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How Long Can a Hydrothermal System Be Sustained by a Single Intrusive Event?

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Abstract

Published numerical calculations show that the convective systems which produce near-surface geothermal systems or ore deposits are likely to cool their intrusion heat source in at most a few tens of thousands of years, even if the intrusion is large. Generally, hydrothermal circulation, near-surface geothermal activity, and magmatic intrusion should be closely tied in time and space. Long-lived (~1 m.y.) hydrothermal activity normally suggests multiple pulses of intrusion with associated pulses of hydrothermal circulation. However, if the permeability of the intruded environment is just above that which allows convection, and the volume of the intrusion is very large, calculations presented here show that a single episode of intrusion can sustain hydrothermal circulation and near-surface geothermal activity for ~800,000 yr. For a deep sill heat source, these unusually long-lived hydrothermal systems can vent through a few very widely separated discharge sites and have the potential to produce isolated massive sulfide deposits of unusually large size.

Introduction

THE SOCIETY of Economic Geologists symposium on the Duration of Hydrothermal Events, from which most of the papers in a special issue (v. 92, no. 7/8) are derived, was convened in part because of the perception that model calculations suggest a shorter duration of geothermal events than does geologic dating. Geologic evidence was thought to suggest that geothermal systems and the hydrothermal circulation which maintains them can be active for ~1 m.y., whereas models suggest that significant hydrothermal activity must be much shorter lived (<10,000 yr) and closely tied to specific intrusive events. One of the surprises of the conference was that modern, high-resolution dating techniques generally show that hydrothermal activity occurs in short-lived pulses. Furthermore, this paper shows that in special circumstances hydrothermal circulation can persist for almost a million years after a single intrusive event. Thus, a consequence of the conference is that there is not a strong dichotomy between models and geologic observations as had been previously perceived. This paper attempts to determine how long, under conditions most favorable to longevity, a hydrothermal system related to a single episode of intrusion can last by numerically modeling the duration of hydrothermal circulation under selected circumstances.

Figure 1 provides a historical context for the discussion. This figure plots the time required to cool an approximately equidimensional plutonic dike to 25 percent of its initial temperature difference with the ambient as a function of the pluton's size and the permeability of the environment into which it is intruded. If the pluton and its environment have zero permeability, cooling is by conduction only, and the cooling time increases as the square of the pluton dimensions. Plutons 10 km wide and 15 km high (a = 5 in Fig. 1) would take a few million years to cool conductively. The maximum duration for conductive cooling is the time it takes to cool the largest conceivable intrusion, a very thick sill of infinite extent with its top at the surface. A point 5 km below the surface will cool in ~4 m.y. Conductive cooling can thus take millions of years, but it will not produce a hydrothermal system with circulating geothermal water. Circulating hot water requires permeability. If the environment intruded is permeable, a hydrothermal convection system can be produced, but the convection greatly decreases the time the intrusion takes to cool. Figure 1 shows that if the permeability is 1 mD, even a 10-km-wide intrusion will cool in a few tens of thousands of years.

An important feature of Figure 1 is the demonstration of a fairly sharp transition between systems that cool slowly by conduction and systems that cool rapidly by convection. An intrusion 2 km wide and 3 km high will cool entirely by conduction if the permeability of the environment is less that 0.05 mD. This conductive cooling will take about 100,000 yr. However, if the permeability is 0.1 mD, the intrusion will cool in 50,000 yr, and if the permeability is 0.5 mD, it will cool in 10,000 yr. Given the very large range of natural permeabilities, an order of magnitude change in permeability is small. It is therefore unlikely that an intrusion which produces a hydrothermal system will have intruded an environment with close to the minimum permeability that allows convection. Intrusions that produce significant hydrothermal systems are likely to have intruded an environment permeable enough that they will be rapidly cooled by convection; hydrothermal activity should be closely tied to specific episodes of intrusion.

Whereas the above conclusions remain generally accepted, the question of how long a convective hydrothermal system could survive after a single intrusive event under optimum conditions has never been specifically addressed. This paper investigates, through numerical modeling, the geologic conditions that can produce very long-lived hydrothermal systems. For the purposes of this study, we define a geothermal system as a convective system that circulates waters of ≥200°C to

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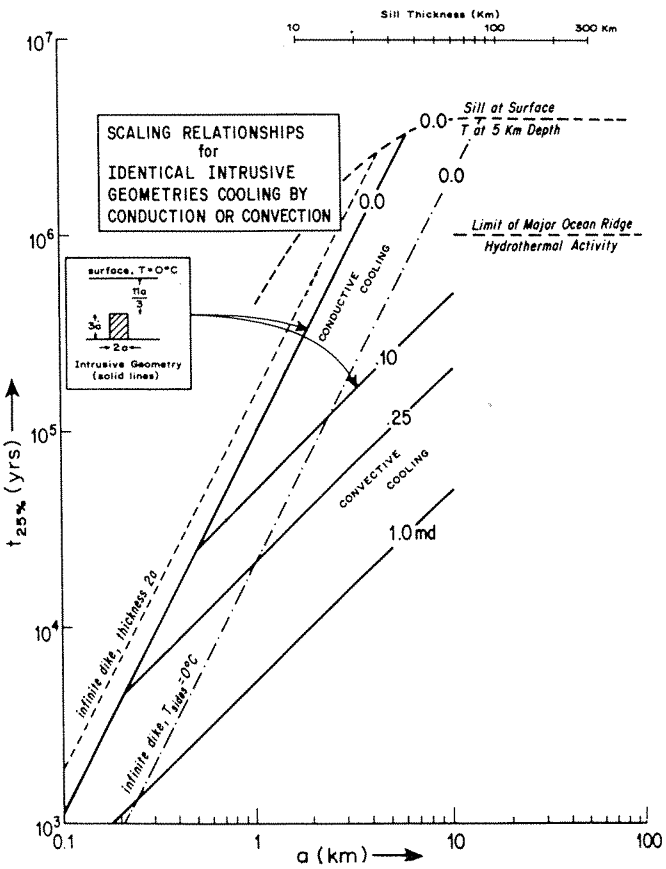

FIG. 1. The time required for an intrusion with the geometry shown in the insert to cool to 25 percent of its initial contrast with ambient is plotted as a function of the size of the intrusion, a. Lines with slope of 2 representing conductive cooling are intersected by lines with slope of 1 representing convective cooling with different host-intrusion permeabilities. Dashed line capping the curves is the time required for an initially hot earth to cool to a 5-km depth. Figure is taken from (Cathles, 1981) and further discussion is available there as well as in the text.

the near surface. We find that under the most favorable conditions a single intrusive event could sustain this kind of a geothermal system for about 0.8 m.y.

Most Favorable Geologic Conditions

From the discussion of Figure 1, it can be inferred for a specified host permeability that the period of time an intrusion will be able to sustain hydrothermal circulation above 200°C is a function of the intrusion's mass and temperature. A larger intrusion will produce a longer lived geothermal system, all other factors being equal. A 1,650°C ultramafic magma contains more heat and sustains a convective system for a longer time than does a 1,250°C mafic magma or an 800°C silicic magma of similar volume. The longest lived hydrothermal systems are thus likely to be those driven by large ultramafic intusions.

Sills provide a geologically plausible way to quickly intrude very large volumes of magma. Sills 40 km in diameter and ~2 km thick containing 2,525 km^3 of magma are not uncommon (e.g., the Fox River sill, Manitoba (Scoates and Eckstrand, 1986)). By contrast, a very large single pulse plutonic intrusion 10 km in diameter and 15 km high would contain only 1,180 km^3 magma. Seismically detected sills underlie many volcanic and geothermal systems (e.g., Ross and Brown, in prep.), including Lardrello (Cameli et al., 1993). Subvolcanic sills are associated with many massive sulfide districts (Campbell; Franklin et al., 1981) and many midocean hydrothermal vents (Humphris; Zierenberg et al., 1995). Some of the ocean sills are small and shallow, but many are very large and at middle to lower crustal depths (e.g., Iceland; Meyer et al., 1985). The longest lived geothermal systems are likely to be associated with large deep ultramafic sills.

Convective Cooling of Sills

We have investigated the time interval over which ultramafic sills can sustain hydrothermal systems by running a large number of numerical finite element modeling experiments. Two-km-thick, 40-km-wide sills were intruded at a variety of depths into host environments having a variety of permeabilities. The shallow sills cooled faster than the deeper sills. The intrusion temperature was 1,650°C and the model sills had zero permeability, reflecting the impermeability of hot (>375°C) as well as hydrated (serpentinized) ultramafic rock. The finite time of actual intrusion was simulated by maintaining the sills at their intrusion temperature of 1,650°C for 50,000 yr.

The equations describing intrusion-driven convection have been presented and discussed in Cathles (1977). The finite element solution was obtained using a standard Galerkin implementation and code called Akcess.Basin (Baker, 1983; Baker and Pepper, 1991). The solution domain was 40 km wide and 25 km deep with an initial temperature gradient (before intrusion) of 16.7°C/km, a basal heat flow of 1×10^{-6} cal/cm^2-sec. The rock thermal conductivity was uniform at 6×10^{-3} cal/cm-sec-°C. The solution domain was divided into 25 vertical and 40 horizontal elements with the sill intruded between a 16- and 18-km depth. The host permeability was given a temperature-dependence that simulated thermal cracking. Between 275° and 375°C the host permeability was exponentially increased by two orders of magnitude. At temperatures above 375°C it was exponentially decreased at the same rate. No convection was allowed through the sill. The temperature-dependence of the host permeability produced a permeable channel above the sill for fluids with temperatures of about 350°C (Cathles, 1993). The geologic appropriateness of this permeability model has been argued in Barrie et al. (1998). If the vertical convective heat flux was more than half the conductive heat flux across the top element, the boundary conditions were changed from fixed temperature to insulating, allowing hot fluids to vent without further cooling (Cathles, 1983).

The model results for a homogeneous 1-mD host permeability are shown in Figure 2A. Forced convection forms a strong convection cell at the edge of the sill. The deep sill shown develops only one stable cell, although a small weak cell tries to develop (see 228 kyr in Fig. 2A). Hydrothermal fluids hotter than 200°C reach the surface after about 50,000 yr and are maintained for about 260,000 yr (Figs. 2A and 3). The location of surface discharge migrates across almost 20 km of section. Broad areas are affected by near-surface hydrothermal fluids.

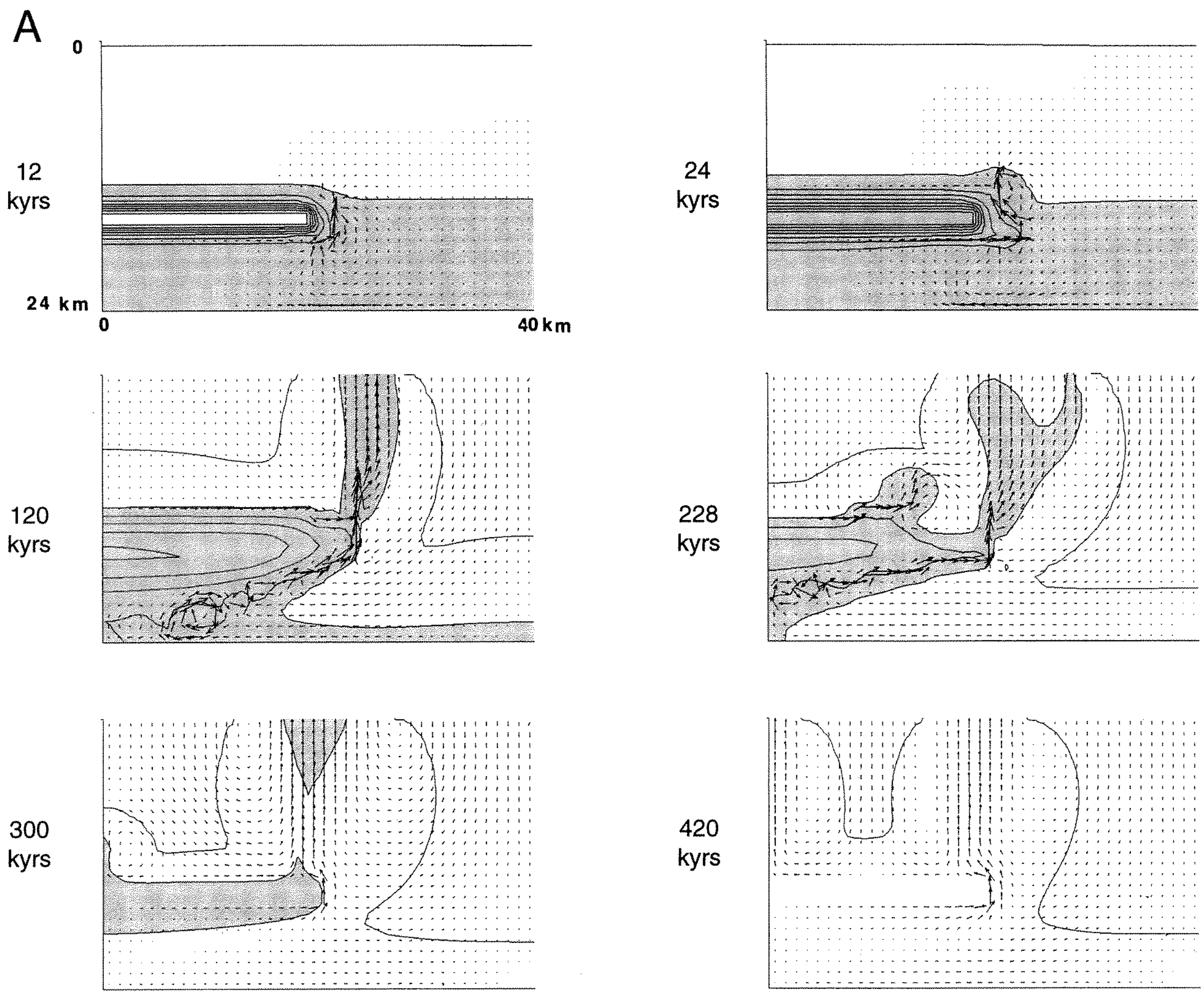

FIG. 2. A. Cross sections showing the convective cooling of a 40-km-wide, 2-km-thick sill intruded between a 16- and 18-km depth into an environment with 1-mD permeability. The ultramafic sill always has zero permeability. The initial host permeability is modified by temperature, at temperatures above 275°C as described in the text. Zones hotter than 200°C are shaded. Temperature contours are every 200°C. Arrows show the direction of pore water circulation. Labels indicate the time since intrusion in thousands of years. The sills were maintained at 1,650°C for 30,000 yr to simulate the finite time of intrusion. The cross sections are 25 km in vertical and 40 km in horizontal dimension. There is no vertical exaggeration. B. Same as (A) except the permeability of the host environment is 0.1 mD.

Figure 2B shows the pattern of convective cooling for a sill intruding a 0.1-mD environment. In this case hydrothermal fluids take almost 300,000 yr to reach the surface, but thereafter maintain hydrothermal activity for about 830,000 yr. The surface discharge pattern is more stable but nevertheless affects a broad zone ~7 km wide. Figure 3A shows that the temperature of maximum surface discharge abruptly rises in both systems as the hydrothermal front reaches the surface, but that the decay in hydrothermal temperatures near the surface is very gradual in the 0.1-mD case.

Figure 3B shows the maximum integrated mass flux in both the 1.0- and 0.1-mD systems. Both systems initially contain exactly the same excess heat. The lower cumulative mass flux for the 0.1-mD system reflects the fact the system permeability in this case is low enough to reduce convective heat transport significantly. This system is significantly cooled by conduction.

This point is reinforced by Figure 4 which shows the time duration of surface discharge hotter than 200° and 300°C as a function of host permeability. For the sill geometry considered, cooling is by conduction for host permeabilities less than ~0.02 mD. The maximum time duration of hydrothermal discharge >200°C is about 800,000 yr for permeabilities of the host environment between 0.04 to 0.1 mD. Systems with host permeabilities more than a few millidarcies maintain >200°C surface hydrothermal systems for less than 100,000 yr.

Discussion and Conclusions

The main focus of our investigation is quite narrow We have deliberately set out to determine, through a set of numerical modeling experiments, how long a single intrusive event could sustain a hydrothermal system, which

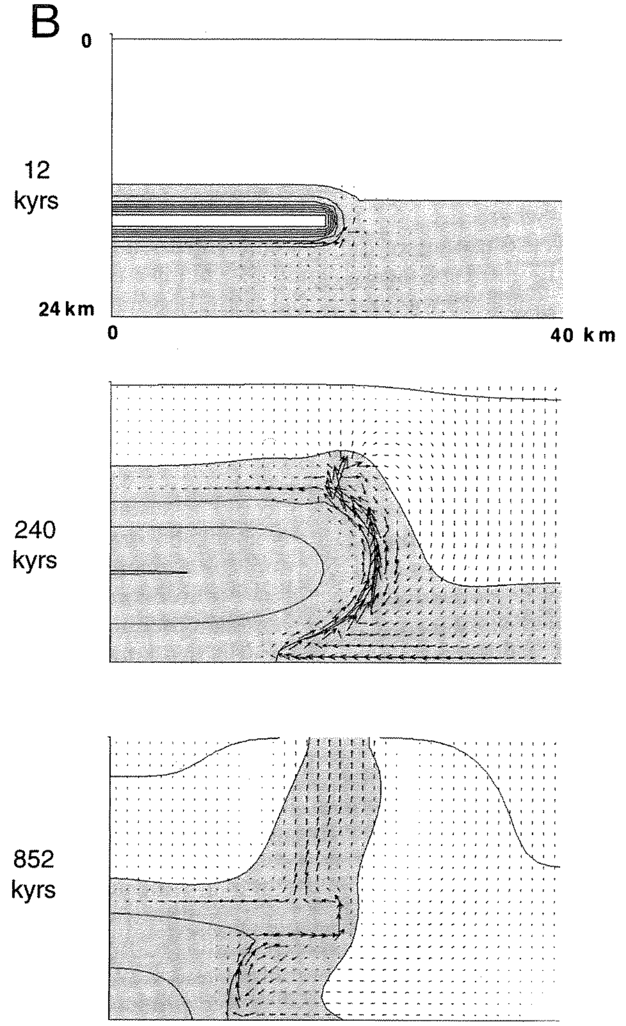

FIG. 2. (*Cont.*)

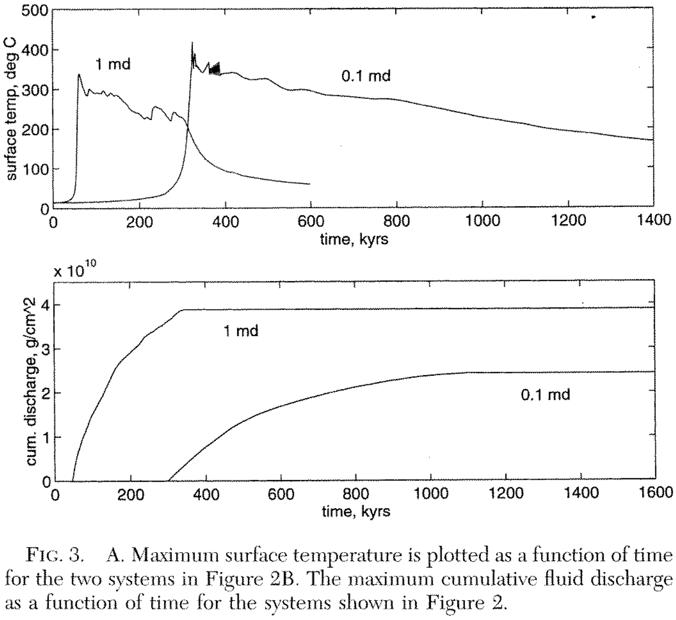

FIG. 3. A. Maximum surface temperature is plotted as a function of time for the two systems in Figure 2B. The maximum cumulative fluid discharge as a function of time for the systems shown in Figure 2.

we arbitrarily define as the convective maintenance of 200°C near-surface waters. We have determined that large and extensive ultramafic sills intruded at a ~15-km depth can sustain a shallow hydrothermal system for about 800,000 yr.

This conclusion is based on calculations subject to specific choices, but we believe that it is of general validity. For example, we choose to model the intrusion in a low heat flow environment where we increase the host permeability between 275° and 375°C and decrease it above 375°C to simulate a thermal cracking zone, the intrusion itself is impermeable (ultramafic), and the venting of hot fluids is allowed. Cooling times might be increased somewhat by prohibiting hot fluids from venting or by increasing heat flow. The most important controls are intrusion size and the permeable cracking zone, however, and the choices we have made here strongly favor longevity. The permeable cracking zone connects venting at a single site to a larger intrusive volume than would be possible with no permeable channel, and the intrusive volume connected to a single discharge site is, after permeability, the single most important control on hydrothermal longevity near the discharge site. It might be possible to

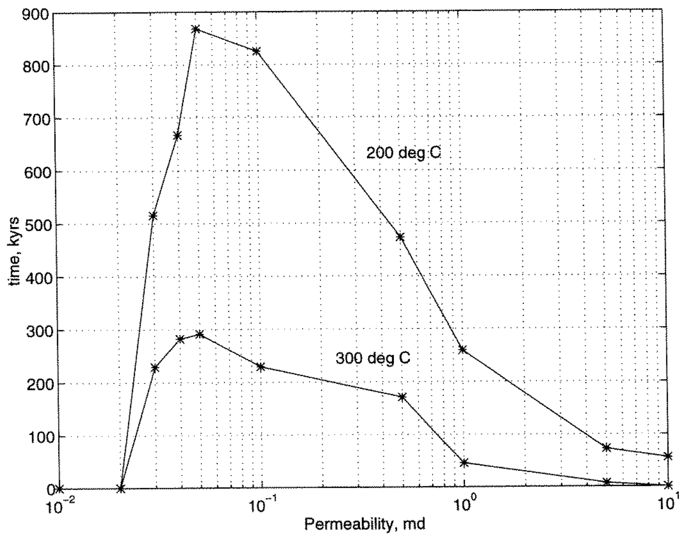

FIG. 4. The duration of surface temperatures equal to or greater than 200° and 300°C as a function of the permeability of the host environment. Large sill intrusions into environments with permeabilities between 0.05 and 0.1 mD can sustain near-surface geothermal systems hotter than 200°C for over 800,000 yr.

engineer longer system lifetimes, but we believe we are already pushing the high end of intrusive size and permeable channel design, and that ~800,000 yr is a reasonable upper bound estimate for the duration of near-surface hydrothermal activity sustained by a single intrusion event. This duration can be achieved if the host permeability is just above the conductive limit.

The models presented in this paper are all for ultramafic sills, but mafic sills would drive hydrothermal systems almost as long-lived. Because mafic intrusion temperatures are less, and because below 375°C mafic sills become permeable and allow the penetration of convecting fluids, mafic sills will cool somewhat faster than ultramafic sills. However, under optimum circumstances a large mafic or ultramafic sill could sustain a near-surface hytrothermal system for between 0.5 and 1 m.y.

There are two other particularly interesting aspects to the calculations. One is the strong tendency for the edges of the sills (where convection is forced as well as free) to produce larger convective cells. Shallow sills produce a number of convective cells over the central portions of the sill (not illustrated by the figures in this paper), but the edge convection cells completely dominate in the case of deep sills, even if the sills are 40 km wide. The strong edge cells are not caused by the enhanced permeability channel. They also occur in models where the premeability channel is absent. In shallow sills, edge effects could explain the observation that 40- × 40-km massive sulfide districts (camps) commonly host small deposits and a few large ones (edge cells). A paper discussing this aspect of sill-driven convection is in preparation. For deep sills, edge cells can vent all the circulating hydrothermal fluids at a single site and produce very widely spaced (or even singular) massive sulfide deposits of exceptional size (Barrie et al., 1998).

A second important aspect of the calculations is that the lower permeability of the longer lived 0.1-mD system allows the sill to heat surrounding mafic rocks substantially above 200°C. This is clearly evident in Figure 2A. If these mafic rocks are thermally cracked as they are later cooled by the convection system, metals could be leached from large volumes of mafic rock. The most extensive metal leaching will occur where the host permeability is high enough to allow convective cooling of the ulramafic intrusion but low enough that the intrusion heats significant volumes of the host rock substantially above 350°C. The critical permeability range is ~0.05 to 0.1 mD. Relatively low host permeablility and a deep ultramafic sill may explain the genesis of the very large, isolated Kidd Creek volcanogenic massive sulfide deposit which is associated with ultramafic extrusions. This is discussed at length in Barrie et al. (1998).

The main purpose of this paper, however, was to investigate how long a geothermal system could be sustained by a single intrusive event. The answer is about 0.8 m.y. It should be kept in mind that such a long duration applies only to systems where the permeability just allows convection. In most cases where a hydrothermal system has been produced, the permeability will be well above this conductive limit. Thus the hydrothermal circulation will have cooled even a very large intrusion heat source in at most a few tens of thousands of years. In almost all cases, hydrothermal circulation, geothermal activity, and intrusion will be closely associated in time and space, and long-lived systems will consist of a series of short-lived pulses of intrusion and hydrothermal circulation. However, in rare cases where environments with permeabilities close to the conductive limit are intruded, long-lived hydrothermal systems can be sustained by a single intrusion event. If the intrusion is a deep sill, these long-lived systems should be characterized by only a few very widely spaced convection cells, and these cells could produce isolated massive sulfide deposits of exceptional size.

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