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Hydrodynamic Constraints on the Formation of Kuroko Deposits*

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Abstract: Simple calculations are presented to illustrate the kinds of constraints hydrodynamic considerations can place on genetic hypotheses. It is tentatively shown that the rhyolite plugs commonly associated with Kuroko deposits are too small to be the cause of Kuroko mineralization. A larger intrusive heat (or magmatic fluid) source at depth is needed. Convective velocities in rocks of reasonable permeability are so much smaller than minimum ocean bottom current velocities that it is very unlikely Kuroko mineralization could have been precipitated from solutions above the sea-sediment (or rock) interface. Hydrothermal solutions would be swept away as soon as they left the protective sediment or rock cover. Finally hydrothermal convection may be expected to promote ore slumping if the permeability of the precipitated ore is low. The "slumped" nature of some Kuroko ores may thus find a natural genetic explanation.

Some of the significant geological and geochemical aspects of Kuroko deposits have been described in the articles accompanying this one. From these descriptions and others it is clear mineralization was deposited from upward convecting hydrothermal solutions. The origin of the solutions and the manner of mineral precipitation is not so clear, however, although isotopes and deposit studies can potentially impose some useful constraints. The purpose of this article is to illustrate the kinds of constraints hydrodynamics can impose on the genesis of Kuroko deposits. I would like to emphasize that it is the intention of this paper to simply *illustrate* and explore the kinds of calculations and considerations that may prove useful. Suggestions made should be regarded as working hypotheses, unproven, at this stage by rigorous comparison with available geochemical and geological data.

One of the most useful kinds of computation that can be made asks the question: given an intrusive of a certain size and initial temperature in host rock of some permeability, how fast will the intrusive cool, and how much water will circulate through the intrusive in the course of cooling? The methods of making this kind of computation in a way which includes the true properties of water (including the effects of boiling and condensation) are described in CATHLES (1977).

Figure 1 shows the cooling and convection history of a Kuroko deposit assuming the heat which drives the convection is supplied only by the small rhyolite plug often (but not always) found associated with Kuroko deposits. The initial temperature of the rhyolite plug is 700°C as shown in Figure 1a, and the permeability of the plug and rock intruded is assumed to be a uniform 0.25 millidarcies. This value of permeability is a little less than the 0.45 millidarcies estimated for oceanic crust by RIBANDO et al. (1976) or the value of 0.62 millidarcies found for the average permeability of the oceanic plate by FEHN and CATHLES (1978) in their preferred model. The sea depth is assumed in the model of Figure 1 to be only 100 m, so the pressure at the sea sediment interface is only 10 bars. The rhyolite plug is small (200 m thick and 300 m wide) and is intruded so its top surface is 200 m below the sea-sediment interface.

Figure 1 shows the cooling of the rhyolite plug is very rapid. The circulating fluids boil as they enter the base of the heat anomaly of the plug (e.g., Figs. 1b and c) and condense as they enter cooler rock overlying the plug. The heat anomaly of the plug migrates upward

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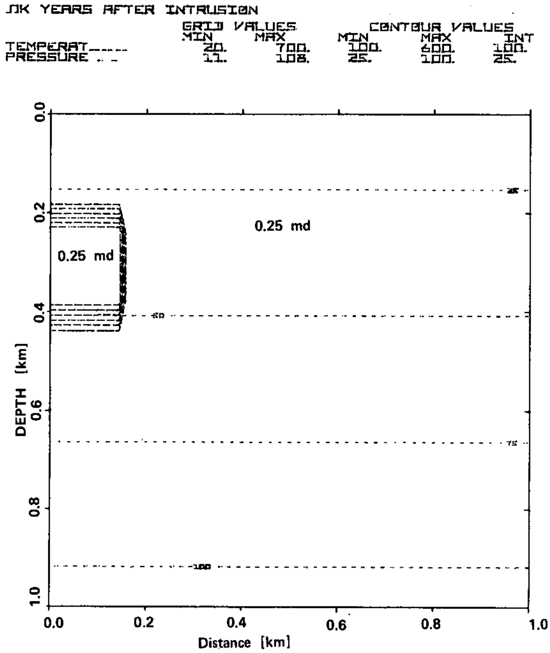
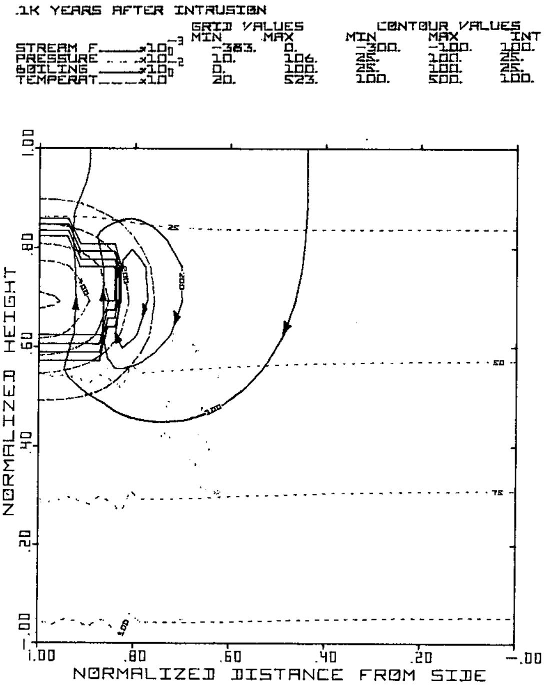
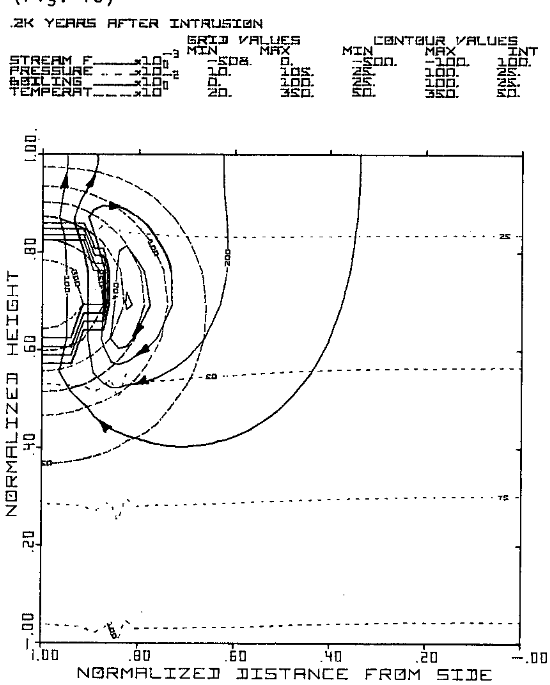
(Fig. 1a)



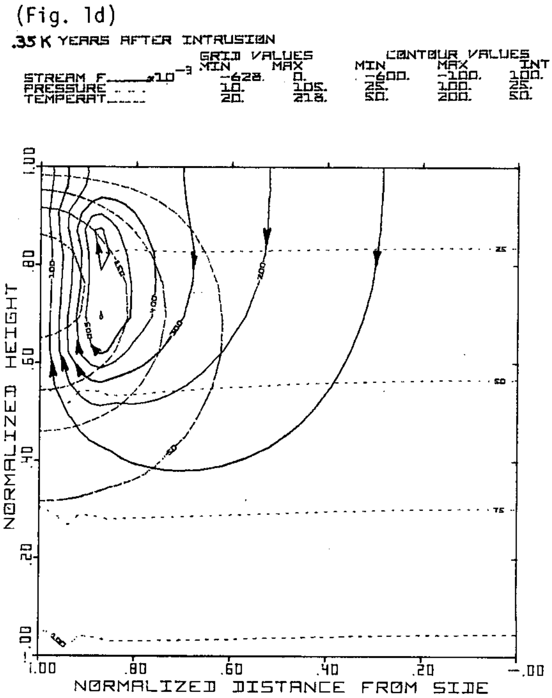
(Fig. 1b)



(Fig. 1c)



(Fig. 1d)



(Fig. 1e)

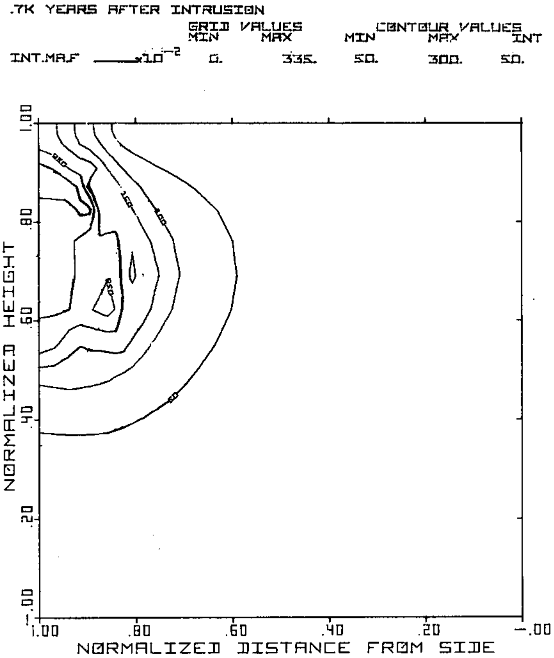


Fig. 1a~e Cooling history of intrusive the size of rhyolite plug often found associated with Kuroko deposits. At most only 3.35 kg hydrothermal solution circulate through 1 cm² of surface area near the intrusive. In this and the following figures, pressure (in bars) is shown by short dashed lines, temperature (in °C) is shown by longer dashed lines, and solid lines with arrows contour the dimensionless stream function and show the direction of fluid convection. Rock and fluid parameters, when not otherwise specified, are as in CATHLES (1977). When fluids are produced (by boiling in this case) which lie on the high temperature side of the two phase curve of water, such 'vapor' zones are assigned a value of 1.0 at each grid point and the boundary of the vapor zones and condensed fluid zones (whose grid values are 0.0) contoured (see Figs. 2b, c). This indicates the location of the vapor zones as well as where boiling and condensation occurs.

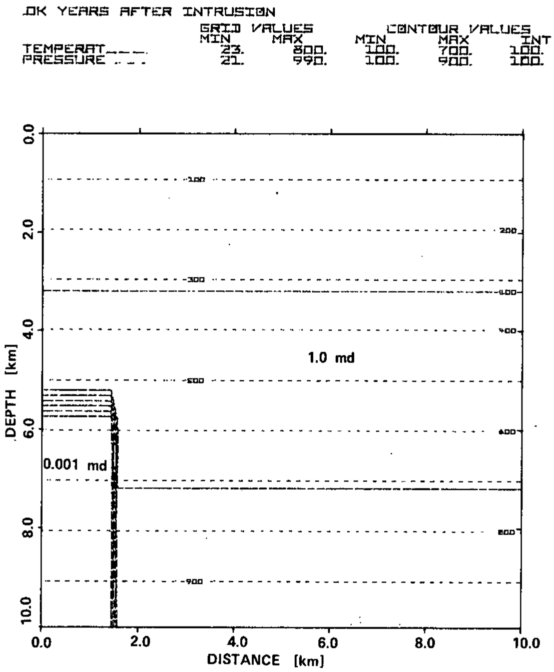
due to the convection. Boiling and condensation occur from the time of intrusion till 300 years after intrusion. Thereafter temperatures are too low and the fluid remains liquid everywhere. After 100 years the intrusive is cooler than 523 °C everywhere. After 200 years cooler than 350 °C, after 350 years cooler than 218 °C, and after 700 years cooler than 138 °C everywhere. After 700 years at most 3.35 kg of water have convected past any one cm² of surface area near the plug. At the sea-sediment interface mass flux values are ~1.5 kg/cm² (Fig. 1c).

Typical Kuroko deposits have ore grades ~1–3% copper, 1–4% Pb, 1–14% Zn, and 10–40% sulfur. Ore bodies have typical horizontal dimensions of 200 × 400 m and ore thicknesses of 6–40 m (ISHIHARA et al., 1974, p. 132). Focusing just on copper, it is easy to see the amount of convection generated in Figure 1d is probably not sufficient to account for the mineral deposition. Copper loadings of 1 gram copper per 1,000 grams hydrothermal fluid and perhaps slightly higher could be entertained as possible in the convecting solutions. Thus one gram of copper per 1,000 grams of water could be precipitated at or near the sea-sediment interface where the fluids cool dramatically or, since ~1.5 kg of water have circulated through each cm² of surface, about 1.5 g of Cu per cm² of sea-sediment surface could have been precipitated. This is sufficient to give a 0.5 m thickness of 3 wt.% ore which is much much less than the 6–40 m of ore thickness typical of Kuroko deposits.

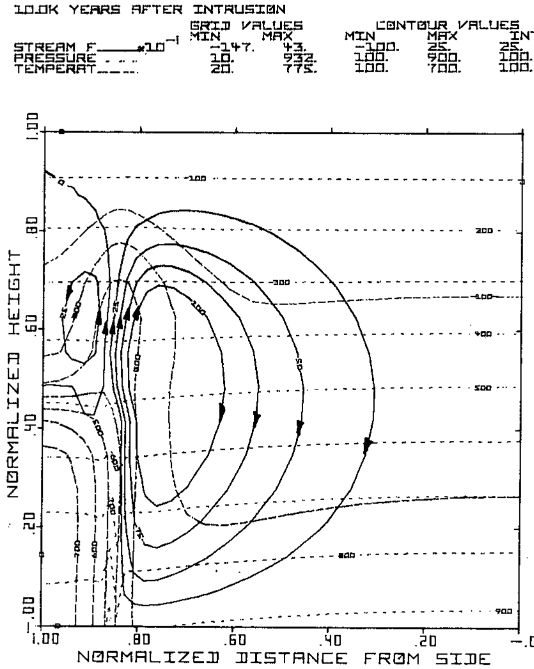
The amount of fluid circulation is not very sensitive to permeability. The amount of fluid circulation for permeabilities 0.25 millidarcies is controlled by the amount of heat in the intrusive available to drive the convection. Increasing the permeability will almost certainly not increase the total (integrated over time) mass flux by more than a factor of two and probably not increase it more than 50% (e.g. see CATHLES, 1977, Fig. 8b, p. 817). These statements need to be verified, but it seems quite unlikely the rhyolite plug itself is a big enough heat source to drive fluid convection sufficient to deposit the volume of mineralization found in Kuroko deposits.

Figure 2 shows, however, that sufficient fluid convection can easily be produced by a larger intrusive at depth. This particular intrusive is three killometers wide and 4.5 km high buried 5.5 km beneath the rock-water interface. The water depth is shallow (~100 m), so the pressure at the rock water interface is

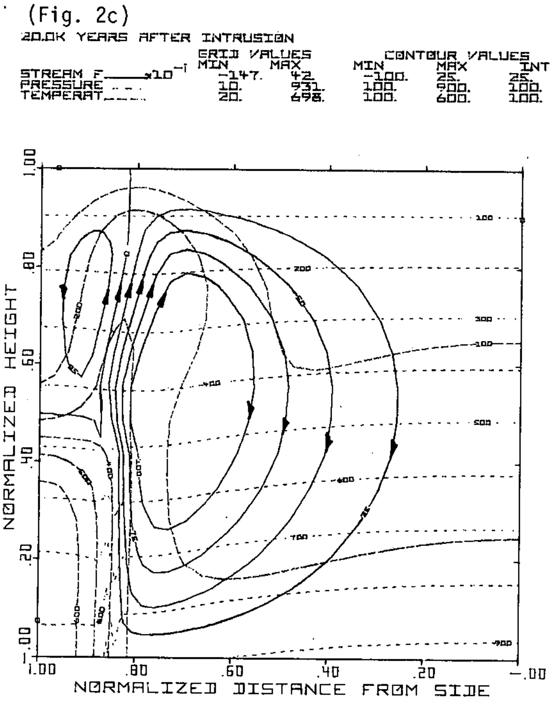
(Fig. 2a)



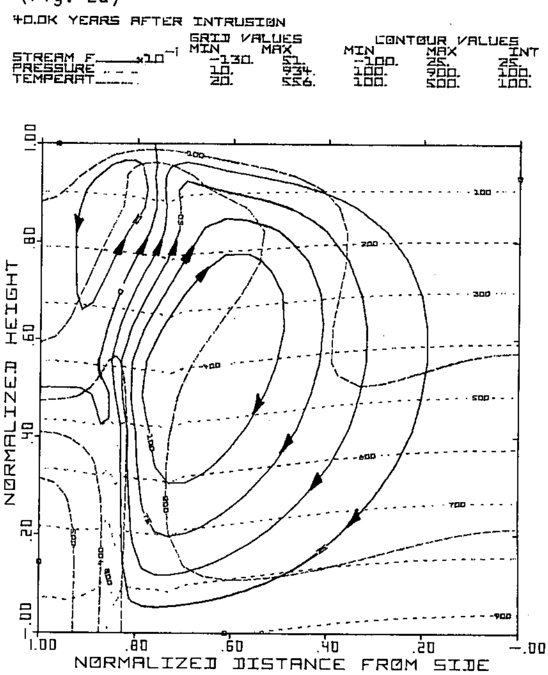
(Fig. 2b)



(Fig. 2c)



(Fig. 2d)



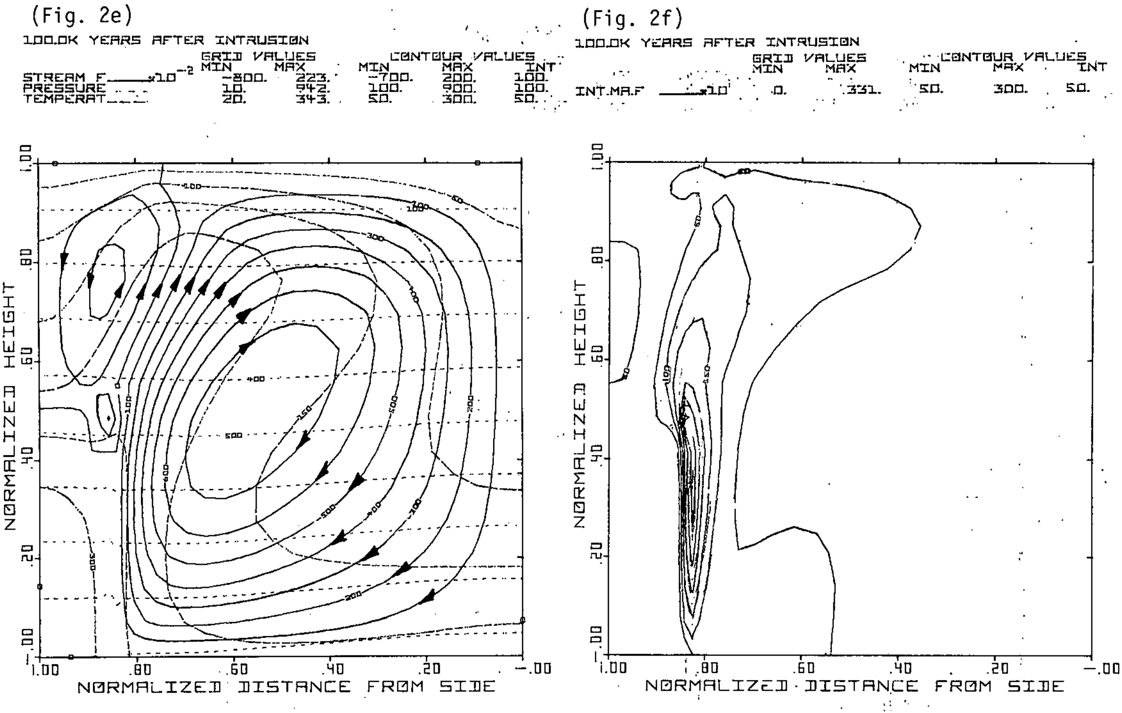


Fig. 2 Cooling history of large intrusive. In 100,000 years 3,310 kg of hydrothermal solution have circulated past the edge of this impermeable (0.001 md) intrusive. Note counter circulation cell over top of intrusive.

10 bars. The intrusive is initially 800°C (Fig. 2a). The permeability of intrusive is 10^{-3} millidarcy; the permeability of intruded formation is 1.0 millidarcies.

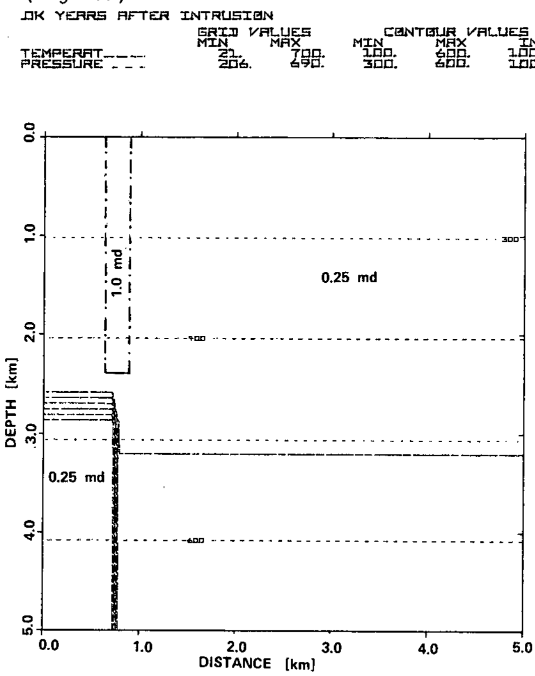
Figure 2f shows that after 100,000 years about 500 kg of water have circulated through the sediment-water interface into the ocean above. If one gram of copper is precipitated from each killogram of such solution, 500 g copper could be precipitated per cm^2, or enough for a 3 wt.% ore lens ~61 m thick. This thickness is compatible with the 6–40 m ore thicknesses observed in Kuroko deposits (loc cit). Of course greater mass fluxes could be achieved in particular zones near the surface where fracturing is more intense or faults occur and the permeability is therefore greater. In such cases less than 1 gram of copper could be dropped per 1,000 grams of convected solution and still produce a Kuroko sized deposit.

Another feature of interest is shown in Figure 2. For the case of fairly large (3 km wide) low permeability pluton in a high permeability domain, clockwise convection in the intruded domain causes a hot plume to rise from the intrusive edge. This hot plume drives counter-clockwise convection above the intrusive. The counter-clockwise cell persists over the entire cooling history of the intrusive, and in fact grows in near surface areal extent as time goes on. If one thinks of the rock immediately above the intrusive as a caldera*, this kind of convection geometry tends to isolate fluids that see only rock within the caldera (counter-clockwise cell) from fluids that circulate well outside the caldera system (clockwise cell). Such fluid isolation might reflect itself in differences in the type of mineralization found in the central regions and more peripheral areas of the "caldera."

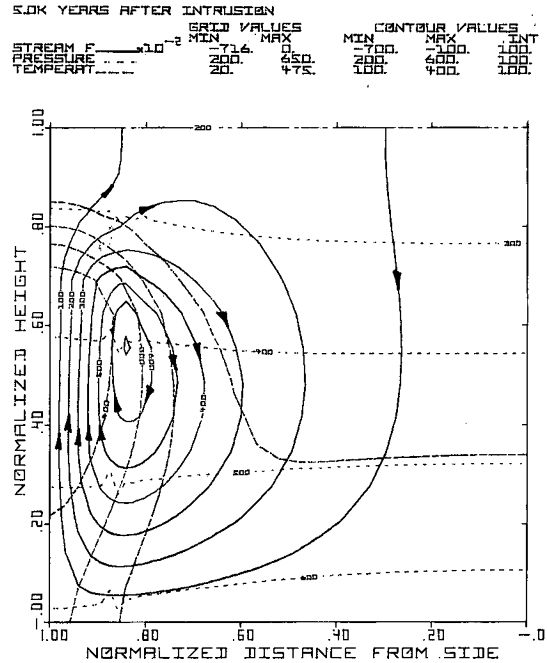
Figure 3 makes the same point as Figure 2 while illustrating that surface pressure can be taken at any value and that strong, fracture-like permeability contrasts can be accounted for in the modeling (a feature also shown in

* OHMOTO (1977) has suggested Kuroko deposits formed in a submarine caldera setting.

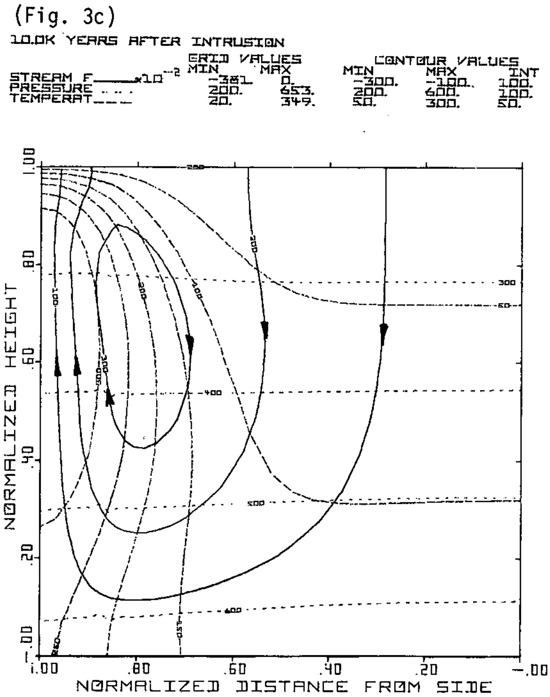
(Fig. 3a)



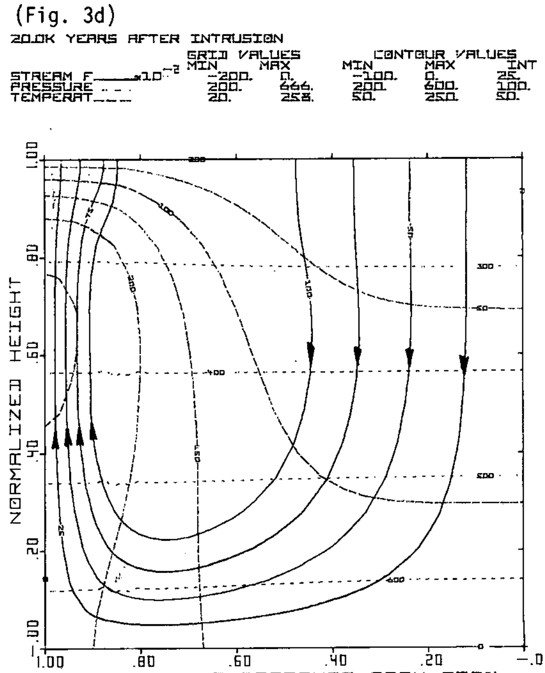
(Fig. 3b)



(Fig. 3c)



(Fig. 3d)



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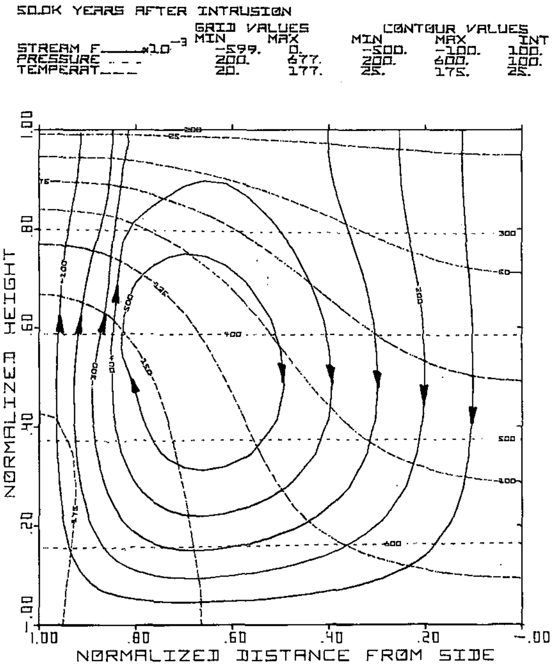

(Fig. 3f)

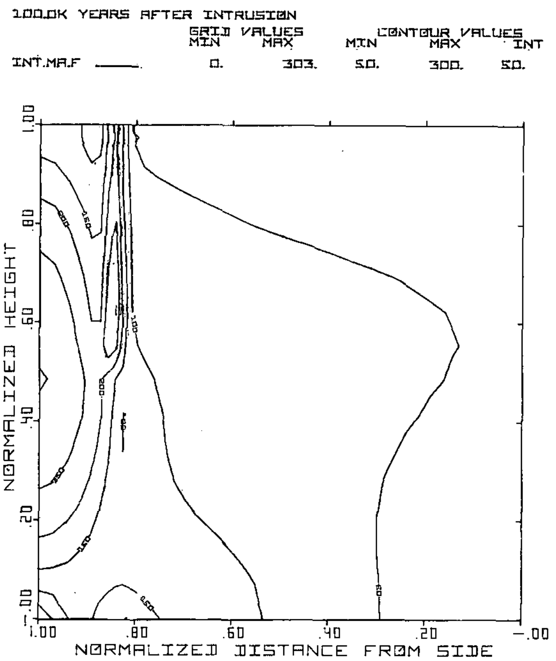

Fig. 3 Cooling history of an intrusive with a higher permeability fracture zone at its edge. Mass flux through the fracture amounts to 200–300 kg/cm² in 100,000 years.

FEHN and CATHLES, 1978). The surface pressure in the case in Figure 3 is 200 bars, corresponding to 2,000 m water depth. The intrusive is half the size (1.5 km wide) of that in Figure 2 and is as permeable as the intruded formation (0.25 millidarcies). There is a 250 m wide, 1.0 md permeability fracture extending upward from the side of the intrusive. The integrated mass flux (Fig. 3f) clearly reflects the presence of the fracture even though its permeability is not large enough to dominate the convective pattern in Figures 3b–e. Within the 250 m wide fracture, ~200 kg of hydrothermal solution have passed each cm² of surface area—enough (at 1 g Cu per 1,000 g solution) to produce a 3 wt.% copper ore shell ~25 m thick.

In summary Figures 1–3 show a Kuroko deposit or groups of Kuroko deposits can be easily formed by hydrothermal convection caused by a reasonable sized intrusive. The small rhyolite plugs found associated with the deposits are too small to produce sufficient convection.

Other points can be made. In the cases shown in Figures 1–3, the rate of fluid circulation is greatest in Figure 2 and even there is always <57 g/cm²–yr. This maximum mass flux is immediately adjacent to the intrusive at ~7 km depth. Near the top surface (sediment-water interface) the mass flux is ~5–10 g/cm²–yr.

A mass flux rate of 10 g/cm²–yr is equivalent to an ocean current of $\sim 3\times10^{-7}$ cm/sec. Unless the ocean bottom is truly stagnant, buoyant hydrothermal solutions could not rise above the sediment-water interface without being swept away. Since the oceans overturn in ~1,000 years with water traveling ~15,000 km from the Antartic to the Arctic, the average bottom velocity is ~0.05 cm/sec. This value is much much greater than the convective value of $\sim 3\times10^{-7}$ cm/sec. Thus it is *very* unlikely Kuroko mineralization could be precipitated above the sediment-water interface. The mineralized solutions would be swept away as soon as they left their protective rock or sediment cover.

Another point of possible interest can be made if we focus on sediment permeabilities in connection with near surface hydrothermal fluid velocities of ~ 5 g/cm²–yr.

The hydrothermal fluid velocity will be determined (in the models we have considered so far) by buoyant forces produced by the intrusive at depth and will be very little influenced by the permeability of a thin sediment covering at the ocean-rock interface. If the sediment cover is of low permeability it can be lifted off the rock interface by the hydrothermal convection. If this is done, or if it is even substantially done, the sediments will tend to slump down even a very gradual slope. Kuroko mineralization, which for the purposes of this discussion might be viewed as chemical sedimentation, is sometimes found in a folded, "slumped" condition (KAJIWARA, 1970).

The sediment permeability below which easy slumping should occur can be estimated by setting the pressure gradient produced by a given (assumed) flow velocity and Darcy's law ($q = (k'/\upsilon)\nabla p$) equal to the "lithostatic" pressure gradient in a sedimentary layer (ρg). If

$$k_s' < \frac{\upsilon q}{\rho g}$$

slumping is strongly promoted. Taking υ = kinematic viscosity of the hydrothermal solution $= 10^{-2}$ cm²/sec, g = gravitational acceleration $= 10^3$ cm/sec², ρ = density of the sediments = 2.7 g/cm³, q = darcy mass flux = 5 g/yr,

$$k' < 6 \times 10^{-13} \text{ cm}^2 = .06 \text{ millidarcies.}$$

This value of sediment permeability is within the range suggested by BRYANT et al. (1974) of 0.1–.001 md. The permeability of Kuroko mineralization is unknown to the present author, but could be measured in laboratory or field. We can conclude at this point that folded or slumped Kuroko ore is consistent with and in fact expected from a genetic model which proposes deep hydrothermal convection and precipitation of low permeability ore "sediment" at or just below the ocean bottom.

We have illustrated some of the constraints or insights hydrodynamic considerations can place on speculation concerning the formation of Kuroko deposits. More detailed consideration of the temperature of ore deposition could constrain the permeability structure more than we have done here. High temperatures near the surface may require high permeability fractures and faster convective flow, for example. Also, we have considered only convective overturn of sea water. It is possible magmatic fluids were vented from intrusives at depth. Magmatic venting and the mixing of magmatic and sea waters during and after venting can be accounted for by models similar to those given above.

Our purpose in this paper is not to provide an exhaustive set of models or model constraints, but simply to illustrate the kinds of useful constraints hydrodynamic considerations can impose on the possible origins of Kuroko deposits. Rigorous interactions of these and similar considerations with geological and geochemical data and careful modeling of particular Kuroko deposits or groups of deposits is needed to advance such analyses of Kuroko genesis beyond the speculative stage. It would also be useful to make a few measurements of the in situ permeability in and near the deposits. This could be done by standard transient well testing techniques (see MATTHEWS and RUSSELL, 1967; EARLOUGHER, 1977).

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水力学からみた黒鉱鉱床の形成に対する束縛条件

L. M. キャスレス

要旨：成因論の仮説に束縛条件を与えるために，水力学の見地立った簡単な計算が行なわれた．黒鉱鉱床によくともなわれる流紋岩プラグは黒鉱鉱床の生成にとって小さすぎる．その代りに，より深部のより大きな熱源としての貫入岩体（またはマグマ水）が必要である．適当と思われる透水係数の岩石中を対流する流体の速度は，海底での海流の最小速度よりかなり小さい．このことは，黒鉱鉱化作用が海水と堆積物（または岩石）の境界面より上の溶液から沈殿し生じたことを否定するであろう．熱水溶液は，海水中に出るとすぐに流れ去ってしまうであろう．沈殿した鉱石の透水係数が低いと，熱水溶液の対流は鉱石のスランピングを起こさせるであろう．いくつかの黒鉱鉱石にみられるスランピングは，このようにして説明される．