WESTERN PACIFIC
REGIONAL BRANCH

Hydrothermal Heat Sources and Evolution

Module 6

Contents

1. Introduction

The heat source for a magmatic-related hydrothermal system is an intrusive body. Some clues as to the existence of a suitable heat source can be gained from the presence of young volcanoes in the area. However, active volcanoes usually either have no convective hydrothermal system, or are associated with systems which have too much magmatic fluid input to be exploitable. Many exploitable systems are not associated with active volcanoes that are young enough to be directly related to the heat source of the system.

Hydrothermal systems go through a predictable life cycle, which must be understood to make sense out of the stage of evolution of any system encountered in exploration.

In this section we will first describe typical changes that a hydrothermal system can go through in a single cycle, and then look at the possibilities of more complicated histories when hydrothermal systems become rejuvenated. These are not just theoretical considerations. They are based on observations in real systems. For example, in the Creede fossil hydrothermal system in Colorado, a great deal of fluid inclusion work has been done, and a “stratigraphy” has been erected based on colour banding in the abundant sphalerite in veins, which permits good time control (*Figure 1*). Twenty separate episodes of sphalerite deposition can be recognised. While these *overall* show a sequence of decreasing salinity and temperature with time, as would be expected with progressive dilution and cooling of a initial magmatic fluid, they also reveal two major cycles of rejuvenation plus some minor fluctuations.

2. Single Cycle

With a single life-cycle of a hydrothermal system, the effects that will produce evolutionary changes are:

- Physical changes as a result of cooling.
- Chemical evolution due to changes in the primary fluid.
- Chemical evolution due to changes in the secondary fluid.
- Erosion.

These are of course all interrelated, but it is convenient to consider them one at a time:

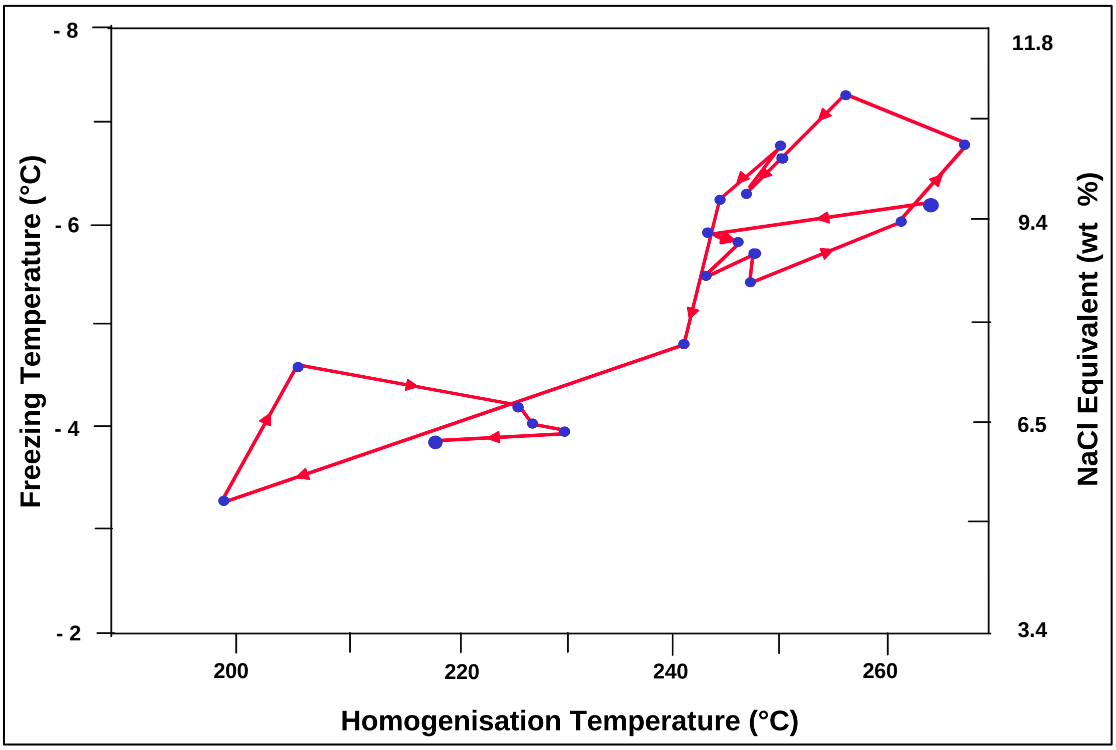

Figure 1 Plot of T_h versus T_m ice (and estimated salinity) for 221 primary inclusions in a 50 mm band of zoned sphalerite from Creede (after Roedder 1984).

2.1 Cooling of Plutons

The simplest model of a hydrothermal system is that it is induced by the emplacement of a pluton, which then interacts with groundwater, and starts to cool. Convection of water is established, which cools the pluton more rapidly. With time thermal fracturing of the pluton occurs, so that the water can penetrate the pluton, extracting heat and leaching minerals (*Figure 2*).

This model is probably an over-simplification for any real system. But even for this simple model, mathematical modelling of the cooling process shows that any point within the surrounding host rock may undergo quite a complex thermal and chemical history due to the different physical properties of water at different temperatures, boiling, and the physical effects of groundwater encroachment to the pluton. It is not as simple as temperatures rising to a peak and then declining (*Figure 3*), since the change of permeability with time as thermal fracturing spreads accelerates convection. Factors such as the exothermic nature of the chemical reactions during alteration will further complicate the picture.

2.2 Changes in the Primary Fluid

When a pluton is first emplaced, it will be partially solid and partially liquid. As crystallisation progresses, the more volatile magmatic component will be concentrated in the residual liquid. These magmatic volatiles are mobile and reactive. They will be released into the convective hydrothermal fluid at a greater or lesser rate. With time, the magmatic volatiles will tend to become depleted and there will be a greater proportion of groundwater. Thus the hydrothermal system at a shallower depth will evolve from a more acidic, high-sulphidation type system to a less acidic, lower-sulphidation type.

2.3 Changes Due to Secondary Fluids

A common sequence is for the accumulation of geothermal gases and their oxidation to build up a zone of acid, sulphate- and/or bicarbonate-rich fluids above and around the margins of a hydrothermal system. As the heat source declines, convection will wane and the pressure gradient may reverse, causing these fluids to encroach back into the systems. This is sometimes called the "thermal collapse" of the system. In fossil systems this occurrence can often be identified as a late-stage acid-bicarbonate overprint on the hydrothermal alteration, perhaps producing a carbonate-kaolinite assemblage. If the system is rejuvenated, the process can be repeated, perhaps several times.

2.4 Erosion

Another evolutionary process is the effect of erosion. The degree of erosion during the lifetime of a hydrothermal system may be considerable, especially in the island-arc setting. Tectonism may accentuate or diminish the effects, as may the constructional effects of volcanism. But in general the effect will be to shift isotherms down with time in relation to the rock, in a sort of conveyor-belt process. This will once again cause overprinting of alteration zones in an apparently retrograde fashion, since the temperature at the surface cannot exceed 100°C in a stable situation.

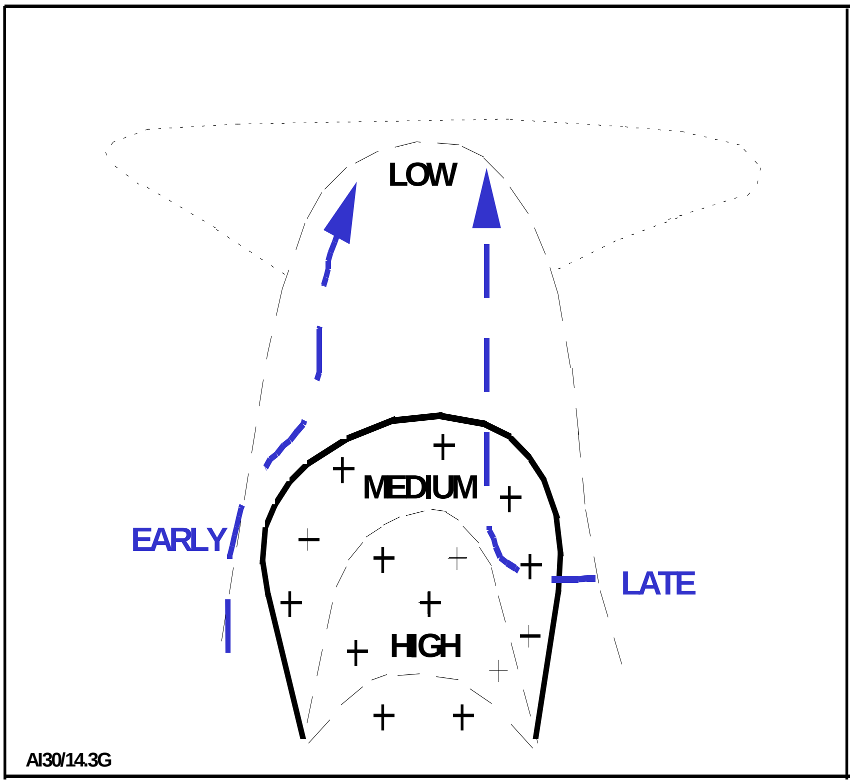

Figure 2 Positioning of fluid flow lines and isotherms about a cooling pluton in uniformly permeable wall rocks. Flowlines, shown by arrows, are for early circulation when the central pluton is unfractured (impermeable), and later circulation when the stock becomes permeable by fracturing. The dotted extension of the "low" temperature isotherm depicts possible spreading due to sealing by an impermeable cap (after Beane 1983).

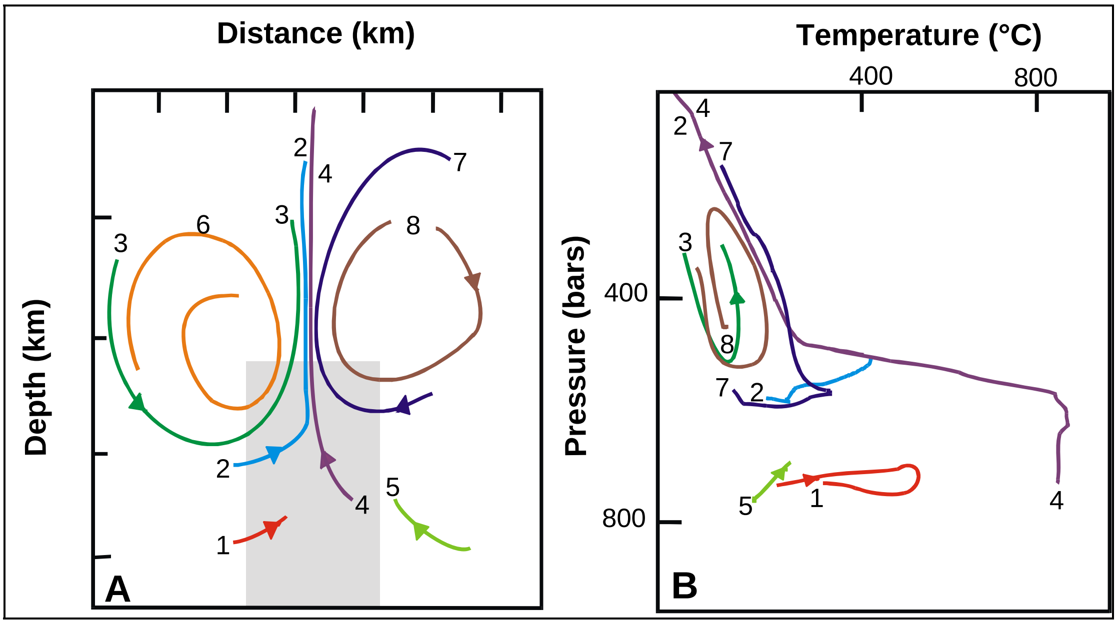

Figure 3 **A**: Examples of fluid pathlines over 200,000 years in a hydrothermal system, representing the redistribution of fluids caused by the thermal anomaly. Arrows indicate direction of fluid motion; tick marks occur every 50,000 years. **B**: Pressure-temperature path of fluid packets that circulate along paths in an evolving hydrothermal system, as above.

3. Rejuvenation of Hydrothermal Systems

3.1 Life-span of Hydrothermal Activity

There is good geological evidence from certain active systems that they are long-lived, in the range of 250,000 to 500,000 years. Longer periods have been estimated by Silberman (1983) based on dating in fossil systems: he suggested a range of 0.6 - 2.5 million years for the total duration of hydrothermal activity (including early, more magmatic activity) for individual Tertiary fossil systems in the Great Basin. Even the shorter estimates raise an immediate problem as to the heat source. A simple energy flux calculation shows that a quite unreasonable amount of magma is required to support activity for that period of time. For example, for the Wairakei system in New Zealand, Grindley (1965) calculated that 3750 km^3 of magma would have to be emplaced and cool to provide the current heat output for the lifetime of the system. Given the size of the upflow zone of the system, it is not possible that this amount of magma could have been emplaced within the crust beneath it. The conclusion must be that the heat output of the system has fluctuated with time. Thus the steady-state models used by geothermal reservoir engineers are not applicable in the longer term.

Having concluded that the heat output of a hydrothermal system varies with time, and must be rejuvenated, the next step is to look for a probable mechanism. The most obvious is intermittent dyke injection. Hydrothermal systems generally occupy zones of structural weakness, where repeated magmatism is to be expected. Estimates of the total heat flux with time in large volcano-tectonic structures such as the Taupo Volcanic Zone show that about half of the heat flux is directly due to volcanism, and the remainder to convective heat transfer through hydrothermal activity (Hochstein *et al.* 1993). Thus the heat output of a hydrothermal system can be expected to vary intermittently on two time cycles: a short-scale cycle in response to hydrothermal eruptions and self-sealing, and a longer time-scale related to magma intrusion (*Figure* 4).

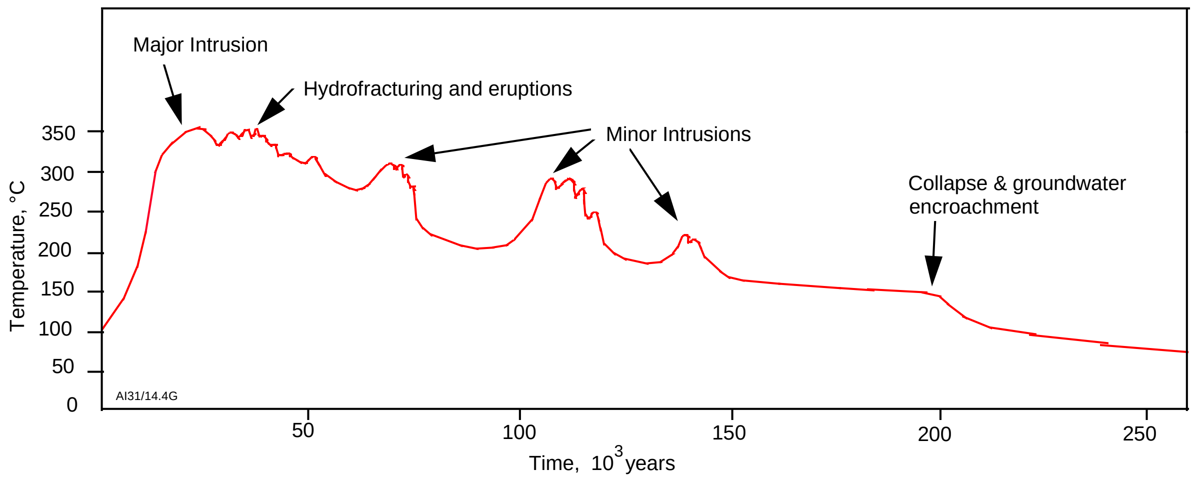

Figure 4 Temperatures with time in an active hydrothermal system

The episodes of magma intrusion can have much greater effects on the hydrothermal system than do the episodic "normal" hydrothermal eruptions, even if the net energy input is not very great. It is easy to imagine a hydrothermal system which with time has built up a convective temperature gradient sitting just on boiling-point for depth. Any input of energy to the bottom of the system (in contrast to a pressure release at the top), can trigger a large release of stored energy as well as the energy actually input to the system by the magma at the time.

3.2 Evidence for Rejuvenation in Active and Fossil Systems

In a number of both active and fossil systems, there is good evidence that pressure and temperature conditions have fluctuated, other than through a simple cooling sequence (Lawless 1988). For active systems, such evidence includes:

- Changes in thermal activity, especially the occurrence of very large hydrothermal eruptions.
- The occurrence of alteration mineralogy out of step with the current physico-chemical conditions (other than simple cooling).
- Evidence for fluctuating water level in the system, other than simply in response to erosion.
- The occurrence of surficial features such as sinter aprons which are not in equilibrium with current fluids.

For fossil systems, evidence for rejuvenation includes:

- The occurrence of cross-cutting veins with varying mineralogy.
- Changes in fluid inclusion data with time, especially where an increase in salinity and temperature with time is indicated, *e.g.* Kelian, Creede.
- Overprinting by high-temperature mineralogy, *i.e.* prograde overprinting.
- Evidence for short-lived temperature transients, *e.g.* lack of replacement of bladed carbonates by silica.
- Late-stage dykes cutting across alteration zoning.
- Late-stage pebble-dykes or large, poorly cemented bodies of breccia.

The possibility of rejuvenation must be borne in mind when interpreting the alteration pattern in an active system, especially in relation to the geophysics. If rejuvenation is not recognised, exploration may be targeted to fossil upflow zones rather than current ones. If relict alteration is not recognised while drilling, temperatures may be assessed as unreasonably high based on the alteration, and hence casing set too shallow. If fossil acid zones are interpreted as current, potential production may be unnecessarily cased off.

4. Exercises

(a) At an early stage in the life of a certain hydrothermal system, the water level is at the surface. Using Table 1 in Appendix 3, what is the maximum stable temperature at a depth of 1004 m?

(b) Refer to Table 2 in Appendix 3. Which of the minerals listed are stable at this temperature?

(c) The erosion rate is 1 m per 100 years. How much will the surface drop in 90,000 years?

(d) What is now the depth of a rock which was at the point in (a) above?

(e) Refer to Table 1. What is now the maximum temperature of this rock?

(f) Which of the minerals listed above are no longer stable at this temperature?

(g) What new minerals (from Table 2) are now stable at this temperature?