HYDROLOGIC ASPECTS OF GOLD DEPOSITS

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Abstract

Physical aspects of freely convecting hydrothermal systems that bear on the genesis and geochemistry of gold deposits are discussed. By "freely convecting" we exclude deposits related to hydrothermal solutions that are squeezed out of compacting basins. The size of the intrusive heat source required to produce a good sized hydrothermal gold deposit is first estimated. Aspects of vapor phase separation in the H₂O-CO₂ system are then considered.

Bibliography


Figure 1. For discussion of the mass of hydrothermal solution an intrusive can circulate, see Cathles (1982, Appendix).

Figure 2. Discharge from a fracture can be focused or diffuse. Diffuse discharge could produce disseminated gold deposits.
SIZE INTRUSIVE REQUIRED

McLaughlin
20 mt at 0.16 oz Au/t
22 mtonnes at 5g/tonne
∼ 120 tonnes Au

Solubility Au ∼ 20 ppb

TONNES HYDROTHERMAL SOLUTION REQUIRED

\[ \frac{120}{20 \times 10^{-9}} = 6 \times 10^9 \]

Mass hydrothermal solution >200°C ∼ \[ \frac{1}{2} \] mass intrusive

MASS INTRUSIVE

\[ \sim 12 \times 10^9 \]

\[ \rho_{\text{rock}} \sim 2.7 \text{ tonnes/m}^3 \]

VOLUME of INTRUSIVE

\[ \sim 4 \times 10^9 \text{ m}^3 \]

HEAT SOURCE REQUIRED

1.6 km

1.6

FRACTURE FOCUSED DISCHARGE MODEL

surface leakage focused or diffuse

0 2 km
Figure 3. The model we consider can treat either flow in a fracture or diffuse porous media flow. The maximum rate of vertical upflow is limited by the magnitude of the cold water head to \( q/k' \leq 3 \times 10^5 \), where \( q \) = mass flow rate in grams fluid/cm\(^2\)/sec, and \( k' \) is the permeability in cm\(^2\) (10\(^{-11}\) cm\(^2\) = 1 millidarcy). Results of calculations are the same for constant ratios of \( q/k' \). For convenience we choose \( k' = 10 \) millidarcies for all calculations and vary \( q \) between 10 and 1000 g/cm\(^2\)/yr. The methods of calculation are discussed by Donaldson (1968). We extend the calculation to higher temperatures, and include the effects of CO\(_2\) in the fluid.

Figure 4. The cold water head limits the rate of upflow such that \( q/k' \leq 3 \times 10^5 \). For \( k' = 10 \) md this translates to \( q < 1000 \) g/cm\(^2\)/yr.
LIMIT on FLOW RATE: must be driven by cold water head.

\[ q = \frac{k'}{\nu} \nabla p' = \frac{k'}{\nu} g (P(T_s) - P(T)) \]

\[ \frac{q}{k'} < \frac{(P(T_s) - P(T))g}{\nu} = \frac{(0.2 g/cc)10^3}{0.002} \]

Donaldson (1968) calculates $1.5 \times 10^5$ for limit at $T \sim 260^\circ C$. We use $3 \times 10^5$ in our diagrams.

We pick $k' = 10 \text{md}$ so \( q_{\text{limit}} = 1000 \text{g/cm}^2 \text{-yr} \)
Figure 5. The model simply requires conservation of water mass, heat, and momentum. If CO$_2$ is included, CO$_2$ mass must also be conserved.

Figure 6. If there is no CO$_2$ the solution is very simple. Conservation of water mass and heat allow us to solve for $q_B$ as a function of the enthalpy or heat content of the vapor ($h_v$), fluid ($h_f$), and source ($h_{source}$). The enthalpies are determined by either temperature or pressure since we are on the two phase curve (vapor plus liquid) of water. Thus at the base, where we specify $T_{source}$, we know $q_f$ and $q_v$, and we can eliminate the $\partial p/\partial z$ term from the momentum equations and solve for the value of liquid saturation that gives the proper values of $k^l_r$ and $k^v_r$ (the relative permeabilities to liquid and vapor).
METHODOLOGY

- conservation water mass: \( q_l + q_v = q_{\text{source}} \)
- conservation heat: \( q_l h_l + q_v h_v = q_{\text{source}} h_{\text{source}} \)
- conservation of CO\(_2\): \( q_l n_l + q_v n_v = q_{\text{source}} n_{\text{source}} \)
- conservation of momentum:
  \[
  q_l = \frac{-k'k_r}{\nu_l} \left( \frac{\partial p}{\partial z} + \rho_l g \right)
  
  q_v = \frac{-k'k_r}{\nu_v} \left( \frac{\partial p}{\partial z} + \rho_v g \right)
  \]

CONSERVATION WATER MASS and HEAT

\[
q_l = q_{\text{source}} \left( \frac{h_v - h_{\text{source}}}{h_v - h_l} \right)
\]

CONSERVATION of MOMENTUM

Eliminate \( \frac{\partial p}{\partial z} \) terms from momentum equations and determine \( \phi_1 \) which gives \( k_r \), \( k' \) values.
Figure 7. The relative permeabilities to liquid ($k^l$) and gas ($k^g$) vary as a function of liquid saturation. Measured relative permeabilities (top) are well approximated by the simple porosity functions of the lower figure for liquid saturations $\leq 0.2$. Note the permeability to gas is very low until $\phi_g$ exceeds $\sim 10\%$.

Figure 8. Donaldson's results for $T_{source} = 260^\circ$C. Note maximum depth of boiling is $\sim 550$ m. As flow rates ($Q$) increase depth of boiling is pushed toward the surface. Note water fraction jumps from 1.0 to $\sim 0.9$ to allow steam phase to be mobile.
RELATIVE PERMEABILITY CURVES USED IN CALCULATIONS

DONALDSON 1968 RESULTS
FOR T = 260°C
Figure 9. CO₂ affects the enthalpy of steam (and to a lesser extent, water). The mass fraction of CO₂ in the liquid (nₐ) and vapor (nᵥ) are related as shown. Using these thermodynamic relations and assuming qₐ, qᵥ, the mass balance CO₂ relation can be solved for nᵥ. nᵥ and nₐ then update hₐ and hᵥ which in turn give a new qₐ, etc. The cycle is repeated until mutually compatible qₐ, qᵥ, nₐ, nᵥ are determined. We then use the fluid flow relations as before to determine the liquid saturation, φₐ. Notice that if hᵥ is less than hₘₚₐᵣₑ, or hₐ, a physically reasonable equilibrium solution may not exist.

Figure 10. Results similar to Donaldson's are obtained. Note for low flow rates (q < 10) and 250°C the maximum depth of boiling is ~600 m. Note temperature exerts a very strong influence on the depth of boiling. At low flow rates and Tₘₚₐᵣₑ = 350°C, the maximum depth of boiling is 2191 meters.
CONSERVATION WATER MASS and HEAT

NOTE PROBLEMS
IF: $h_v < h_{\text{source}}, h_1$

$$q_1 = q_{\text{source}} \left( \frac{h_v - h_{\text{source}}}{h_v - h_1} \right)$$

if CO$_2$ iterate to get $h_v, h_1$ with CO$_2$ in liquid and vapor in equilibrium:

$$h_1 = n_1 h_{lc} + (1 - n_1) h_f$$

108 \hspace{1cm} 259 \text{ cal/g} \hspace{1cm} 250^\circ\text{C}

$$h_v = n_v h_{vc} + (1 - n_v) h_{vs}$$

54 \hspace{1cm} 670

$$n_1 = \alpha P_c$$

$$n_v = \frac{P_c}{P}$$

$$P_s = (1 - n_v) P$$

$$\frac{\alpha n_v P_s}{(1 - n_v)} q_1 + n_v q_v = q_{\text{source}} n_{\text{source}}$$

EFFECT OF TEMPERATURE

[CO$_2$]$_{\text{source}} = 0$

VARIABLE FLOW RATES

![Diagram showing temperature vs depth with different flow rates indicated by q>100 and q<100.](image-url)
Figure 11. Our approximation to $k_r^y$ gives liquid saturation curves very similar to Donaldson's (see Figure 8).

Figure 12. CO$_2$ also increases the depth of two phase separation. 10 wt% CO$_2$ increases the depth of two phase separation for low flow rate (or very permeable) systems by ~600 m from ~1200 to ~1800 m. Two phase separation does not necessarily begin at very shallow depths.
FRACTION PORE SPACE FILLED WITH LIQUID
\[ T_{\text{source}} = 300^\circ \text{C} \quad [\text{CO}_2]_{\text{source}} = 0 \quad \text{VARIABLE } q_{\text{base}} \]

- Liquid Saturation vs. Depth (m)

EFFECT OF CO₂
\[ T_{\text{source}} = 300^\circ \text{C} \]
VARIABLE FLOW RATES

- Temperature (°C) vs. Depth (m) with different CO₂ concentrations and flow rates.
Figure 13. Liquid saturation decreases strongly at shallow depths. This represents a static picture of how much vapor and how much liquid occupy the pores of the rock formation at various depths.

Figure 14. Vapor travels much faster than liquid. This gas slippage means the chemistry of deep solutions can, through the rapidly moving gas phase, affect the chemistry of higher solutions. At $q_g = 10$ g/cm$^2$-yr and a formation porosity of 0.1%, $v_g = 100$ m/yr and $v_g$ can be 1 to 100 km/yr in the upper parts of the system.
LIQUID SATURATION vs DEPTH

$T_{source} = 300^\circ C$  
$q_{source} = 10, 100, 1000 \text{ g/cm}^2 \cdot \text{yr}$  
$[\text{CO}_2]_{source} = 0, 0.05, 0.10 \text{ wt \%}$

VAPOR VELOCITY  
LIQUID VELOCITY vs DEPTH

$[\text{CO}_2]_{source} = 5 \text{ wt\%}$  
$q_{source} = 10 \text{ g/cm}^2 \cdot \text{yr}$

$T_s = 350^\circ C$  
$T_s = 250^\circ C$  
$T_s = 300^\circ C$
Figure 15. If we look at the mass fluxes of liquid and vapor, we can easily calculate the fraction liquid converted to vapor. Enough liquid is boiled off to potentially cause precipitation of minerals.

Figure 16. Other parameters of interest. The mass (as opposed to volume) fraction of vapor in the liquid filled pores of the rock is never high (less than 2%). The CO₂ content of liquid and vapor varies in a reasonable fashion. Loss of CO₂ from the liquid can lower liquid pH and thereby cause mineral precipitation.
FRACTION LIQUID CONVERTED TO VAPOR AS FUNCTION OF DEPTH

\[ [\text{CO}_2]_{\text{source}} = 5 \text{ wt\%} \]
\[ q_{\text{source}} = 10 \text{ g/cm}^2 \cdot \text{yr} \]

![Graph showing fraction liquid converted to vapor as function of depth at different temperatures (350°, 300°, 250°).]

CHARACTERISTICS OF LIQUID AND VAPOR PHASES

\[ [\text{CO}_2]_{\text{source}} = 5 \text{ wt\%} \]
\[ q_{\text{source}} = 10 \text{ g/cm}^2 \cdot \text{yr} \]

![Three graphs showing mass fraction of \text{CO}_2 in vapor and liquid phases at different temperatures (250°, 300°, 350°).]
Figure 17. Silica solubility is controlled by temperature (numbers along curve beginning at origin) and by the fraction of liquid boiled off (numbers along other curve). From these numbers we can calculate the amount of silica deposited by temperature decrease and boiling in any depth interval and determine that silica will be deposited most strongly near the surface (Table).
PHYSICAL PARAMETERS MOST DIRECTLY AFFECTING CHEMISTRY

\[ T_{source} = 300^\circ C \]
\[ [CO_2]_{source} = 5 \text{ wt \%} \]

<table>
<thead>
<tr>
<th>TEMPERATURE RANGE (°C)</th>
<th>ΔSiO₂ SOLUBILITY (ppm)</th>
<th>SiO₂ PRECIP. BY BOILING (ppm)</th>
<th>TOTAL SiO₂ PRECIPITATION (ppm)</th>
<th>DEPTH INTERVAL (m)</th>
<th>SiO₂ PER METER (ppm/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300-250</td>
<td>183</td>
<td>70</td>
<td>253</td>
<td>1525-630</td>
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<tr>
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<td>185</td>
<td>630-230</td>
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<td>10</td>
<td>133</td>
<td>230-58</td>
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<td>150-100</td>
<td>77</td>
<td>3</td>
<td>80</td>
<td>58-0</td>
<td>1.38</td>
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</tbody>
</table>
Figure 18. Summary diagram relating physical aspects of fluid flow to sulfide complex chemistry. Sulfides deposit in the deep part of the system as temperature drops from 300°C+ to <250°C. Silica precipitates increasingly strongly near the surface as a result of temperature drop and boiling. Advanced argillic alteration is produced near the surface by the combined processes of oxidation and vapor condensation—both caused by near surface mixing with ground water. Gold precipitation beneath (and in?) the advanced argillic alteration is the result of oxidation of the reduced solution.

Figure 19. Summary of principal conclusions.
CONCLUSIONS

- small intrusive heat source adequate for even large Au deposits

- vapor separation can occur at $1 \frac{1}{2}$ to 2 km depths for 300–350°C systems

- vapor separation will lead to zoned mineral precipitation similar to that observed:
  ALUNITE (adv. Argillic)...vapor condensation and oxidation
  GOLD .......................... oxidation
  SILICA.......................... $\uparrow$ T (upper levels)
  SULFIDES....................... $\downarrow$ T (lower levels)