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Punctuated Equilibrium and Paleohydrology

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ABSTRACT

The similarities between active hydrothermal systems and epithermal mineral deposits are well known, and exploration based on applying models of fluid behaviour developed in active hydrothermal systems to exploration for economic precious metal deposits is becoming increasingly commonplace. However, not all hydrothermal systems produce economic deposits. It seems that some "special event" is necessary for an economic concentration of precious metals to be formed. In some cases, these "special events" can be linked to profound hydrological disturbances of the fossil hydrothermal system. There is also evidence for fluctuating hydrological regimes within known active hydrothermal systems. Over the life time of a large hydrothermal system, such disturbances caused by tectonic activity, magmatism, volcanic activity, erosion, climatic changes or other processes may occur at long intervals, but be responsible for producing some of the most significant characteristics of the system, including economic mineral deposits. Such activity may best be regarded as representing a state of punctuated equilibrium, rather than strict uniformitarianism. Recognition of this principle can be of value in exploration for both geothermal energy resources and mineral deposits.

INTRODUCTION

The similarities between active hydrothermal systems and epithermal mineral deposits are well known (e.g. White, 1981). The application of principles learned and models developed in the course of exploration for geothermal resources have become powerful tools for guiding mineral exploration, especially for precious metals in active and fossil volcanic arcs (Henley, 1985). However, not all high temperature hydrothermal systems produce economic mineral deposits. The number of known high temperature active hydrothermal systems on the Earth's surface is about comparable to the number of known economic (or mined out) gold deposits (several hundred), not all of which are of hydrothermal orign. A simple comparison of the life span of a typical hydrothermal system ($<10^6$ years) to that of the age of the Earth's crust (about 3×10^9 years), and the proportion of the earth's surface made up of old volcanic belts where such systems are most likely to occur, suggests that if all high temperature hydrothermal systems produced economic gold deposits, their occurrence in the fossil record should be much more frequent, even allowing for the effects of subduction and the existence of undiscovered resources.

This paper addresses some of the reasons why certain hydrothermal systems produce economic gold deposits and others do not. The processes considered lead to the conclusion that, while a simple steady-state model of a hydrothermal system has value, it is also useful to consider hydrothermal systems as both evolutionary, and subject to catastrophic events.

MECHANISMS AND QUANTIFICATION OF GOLD DEPOSITION

It has been demonstrated that the fluid in typical hydrothermal systems is capable of carrying enough gold to produce deposits containing an economic quantity. For example, Brown (1986) has estimated that 4.7 kg of gold per year is being transported through the Broadlands geothermal system, thus theoretically permitting the formation of a world-class economic deposit of 100 tonnes of gold in less than 25000 years, well within the life-span of a large hydrothermal system (see below).

However, in economic terms, the concentration of gold in ore is more important than the total quantity present, which may be widely disseminated in a large volume of rock. The lowest grade deposits that are currently mined (excluding certain alluvials), even using bulk extraction and cheap heap-leaching methods of extraction, have gold concentrations of around 1 mg/kg of ore. If the above 100 tonnes of gold was distributed evenly through a modest-sized geothermal reservoir of 12 km^3, it would be present at a concentration of only 0.003 mg/kg. So economic gold deposits will be produced only where some specific mechanism causes the focussing of gold deposition into a small volume of the reservoir.

Gold, under the typical physical and chemical conditions of hydrothermal fluid, is transported principally as a bisulphide complex, with some contribution from chloride complexes and in certain cases tellurides (Seward, 1984). The bisulphide complex equilibrium can be de-stabilised, and hence gold deposited, by cooling; water-rock interaction; fluid mixing causing a change in pH or sulphide concentration; or boiling causing a loss of H_2S (along with other gases), a change in pH (due to loss of CO_2) and a concentration of solutes (Drummond and Ohmoto, 1985). Of these processes, cooling must be the least effective at causing localised gold deposition in a specific zone, whereas boiling has the greatest potential as it causes the most rapid localised change in chemistry. Furthermore, prolonged, vigorous boiling will be more effective than slow, gentle boiling (Reed and Spycher, 1985). So processes within a hydrothermal system which cause vigorous boiling through a restricted volume of the reservoir will be the most effective in producing concentrated gold deposits. Flashing associated with hydraulic brecciation on structurally localised zones, especially where it vents to the surface as a hydrothermal eruption, is now accepted as a particularly important mechanism for gold deposition (e.g. Sillitoe *etal.,* 1984).

EVOLUTION OF HYDROTHERMAL SYSTEMS

A simple model of a high temperature hydrothermal system incorporates the intrusion of a body of magma at depth, causing the heating of groundwater, and the establishment of a convective fluid system. Over the lifetime of the system, temperatures would rise relatively rapidly to a peak and then gradually decline as the heat source becomes exhausted. The history of the system, as recorded by the alteration mineralogy at any point, would record a temperature peak, followed perhaps by lower temperature argillic overprinting as the cessation of convection allowed the ingress of previously-overlying cool acid-sulphate or bicarbonate secondary fluids.

However, numerical analysis reveals that even for a single intrusion into homogeneous formations, this may be a considerable over-simplification and the reservoir rocks at any one point may record several cycles of thermal and chemical fluctuations, due to the varying properties of water at different temperatures, boiling, and the effects of progressive encroachment of groundwater into the pluton through thermal fracturing (Cathles, 1977; Norton and Knight 1977; Parmentier and Schedl, 1981). The effects of the release of magmatic volatiles, and inhomogenities in the reservoir rocks will add further complexity.

There is good evidence that large hydrothermal systems such as Wairakei, Kawerau, and Yellowstone may be as much as half a million years old (Grindley, 1965; Browne, 1979; Muffler *etal.,* 1971). It has long been recognised that to postulate a continuous heat flow of the present magnitude for such long lived systems requires a quite unreasonable amount of magma (e.g. 3750 km^3 in the case of Wairakei; Grindley 1965), if the mechanism is the cooling of a single intrusive. It is therefore more likely that there have been repeated injections of smaller plutons, perhaps dikes, and that thermal activity has consequently been episodic. The renewal of thermal activity in the same location, rather than another area, is perhaps to be expected, as hydrothermal systems are frequently established in zones of structural weakness, allowing the intrusion of magma at depth.

The next section presents evidence for fluctuating physical conditions within several active hydrothermal systems, and discusses possible causes.

CHANGES IN ACTIVE HYDROTHERMAL SYSTEMS

Some areas of thermal activity in Europe and China have very long recorded histories, and have shown little change over many hundreds of years. In other cases, there is gooc evidence that drastic hydrological changes have occurred. Some examples of these are:

Tauhara, HZ. Comparison of mineralogical data from the Tauhara wells (Kakimoto, 1983) with fluid chemistry (Henley and Stewart, 1983) shows that relict alteration mineralogy diagnostic of neutral pH chloride fluids occurs in the shallow part of the reservoir occupied by two-phase and steam-condensate fluids (even before the effects of Wairakei exploitation on Tauhara lowered the water level). This shows that water levels in the Tauhara reservoir have fluctuated by some tens of metres. A decline in temperature (>30°C) has also been inferred at Tauhara on the basis of fluid inclusions (Youngman, 1985). If temperature gradients followed a boiling-point-for-depth relationship for pure water, this implies a minimum change in water level of 320m.

It is possible that the hydrological fluctuations at Tauhara were caused by variations in the groundwater regime due to the draining of Lake Taupo by the 180 AD eruption (Northey, 1983). It is also interesting to speculate how much effect fluctuations in the level and course of the Waikato River due to volcanic activity have had on the other hydrothermal areas in the Taupo-Atiamuri area, such as Rotokawa, Ngatamariki, Orakei-Korako, Broadlands, Atiamuri, Mokai and Mangakino, all of which lie adjacent to or across the present course of the river.

Rotokawa, HZ. There has been a series of large hydrothermal eruptions at Rotokawa (Collar and Browne, 1985); the largest of which produced about 10^6 m^3 of debris. Eruptions on this scale indicate profound hydrologfcal disturbance to the geothermal reservoir. These eruptions apparently occurred in several phases. The last major eruption was about 3700 years bp.

On a smaller scale, the author has noted siliceous sinter, obviously deposited by flowing springs, as high as 18m above the present spring water level. Small scale fluctuations such as these could perhaps be due to changes in the near-surface hydrology by silica sealing and hydraulic fracturing (Facca and Tonani, 1967), but this mechanism seems inadequate to produce the larger hydrothermal eruptions. They may represent episodes of dike injection, perhaps into a hydrothermal system that was already close to boiling-point-for-depth.

Waiotapu, HZ. Hedenquist and Henley (1985) have documented evidence for numerous hydrothermal eruptions at Waiotapu, and have commented that these seem to be episodic, with the most recent phase of activity about 900 years ago. They ascribe the occurrence of individual eruptions to a self-sealing mechanism, as described above, with the addition of gas accumulation to provide a trigger. This mechanism is probably correct for any individual eruption, but the occurrence of a definite episode of eruptions may have some more deep-seated cause, such as tectonic activity or magmatism.

Waimangu, HZ. The Waimangu thermal area became established immediately following the 1886 volcanic eruption of Mt Tarawera (Lloyd and Keam, 1965). It lies on the same structural trend as Tarawera and Rotomahana (where a phreatomagmatic eruption occurred at the same time; Nairn, 1979). It can be concluded that the present hydrothermal system was initiated by the intrusion of a dike along this structural trend, during the same magmatic event as was responsible for the eruption.

Hgawha, HZ. There are numerous eruption craters in the vicinity of the Ngawha thermal area, observed by the author and documented by Skinner (1981). There are no historical records of hydrothermal eruptions, but a consideration of the deep pressure profile (reported by Grant, 1981) shows that when extrapolated upwards it intersects a lithostatic gradient at a depth of 100m. It is therefore easy to imagine that the craters at Ngawha were produced by hydrothermal eruptions, but that these have occurred only episodically, perhaps in response to faulting which has breached the largely impermeable 500m of Cretacio-Tertiary allocthon overlying the hydrothermal reservoir. The present accumulation of pressure shows that conditions are ripe for another episode of eruptions, given a suitable initiating mechanism such as tectonic activity.

Tongonan, Philippines. The Tongonan area is a good example of a hydrothermal system where the reservoir rocks record both current and relict alteration. In the Mahiao sector of the reservoir, alteration mineralogy zoning based on known mineral stability temperature ranges corresponds closely to the current temperatures. However, in the adjacent Malitbog sector (which is now an outflow zone), high temperature mineralogy occurs at shallower levels. For example, epidote, indicating a temperature of at least 240°C, occurs where current temperatures are less than 150°C (Leach, Wood and Reyes, 1983).

If these minerals were formed under boiling-point-for-depth conditions then at least 340m of erosion has occurred. The true amount of erosion is probably much greater, as the upper part of the present geothermal reservoir has a temperature profile which is well below boiling-point-for-depth, i.e. the reservoir effectively has a deep water level. It is hard to imagine that this amount of erosion could have occurred during the lifetime of the present system, unless the heat source was renewed by repeated intrusion. It has been suggested that repeated dike intrusion adjacent to a larger plutonic body (which is not the heat source for the current phase of hydrothermal activity) may be responsible (TM Leach, *pers comm.,* 1983).

Bacon-Manito, Philippines. Most of the alteration mineralogy within the Bacon-Manito hydrothermal reservoir is in equilibrium with current temperatures, and mineralogical zonation closely follows isotherms (Lawless *et al.,* 1983; Leach *et al.,* 1985). However, the distribution of secondary biotite, which is considered to form in excess of 300°C, does not follow present isotherms, but extends into zones now as cool as 150°C. The distribution of biotite does correlate with the occurrence of shallow dikes, and this has been taken as evidence that the biotite was formed during short term, high-temperature transients within the hydrothermal system in response to dike injection. In both this system and at Tongonan, repeated injection of dikes has been suggested as the hydrothermal heat source (KRTA, 1985).

Yellowstone, USA. Large hydrothermal eruptions have occurred at Yellowstone at certain definite periods. Muffler *et al.,* (1971) have correlated these with hydrological changes lowering the groundwater level, caused by the melting of ice in response to Pleistocene climatic changes. On a smaller scale., changes in thermal activity, including the initiation of hydrothermal eruptions and geysering, have been observed following seismic activity (Marler and White, 1975).

HYDROLOGICAL CHANGES IN MINERAL DEPOSITS

Examples of hydrological changes in mineral deposits of hydrothermal origin are less well documented than in active hydrothermal systems, since the evidence is usually less clear, and many of the relevant data are unpublished. Nevertheless the following examples are informative.

In numerous "epithermal" gold deposits (e.g. *Golden Cross, HZ;* de Ronde, 1986: the *Boise Basin,* Idaho, USA; Krilsguard *et al.,* 1986), high grade mineralisation is localised in veins. These are usually of quartz, but often with lesser quantities of carbonates, frequently in bladed forms (or more usually pseudomorphs of carbonates), adularia and sulphides. By analogy with the mineralogy of veins from active hydrothermal systems, such textures are considered to be indicative of a boiling fluid. This is supported by direct evidence from fluid inclusions from these veins, which are frequently vapour-rich, and have a wide range of vapour/liquid ratios and homogenisation temperatures, indicating they have trapped a two-phase (boiling) fluid. The veins are very frequently rhythmically banded, with layers of coarser and finer quartz or chalcedony, or varying amounts of other minerals in addition to a silica phase. Veins with many tens of bands, in a total width of a fraction of a metre, are not uncommon (Christie and Brathwaite, 1986).

Such textures are empirically well known to be associated with gold mineralisation (e.g. Bateman, 1950). Gold mineralisation is often concentrated within certain bands within veins, or, if more than one generation of cross-cutting veins can be distinguished, within one particular set of veins.

Each band represents a particular set of physical and chemical conditions prevailing at the time of deposition. Where veins are finely laminated, similar conditions and similar cycles of variation must have occurred many times over. The most probable mechanism to produce such regular but punctuated events is self sealing by mineral deposition and subsequent hydraulic fracturing (Facca and Tonani, 1967; White *et al.,* 1975). This is consistent with the frequent occurrence of hydraulic brecciation textures in such veins.

Where veins are massive rather than banded, or where one set of veins cross-cuts another, more drastic changes in the hydrological environment are indicated. Changes of this nature may correspond to those more major events observed in active hydrothermal systems, where large eruptions have followed seismic activity or renewed magmatism.

The *Kelian* gold deposit in Kalimantan, Indonesia (Fergusson, 1986; Van Leeuwen *et al.,* 1988) is unusual in that it provides a good example of renewed magmatism within a hydrothermal system, and of related gold deposition. This deposit lies within a fossil hydrothermal system, hosted in and adjacent to a series of small, deeply eroded andesitic intrusives. The author and others (unpublished data) have established that most of the alteration has been caused by hydrothermal fluids of low (<5 wt% NaCl) salinity, at up to 300°C, with permeability strongly structurally controlled. However, the latest-stage veining has mineralogical and fluid inclusion evidence for hotter (up to 350°C ?) fluids, with a salinity of around 10 %.

There was extensive explosive brecciation associated with the latest phase of veining, producing large bodies of fluidised breccia which are not cemented by hydrothermal minerals, suggesting that this activity took place late in the history of the hydrothermal system, and with vapour as the mobile phase rather than liquid. It is this latest stage of activity that is responsible for the most significant gold mineralisation.

It is considered that the earlier alteration was caused by a more-or-less-stable convective hydrothermal system, but that late in its history a small instruvive was injected into the hydrothermal system (at greater than drilled depth), causing a rapid rise in temperature and pressure and thus inducing explosive brecciation and violent boiling of the fluid. The high salinity was caused by the release of magmatic volatiles into the hydrothermal fluid.

The *Lihir* gold deposit has been described by Davies and Ballantyne (1987). It is located on an oceanic volcanic island, and has been interpreted (Bogie and Lawless, 1987) on the basis of fluid chemistry and alteration mineralogy to have been formed by the episodic sealing of seawater recharge to the hydrothermal system by anhydrite deposition, followed by tectonic breaching and subsequent violent boiling leading to gold deposition. Repetition of this cycle has produced an unusually large and rich boiling-zone deposit, containing mineable reserves in excess of 375 tonnes of gold. There are similarities to cyclic thermal processes in the East Kilauea Rift Zone of Hawaii (Thomas, 1985).

Further evidence that epithermal-mesothermal mineral deposition in a volcanic environment is related to certain magmatic events, rather than a simple model of a single-stage large intrusive producing a convective hydrothermal system, is provided by Sillitoe and Gappe's review (1984) of copper porphyry deposits in the Philippines. These deposits, some of which are now mined mainly for their gold content rather than the copper, are of magmatic-hydrothermal origin, related to sub-volcanic dioritic intrusives, and are the more deeply-eroded analogues of active hydrothermal systems in this island arc setting. However, mineralisation and alteration is most closely related to late-stage dikes marginal to the main intrusive bodies, which is reminiscent of the heat source proposed for modern hydrothermal systems such as Tongonan (see above), and the evidence for late-stage magmatism at Kelian.

Evidence that specific magmatic events are associated with mineralisation in some epithermal deposits, as at Kelian, sheds light on one of the more significant differences in alteration zoning between epithermal mineral deposits and most active geothermal systems. In many epithermal deposits, alteration close to veins or other permeable zones is described as phyllic or sericitic, consisting of well-crystalline illite, plus quartz, with only minor amounts of other minerals. This grades out into a more widespread propylitic zone (see Heald *et al.,* 1987, for numerous examples), and downwards into a potassic alteration zone, as recognised in the classical Lowell and Guilbert model (1970).

However, in active hydrothermal systems, extensive sericitic alteration is less common, and alteration is predominantly propylitic, grading into potassic alteration in the hotter zones. Phyllic zones may be present, but usually are shallower and contain less well-crystalline illite than in epithermal deposits. These differences are explicable if the permeable channels within epithermal deposits carry (intermittently ?) a component of magmatic volatiles, lowering the pH to the point where illite is stable but not chlorite, epidote or adularia. Away from the permeable zones, water-rock interaction neutralises the fluids and more propylitic assemblages result. The shallow, lower-temperature phyllic zones in active hydrothermal systems are more likely to reflect variations in pH due to release of CO_2 by boiling, and its subsequent re-solution in condensates.

These differences should be seen as gradational rather than constituting separate types of hydrothermal system. Mahon and McDowell (1977) pointed out that up to 10% of magmatic steam could be present in "normal" groundwater-derived hydrothermal fluids. Active hydrothermal systems with a distinctly "magmatic" character have been reported (e.g. Lawless and Gonzalez, 1982). Rather than constituting a distinct class, it might be more correct to say that hydrothermal systems with more episodes of magmatism are more likely to produce economic gold deposits, principally because of their potential for physical hydrological fluctuations, not because of their special chemical characteristics.

CONCLUSIONS AND IMPLICATIONS

A simple model of a steady-state hydrothermal system, formed by a single intrusive event, does have value, both for the exploration and modelling of active geothermal systems as energy resources, and in the location and recognition of fossil hydrothermal systems with economic mineral potential. This could be described as a "uniformitarian" model, where the present steady-state system is seen as the key to locating and understanding fossil analogues.

However, such a simple model may be inadequate for the fuller understanding of active systems, and for locating those portions of fossil systems where economic mineral concentrations occurred. As the above examples show, special "one-off" events may be more significant in this context than the steady state. These may be quasi-cyclic on a short time scale, as in the case of the repeated sealing and hydraulic fracturing of rocks within the hydrothermal system; they may be unique events, as in the case of tectonism; or they may lie somewhere in between, as in the case of repeated intrusion of dikes as the heat source for long-lived hydrothermal activity. In the latter case the events concerned are of random occurrence on a short time scale but can be expected to occur repeatedly throughout the history of a long-lived hydrothermal system.

Recognition of the quasi-cyclic and episodic nature of these events within the lifetime of a hydrothermal system could be described as leading to more "catastrophic" models. There are similarities to the concepts of punctuated equilibrium recently proposed in paleontology and biological evolution (Gould, 1978), or to the development of geomorphological concepts from Davisian uniformatarianism to more modern theories which stress the importance of extreme climatic events (Thombury, 1954). These concepts emphasise the importance of specific events which are of random occurrence on a short time scale but statistically predictable on a longer scale.

Recognition of these principles can be valuable both to the investigation of active hydrothermal system as energy resources, and to exploration for economic mineral deposits. Establishment of past changes in active systems permits the quantification of the seriousness of man-made hydrological disturbances. For example, if changes in water level of hundreds of metres have naturally occurred within a geothermal system, then man-made changes of a few tens of metres in response to exploitation could be seen to impose little additional risk of hydrothermal eruptions. Recognition of relict alteration mineralogy, and its effects on resistivity, is also vital to successful geothermal exploration.

Recognition of hydrological changes that have occurred within fossil hydrothermal systems, and the relation of these to mineralisation, is of obvious value in mineral exploration. It may explain the reasons for structural localisation of mineralisation, and assist with interpreting its history. If there has been more than one cycle of hydrothermal activity, then appreciating this will be essential to successfully applying the principles of paleo-hydrological reconstruction to mineral exploration.

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