Some fluid dynamics and ore genesis

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Synopsis
Hydrothermal ore deposits are the fossil remnants of former fluid flow systems in the earth's crust, and their present-day analogues are the geothermal systems which occur in New Zealand, Japan, Mexico, etc. The physical characteristics of such systems are discussed, and it is shown that free convection of fluid is the heat- and mass-transfer process which operates in these areas. The components of geothermal systems are compared with a scheme for hydrothermal ore genesis, and some convective models are discussed which may apply to the range of conditions which have governed the formation of orebodies. An order of magnitude calculation shows that ore genesis at Morro Velho, Brazil, involved very high Rayleigh number convection. Some corollaries of the convective schemes concern the origin of pipe-shaped orebodies and the spatial distribution of lode deposits.

The purpose of this paper is to explore some aspects of fluid dynamics of direct relevance to the understanding of the origin of hydrothermal ore deposits. Such deposits result from deposition from hot aqueous solutions passing through restricted sections of the earth's crust for extended periods of time, probably of the order 10^4–10^6 years. As such, they are the fossil remnants of former geothermal systems, so it is relevant to look to the physical characteristics of present-day systems to learn something of the dynamics of ore emplacement.

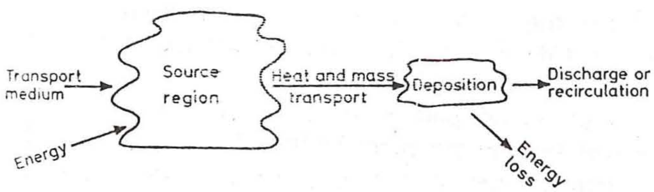

Fig. 1 Flow chart for processes which operate during ore genesis

As a first step it is necessary to review briefly what exactly is meant by the phrase 'genesis of an ore deposit'. A hydrothermal ore deposit, be it at Butte, Morro Velho or in the Mississippi Valley, may be defined, non-economically, as an anomalously high concentration of metals restricted to very small volumes of the earth's crust and derived from the passage of hot aqueous solution. This statement can be illustrated by a flow chart (Fig. 1), which summarizes the combination of physical and chemical processes which constitute 'ore genesis' (and which, incidentally, has a broader application embracing any type of ore deposit—not just hydrothermal deposits). It is of interest to note also the similarity of the scheme to the flow charts of industrial chemical plants and, in summary, that ore genesis is a process of *heat and mass transfer* through the earth's crust.

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Some physical aspects of geothermal systems

Geothermal systems are now well known around the globe, particularly in zones of recent crustal movement and volcanism. The heat and mass flow budget of these systems has been studied exhaustively on account of their potential as sources of power, where it is of prime importance to judge the optimum rate of hot water extraction and, hence, estimate the lifetime of the fields.

Perhaps the most intensively studied system is that at Wairakei in the Taupo Volcanic Zone of New Zealand. This system has some original surface expression in the form of hot springs, etc., and the geology of the area has been fully described by Grindley.[1] Elder's[2]

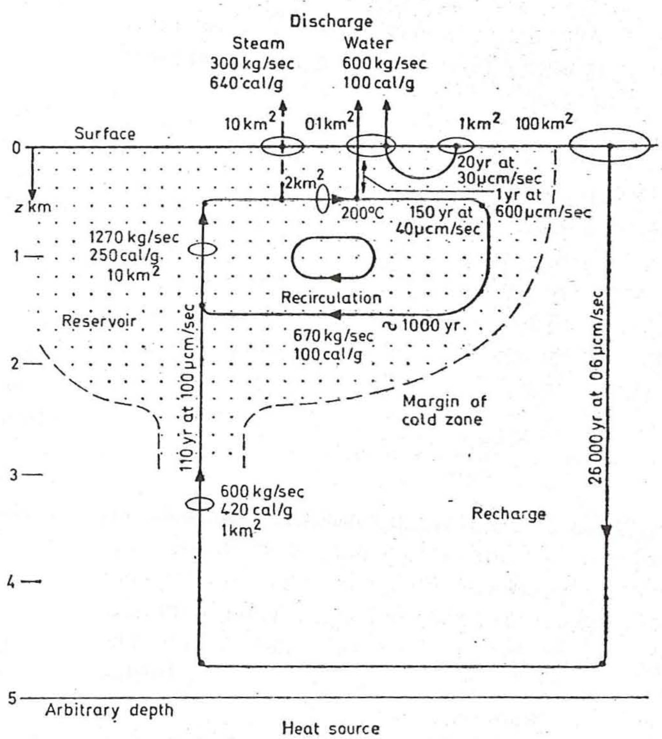

Fig. 2 Schema of pipe model for Wairakei system illustrating orders of magnitude of fluid flux, energy, etc., involved in hydrothermal ore formation: flow in kg/sec, enthalpy in cal/g, cross-sectional area in km², velocities in micro cm/sec, time in years. Reproduced by courtesy of Elder[2]

schematic heat and mass balance model (Fig. 2) for this system gives a first impression of the scale of heat- and mass-transfer processes associated with the 'geochemical engines' of ore genesis.

A particularly important aspect of the Wairakei system is that it is *buoyancy*-driven, the heat and mass transfer operating by *free convection* of hot fluid. Physical description of fluid convection in the crust is a complex problem which has been investigated by means of dimensionless mathematical analysis, high-speed computation and laboratory modelling. Only a short review will be given here, but the reader is referred to Elder's[2] comprehensive coverage of the subject.

Fluid flow through porous media, such as fractured rocks, may be described by Darcy's law*

$$Q = \frac{K}{\mu} \nabla P$$

The equation refers to laminar (low Reynolds number) flow through fractures, etc., such that the thickness of the individual channels is of the same order as the boundary layer of the fluid motion. In hydrological problems ∇P usually refers to some 'head' or other pressure gradient established over the flow path. Where buoyancy operates, however, the Darcy law expression must contain a more complex term for the buoyancy force which takes the place of ∇P. Thus,

$$\text{Buoyancy force} = \beta g \, \Delta\theta$$

It can be shown that this force initiates flow rates greater in magnitude than that due to any normal lithostatic gradients.[3]

To satisfy heat balance requirements, expressions for fluid flow must also include such terms as c_p, to consider heat transported by the fluid, and κ_m, relating to thermal conductivity through the medium.

Lapwood[4] carried out a mathematical analysis of the idealized problem—convection of fluid in a porous layer heated from below—and derived a critical value for the convection-controlling dimensionless number, the Rayleigh number

$$R = \frac{K\beta \, \Delta\theta \, gH}{\kappa_m \, \nu} \geqslant 4\pi^2$$

The magnitude of the Rayleigh number expresses the 'vigorousness' of the convection, and below the critical value the convection system has only transient existence. Elder estimated that the Rayleigh number for the Wairakei system is of the order of 10^4. The above dimensionless expression can be extended further to predict the geometrical form of the systems (cf. Donaldson[5]), the procedures involved becoming complex, but some success has been achieved in modelling the known temperature and flow pattern of the Wairakei system.

Studies in the laboratory are facilitated because fluid flow in isotropic porous media can be approximated by the use of a Hele–Shaw cell—two parallel close-spaced glass sheets with the heated fluid between. With such a cell Elder[6] was able to model the form of such convective systems heated from below. The form of the model systems is compared, in Fig. 3, with the distribution of isotherms in the Wairakei system. It can be seen that at high Rayleigh numbers the buoyancy-driven flow has the form of a jet, which mushrooms out on contacting the essentially impermeable ground–air interface. In the crust local discharge from the system and mixing of local

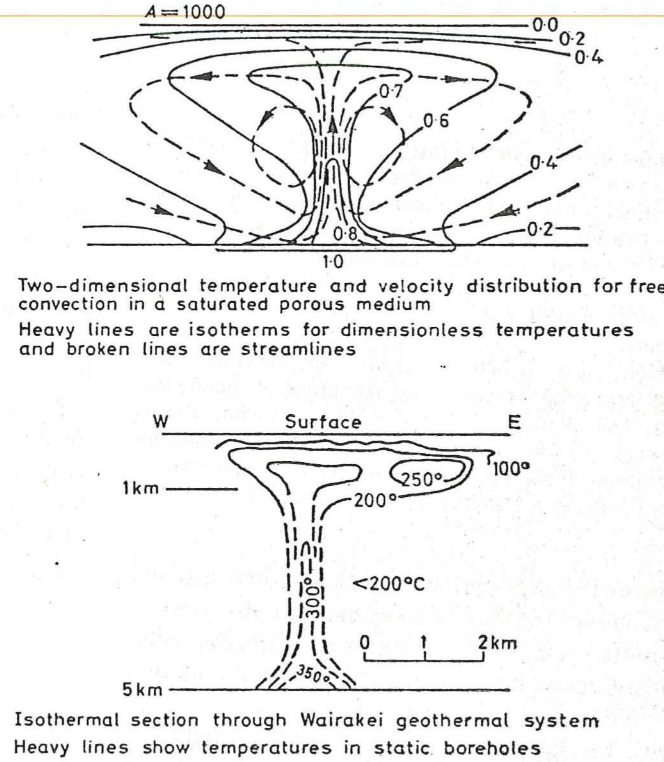

Fig. 3 Distribution of isotherms in a laboratory convection system and at Wairakei. From Elder[2]

groundwaters would be superimposed on the idealized scheme.

The forms of the Wairakei and the model systems provide visual aids to achieving conceptions of how ore-forming systems may have looked. There are obvious complications, particularly those due to the inadequacy of data on the permeability of ore zones, formation temperatures and pressures, etc., which

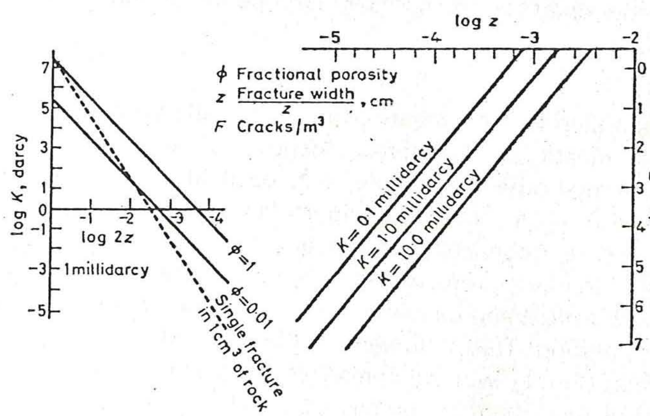

Fig. 4 Relationship between permeability and fracture width and fracture density in a rock

would allow calculation of the Rayleigh number for a system and then flow rates, heat and mass balance, etc. Obtaining permeability data may not be an insuperable problem. The majority of rocks, in thin section, show rehealed fractures up to 100 μm in width and only a few of these per cubic metre of rock can

*Definitions of the symbols used in this paper are given on page B8.

support considerable fluid flux. Permeability can be estimated on the basis of flow through tabular channels

$$K = \tfrac{2}{3} z^3 F \times 10^{-2}\ \text{cm}^2$$

for fractures in a cube of side 1 m. The relationship is illustrated in Fig. 4, and Snow[7] has provided more rigorous functions for this.

With the availability of so many fractures the above idealization of an isotropic medium may not be far removed from actual crustal processes. The presence of major 'channels' may, however, affect the overall form of the convective system. Elder observed this aspect in model studies, and Fig. 5 illustrates the effect of discharge points (faults, etc.). Flow through these would

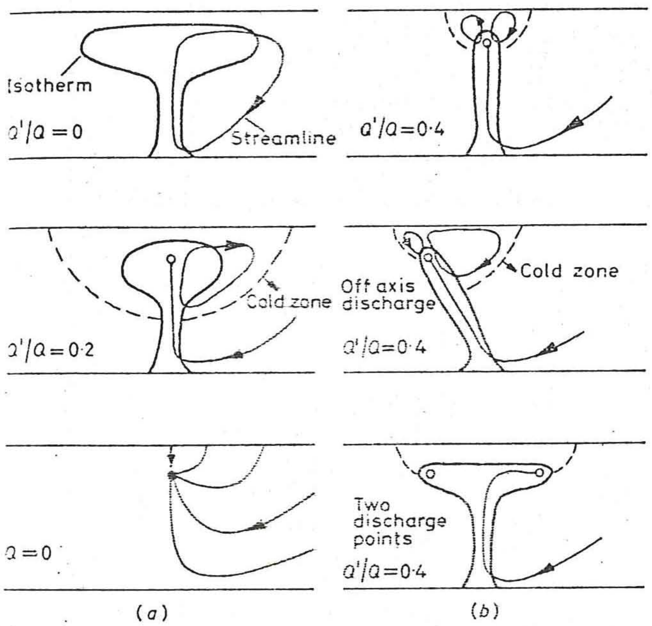

Fig. 5 Influence of discharge point on temperature–velocity distribution in convection systems. Q_1 = power input and Q is power output of discharge. From Elder[2]

occur at higher rate than through the medium, provided that the fluid supply is not too rapidly exhausted and that $P_{H_2O} \geqslant P$ load in order to keep the channel open. If the discharge rate is sufficiently high, the system undergoes little recirculation and becomes a single-pass convection system; at Wairakei recirculation may amount to only about 20 per cent. The consideration of such major changes in permeability is of great importance, as it is these which constitute the 'structural controls' observed in many ore fields.

The exact nature of the heat source at Wairakei is unknown, but isotope studies have indicated that the geothermal fluids are derived from meteoric water. The fluid, with subsurface temperatures at least up to 250°C, is a concentrated brine, also carrying sulphur and metals, with solutes derived by leaching and cation-exchange reactions with the country rock. Such brines have been widely heralded as the analogues of ore-bearing solutions, although their range of sulphur and metal contents (e.g. the contrast between Salton Sea

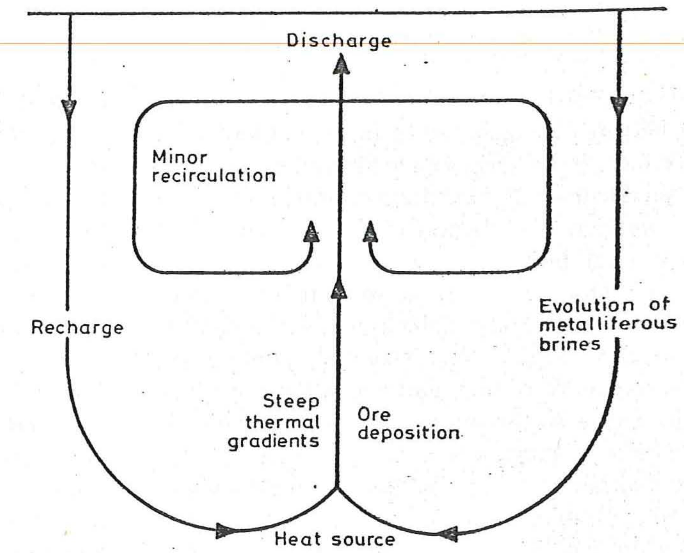

Fig. 6 Schema for convective model of hydrothermal ore genesis

and Wairakei) is the source of some dispute with respect to the nature of metal complexing in the solution.

Before proceeding to an investigation of the application of convective flow to ore genesis it is worth noting that the essential features of convective systems are heat source, fluid recharge, discharge and recirculation and these are the major physical factors in the ore-genesis scheme of Fig. 1. This outlines a convective ore-genesis model (Fig. 6).

Convection and ore genesis

One very important aspect of convective hydrothermal systems is the *flow of fluid across thermal gradients*, both from cold to hot and then vice versa. This too is the main feature of Schäfer's[8] chemical transport reactions, by means of which materials are transported and crystallized—the analogues of ore transport and deposition.

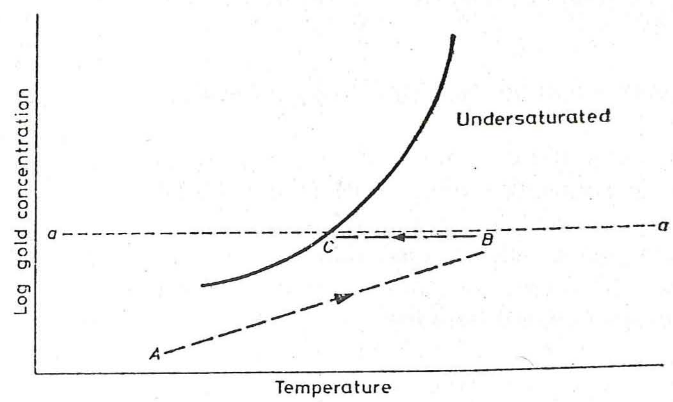

Fig. 7 Variation of base-metal content of solution during cycle; heating with leaching, cooling and metal deposition

Fig. 7 shows the typical form of the solubility curve in an f_{O_2} and pH buffered brine,[9] and applies to the transport of gold or base-metal sulphides through the crust. The line *a–a* represents the metal content of a solution in which the metal has been derived by leaching the total available trace element from country rock in the manner experimentally demonstrated by Ellis and Mahon.[10] A cool brine entering a convective cycle extracts trace metal while heating, so its metal content follows the path *A–B*. This results in a solution, undersaturated in the metal at the elevated temperature, which is then capable of transport over a long distance without deposition. As the solution subsequently passes through the jet and is cooled, it eventually intersects the solubility curve at *C*, resulting in deposition of metal or sulphide. This combination of a geochemical transport reaction and convective flow is thus capable of concentrating trace metals from a disperse course and depositing them as a concentrate or orebody.

The above is evidently an idealized scheme, but one which does incorporate all the necessary features of an ore-genesis model. It refers to any fluid convection system where the fluid may be derived from groundwaters, metamorphic dehydration reactions or expulsion from crystallizing melts, and a whole range of possibilities is open for the development of the necessary geothermal gradients to instigate fluid convection. Sulphide deposition, although probably dominated by decreasing temperature, also involves other changes in solution parameters—for example, those due to wallrock alteration reactions.

Application to specific ore-forming environments necessarily involves intensive study of the original permeability of the ore-forming system and determination of the nature of the heat source. The permeability aspects have been tackled by Naumov and co-workers[11] for the Erzgebirge deposit. Even with this information the actual ore-forming hydrothermal system will be found to conform to the physical characteristics of a *hybrid* system lying between two end-member models described below.

Model A: injection of hot fluid into a dry permeable medium

Such a model would conform to the concept of ore genesis on the igneous-hydrothermal theory. Metalliferous brines released during crystallization of granitic magmas are periodically injected into country rock along permeable zones, and ore deposition occurs as the fluid moves outward from the intrusive and cools. The numerical analysis of this problem would be extremely complex as it would involve transient isotherm distributions, changing as the heat and mass of the hot 'squirt' become dissipated through the country rock. Chappelear and Volek[12] studied the case of injection into a saturated medium, this conforming to a model halfway between models *A* and *B*.

A major difficulty to the acceptance of this genetic model has been the lack of corroboratory geochemical data for the process. For hypothetical granite-derived brines Holland[13] has shown that quite high metal contents are possible; however, recent papers have suggested that many granites could not have contained sufficient excess water and still have risen to their present sites.[14,15] For these and other reasons the original igneous-hydrothermal model has taken a diversity of forms, reviewed by Burnham,[16] and they correspond to various combinations of the end-member models under discussion.

Model B: free fluid convection in a saturated medium

Model *B* conforms to ore genesis within the geothermal convective systems described at length above. Here the fluid source is groundwater, the metal source is the dispersed trace element in the 'aquifer' and the heat source may be an intrusion or an abnormally high local geothermal gradient. The idealized system would have the form of Fig. 8, although the distribution of isotherms and streamlines would vary in time and place as the heat source itself evolves. Sufficient permeability

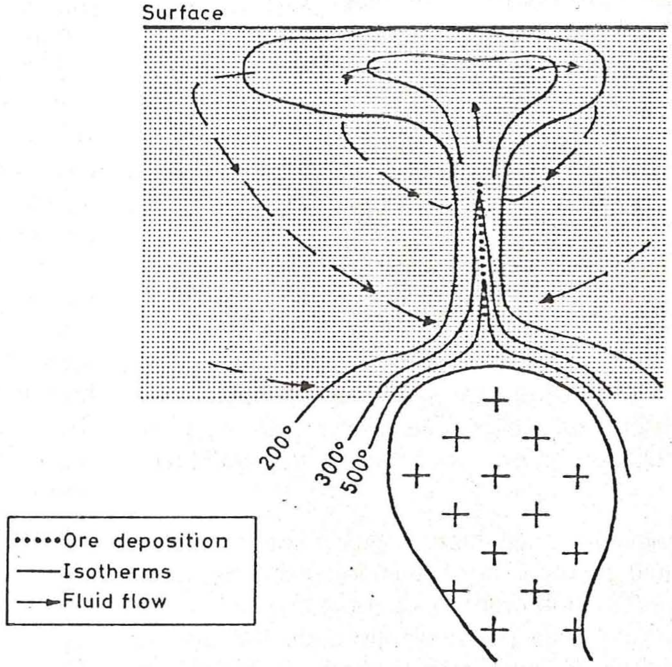

Fig. 8 Hydrothermal systems of type *B* (discussed in text)

may be generated by the movement of the diapir through the brittle country rock,[17] although in the field one may see more specific permeability controls. The model may be further complicated if satellite hydrothermal systems exist, with local admixture of cooler groundwaters, or if some fluid is injected from the cooling diapir.

Base-metal sulphide zonation around a diapir can be accounted for by this model, which does not suffer from possible water deficiency or lack of analytical evidence for the origin of the metals. As the diapir cools and solidifies, it, in turn, will fracture, allowing through flow of solutions, which could result in metal leaching, alteration and ore deposition within the granite itself.

as is commonly the case with the so-called hypothermal ores such as those of tin and tungsten.

With respect to this model, it is of great interest to note the recent results of Taylor and co-workers,[18,19] who have studied the distribution of the oxygen isotope ratios of silicates in and around high-level intrusives. These workers have shown that the zoned ratio distributions conform to a model of groundwater *circulating* around and through the intrusive, in the manner described above, and Helgeson[20] has commented on the chemical significance of this flow pattern with respect to ore genesis at Butte, Montana.

A number of authors have used the terms migration, circulation, convection, etc., but mainly to denote transport of metalliferous fluids from place to place without consideration of the specific physical process to which these terms apply. Models for ore genesis in the Mississippi Valley,[21] the Pennines[22] and Archaean gold belts[23] therefore adhere broadly to the principles outlined above, the major features of which are, in summary, buoyancy drive and mass transport across thermal gradients.

An example

Order of magnitude calculations can be made for some ore deposits to give some idea of the scale of the heat- and mass-transfer processes involved in the ore genesis.

The Morro Velho orebody[24] in Brazil has been mined for gold for several decades and is a large pipelike body with dimensions 50 ft × 500 ft × 9000 ft (6·4 km^3). Extracted ore and reserves amount to 20 × 10^6 tons of ore bearing 3 × 10^8 g of gold.

If the gold were derived by leaching ordinary rocks (averaging 3 × 10^{-3} ppm gold), the minimum source volume is about 33 km^3. Such a volume of rock undergoing greenschist to amphibolite facies transition may release up to 2 per cent by weight of water, amounting to 2 × 10^{15} g. Assuming 100 per cent efficiency for the leaching process, these figures indicate a maximum gold content for the solution of 0·15 ppm, a figure coincident with other geological estimates (e.g. Helgeson and Garrels[25]). Smaller solution volumes, but less efficient leaching, would give gold contents of similar magnitude.

Gold deposition was probably only a minor phase of the hydrothermal activity. If the sulphur content of the solution were similar to today's geothermal solutions (about 100 ppm), the sulphur content of the orebody would have required total deposition from at least 2·8 × 10^{16} g solution, itself derived from a minimum of 500 km^3 of rock.

Fig. 9 illustrates an ore-genesis scheme for the Morro Velho situation. The source rock corresponds to a cylinder, 5 km deep and 5·6 km in radius, consisting of low-permeability rocks. If the Rayleigh number for convection in the source were as low as 50, the flow rate would amount to 10^6 cm^3 sec^{-1}, so total throughflow would take 1700 years. For the same time convection through the pipe would be vigorous, with $R = 10^6$,

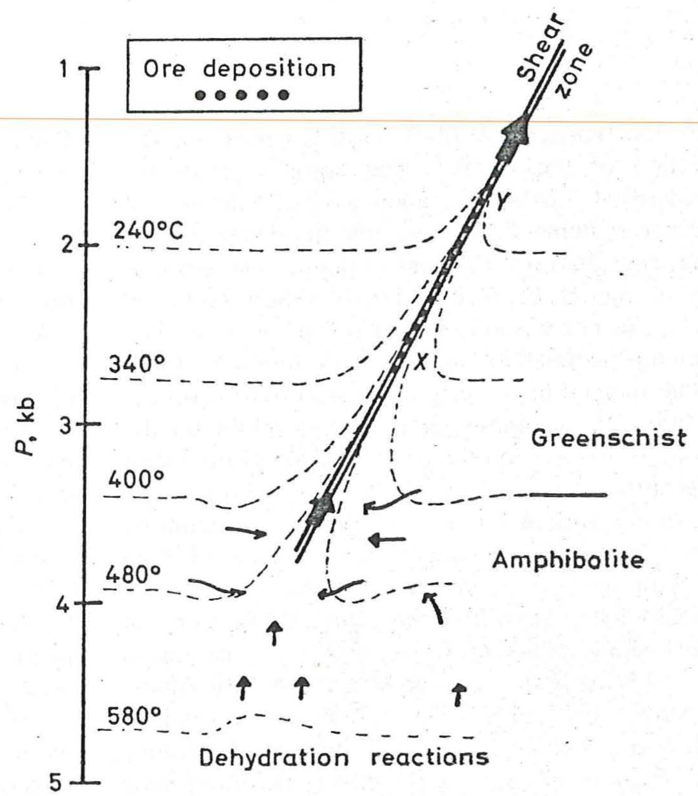

Fig. 9 Proposed scheme for ore genesis at Morro Velho, Brazil

and the pipe itself would have required a permeability of about 1 Darcy. For lower permeabilities the convective flow would necessarily have been much more vigorous, consistent with the ideas for development of such pipes, as is discussed below. Corresponding figures can be computed for slower flow rates.

Although scarcely definitive, these order of magnitude calculations contribute to obtaining a visual picture of the dynamics of ore emplacement.

Some corollaries

Recognition of convective heat and mass transfer in ore genesis has some interesting corollaries.

One aspect is the spatial distribution of buoyancy-driven jets through a geothermal field. In the Taupo Volcanic Zone the individual geothermal systems seem to be regularly spaced about 10 km apart. McNabb[26] has attempted an analysis of this distribution on the basis of high Rayleigh number convection above a heated plate in a saturated layer with the dimensions of the Taupo zone. Such an analysis is a formidable problem, but it appears that the distribution may be accounted for purely on the physical basis of convection. Perhaps fossil geothermal systems or ore-bearing systems show similar distribution.

A number of authors have noted this kind of behaviour, which may be revealed by *grouping* of ore deposits in a field. Knopf[35] recognized such grouping of *lodes* in the Mother Lode Gold Belt, where each group is separated by 6–10 km. More recently, Taylor and Steveson[27] revealed the very strong grouping of tin lodes in the Herberton field of north Queensland. The distribution of these lodes may correlate with the distribution of 'hot spots', such as the fluid jets of convection systems. In this example the mineralization may have resulted from a suite of geothermal systems similar to model *B*. A useful exploration concept? Possibly, but not without the collection of basic data concerning permeability or Rayleigh numbers for a particular mineral field. Two additional controls on the distribution of the geothermal systems might be the distribution of nodes on the upper surface of the diapir or local structural controls generated by the intrusive.

The origin and distribution of pipelike mineralized bodies may also be a direct consequence of fluid convection at high Rayleigh numbers. Sillitoe and Sawkins[28] have described the structural features of copper-bearing pipes in Chile, and other examples occur at Morro Velho, and at Messina, South Africa. Such pipes could form where very high fluid flux occurs in a low-permeability medium. With large buoyancy forces, $P_{H_2O} >> P_{load}$ and hydraulic fracturing may occur, perhaps localized by planes of weakness in the rock. The hot fluid would then be able to pass upward as a high Rayleigh number jet in a very restricted pipelike zone. From the expression for the Rayleigh number and Darcy's law the fluid flux through the pipe can be calculated:

$$Q = \frac{R\kappa_m A}{H}$$

At higher levels the energy of the system becomes less, and a less restricted permeable zone may be intersected or generated, *R* decreasing concomitantly with increasing *A* and *Q* remaining constant (cf. Fig. 10).

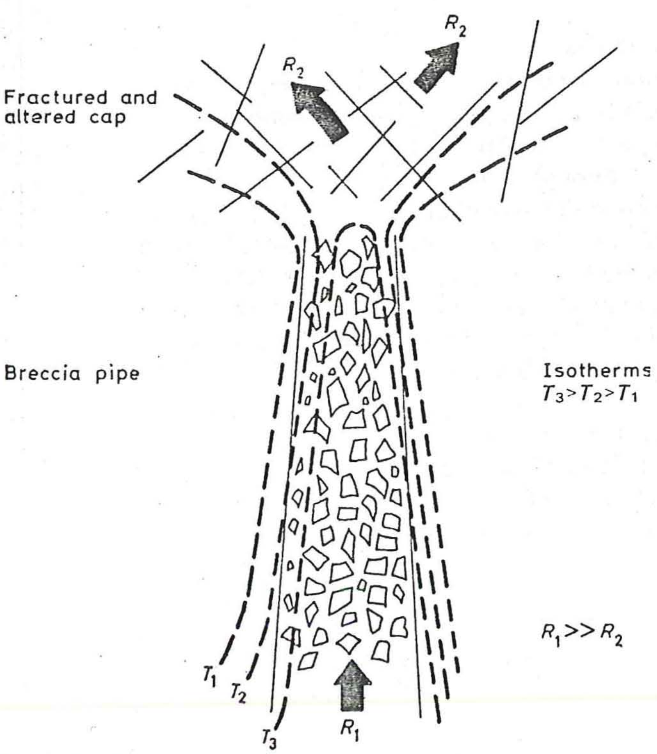

Fig. 10 Proposed mechanism for origin of breccia-pipe orebodies

Provided that the high-velocity flow remains laminar, the original material in the pipe will be simply brecciated and the fragments held apart while $P_{H_2O} > P_{load}$. Only in the case of very high-velocity flow becoming turbulent need attrition of the fragments occur, as was observed in the Swabian pipes described by Holmes.[34]

Much attention has been paid to the possible sources of ore metals.[29] The convective genetic schemes discussed above require availability of readily leached trace metals in a large source volume. This condition is most often fulfilled by sedimentary-volcanic material, which is in disequilibrium with respect to its depositional environment.

Where trace elements are sited on crystal discontinuities (cf. Goni and Guillemin[30]) the rocks are readily leached of trace elements during diagenesis and metamorphism, so it would be hardly surprising to find a relationship between hydrothermal ore deposits and volcanic source rocks. Anderson[31] has discussed this association, mentioning such examples as the Kuroko ores of Japan, where the heat source was provided in the self-same volcanic rocks, and the gold–base-metal ore of the Archaean gold belts, where the necessary energy was available from high geothermal gradients during metamorphism or igneous intrusion. The genetic schemes conform to Krauskopf's suggestion of two-stage genesis, although, in this case, the metal concentration of the source bed is not considered to be so high as he suggested. In the absence of evidence for non-volcanic degassing of the mantle, volcanism is the only mass-transfer mechanism which operates over the mantle–crust boundary. Volcanic eruption followed by geothermal leaching may provide the genetic connexion, discussed by a number of authors, between ore deposits and the mantle.

It is of interest to find that the convective genetic schemes find support in isotope analyses where lead is used as a tracer. Richards[32] found, by this method, that ore material in the Coromandel Ranges of New Zealand was most likely derived from the extensively altered andesites of that region and Doe and Delevaux[33] found a similar link between southeast Missouri ores and an adjacent sandstone aquifer.

Concluding remarks

The above discussion will have achieved its aim if it has stimulated interest in the applications of fluid dynamic principles to problems of ore genesis. In this paper the writer has attempted to qualify the term *convection* in its application to ore genesis and to provide some *dynamic* concepts for the emplacement of hydrothermal ores, rather than the *kinematic* concepts which have dominated genetic schemes published to date. Ore genesis is the result of a combination of physical and chemical processes, and the dynamics of fluid flow in permeable media provide the most important link, controlling the transport of the ore material and its ultimate depositional site. More quantitative application of fluid dynamics awaits the availability of data on permeability and temperatures around an ore zone and its associated source.

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