same water-to-rock ratio (see Fig. 7) if its permeability is 0.25 md. This period of time is of the same magnitude as the 6.5 m.y. required for a pluton with a heat generation rate of 20 HGU ($=20 \times 10^{-13}$ cal/cm^3-sec) to generate the 150 cal/g which a cooling pluton releases. The mass of water convected through radioactive granite plutons in a few million years is thus as large as the quantity which is potentially convected during the initial cooling of the plutons.

Support for the hypothesis that uranium deposits are sometimes formed as a result of convection driven by radioactive heat generation is provided by the observed distribution of pitchblende ages in hydrothermal uranium deposits found in the vicinity of abnormally radioactive granites. Pitchblendes are often considerably younger than the associated granites. In Haut Limousin, France, for example, the granites are 320 m.y. old; the uranium mineralization apparently took place about 250 m.y. ago (Duthou and Vialette, 1972). Darnley et al. (1965) report ages of 290, 225, 160, and 50 m.y. for uranium ore in Cornwall that is associated with 290 m.y. old granites (Miller and Mohr, 1964). In the Erzgebirge, granites approximately 320 m.y. old (Haake, 1972) contain uranium ores which were apparently deposited 250, 150, 90, and 60 m.y. ago (Leutwein, 1957; Legierski and Sattran, 1967). Some of the later episodes of uranium mineralization in these areas seem to be related to igneous events; others are apparently unrelated to such events. Hydrothermal convection caused by radioactive heat generation is a mechanism which could have formed the uranium deposits which are unrelated to igneous or other known external thermal events. The beginning and ending of the necessary convective circulation depends mainly on changes in the permeability distribution in plutons of sufficient size and rate of heat generation. Convection can follow the opening of fractures by tectonic events and can be stopped by the closing of fractures, for example, by quartz precipitation. Unlike the cooling of an intrusive, which can cause hydrothermal convection only during a limited period of time after intrusion, heat generated by radioactive decay within a pluton can drive hydrothermal convection at any time and repeatedly in the same location.

It is of interest to inquire where in such convection cycles uraninite or pitchblende is likely to be deposited. Solubility data for UO_{2+x} are still quite incomplete (see, for instance, Rich et al., 1977, and Nguyen and Poty, 1976), but it is clear that UO_{2+x} precipitation can follow both the reduction of U^{+6} complexes in aqueous solutions and a drop in the temperature of aqueous solution which are saturated with respect to UO_{2+x}. Reduction of U^{+6} and U^{+4} takes place whenever uranium-bearing hydrothermal solutions encounter suitable reducing agents. Oxidized ground waters, which have assimilated U^{+6} either before or after entering a homogeneous granite, tend to become gradually more reducing. Progressive reduction may therefore lead to UO_{2+x} precipitation during the downward movement of the solutions. Reduction may, however, be sufficiently far advanced only after a batch of solution is close to the completion of a flow cycle through a granite; UO_{2+x} precipitation then takes place during the rising and cooling of the solutions. Supersaturation of the solutions with respect to UO_{2+x} due to cooling alone is apt to lead to UO_{2+x} precipitation in the rising part of the cycle.

Unequivocal evidence for the flow direction of solutions during the precipitation of UO_{2+x} in hydrothermal uranium deposits is generally lacking. However, the occurrence of quartz in these deposits may be used as an indicator of the flow direction. In approximately 50 percent of the hydrothermal uranium deposits studied in Rich et al. (1977), quartz is closely associated with pitchblende both in time and space. Quartz deposition normally accompanies falling rather than rising temperatures in hydrothermal systems. It seems likely, therefore, that in these hydrothermal uranium deposits, UO_{2+x} deposition also took place in solutions which were cooling during upward flow. In the other half of the hydrothermal uranium deposits, pitchblende was deposited alone or together with minerals other than quartz. In these deposits, pitchblende may have been deposited per descensum. Since the cycling of solutions through a Conway-type granite could produce uranium deposits in both the downwelling and upwelling portions of a convective system driven by heat generation within the granite, prospecting for uranium deposits should be directed both at areas of potential intense downflow and of intense upflow during periods of hydrothermal convection.

Conclusions

Heat generation in large plutons like the Conway Granite, which contain abnormal amounts of radioactive elecents, can cause rather intense hydrothermal convection. Flow rates and the size and location of circulation cells depend critically on the permeability distribution in the pluton and in its environs. Burial depth, distribution of heat sources within the pluton, and small heat generation rates in the surrounding country rock were found to exert only a second order influence on the development of fluid convection within and around the pluton. Ground-water flow due to topographic relief is unlikely to change significantly the amount of hydrothermal convection but can influence the location of discharge and recharge areas.

Within a few million years, the integrated fluid mass circulated through a Conway-type pluton is of the same magnitude as that which can circulate through such a pluton during cooling shortly after intrusion. If the permeability of a Conway-type pluton and that of the surrounding country rock is on the order of 0.5 millidarcies, fluid flow driven by radioactive heat generation is sufficient to develop a hydrothermal deposit of 10^{10}g (10,000 tons) of uranium in a period of 2 m.y., provided 0.1 μg of uranium is precipitated from each gram of solution in the area of ore deposition. Hydrothermal uranium deposits commonly found associated with radioactive granites could therefore be produced by convection driven by radioactive heat generated in the intrusive itself. The age distribution of such uranium deposits supports this hypothesis.

Pitchblende deposition is apt to take place in response to reduction of U^{+6} to U^{+4} and to cooling of the solutions. Although these conditions could be met anywhere in the cycling of the solutions through a granitic pluton, they are most likely to occur during vertical movement of the solutions. Prospecting for such deposits should therefore be concentrated in areas of intense upward or downward solution flow.

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APPENDIX

Effect of Topography on Ground-Water Flux

Ground-water movement normally occurs in response to inclined water tables. The relationship between topographic slope and the slope of the water table is mainly a function of rock permeability and of the recharge rate. If permeabilities are similar to those used in our calculations ($k \sim 0.5$ md), the water table follows the topography very closely as long as rainfall exceeds 10 cm/yr (Warrick and Loman, 1974). The near-surface ground-water flux due to a water table slope, dh/dL, in a formation of permeability k is given by Darcy's law (1) which can be written in the form

$$q_0 = \frac{k\rho g}{\nu} dh/dL. \tag{8}$$

A water table slope of 0.15, for instance, produces a mass flux of 2.25 g/cm²-yr in a formation of 0.5 md permeability. This flux is similar to the mass flux found in our calculations for rock units of the same permeability. If a layer of high permeability exists at or close to the surface, as is the case in many formations, the flux due to a water table slope is essentially restricted to this high-permeability layer (Selim, 1975). In areas of uniform permeability, fluid flow occurs throughout the permeable layer, but fluid velocities decrease strongly with depth. The decrease in the two components of fluid mass flux can be approximated by the following expressions (Toth, 1963):

$$q_z(z) = q_{z0} \sinh(\pi z/L)/\sinh(\pi d/L) \qquad (0 < z < d) \tag{9}$$

$$q_v(z) = q_{v0} \cosh(\pi z/L)/\cosh(\pi d/L) \quad (0 < z < d) \qquad (10)$$

where L is the distance between recharge and discharge area and d is the thickness of the permeable layer.

L is not necessarily the distance between topographic highs and adjacent topographic lows. Ground-water flow in regions of irregular topography can be classified according to the distribution of recharge and discharge areas (Toth, 1963). Local zones have recharge areas at topographic highs and discharge areas at adjacent topographic lows; intermediate zones have recharge and discharge areas which are separated by one or more topographic highs and lows but do not occupy the highest and lowest places in a region; finally, regional zones connect the highest and lowest places in a region. The distribution of flow between such zones depends on the regional topography: if the general inclination of a region is large compared to local irregularities in the topography, intermediate and regional zones will account for a substantial portion of the ground-water flow. In regions where the height differences between adjacent topographic highs and lows are of the same magnitude as the regional height difference, intermediate and regional zones are practically absent.

The ground-water flow due to topography in the Conway area can be estimated reasonably well (see Fig. 8). Since the elevation difference between the highest and lowest point of the Conway pluton is of the same magnitude as the local differences in elevation, the effects of intermediate and regional zones are probably negligible for ground-water flow. Slopes in the Conway area are generally smaller than 0.15; steeper slopes exist only over small distances. If we assume that the Conway area is of uniform permeability ($k = 0.5$ md), ground-water movement due to water table slopes in that area is essentially restricted to the upper 500 to 1,500 m. Below 1,500 m, fluid velocities due to water table slopes are small compared to those caused by radioactive heat generation.