

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 H_2O-CO_2 system are then considered.

Bibliography

1. Cathles, L. M., 1981: Fluid flow and the genesis of hydrothermal ore deposits. Econ. Geol., 75th Anniv. Volume, pp. 424-457.
2. Donaldson, I. G., 1968: The flow of steam-water mixtures through permeable beds: A simple simulation of a natural undisturbed hydrothermal region. New Zealand Jour. Sci., 11: 3-23.
3. Elder, J., 1981: Geothermal Systems. Academic Press, New York, 508 pp.

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

$$\therefore \text{TONNES HYDROTHERMAL SOLUTION REQUIRED} = \frac{120}{20 \times 10^{-9}} = 6 \times 10^9$$

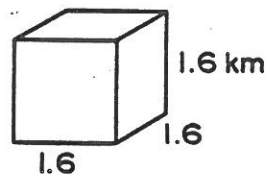
Mass hydrothermal solution $> 200^\circ\text{C}$ $\approx \frac{1}{2}$ mass intrusive

$$\therefore \text{MASS INTRUSIVE} \approx 12 \times 10^9$$

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

$$\therefore \text{VOLUME of INTRUSIVE} \sim 4 \times 10^9 \text{ m}^3$$

HEAT SOURCE REQUIRED



FRACTURE FOCUSED DISCHARGE MODEL

surface leakage
 focused or diffuse

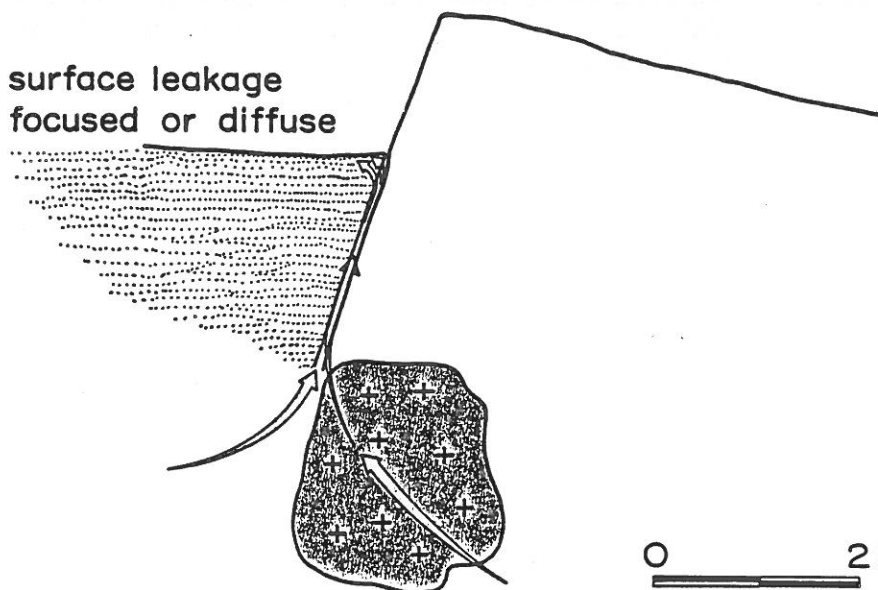
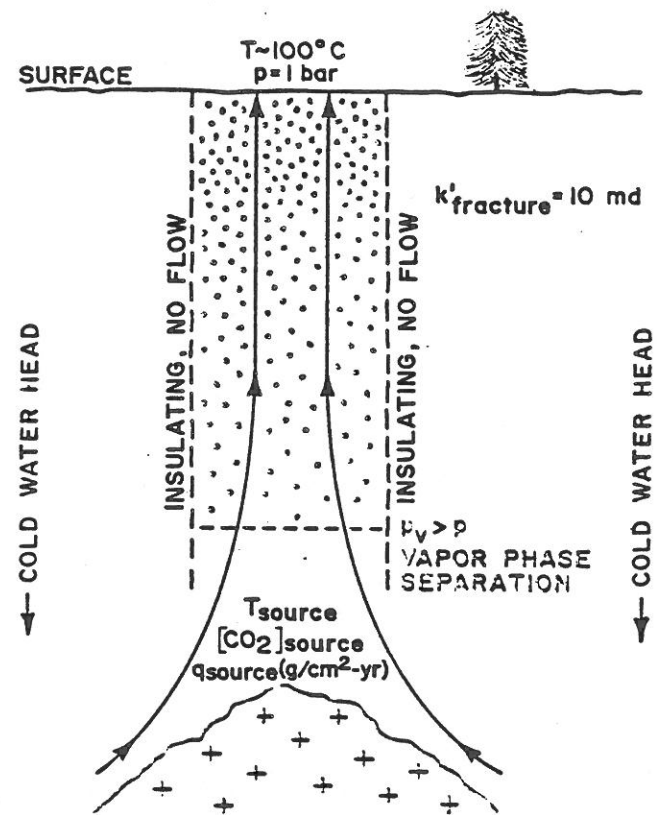


Figure 3. The model we consider can treat either flow in a fracture or diffuse porous media flow. The maximum rate of vertical upflow is limited by the magnitude of the cold water head to $q/k' < 3 \times 10^5$, where q = mass flow rate in grams fluid/cm²/sec, and k' is the permeability in cm² (10^{-11} cm² = 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/cm²/yr. The methods of calculation are discussed by Donaldson (1968). We extend the calculation to higher temperatures, and include the effects of CO₂ in the fluid.

Figure 4. The cold water head limits the rate of upflow such that $q/k' < 3 \times 10^5$. For $k' = 10$ md this translates to $q < 1000$ g/cm²/yr.

CROSS SECTION IN FRACTURE PLANE



LIMIT on FLOW RATE: must be driven by cold water head.

$$q = \frac{k'}{v} \nabla \rho' = \frac{k'}{v} g(\rho(T_s) - \rho(T))$$

$$\frac{q}{k'} < \frac{(\rho(T_s) - \rho(T))g}{v} = \frac{(0.2 \text{ g/cc}) 10^3}{.002}$$

$$\frac{q}{k'} \lesssim 10^5$$

Donaldson (1968) calculates 1.5×10^5 for limit at $T \sim 260^\circ\text{C}$. We use 3×10^5 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_l as a function of the enthalpy or heat content of the vapor (h_v), fluid (h_l), 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_l 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_r^l and k_r^v (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:

$$q_l = \frac{-k'_r k_r^l}{\nu_l} \left(\frac{\partial p}{\partial z} + \rho_l g \right)$$

$$q_v = \frac{-k'_r k_r^v}{\nu_v} \left(\frac{\partial p}{\partial z} + \rho_v g \right)$$

CONSERVATION WATER MASS and HEAT

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

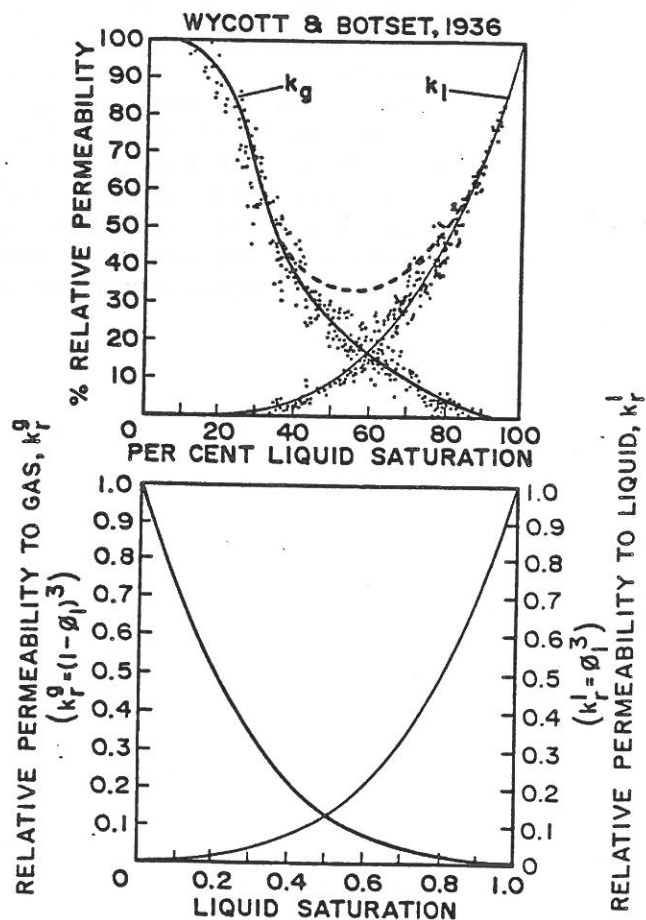
CONSERVATION of MOMENTUM

Eliminate $\frac{\partial p}{\partial z}$ terms from momentum equations and determine ϕ_l which gives k_r^l , k_r^v values.

Figure 7. The relative permeabilities to liquid (k_r^l) and gas (k_r^v) 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 $\gtrsim 0.2$. Note the permeability to gas is very low until ϕ_l exceeds $\sim 10\%$.

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

RELATIVE PERMEABILITY CURVES USED IN CALCULATIONS



DONALDSON 1968 RESULTS FOR $T = 260^\circ\text{C}$

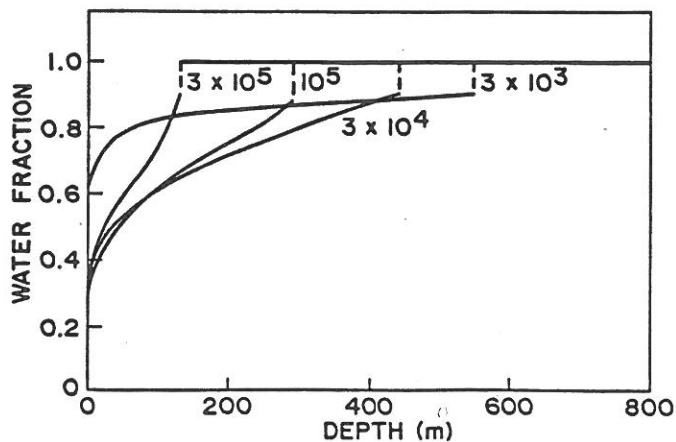
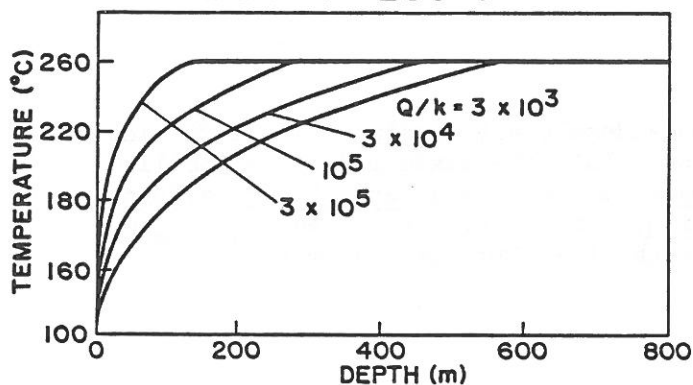


Figure 9. CO_2 affects the enthalpy of steam (and to a lesser extent, water). The mass fraction of CO_2 in the liquid (n_ℓ) and vapor (n_v) are related as shown. Using these thermodynamic relations and assuming q_ℓ , q_v , the mass balance CO_2 relation can be solved for n_v . n_v and n_ℓ then update h_ℓ and h_v which in turn give a new q_ℓ , etc. The cycle is repeated until mutually compatible q_ℓ , q_v , n_ℓ , n_v are determined. We then use the fluid flow relations as before to determine the liquid saturation, ϕ_ℓ . Notice that if h_v is less than h_{source} or h_ℓ , 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 $T_{\text{source}} = 350^\circ\text{C}$, the maximum depth of boiling is 2191 meters.

CONSERVATION WATER MASS and HEAT

NOTE PROBLEMS

IF: $h_v < h_{source}, h_l$

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

if CO_2 iterate to get h_v, h_l with CO_2 in liquid and vapor in equilibrium:

$$h_l = n_l h_{lc} + (1 - n_l) h_f$$

108
259 cal/g
250°C

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

54
670

$$n_l = \alpha P_c$$

$$n_v = P_c / P$$

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

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

$$n_l = \frac{\alpha n_v P_s}{(1 - n_v)}$$

EFFECT OF TEMPERATURE

$[CO_2]_{source} = 0$
VARIABLE FLOW RATES

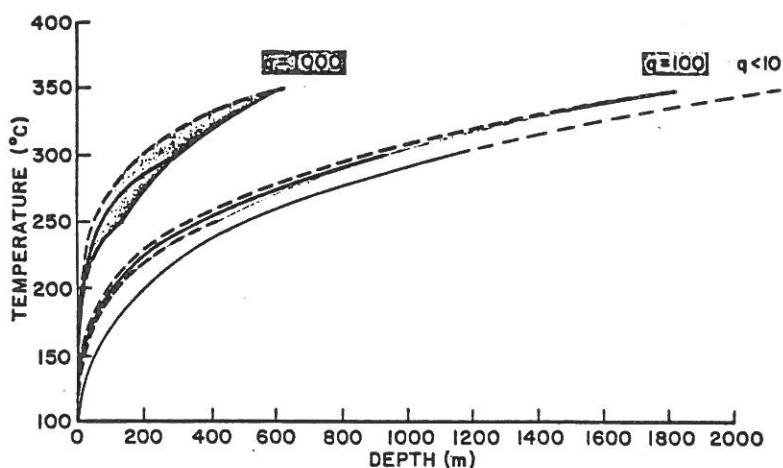
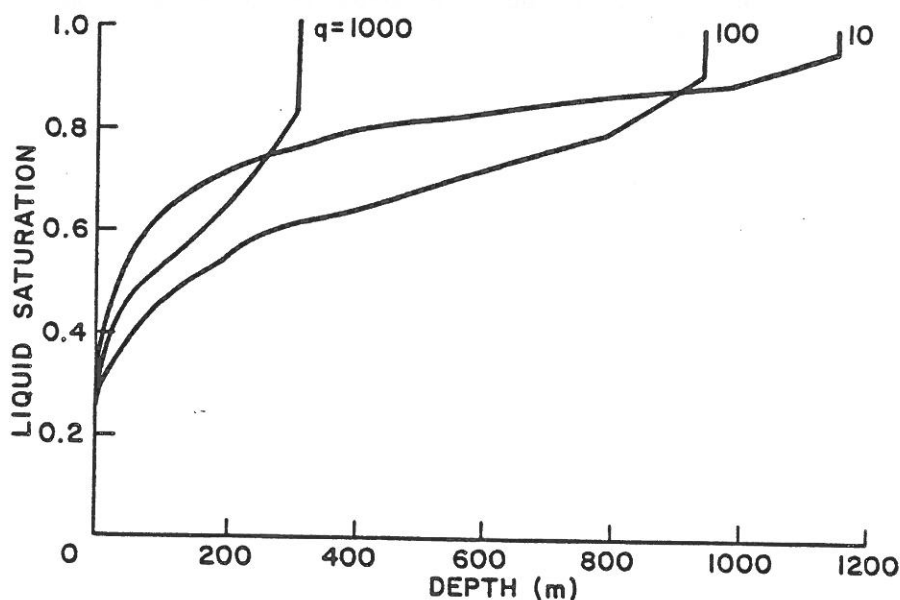


Figure 11. Our approximation to k_r^v gives liquid saturation curves very similar to Donaldson's (see Figure 8).

Figure 12. CO₂ also increases the depth of two phase separation. 10 wt% CO₂ 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

$T_{\text{source}} = 300^{\circ}\text{C}$ $[\text{CO}_2]_{\text{source}} = 0$ VARIABLE q_{base}



EFFECT OF CO_2

$T_{\text{source}} = 300^{\circ}\text{C}$
VARIABLE FLOW RATES

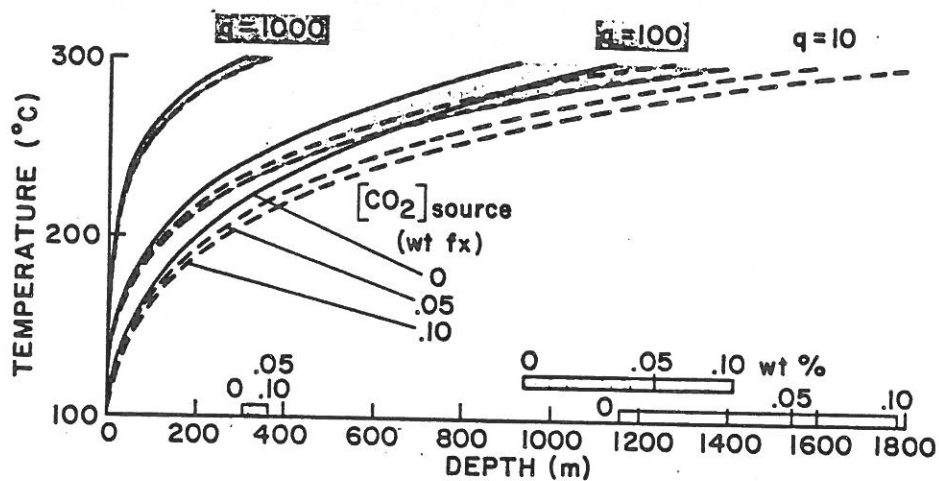


Figure 13. Liquid saturation decreases strongly at shallow depths. This represents a static picture of how much vapor and how much liquid occupy the pores of the rock formation at various depths.

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 $q_l = 10 \text{ g/cm}^2\text{-yr}$ and a formation porosity of 0.1%, $v_l = 100 \text{ m/yr}$ and v_g can be 1 to 100 km/yr in the upper parts of the system.

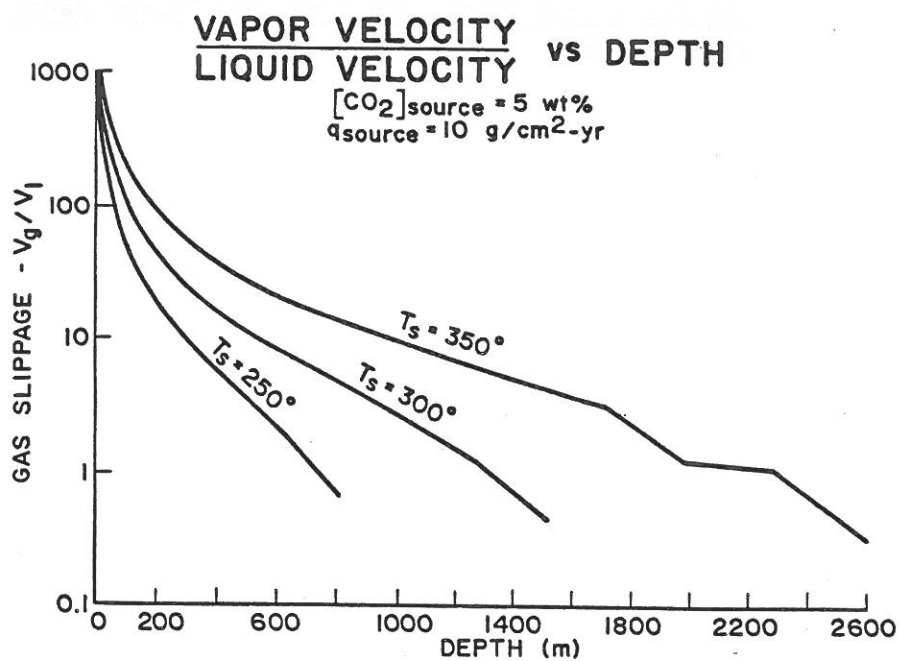
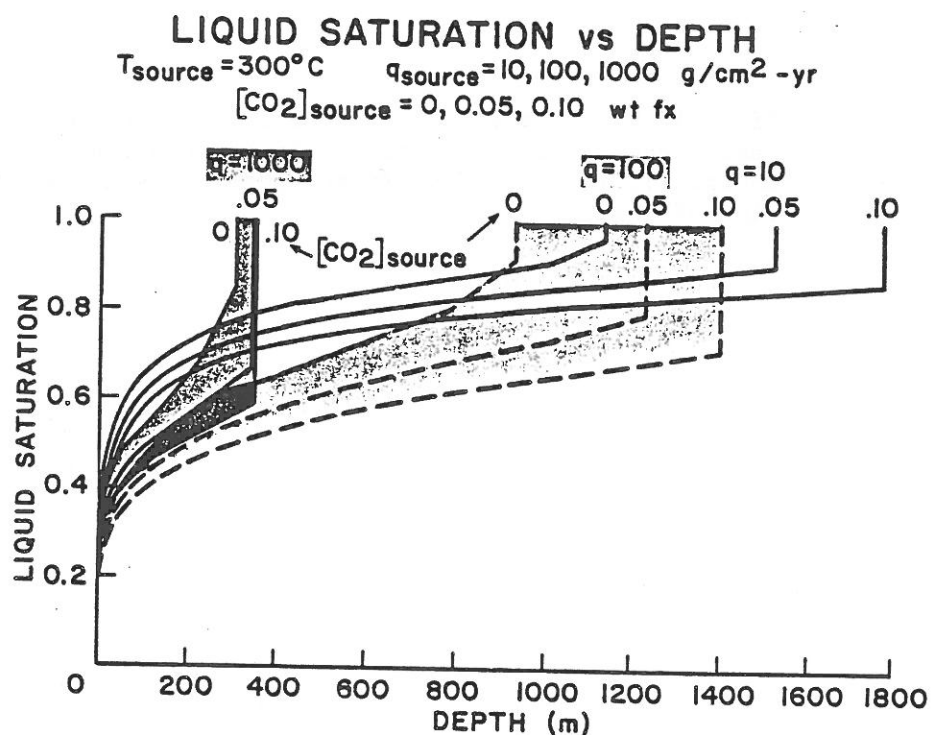


Figure 15. If we look at the mass fluxes of liquid and vapor, we can easily calculate the fraction liquid converted to vapor. Enough liquid is boiled off to potentially cause precipitation of minerals.

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 CO_2 content of liquid and vapor varies in a reasonable fashion. Loss of CO_2 from the liquid can lower liquid pH and thereby cause mineral precipitation.

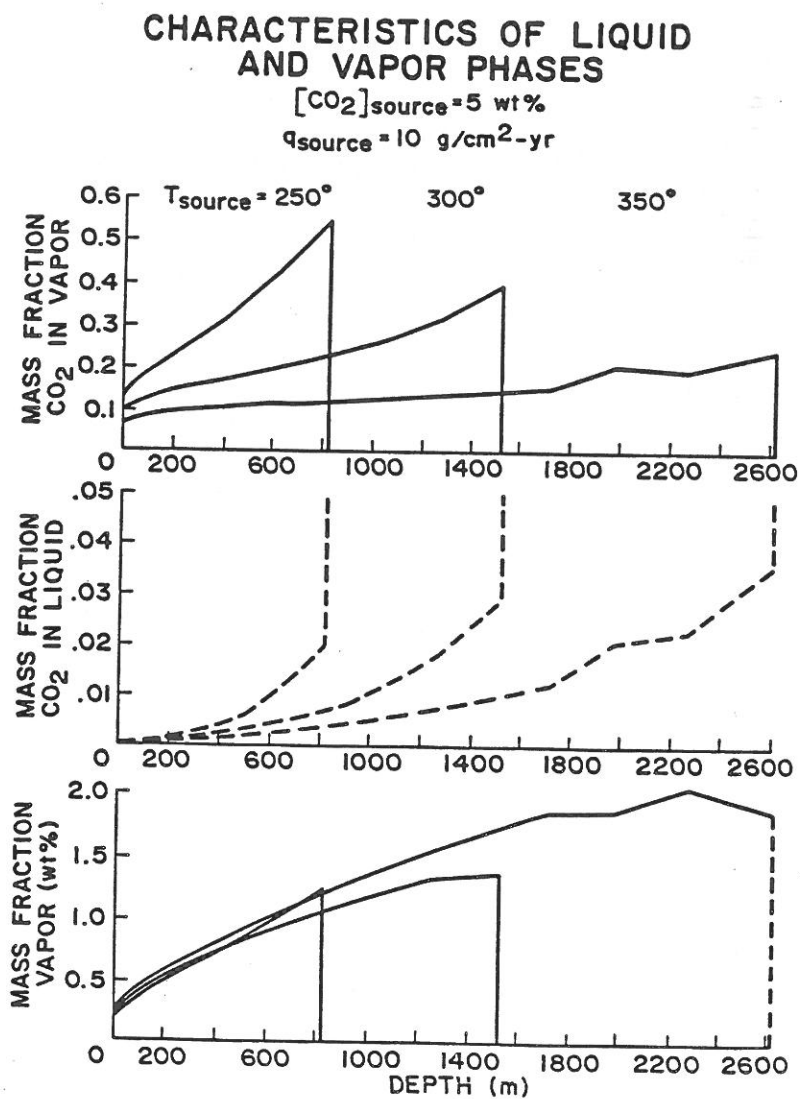
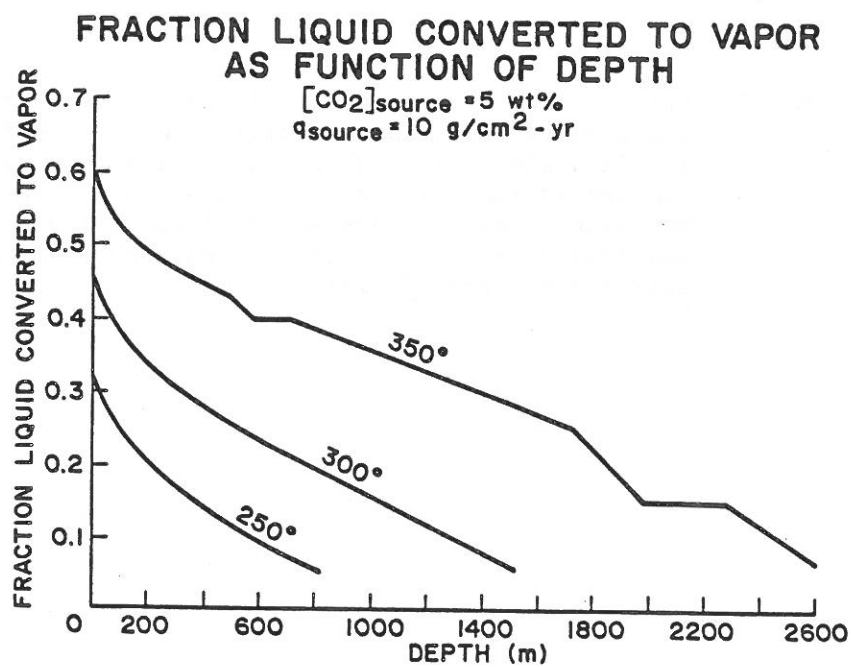
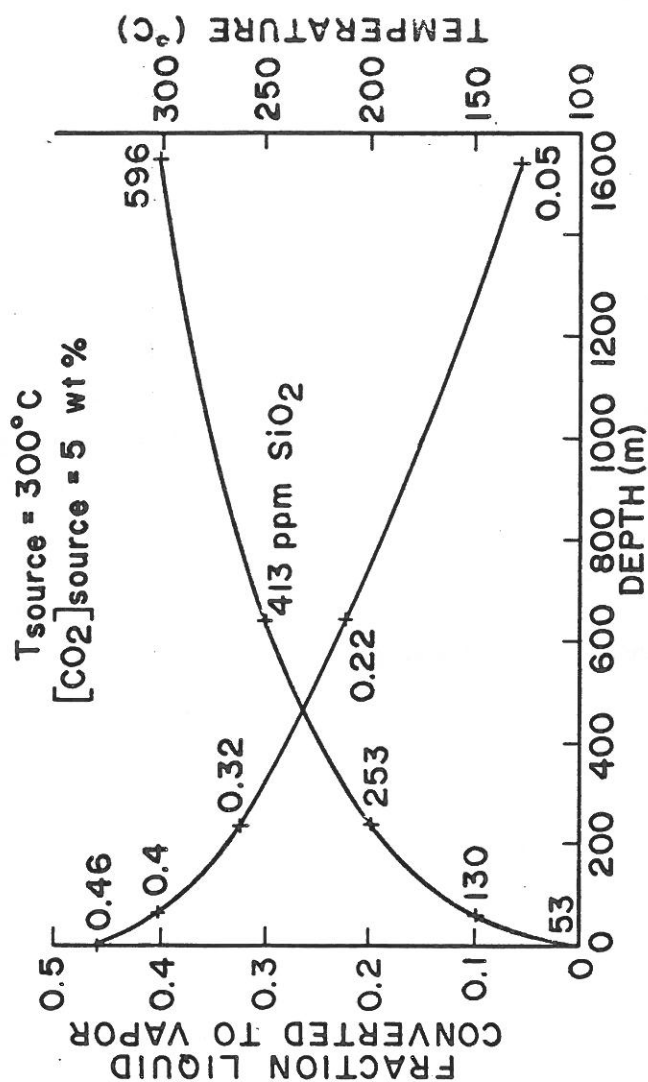


Figure 17. Silica solubility is controlled by temperature (numbers along curve beginning at origin) and by the fraction of liquid boiled off (numbers along other curve). From these numbers we can calculate the amount of silica deposited by temperature decrease and boiling in any depth interval and determine that silica will be deposited most strongly near the surface (Table).

PHYSICAL PARAMETERS MOST DIRECTLY AFFECTING CHEMISTRY

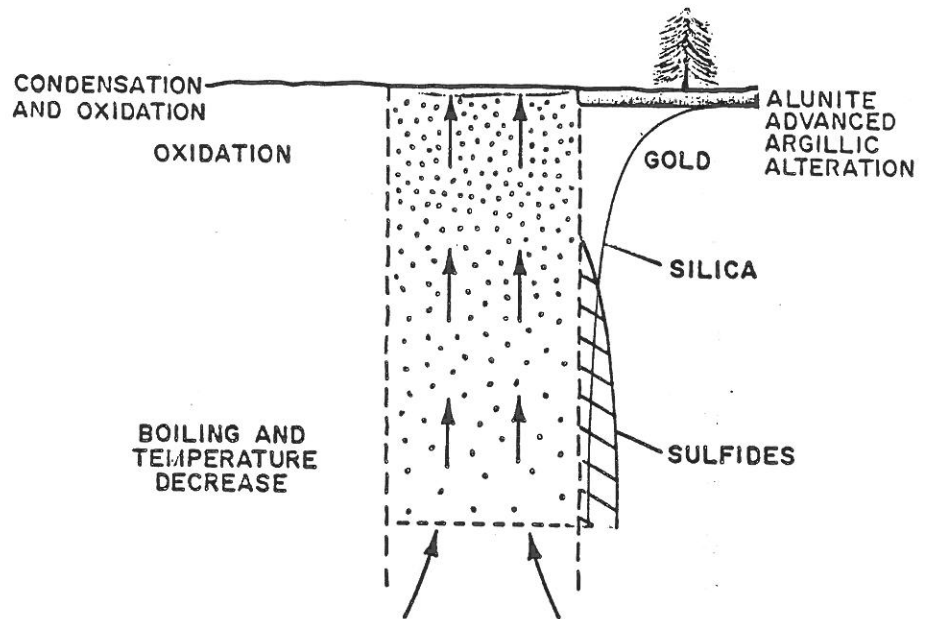


TEMPERATURE RANGE (°C)	ΔSiO_2 SOLUBILITY (ppm)	SiO_2 PRECIP. BY BOILING (ppm)	TOTAL SiO_2 PRECIPITATION (ppm)	DEPTH INTERVAL (m)	SiO_2 PER METER (ppm/m)
300 - 250	183	70	253	1525 - 630	0.28
250 - 200	160	25	185	630 - 230	0.46
200 - 150	123	10	133	230 - 58	0.78
150 - 100	77	3	80	58 - 0	1.38

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.

EXPECTED MINERAL ZONING



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
 GOLDoxidation
 SILICA.....↓ T (upper levels)
 SULFIDES.....↓ T (lower levels)

