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Modeling of the Fault-Controlled Hydrothermal Ore-Forming Systems

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ABSTRACT

A necessary precondition for the formation of hydrothermal ore deposits is a strong focussing of hydrothermal flow as fluids move from the fluid source to the site of ore deposition. Balance assessments lead to the conclusion that the degree of focussing of the ore-forming fluids is typically up to hundreds of times or even greater. The spatial distribution of hydrothermal deposits favors the concept that such fluid flow focussing is controlled, for the most part, by regional faults which provide a low resistance path for hydrothermal solutions. Results of electric analog simulations, analytical solutions, and computer simulations of the fluid flow, in a fault-controlled single-pass advective system, confirm this concept.

The influence of the fluid flow focussing on the heat and mass transfer in a single-pass advective system was investigated for a simplified version of the metamorphic model for the genesis of greenstone-hosted gold deposits. The spatial distribution of ore mineralization, predicted by computer simulation, is in reasonable agreement with geological observations. Depending on the boundary conditions, a fault-controlled system can develop vein-type ore bodies within the fault zone, funnel-type ore bodies at the upper termination of the fault zone, or stratabound-type ore bodies above the upper termination of the fault zone.

Computer simulations of the fault-controlled thermoconvective system revealed a complex pattern of mixing hydrothermal solutions in the model, which also simulates the development of the modern hydrothermal systems on the ocean floor. The specific feature of the model considered, is the development under certain conditions of an intra-fault convective cell that operates essentially independently of the large scale circulation.

These and other results obtained during the study indicate that modeling of natural fault-controlled hydrothermal systems is instructive for the analysis of transport processes in man-made "hydrothermal" systems that could develop in geologic high-level nuclear waste repositories.

INTRODUCTION

The principal results of a modeling investigation to clarify fault controlled hydrothermal ore-forming processes are presented in concise form in this report. The investigation consisted of five tasks.

1. Conceptual formulation of the problem.
2. Electric analog modeling, analytical solution, and computer simulation for 2-D steady state fault-controlled advective flow.
3. Computer simulation of the heat and mass transfer problem for a metamorphic model of genesis of greenstone hosted gold deposits.
4. Computer simulation of fault-controlled hydrothermal convection in the spreading centers in oceanic crust.
5. A brief consideration of the possible significance of the results obtained from an analysis of the transport processes in the vicinity of a geologic high-level nuclear waste repository.

The investigations were carried out at the Institute of Ore Deposits, Petrography, Mineralogy and Geochemistry (IGEM) of the Russian Academy of Sciences (RAS).

FLUID FLOW FOCUSING AS A NECESSARY PRECONDITION FOR FORMATION OF HYDROTHERMAL ORE DEPOSITS

As is shown in the Figure 1, every hydrothermal ore-forming system includes as indispensable elements: fluid, heat, and ore-forming elements sources, a site of ore deposition, and a process that provides for the transport of ore-bearing fluids from the source region to the site of ore deposition. Basically, two principal types of ore-forming

system can be distinguished with either forces or free thermal convection transport. For both types, it is easy to show that the generic feature of the transport process is the strong focussing of fluid flow as solutions move from the source region to the site of ore deposition (Pek, 1989).

For hydrothermal systems, which produce base metal deposits, the typical concentration of ore elements in the ore-forming solutions is $\sim n \times 10$ ppm (Hemley and others, 1992). The ore reserves in medium size deposits are $\sim 5 \times 10^5$ t (Laznicka, 1983). Assuming that the decrease in concentration of the ore transporting solutions while passing through the site of ore deposition is equal to 50 ppm, then the mass of the ore-forming fluids required to form the deposit can be rounded to $\sim 10^{10}$ t.

Forced fluid convection is characteristic of the systems in which the source of fluid is due to magmatic activity, metamorphic dehydration, or displacement during compaction and diagenesis. Consider, for example, a magmatic source with a typical water content of 2-3 mass %, then, for the given above estimate of the volume of ore-forming fluids, the volume of the magma chamber should be of ~ 150 km³. The volume of the ore in a deposit with reserves of 5×10^5 t and a typical ore grade of 1 mass % is ~ 0.02 km³. Thus, the source magma chamber/ore deposit volume ratio is $\sim 7.5 \times 10^3$.

The degree of fluid flow focussing can be determined quantitatively as the decrease in the cross section area of the fluid stream as it moves from the source region to the site of ore deposition. For a given source/deposit volume ratio, the degree of focussing depends on the geometrical form of the related volumes. For the case when both volumes are approximated as cubes, the degree of focussing is given in Table 1. This means that in the case of a source/deposit volume ratio of $n \times 10^3$, typical values of the fluid flow focussing are (1-4) 10^2 .

Free thermal convection is characteristic of hydrothermal ore-forming systems with a local heat source such as an igneous intrusive body, which creates the "thermal

engine" for groundwater flow. Because the fluid recirculates, a fluid balance cannot be used to estimate the degree of fluid flow focussing in such thermoconvective systems. However, certain indications can be derived from ore metal balancing. The crustal abundances for such base metals as Cu, Zn, Pb are: Cu - 75 ppm, Zn - 80 ppm, Pb - 8 ppm (Taylor, McLennan, 1985). Assuming that the extraction efficiency of the base metals by circulating fluids through the source region is equal to ~ 10 ppm, then the volume of the source region that is necessary for formation of a deposit of $5 \cdot 10^5$ t is 20 km^3 . The ore element source region/ore deposit volume ratio is then correspondingly $\sim 10^3$. For thermoconvective systems, the spatial relation of the source region of ore forming elements to the site of ore deposition is different from that of single-pass advective systems. Nonetheless the comparable source/deposit volume ratio suggests that the degree of fluid flow focussing should be comparable.

Thus, we come to the conclusion that fluid flow focussing by a factor of $n(10 - 10^2)$ is a necessary precondition for the formation of hydrothermal ore deposits with considerable ore metal reserves. This conclusion raises the question of the mechanism of fluid flow focussing.

ELECTRIC ANALOG MODELING AND ANALYTICAL SOLUTION FOR 2-D STEADY STATE FAULT-CONTROLLED ADVECTIVE FLOW

ELECTRIC ANALOG MODELING

The results of electric analog modeling of the 2-D steady state fault-controlled advective flow problem are summarized in Pek (1982). Electric analog models were made using electroconductive paper with different values of electric conductivity. The hydrodynamic interpretation of the electric analog modeling was based on the mathematical analogy between Ohm's law for electric current and Darcy's law for fluid flow in porous media.

Figure 2 illustrates the flow net for advective flow controlled by a vertical highly permeable fault zone which penetrates from the Earth's surface to the depth L . The upper boundary of the model represents the Earth's surface with the zero hydrodynamic fluid pressure (hydraulic head). The hydrodynamic pressure at the lower boundary is taken to be equal to 1. The left and right boundaries of the model are assumed to be impermeable. The permeability of the enclosing rocks is constant. The permeability of the fault zone is much higher than that of the enclosing rocks.

The degree of the fluid flow focussing was determined as the ratio of the width X of the stream which flows into the fault zone, measured at the lower boundary of the model, to the width H of the fault zone. The X/H ratio is equal to the $V_{f(max)}/V_r$ ratio, where $V_{f(max)}$ is the flow velocity at the outlet of the fault zone and V_r is the background velocity of the undisturbed flow. From the flow net it turns out that $X \sim 2L$. Thus, the flow velocity increase in the fault zone is $V_{f(max)}/V_r = X/H = 2 L/H$. Typical values of the L/H ratio for the fault zone are $n(10^2 - 10^3)$. This means that, as the result of flow focussing, the flow velocity in the fault zone increases, correspondingly, by a factor of $n(10^2 - 10^3)$.

In Figure 2 is given the flow net for a "blind" fault, which does not reach the Earth's surface. The flow pattern in this case is characterized by fluid inflow into the lower part of the fault zone with subsequent outflow from the upper part. The proximity of the upper termination of the fault zone to the upper boundary of the model leads to an incomplete defocussing of the outflowing stream. In the model with the infinitely remote boundaries the flow net is symmetric about the horizontal line intersecting the fault at its vertical half-length. The degree of fluid flow focussing in such "blind" fault model is two times less than in the "open" fault model considered above.

The diagram for the "open" fault model in Figure 4 shows on a percentage basis how the flow velocity value changes along the fault zone vertical length. The flow velocity, V_f , reaches its maximum value V_{max} at the outlet of the fault.

Down the dip of the fault, the flow velocity decreases at a rate that increases with depth, 1.

The X/L dependence on the permeability ratio, K_1/K_2 , of the fault zone and enclosing rocks in the "open" fault model is given in Figure 5. For highly permeable faults, as in the model, given in Figure 2, $X/L \sim 2$. With decreasing K_1/K_2 ratio, the X/L value decreases with a corresponding decrease in the degree of fluid flow focussing.

The results of electric analog simulation, given above, can be summarized as follows:

1. For highly permeable faults the degree of fluid flow focussing can be up to hundreds or even thousands of times.
2. For faults which penetrate the crust from the Earth's surface, i.e., "open" faults, the advective flow pattern is characterized by fluid inflow into the fault zone. For faults which do not reach the Earth's surface, i.e., "blind" faults, the advective flow pattern is characterized by fluid inflow in the lower part of the fault zone with subsequent outflow in the upper part.
3. In accordance with the fluid flow pattern, advective flow velocity changes along the vertical length of the fault zone. In the "open" fault model, flow velocity increases along the whole length of the fault. In the "blind" fault model flow velocity increases in the lower part of the fault zone, reaches its maximum value at the fault half-length, after which it decreases.
4. A decrease of the fault zone/enclosing rock permeability ratio leads to a decrease of the fluid flow focussing at a rate which depends on the value of permeability ratio.

ANALYTICAL SOLUTION

The analytical solution for the flow problem considered above was obtained by A.V. Gurevich and others (1988; 1989).

A scaling parameter for the process was identified as the dimensionless hydraulic conductivity $T = (k_f H) / (K_r L)$, where K_f and K_r correspond respectively to the permeability of the fault zone and enclosing rocks (equal to K_1 and K_2 in the electric analog modeling). The expressions for calculating the maximum fluid flux at the half-length of the fault for the different T values were derived. The flow nets for advective flow controlled by the faults with low ($\lg T \ll 1$) and high ($\lg T \gg 1$) dimensionless hydraulic conductivity are given in Figure 6 and Figure 7. The dependence on T of the Q_{\max} , maximum mass fluid flux at the half length of the fault, is given in Figure 8.

The principal results from the analytical investigation of the problem can be summarized as follows:

1. The analytical solution confirmed and refined the results of electric analog modeling.
2. A scaling parameter for the flow problem was identified as the fault zone dimensionless hydraulic conductivity, $T = (K_f H) / (K_r L)$.
3. With an increase of the dimensionless hydraulic conductivity, a change of mechanisms takes place that limits the fluid flow focussing. For poorly-conductive fault zones ($T \ll 1$) the maximum fluid flux is limited by the fault zone hydraulic conductivity $K_f H$ (see Figure 6), while for the highly conductive faults ($T \gg 1$) the limiting factor is the vertical length, L , of the fault.

**FORMATION OF GOLD DEPOSITS IN ARCHAEOAN GREENSTONE BELTS:
COMPUTER SIMULATION OF HEAT AND MASS TRANSFER PROCESSES FOR A
METAMORPHIC-REPLACEMENT MODEL**

CONCEPTUAL SCHEME

Many large Archaean gold deposits in greenstone belts exhibit a marked spatial relationship to regional faults.

The origin of such deposits has been attributed by a number of authors to focussed advection of gold-transporting solutions via fault channelways (Fyfe, Kerrich, 1984; Kerrich, 1986; Fyfe, 1987; Eisenlohr and others, 1989).

Fluid focussing was invoked to explain the large volumes of solutions involved in formation of ore deposits. However, the role of channelized flow is not restricted to the problem of fluid supply. Focussed fluid advection implies focussed heat advection that leads to the development of fault-related thermal anomalies. Downstream thermal gradients in the anomalies influence ore precipitation, the process causing the development of geochemical anomalies.

To examine the geochemical role of channelized fluid advection, a dynamic model that includes solution flow, heat transport and ore precipitation was set up for computer simulation (Pek, Malkovsky, Arseniev, Topor, 1987; Malkovsky, Pek, Arseniev, Topor, 1988; Pek, Arseniev, Verkhovsky, 1990; Arseniev, Pek, 1991; Pek, Arseniev, Malkovsky, 1991). The computer model was based on a metamorphic-replacement genetic model for Archaean greenstone-hosted gold deposits, as outlined by D.I. Groves and his co-authors (Groves and Phillips, 1987; Groves and others, 1987). The distinctive features of this model are:

1. Fluid source: mantle and lower crustal metamorphic and magmatic fluids.
2. Source of ore elements: mantle, lower crust and greenstone components.
3. Flow system: single-pass, advective.
4. Structural control of fluid flow: advective stream focussing by permeable crustal-scale fault zones penetrating at least to 10-15 km depth.
5. Structural control of ore localization: of vein type or "stratabound" ore bodies hosted by second-order structures associated with first-order faults. The first-order faults

can host ore mineralization but are usually largely unmineralized.

6. Temperature and pressure of ore deposition: temperature 300-400°C, pressure 1-2 kb.

7. Ore precipitation mechanism: A decrease in gold solubility with falling temperature, combined with selective fluid-rock interaction.

A schematic diagram showing the major features of the metamorphic-replacement model for gold mineralization in Archaean greenstone belts is given in Figure 9. The results of computer simulations carried out for a simplified version of the model indicate that the observed tectonic control on spatial distribution of ore mineralization depends on the dynamics of transport processes in the hydrothermal ore-forming system.

CALCULATION SCHEME

We considered a two-dimensional model for hydrothermal advection in a 20 km deep crustal profile that contains a vertical, blind, highly permeable fault zone. The dimensions of the fault zone are taken as: height $L = 10$ km, transverse width $H = 200$ m, up-dip termination at 3 km, down-sip termination at 13 km. The fault zone/enclosing rocks permeability ratio was set at $k_f/k_r = 1000$. The initial geothermal gradient in the model is assumed to be 25°C/km with temperatures at the top and bottom boundaries equal to 0°C and 500°C respectively. The scheme of the model together with data on accepted parameter values is given in Figure 10.

The general mathematical formulation of the problem is given in Table 2. Hydrothermal advection was simulated by uniform fluid input through the lower boundary of the model. Fluid and rock properties in the process were taken to be time-independent. This assumption permits division of the simulation procedure into a three-step sequence (1) flow, (2) heat transfer, and (3) mass transfer problems. The flow

problem was solved by a steady state approximation; heat and mass transfer problems were solved for transient conditions (Malkovsky and others, 1988).

FLOW PROBLEM SIMULATION

The results obtained for the flow problem simulation are given in Figure 11. Flow vectors in Figure 11A indicate that, as in the above considered schemes, the flow pattern is characterized by advective stream focussing in the lower part of the system with subsequent defocussing in the upper part. The distribution of flow velocity values, given in Figure 11B, indicate that, as a result of such a flow pattern, the flow velocity values in the enclosing rocks increase in proximity to the lower and upper terminations of the fault and decrease in the middle part of the fault-controlled stream. As a result of fluid flow focussing, the Darcy velocity, V , in the fault zone increases, in comparison with the flow velocity, V_0 , in the undisturbed flow (at the lower boundary of the model). The maximum flow velocity value V_{\max} is attained at approximately the half-length of the fault. The dimensionless maximum flow velocity increase (V_{\max}/V_0) is ~47. The average value of the along fault normalized flow velocity is ~38.

HEAT TRANSFER SIMULATION

The results obtained for the heat transfer simulation are given in Figures 12, 13, and 14. The temperature distribution in the vicinity of the fault, given in Figure 12, indicates that fluid flow focussing leads to enhanced heating of the fault zone, as compared to the enclosing rocks far from the fault. As a consequence, the fluid outflow from the fault results in the development of a fault-centered dome-shaped thermal anomaly. The main parameters influencing the process are time, geothermal gradient, flow velocity, V_0 , of the feeding stream, dimensionless fault zone hydraulic conductivity, T , and vertical length, L , of the fault zone.

In Figure 13 is shown the temperature distribution along the vertical centerline line of the model for different times from the onset of the process. A comparison of the curves indicates that the temperature in the system increases with time. Such prograde heating is characteristic for the early stage of hydrothermal ore-forming system evolution, whereas, the system full life-cycle includes transition from the early heating to the late cooling stage. However, the transition to the cooling thermal regime cannot be simulated under the boundary conditions adopted in the initial simulations. In order to simulate the full life-cycle of the system, a new boundary condition for V_0 is introduced that implies that the deep seated fluid source undergoes gradual depletion. After a number of test calculations, a model with exponential V_0 decrease from an initial value of $1 \cdot 10^{-9}$ m/s after 1.0 m.y. was selected for further investigation. With such a boundary condition, the time-integrated fluid discharge through the fault zone is $\sim 4 \cdot 10^{10}$ metric tons, which is sufficient for the formation of a large ore deposit.

The time dependent temperature change at the up-dip termination of the fault is given in Figure 14. The simulated temperature trend presents a realistic version of the thermal life-cycle of the system. The temperature rises from an initial value of 75°C to a maximum value of 350°C is attained after ~ 200 thousand years. Thereafter, it gradually decreases to $\sim 260^\circ\text{C}$ 0.5 m.y. after onset of the process.

SIMULATION OF ORE DEPOSITION

Ore deposition was simulated by having the ore elements precipitate at the moving thermal barrier. The solubility of the ore elements was considered to follow a logarithmic law with 90% decrease in solubility after a 100°C decrease in temperature. Calculations were performed for four versions of the process with initial temperatures of ore precipitation T_s set at 425, 375, 325 and 275°C . The results obtained are given in Figures 15-17.

In Figure 15 is given the normalized concentration of ore elements in the ore forming fluid along the vertical line of the model at different times. The concentration of ore-forming elements in the inflowing solutions (that is, at the lower boundary of the simulated domain) is equal to the saturation concentration at $T_s = 325^\circ\text{C}$. Because the temperature at the lower boundary of the model is 500°C , a boundary condition of $T_s = 325^\circ\text{C}$ implies that the ore transporting solutions at the lower boundary of the model are undersaturated. When the temperature in the upwelling stream reaches T_s , ore minerals start to precipitate. During the prograde stages of ore deposition, the temperature builds up over time and initially precipitated ore minerals undergo partial or full redissolution. The concentration of ore elements in the ore-forming solutions therefore increases (e.g., see the development of concentration maxima on the concentration curves for 52 and 206 t.y.) and the corresponding temperature of ore precipitation rises. As a result, a "rolling" ore front develops. The spatial position at different moments of time of such a "rolling" front caused by reprecipitation of ore minerals on the moving thermal barrier is given in Figure 16.

As the system passes into the retrograde stage of its lifecycle, the reprecipitation process ceases, and self-enrichment of the ore-forming solutions likewise ceases. (In Figure 15, compare the concentration curves for the prograde stage at 52 and 206 t.y. with concentration curve for the retrograde stage at 516 t.y.) Precipitation of ore minerals proceeds now from the ore-forming solutions with the concentration equal to saturation concentration at the lower boundary of the model. Because the system cools with time, the horizon at which ore precipitation occurs gradually moves downward.

In Figure 17, the results of computer simulation are given for the spatial distribution of the ore mineralization accumulated upon completion of the process (at $t = 0.52$ m.y.). The results are presented for four cases with different concentrations of ore elements in the pregnant

solutions, equal to saturation concentrations at 425, 375, 325 and 275°C, respectively.

In Figure 17a, spatial distribution of the ore mineralization is given for the case where the ore element concentration in the pregnant solutions (at the lower boundary of the model) is equal to the saturation concentration at $T_s = 425^\circ\text{C}$. The high-grade mineralization with normalized concentration values in the solid phase $q/q_{\text{max}} > 0.6$ accumulates within the fault zone and forms a lode-type ore body that stretches from ~11 to ~7 km. In the upper part of the structure, a fault-centered primary dispersion aureole develops, which is caused by fluid outflow from the fault zone. At the depth interval from ~12 to ~9 km an isolated subhorizontal geochemical anomaly forms in the enclosing rocks which is caused by advective flow that bypasses the fault zone. Because of the fluid flow velocity distribution in the enclosing rocks, as shown in Figure 11B, this geochemical anomaly is separated from the fault.

In Figure 17b the spatial distribution of the ore mineralization for the model where the ore element concentration in the pregnant solutions is equal to saturation concentration at $T_s = 375^\circ\text{C}$, which is lower than in the previous case. The high-grade mineralization is localized within the fault zone close to its up-dip termination. The primary dispersion aureole is wider than in the previous case. The isolated anomaly in the enclosing rocks has moved up to a depth interval from ~9 to ~7.5 km.

In the case where $T_s = 325^\circ\text{C}$, given in Figure 17c, the high-grade mineralization forms a funnel-shaped ore body with its root at the upper end of the fault. The primary dispersion aureole and the anomaly in the enclosing rocks has fused into a broad subhorizontal halo.

In the last case, where $T_s = 275^\circ\text{C}$, given in Figure 17d, the high-grade mineralization forms a subhorizontal body above the fault zone at the depth less than 1 km.

DISCUSSION

The above preliminary results of computer simulations are broadly compatible with the metamorphic model for the formation of Archaean gold deposits in greenstone belts, developed by Australian geologists (Groves, Phillips, 1987; Groves and others, 1987; Eisenlohr, Groves, Partington, 1989; etc.). A mass balance assessment of the model results shows that the principal characteristics of the ore-forming model are reasonable:

- The time-integrated volume of ore-transporting solutions discharged for each 1 km of fault zone strike length is $\sim 43 \text{ km}^3$.
- A fluid source, derived from basaltic or pelitic rocks undergoing metamorphic dewatering, liberates $\sim 3 \text{ wt.}\%$ of aqueous fluid (Fyfe, 1987). To liberate 43 km^3 , the fluid source volume should be $\sim 500 \text{ km}^3$.
- For the model considered, assuming that the strike length of the fault zone is equal to 10 km, the thickness of the metamorphic pile undergoing dewatering should be $\sim 5 \text{ km}$.
- Assuming an average Au abundance in the source volume of 2 ppb and 50% leaching efficiency, the total mass of gold mobilized is $\sim 1400 \text{ t}$, which is sufficient for the formation of a large gold deposit.
- The gold concentration in the ore-forming solutions would then be $\sim 30 \text{ ng/ml}$. This value is reasonable when compared with the gold precipitating capacity of ore-forming solutions, $\sim 25 \text{ ng/ml}$, derived from the silica/gold ratio in the typical quartz-gold veins (Fyfe, Kerrich, 1984).

To conclude, the computer simulation of fluid, heat and mass transport in the advective fault-controlled hydrothermal system permitted development of a preliminary quantitative model for the generalized theoretical concept for the genesis of Archaean gold deposits. These deposits are a source of a substantial part of the world's gold production. The problem

certainly deserves a more detailed site-specific investigation.

THERMAL CONVECTION MODEL FOR FAULT-CONTROLLED HYDROTHERMAL SYSTEMS

CONCEPTUAL SCHEME

Active submarine hydrothermal convection systems were taken as a natural analogue to formulate the problem. The most spectacular evidence for hydrothermal convection in the oceanic crust comes from thermal springs at the ocean ridge spreading centers, e.g., at the Galapagos Spreading Center, East Pacific Rise and Juan de Fuca Ridge.

Convection of sea water in the oceanic crust is driven by thermal energy supplied by shallow magma chambers. According to seismic surveys, the top of magma chamber is usually at the depth 1.2 to 2.5 km below the sea floor (Detrick and others, 1987; Morton and others, 1987; Rohr and others, 1988). The magma chamber width is, however, much less than predicted for the shallow pluton models with conduction as the only cooling mechanism (Wilson D.S., D.A. Clauge, N.H. Sleep, J.L. Morton, 1988). Such narrow magma chambers can form only if the magma body is also cooled, along with conduction, by deep convective circulation of sea water. Deep sea-water convection is indicated by the several kilometer wide bands of depressed heat flow that are parallel to the ridge axis. The axial sea water convection contributes significantly to the Earth's heat balance: ~40 km³ of 350°C fluids vent at ocean ridge axes each year (Cathles, 1990).

The convective cells in the spreading ridges are "open", that is to say, they are recharged from and discharge into the ocean reservoir. The recharge inflow into the convective system is from a wide sea floor area, the discharge outflow is strongly channelized. At the spreading centers, the

channelized fluid discharge is controlled by the axial fault zones.

As a result of fluid-rock interaction, fluids in the convective cell change their chemical composition. Under favorable conditions, they leach ore forming elements from the enclosing rocks, mainly Fe, Zn, and Cu. The high temperature metal-charged fluids reach the cold sea floor environment, where they precipitate their ore burden in the form of sulfide minerals. As a result, "black smoker" plumes containing sulfide particles are formed. The vents of such black smokers locally mark the controlling fault zone (Rona and others, 1983).

A geological cross-section of an ocean ridge spreading center includes basalt lava flows, dikes and plutons of gabbro, and ultramafic rocks, which can have orders of magnitude differences in permeability. The ocean floor relief can also influence the fluid circulation. Thus, a generic model for the simulation of sea water thermal convection in the ocean ridge zones should include the following features:

1. Heat source: shallow magmatic chamber.
2. Fluid source: sea water.
3. Physical nature of the transport process: free thermal convection.
4. Structural features:
 - ocean floor relief;
 - shape of the magma chamber;
 - heterogeneous, usually layered, permeability distribution in the geological section;

- highly permeable fault zone which transects the geological section from the roof of the magma chamber to the sea floor.

The conceptual scheme of the model is given in Figure 18.

CALCULATION SCHEME

A mathematical formulation of the flow and heat transfer scheme is given in Table 3. The computer code was formulated using the finite element method.

For a preliminary investigation, a simplified version of the conceptual model outlined above is illustrated in Figure 19. The simulation was carried out for 4,000 years from the onset of the process. The results are given for four different cases with different permeability values for the fault zone, K_1 , and the lower and upper layers, K_2 and K_3 respectively:

1. Model 1: $K_1 = K_2 = K_3 = 10^{-16} \text{ m}^2$.
2. Model 2: $K_1 = 10^{-14} \text{ m}^2$, $K_2 = K_3 = 10^{-16} \text{ m}^2$.
3. Model 3: $K_1 = 10^{-14} \text{ m}^2$, $K_2 = 10^{-15} \text{ m}^2$, $K_3 = 10^{-16} \text{ m}^2$.
4. Model 4: $K_1 = 10^{-14} \text{ m}^2$, $K_2 = 10^{-16} \text{ m}^2$, $K_3 = 10^{-15} \text{ m}^2$.

SIMULATION OF THE FLOW PROBLEM

The results obtained for Case 1 are given in Figure 20. As it can be seen from the flow vectors, an open convective cell develops in the domain. During the early stages of the process, fluids move along the hot magma chamber roof as a strongly focussed stream. With time, as the rocks overlying the magma chamber heat up, the degree of focussing decreases. The upwelling fluids discharge at the ocean floor as a distributed flow in a zone more than 1 km wide. Beyond this

zone, the process of downward movement of sea water into the ocean crust is observed.

The results obtained for Case 2 are given in Figure 21. This case differs from the previous case in that there is a highly permeable fault zone along its axis. The influence of the hot magma chamber on fluid circulation resembles that in Case 1. But, because of the fault zone, the fluid flow pattern is different. The fluid discharge at the ocean floor is strongly focussed, when compared to that in Case 1. The discharge zone includes the fault zone and a narrow band of rocks adjacent to the fault zone. Within the fault zone a local intra-fault convection develops. During the early stages of the process this intra-fault convection is closed, but after 3,000 years it transforms to an open intra-fault convective cell.

The results obtained for Case 3 are given in Figure 22. This case differs from Case 2 in that permeability of the lower layer 3 is one order of magnitude higher. This modification of the calculation scheme results in suppression of the intra-fault circulation.

The results obtained for Case 4 are given in Figure 23. This case differs from Case 2 in that one order higher permeability was prescribed for the upper layer. As can be seen from the flow vectors, an intra-fault convective cell develops for this case as in Case 2.

DISCUSSION

The results given above are preliminary. Nevertheless, they reveal effects which essentially provide an understanding of the role of faults in thermoconvective ore-forming systems.

One of the principal mechanisms leading to hydrothermal ore precipitation, is inferred to be the fluids of different temperature and chemical composition. The flow patterns obtained demonstrate that such mixing strongly depends on the

permeability distribution. The presence of a highly permeable fault induces intra-fault convection. As a result, at first glance, a surprising process can develop where fluids emerging from enclosing rocks into the fault zone will move not up to the ocean floor, as one would anticipate, taking into account the fact that the fault serves as the main feeder for the hydrothermal vents, but down to the deep-seated heat source and only later up to the vent.

In the natural environment, fluid circulation can be much more complicated than is the given above examples. In general, fluid flow in thermoconvective fault-controlled systems should be three-dimensional with large-scale ad intra-fault convection cells, as in the cases considered, interacting with the intra-fault convection that develops in the plane of the fault zone. The scale of this along-strike convection can provide a possible explanation for observations concerning the distribution of discrete ore mineralization along strike of the faults, as it is established for gold deposits in the famous Mother Lode tectonic zone in California.

Fault-controlled hydrothermal convection is related not only to the genesis of hydrothermal ore deposits. Among other lines of investigation can be mentioned interpretation of the data on the chemical and isotopic composition of active hydrothermal springs, on variations of the regional heat flow, and an assessment of the depth of fluid penetration into the Earth's crust. These problems deserve further investigation.

WHAT CAN AN INVESTIGATION OF NATURAL HYDROTHERMAL ORE-FORMING SYSTEMS PROVIDE TO INCREASE OUR UNDERSTANDING OF TRANSPORT PROCESSES IN A RADIOACTIVE WASTE REPOSITORY?

In the nuclear waste management practice, ore deposits and specifically those of radioactive elements are usually considered as natural analogues of radioactive waste repositories. According to such an understanding, the primary objective of the relevant investigation is the

magnitude of radionuclide migration from the ore deposit to the environment. The concept that we would like to emphasize is that the investigation of ore deposits and specifically of ore-forming systems can give valuable information in understanding transport processes which can be induced during radioactive waste disposal in geologic formations. The general basis for such an understanding is that nature does not know our classification of elements into such categories as "ore" or "waste"; the processes which lead to ore and waste element transport, dispersion and accumulation are basically the same.

The results given above permit us to illustrate this approach with two examples.

1. The numerical simulation of the ore precipitation process revealed that the size and scale of ore deposition are highly sensitive to variations of parameter values in the ore forming system. As a result, high-grade ore mineralization originating from a deep source can accumulate at shallow depth (see Figure 17). In such a process of ore accumulation, the concentration of ore species in the solid phase can increase many thousands of times in comparison with their concentration in the ore-forming fluids. For example, the concentration of gold in the gold-forming solutions is estimated as $n \times 10$ ppm, but from such dilute solutions native gold precipitates. In research projects for the assessment of geological disposal of radioactive wastes, attention was paid primarily to the investigation of radioactive waste leaching from the underground repository. The processes which can lead to subsequent accumulation of leached radionuclides in the solid phase have been examined in less detail. The data on ore-forming systems which indicate that such processes can lead to accumulation of high local concentrations of radionuclides at shallow depths point to the desirability of investigating the problem in greater detail.

2. The results the simulation of thermal convection for fault-controlled hydrothermal systems (see Figure 21 and Figure 23) suggest that if a permeable fractured zone were to

develop in the rocks overlying the repository, then a complex three-dimensional intra-fault convective system could develop. Such an intra-fault system could lead to intrusion of oxidizing water from the Earth's surface into repository with subsequent leaching of emplaced wastes and direct transport of leached radionuclides to the biosphere.

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