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Fluid Flow and Genesis of Hydrothermal Ore Deposits

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Abstract

Hydrothermal ore deposits are formed when metal components precipitate from migrating solutions. The causes of fluid movement are reviewed for several deposit settings: hydrothermal circulation near a mid-ocean ridge spreading center (Cyprus-type massive sulfide deposits), convection associated with intrusives in an island-arc or continental setting (geothermal systems, porphyry copper and uranium vein deposits), and the stratafugic flow of pore fluids from compacting basins (Mississippi Pb-Zn and certain types of sedimentary copper deposits). Attention is focused particularly on the amount of fluid flow that can be produced by various mechanisms, the length of time such flow can persist, the aspects of fluid flow that have practical exploration significance, and the insights fluid flow models provide for deposit genesis. Simple analytic expressions are derived and a diagram is constructed that allow easy estimation of the time required for an instrusion to cool and the amount and rate of hydrothermal circulation produced in the process. Theoretical and field studies are reviewed to obtain an upper bound on the bulk fluid-rock mass ratio produced by natural convective systems. Areas are identified where further work is needed.

Contents

GLOSSARY

A	Cross-sectional area of intrusion (cm^2)
A'	Volumetric heat sources or sinks in cal/cm^3-sec
C_m	Heat capacity of water-saturated rock formation (cal/g-°C)
C_f	Heat capacity of fluid phase in cal/g-°C
$d_{1/2}$	Half the average distance between the connected fractures that allow flow
D'_E	Effective diffusional porosity of impermeable matrix rock
g	Acceleration of gravity in cm/sec^2
H	Height of the intrusion (cm)
h_s	Enthalpy of steam in cal/g-°C
h_w	Enthalpy of water in cal/g-°C
k'	The bulk permeability of the porous media or fractured rock formation in cm^2 (10^{-11} cm^2 = 1 millidarcy)
k_{r_w}	Factor expressing relative permeability of porous media to water as a function of S_w
k_{r_s}	Factor expressing relative permeability of porous media to steam as a function of S_w
K	Thermal conductivity of the rock formation in cal/cm-sec-°C
κ	Thermal diffusivity of the rock formation in cm^2/sec ($\kappa = K/\rho_m C_m$)
M_I	Mass of a plutonic intrusion (g)
p	Fluid pressure in dynes/cm^2
p'	Net fluid pressure in dynes/cm^2; defined to equal $p + \rho_0 gz$
q_w	Mass flow rate of water in g/cm^2-sec
q_s	Mass flow rate of steam in g/cm^2-sec
q	Mass flux of steam or water (assumes two phases are not mixed)
q_z	Vertical mass flux of unmixed steam or water (g/cm^2-sec) (vertical component of g)
Q_{oce}	Mass of water circulated through the earth's oceanic crust in one year (g/yr)
Q	Mass of water required to cool an intrusion of a given size to a given fraction of its intrusion temperature (g)
Ra	Rayleigh number, $Ra = C_f g k' \rho_0 \alpha T_0 B/\nu K$, B = thickness of convecting layer, T_0 = temperature at base
S_s	Fraction of pore space occupied by steam
S_w	Fraction of pore space occupied by water; in our case $S_w + S_s = 1$
t	Time in seconds
t_c	Characteristic convective cooling time defined in the Appendix
T	Temperature of fluid and rock in °C
ΔT	Temperature contrast of an intrusion relative to ambient formation temperature (°C)
ΔT_0	Temperature contrast of an intrusion relative to ambient at the time of intrusion
V_s	Darcy velocity of steam in cm/sec ($V_s = q_s/\rho_s$)
V_w	Darcy velocity of water in cm/sec ($V_w = q_w/\rho_w$)

TABLE 1. Comparison of Bulk Water/Rock Mass Ratios Calculated for the Ocean Ridge System by Various Means

Authors	Bulk water/rock ratio for first million years of hydrothermal circulation in oceanic plate	Method of calculation or comments
Parmentier and Spooner (1978)	<6.6	Assume theoretical conductive heat flow at 0.5 m.y. drives cylindrically symmetric upwelling in 2-km-thick, 0.1-mD crust; rate of convection at 0.5 m.y. assumed to overrepresent rate 0–1 m.y.
Wolery and Sleep (1976) global average	3.5	Estimation of total heat-flow deficiency assuming average effective exit temperature ~150°C and convection in upper 5 km of plate
Fehn and Cathles (1979) slow-spreading ridges	~2.0	Calculated using inflow zones to determine plate permeability; assumes convection in 3.5-km-thick crust
Ribando et al. (1976) estimates from 0.14-to-1-m.y.-old crust near Galapagos spreading center	0.5	Present convection pattern deduced from observed heat-flow pattern; assumes convection in 3.5-km-thick crust
Spooner and coworkers (see references in text) upper 2 km of Troodos Massif, Cyprus, which is thought to be oceanic crust formed within 6 km of a ridge axis	5.6	Average strontium isotopic shift in rock complex
	0.75	Shift in $\delta^{18}O$
	0.43	Based on sulfur content of typical deposit, assumed volume of rock associated with each deposit and 20 mg sulfur precipitated from each kg of solution venting through the deposit
	1,000 or 5 or less	Observed increase in oxidized iron, assuming reaction with oxygen dissolved in convecting sea water or reaction with oxidant carried as SO_4^{-2} in sea water or hydrolysis of water

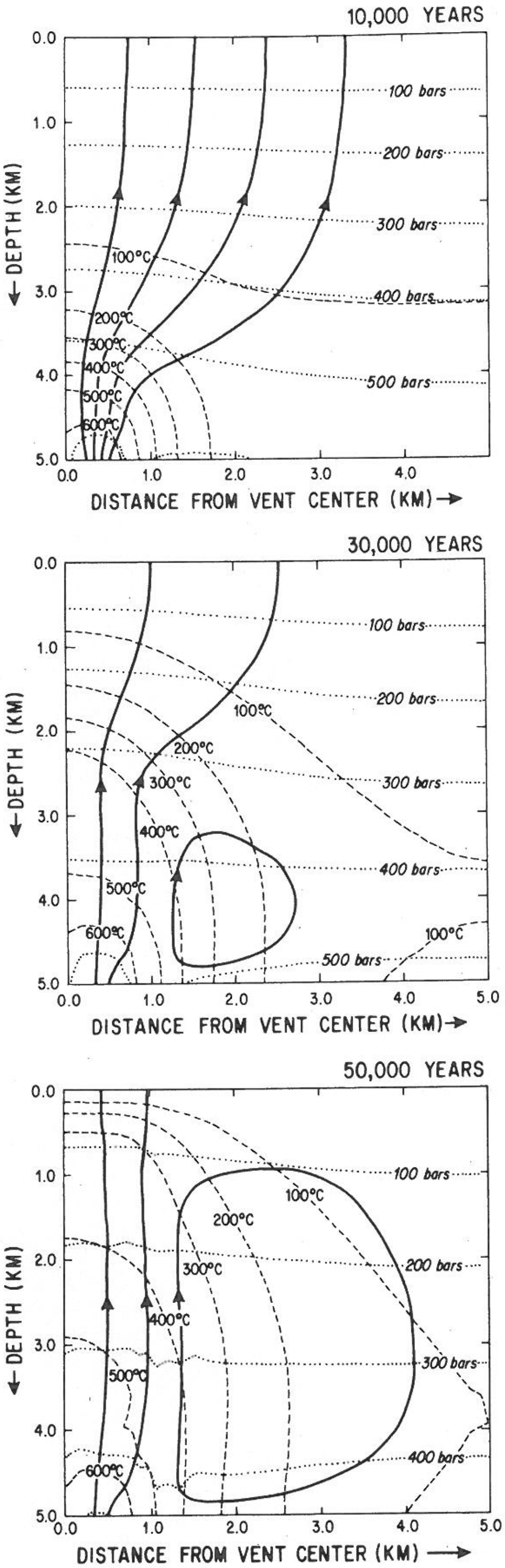
below the ore deposits or hydrothermal vents. The boundary between zeolite and greenschist facies metamorphism is not observed to be as deep near the deposits as predicted by the model. This problem is removed completely if the deposits are considered multiple vents and hydrothermal fluids to be generally upwelling in the whole area, although much more rapidly at the deposit locations, as Solomon suggests.

The difficulty is that, as Spooner and coworkers have pointed out, the oxidation of the ophiolite suite strongly suggests that fluid is circulating downward into the sea floor in the neighborhood of the massive sulfide deposits in Cyprus.

A resolution of this dilemma is suggested by Figure 5. This figure shows that deep upward-venting solutions will tend to cause secondary circulation in the neighborhood of where they vent. The deep upward venting is decoupled from this shallow or satellite circulation. The rate of satellite circulation is controlled by the permeability of the rock surrounding the vents of more deeply circulating solutions. In other words, we can, at least under some circumstances, expect "satellite" downward circulation in areas where deeply circulated solutions are venting at multiple discharge points (as suggested by Solomon, 1976). This downward circulation can explain the rock alteration documented by Spooner and coworkers, but, because it is not required to supply all of the water for the discharging solutions, the inflow can be weak enough to avoid cooling of rock near the deposit below the observed metamorphic facies. Satellite or parasitic circulation has recently been discussed by Henley and Thornley (1979).

Fractures and the temperatures of venting solutions: Fractures must concentrate venting hydrothermal solution in plate older than about 0.2 m.y. The question of whether inflow of solutions is dispersed or localized in major fractures is presently under debate. Alteration and isotopic studies appear to require a general downwelling of solutions at Cyprus, but this circulation may be secondary. Bodvarsson and Lowell (1972) and Lowell (1975) have argued in favor of connected high permeability fracture loops where major vertical fractures are connected at depth, perhaps by major horizontal fractures. If such fracture loops exist, they will dramatically concentrate both fluid inflow and outflow and greatly reduce the surface heat flow in between. If vertical fractures are not connected at depth, the concentration of fluid inflow does not appear to be severe, although outflow is strongly concentrated (Fehn and Cathles, 1979).

Fracture loops would probably be unfavorable for the generation of ore deposits because they would reduce the opportunity for water to scavenge metals from rock. Slow-spreading ridges that are typically block faulted may thus be less favorable sites for ore deposits than fast-spreading ridges.



Sleep and Wolery (1978) have analyzed the spacing of hydrothermal vents and considered the susceptibility of the vents to clogging by mineral (mainly silica) precipitation. Because the heat flow anomaly is finite and of known magnitude, they find fractures venting hot solutions to the sea floor can occur only on crust less than about a million years old and must be spaced on the order of kilometers apart. Localized springs venting hot solutions (tubular vents) can occur on crust 1 to 10 m.y. old, but they must also be spaced on the order of kilometers from neighbor vents.

Sleep and Wolery (1978) found that the flow velocity required for hot (100°C) vents is only a factor of 2 to 3 greater than that required for warm vents. Only conductive cooling of the solution in the near-surface area is considered in the calculation; mixing with sea water near the surface is ignored. The exit temperature is considered to be that at which mixing begins. Sleep and Wolery argue that clogging is greatest for intermediate temperature (and intermediate flow velocity) vents. For slow, cool vents, mineral precipitation occurs in a large, deep volume of rock and has less impact. Hot venting solutions precipitate minerals mainly above the sea floor and thus tend not to clog.

The salinity of hydrothermal fluids determines what happens once they vent into the ocean. Brines are ponded in sea-bottom depressions of the Red Sea because, despite being hot (~60°C), they are more dense than the surrounding sea water. A large ore deposit has been deposited presumably from the hotter precursors of the present-day brines. White (1981) considers ore deposition in the Red Sea in more detail. Sato (1972), Turner and Gustafson (1978), and Solomon and Walshe (1979) have considered what might happen to solutions venting from the sea floor as a function of the salinity of those solutions.

Nature of intrusive and extrusive activity at ridges and associated hydrothermal activity: Available measurements suggest that the permeability of the oce-

FIG. 5. Series of cross sections showing the development of a thermal plume as the result of the 10 g/cm^2-yr venting of 700°C hydrothermal solutions into the lower left base of the diagram. The solution enters as a supercritical fluid with specific volume approximately 9. The deep venting solutions at first fan out (uniform permeability is assumed) but are later confined by water convection driven by the plumes' thermal anomaly. In this case, the sea-water circulation is entirely secondary and driven by the hot plume developed by the venting solutions. The rate at which this secondary circulation occurs is determined by the permeability of the rock adjacent to the vent, here assumed to be 0.05 millidarcies. Near the surface the solutions condense along the two-phase curve of water. In the text it is suggested this kind of secondary circulation may enable clusters of massive sulfide deposits to represent multiple discharge points from a common deep thermal plume, as suggested by Solomon (1976), but still allow downwelling convection near each deposit as required by isotopic and alteration evidence from the Cyprus deposits (Spooner, 1977). Most of the cooling of the mature (50,000-year-old) plume occurs near the base of the domain where circulating fluids first have access to the upwelling plume. These calculations were carried out by the author and R. K. McConnell.