HYDROTHERMAL ERUPTIONS: MECHANISMS AND IMPLICATIONS FOR PREDICTION

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SUMMARY – Hydrothermal eruptions are common in both exploited and unexploited geothermal systems. They vary in scale and frequency over several orders of magnitude. Not all hydrothermal eruptions are the same – at least 5 different mechanisms can be postulated, covering a wide range of pre-eruption physical conditions. At one extreme hydrothermal eruptions might require super-lithostatic fluid pressures to initiate. These would be reasonably easy to detect, and therefore predict given a sufficient number of monitor drillholes. At the other extreme, hydrothermal eruptions can start from a free water surface with no excess confining pressures. The occurrence of that type of eruption is more difficult to monitor for and predict. Potentially any hydrothermal system with boiling springs could generate a hydrothermal eruption. However, very large eruptions probably require some special geological event and so are rare.

1. INTRODUCTION

Hydrothermal eruptions are very frequent in geothermal fields undergoing exploitation. These have been mainly very small events, lasting up to a few hours and produce craters up to 50 m across. A key question in this case is whether exploitation has in some way caused the eruptions (since that offers clues to understanding their mechanisms and whether mitigation is feasible), or whether they are "natural" events which were reported because they occur in much visited areas. Some of the observed eruptions described below, such as those at Rotorua and Tongonan, cannot be directly linked to exploitation and their occurrence during a period of exploitation appears to be coincidental. In other cases, such as at Wairakei, there is a clear link between the eruptions and exploitation-induced pressure changes in the reservoir, or modification of the overburden through landslides or excavation.

This paper is a based on a recent review by Browne and Lawless (2001). The mechanisms of hydrothermal eruptions from that review are summarised here and some of the implications for monitoring and predicting hydrothermal eruptions are pointed out. This is timely, because of the recent occurrence of a series of hydrothermal eruptions in Rotorua which are the only examples known of eruptions occurring as a results of *cessation* of exploitation. The water level in the Rotorua geothermal system was drawn down by some 7 m due to exploitation by 1987, causing a drastic reduction in natural thermal activity, including the geysers which are a major tourist attraction. In that year a large number of geothermal bores were compulsorily closed, and fluid withdrawal since then has been strictly measured and regulated. This has allowed reservoir pressures to recover by about half of the previous drawdown, and the geysers are now very active again. However this also led to hydrothermal eruptions near Kuirau Park, damaging houses which had been built close to the thermal areas during the period of inactivity.

2. MECHANISMS OF HYDROTHERMAL ERUPTIONS

It is necessary to recognise that not all hydrothermal eruptions are the same. The following types can be distinguished and are presented here in the order of requiring progressively lower sub-surface fluid pressures:

2.1 Pressures Exceeding Lithostatic.

The simplest model of a hydrothermal eruption is one whereby a field wide 'cap' or cover rock allows pressures within the reservoir to increase until they exceed lithostatic pressure, plus the tensile strength of the rock (if any), at some place. When this happens there is a single, short eruption (though the eruption may then continue driven through other mechanisms), originating within the reservoir that brecciates the host rocks, then ejects the resulting clasts. This mechanism is probably most common in the case of very small, near-surface eruptions, but it does not account for the following observations and features:

- Hydrothermal eruptions occur in some geothermal fields where measured pressures may only slightly exceed hydrostatic.
- Very few active hydrothermal fields have field-wide lithological cap rocks, otherwise they could not discharge any steam or water derived from the reservoir. Condensation of steam would usually make such a situation

short-lived. *An* absence of surface activity above a hydrothermal system is usually due to hydrological factors (eg. steep terrain), not because it has a lithological 'lid'. The hydrological importance of near-surface low permeability caps, where they do occur, is mainly to keep cold water out of a reservoir rather than hot water in.

- Since hydrothermal eruptions are typical features of so many geothermal systems, it should not be necessary to invoke complex or unusual mechanisms to explain their occurrence. They are probably most frequent when a geothermal system is young, as is the case at Waimangu, or perhaps under stress, as may have been the condition at Waiotapu following injection of magmatic gases into the reservoir fluids (Hedenquist and Henley, 1985). The latter were magmatic-hydrothermal eruptions following, perhaps, the injection of dykes (Lawless, 1988). However, even long-established systems, such as those at Orakeikorako and Kawerau (Lloyd, 1972; Nairn and Wiradaradja, 1980), have been the sites of large hydrothermal eruptions; the latter system, for example, has been active, in some form or other, for the past 360,000 years (Browne, 1979).
- Any model of hydrothermal eruption mechanisms must also account for the frequent occurrence of eruptions in exploited systems, where there has very rarely been observed any chemical changes consistent with a sudden input of magmatic volatiles. The question which then arises is whether or not there are any genetic differences between the small hydrothermal eruptions which occur in both the exploited and non-exploited fields and those of much greater magnitude, whose effects penetrate to several hundred meters depth. There is no evidence that hydrothermal eruptions which occur in exploited geothermal areas are any different, except in their magnitudes, from those that take place during a geothermal system's natural evolution.
- Hydrothermal eruptions observed at Wairakei lasted from 15 minutes to several hours (Allis 1986). During this time material was ejected (and on falling back re-ejected); i.e., these events were not over instantly, which would probably have been the case were they single eviscerating eruptions that originated deep within a reservoir with almost all the energy being released at once.
- Hydrothermal eruptions re-occur repeatedly at the same sites, e.g. at the Puarenga Stream, Rotorua, in some instances after less than a year. This is true of both small and larger eruptions and requires that the hydrology of the field be restored nearly to its previous condition between eruptions. The extreme case was the Waimangu "Geyser" which was a cyclical hydrothermal eruption feature with a periodicity averaging 36 hours, but on occasion as short as 8 minutes (Keam, 1962). It is hard to see that super-lithostatic pressures could be built up this quickly and repeatedly.

2.2 Accumulation of Steam and/or Gas

Eruptions can occur when ascending steam reaches a depth where its pressure exceeds that of lithostatic. The shallower the steam zone extends, the lower the initiation pressure, that is to say cooler steam can create an eruption risk if it reaches shallow levels. The only precursory condition is that there is sub-surface boiling occurring at *any* depth, and there is sufficient permeability for the steam to ascend.

This is the mechanism that is thought to cause hydrothermal eruptions in exploited fields. Here declining water levels permit higher steam pressures to develop close to the ground surface as boiling conditions descend deeper into the reservoir. Also, water draining from the formations generates a higher steam flux as it boils, deriving its energy to do so from the rocks.

Most commonly, such an accumulation of steam occurs only at shallow depths (down to a few tens of metres), due to near-surface dewatering. It would usually be preceded by some surface emissions of steam. Less commonly, higher-pressure accumulations of steam could occur at depth, due to deeper changes within the reservoir. These may lead to larger hydrothermal eruptions, with no warning at the surface. The collection of carbon dioxide gas, near the surface, but below a seal, may accentuate the effect, as unlike steam, it will not condense (although a portion will dissolve in the steam condensate).

Giggenbach et *al.* (1991) refer to the 1979 Dieng eruption as being "pneumatic", and describe it as essentially the eruption of cold gas. It is questionable therefore whether it should be included as a hydrothermal eruption despite having occurred close to a hydrothermal field.

2.3 Sub-Surface Pressure Release

If pressures are released suddenly at depth in a geothermal system, steam will form and gas separated from the liquid phase will be released, whereupon the eruption follows the same course as that described above. A pressure release could be due to sub-surface hydraulic fracturing, or result from local tectonic dilatancy, or be caused by removal of overburden through erosion, landsliding, draining of a lake, or even lowering of the water table due to dry weather.

If sub-surface fracturing connects permeable channels between zones of higher and lower pressures, permitting fluid to flow rather than flash, then this may trigger an eruption immediately, or it may delay it until enough fluid accumulates.

The necessary condition for an eruption of this type to occur is that water at the local boiling temperature exists at some depth. This water does not have to reach the surface initially, but simply be close enough to connect with it when a fracture opens.

2.4 Addition of Magmatic Heat or Gas

Addition of heat to an active geothermal system could trigger a large eruption, but this should strictly be classed as a magmatic-hydrothemal eruption, not a hydrothermal eruption per se.

This distinction has rarely been made, although the concept was mentioned by Nairn (1979) and White (1955). Browne and Lawless (2001) defined a magmatic-hydrothermal eruption as an eruption that occurs when injection of magmatic material into a pre-existing convecting hydrothermal system causes a heat pulse that triggers an eruption. In this case the bulk of the energy responsible for the eruption is derived from the hydrothermal system itself, but the magmatic input has an essential triggering role. The resulting eruption may be larger than would be possible for a purely hydrothermal eruption or for a phreatic eruption involving the same amount of magma. Juvenile magmatic material may or may not be identifiable. One of the clearest examples of an historic magmatic-hydrothermal eruption was the 1886 eruption at Rotomahana (Simmons et *al.,* 1993).

In practice, unless there was some distinctive hydrothermal mineralogy formed in the process it would be very hard to distinguish this event from a "normal" hydrothermal eruption. If such an event occurred within an exploited system it could be expected to cause observable chemical changes; that such changes have rarely been observed in the fluid chemistry suggests this mechanism is not common.

2.5 Progressive Flashing: The "Top-Down" Model

This is the mechanism that we consider is the most common cause of hydrothermal eruptions, especially in fields with relatively low sub-surface pressures.

All the causes suggested earlier require a liquid near boiling temperature, a sudden lowering of pressure and the formation of steam. We propose here that most natural hydrothermal eruptions start at the ground surface, or very close to it, and penetrate downwards into the reservoir. With this mechanism there is no need for any confining pressure and, indeed, it is possible that an eruption of this type could start from a free water surface, as at the Waimangu "Geyser". The conditions necessary for an eruption of this type to occur are that boiling water exists at, or close to, the surface and this is underlain by water at a boiling point for depth temperature gradient.

We think it unlikely that large eruptions often begin at great depth within a geothermal reservoir since brecciating and lifting, almost instantaneously, a cone-shaped mass of rock above a single focal point deep within a reservoir requires a large amount of energy. This energy would be needed to overcome a combination of the tensile strength (if any) of the overlying rocks and the high lithostatic pressures they impose.

It is energetically much easier for a hydrothermal eruption to begin within a meter or so of the ground surface below a very thin cap. The initial steam burst ejects the covering materials together with entrained water and mud. Because the initial eruptive phase reduces pressures still further within the reservoir, more steam then forms from any residual meteoric or thermal water present. This steam then provides the lift required to brecciate and disperse more rocks.

The result is that the flashing front and brecciation surface descends within the reservoir followed by the eruption front. Water present in joints or cracks adjacent to the developing crater or fracture also flashes to steam as pressures reduce suddenly, causing the sides of the enlarging vent to brecciate and implode. This may occur more readily where the host rocks are brittle, perhaps through their being silicified. Ductile rocks or sediments are less likely to shatter and brecciate, rather they absorb much of the energy released by the formation of the steam.

Most of the erupted material (rock, mud, and water) probably falls back into the crater, to be re-erupted more than once. This results in breccia deposits outside and within the crater that are mixed with respect to clast rock type, i.e., the resultant deposits do not show a vertical sequence of clast lithology that is the inverse of the stratigraphic sequence of the reservoir rocks. The very earliest-deposited material, however, must be fiom nearest the ground surface. The hydrothermal eruption continues until the steam forms too slowly to provide sufficient lifting power to eject rocks from the crater, although some steam may continue to discharge for several years or longer.

The maximum depth of disruption within the reservoir, or the apparent focal depth of the eruption, depends on several factors. These include the physical properties of the host rocks, especially the presence of near-vertical permeable pathways, such as fractures, the depth of the piezometric surface, the availability of meteoric water, and the amount of energy available from the host rocks which must also be at temperatures close to boiling. It has been recognised that thermal equilibrium may not be rapidly achieved in the erupted material (Mastin, 1995), but the significance of heat transferred from wall rock to fluid in fractures may have been underestimated in the past (Henley and Hughes, 2000; Scott and Watanabe, 1998)

The hydrothermal eruptions that penetrate to the greatest depths are those which have the most permeable reservoir rocks. This is because they can provide large amounts of water that can flash to steam to sustain and provide lift for the ejecta. The size of a hydrothermal eruption, therefore, largely depends upon the volume and supply rate of near-boiling water.

Where the consequences of a hydrothermal eruption, such as rapid cooling, hydraulic fracturing and brecciation, penetrate to considerable depths, highly permeable conditions extend to the surface and sudden, severe changes to the hydrology of a field may result in, for example, mixing between condensate, meteoric and thermal fluids. Because of the enhanced permeability and steep thermal gradients, hydrothermal mineral deposition in the brecciated zone is fast, and sealing of cracks and cementing of clasts proceeds rapidly. This eventually produces horizons of brittle, coherent rocks that may participate in hydrothermal eruptions that occur after the hydrology of the field has been more or less restored. This has happened at Kawerau, for instance, where a period of 5,500 years separated large hydrothermal eruptions from the same site (Nairn and Wiradiradja, 1980).

When an eruption ceases, the sides of the craters commonly collapse as a result of slumping, or later from acid dissolution of surrounding rocks. Some craters develop lakes (e.g. at Waiotapu), but the craters of hydrothermal eruptions are seldom spectacular in appearance or long lasting. Those older than about 1,800 years in the Taupo Volcanic Zone, for example, have little expression and have been recognised almost entirely from the distribution and nature of the deposits they ejected.

Initiating Mechanisms

The trigger which initiates a hydrothermal eruption of the "top down" type is uncertain except in cases where overburden is removed. Seismic activity is a likely trigger (Marler and White, 1975) but does not always occur. The Occurrence of eruption vents aligned in a north-east direction at Rotokawa (Collar, 1985) indicates a strong structural control that here parallels the regional fault pattern. Many hydrothermal eruptions are probably initiated by small and subtle events such as a reduction in atmospheric pressure (*Allis,* 1986) that affect a reservoir filled with water very close to boiling temperatures.

Terminating Mechanisms

Hydrothermal eruptions that result from local and shallow overpressuring will cease within a few seconds. By contrast, hydrothermal eruptions that occur in the manner described in our model may last for hours or more and their level of intensity declines slowly. In this case they are analogous to well blow outs whose effects continue for some time and also gradually diminish in their activity. The case of well WK 204 at Wairakei is instructive in this regard (Thompson, 1976): following a blow-out it discharged episodically for 13 years, ejecting much solid material and forming a crater about 15 m across, before the discharge gradually became wetter and spontaneously ceased.

The most obvious cause for a cessation of activity is for the supply of hot water to run out or to become insufficient to generate enough steam to brecciate and lift any more rocks clear of the vent. It is notable that vents at the Craters of the Moon continued to discharge dry steam, but not rocks, after observed eruptions there ended (our observations); this is consistent with our model. Eruptions will also end when the vents become flooded with ground water, effectively quenching them as in the case of WK 204 described above. Hydrothermal eruptions originating below a lake, for example, will cease when their vents are flooded with cold lake water. Vents may become blocked as their sides collapse. A slower but effective mechanism is one whereby deposition of hydrothermal minerals blocks channels supplying fluid to a vent, in a way analogous to the manner in which geothermal wells can block by mineral deposition, sometimes within a matter of days.

3. PREDICTING AND PREVENTING HYDROTHERMAL ERUPTIONS

3.1 Predicting Eruptions

Both shallow and deep focus hydrothermal eruptions are potentially damaging to life and property. They are difficult to predict since there is no limiting pressure or depth below which they will not penetrate. Rather, it is a matter of identifying danger signs and comparing the nature of a reservoir with others where hydrothermal eruptions have occurred. Danger signs could include the following:

- Evidence of previous hydrothermal eruptions, such as craters and eruption breccias. Where possible these should be dated. Identifying past eruptions as having been pneumatic, phreatomagmatic or magmatic-hydrothermal, rather than strictly hydrothermal, is particularly important in this regard, since hydrothermal eruptions *(sensu stricto)* may take place on a more or less regular (and repeatable) time scale (depending on the rate of energy throughput of the convective hydrothermal system and possibly shallow self-sealing). By contrast, the occurrence of the other types of eruptions is more stochastic within the time scale of human activities and these may be triggered by external events, such as an earthquake or sudden unloading, but such occurrence can be expected to be less frequent.

- Evidence for extensive self-sealing, such as the occurrence of silica aprons, or other near-surface impermeable formations, such as clay-rich lacustrine sediments.
- Liquid-dominated systems with pressure profiles that equal, or exceed, boiling temperatures for depth from the surface downwards.
- Superheated steam emissions, or shallow steam and gas accumulations. However, to monitor these comprehensively would require very many wells with a range of depths at each location. In practice, a compromise would probably be reached by specifying a finite number of monitoring places, having regard to what is known of the near-surface hydrology.
- Shallow well "kicks" during drilling.
- Reservoir fluids with high gas contents, say over 1 wt %.
- Changes in thermal activity following exploitation, especially falling water levels or drying up of previously boiling springs, higher chemical geothermometer temperatures, or a change in water composition from neutral chloride to acid sulphate.
- Evidence of fluctuating groundwater levels.
- Signs of slope instability in thermal areas that could lead to sudden removal of overburden.

The general nature of reservoir response to exploitation can be predicted by numerical simulation modelling, but this will not make unambiguous predictions of the occurrence of individual eruptions or their locations.

3.2 Avoiding Eruptions

It is noteworthy that almost all known historic hydrothermal eruptions, in both undisturbed and exploited fields (except those with a clear magmatic character, such as the activity at Waimangu that followed the Tarawera volcanic eruption in 1886), have been from sites of previous thermal activity, albeit apparently extinct. In the sole case that we know of where this was not so, namely the third recorded eruption at Tiwi (Grindley, 1982), its site lay along the strike of a fault known fiom previous thermal activity and eruptions.

A simple precaution for avoiding effects from future eruptions, therefore, is to not site any facilities on, or close to, areas of present or past thermal activity. In view of the small size of eruptions observed in exploited fields, a safety zone of 200 metres should be adequate.

If disturbing sites of present or past thermal activity is unavoidable, then it is better not to excavate the ground surface, so as not to lower overburden pressure and thereby initiate an eruption, as happened at Nakano-yu (Yuhara, 1997). If ground disturbance is essential, then using gravel pack fill will allow easy escape for steam. This has been done successfully at geothermal projects in Indonesia and the Philippines. Installing large areas of asphalt or concrete slabs should not be done.

It is noteworthy that there are three high-temperature, liquid dominated geothermal fields in the world which have been exploited on a large scale with only partial, or no, reinjection of spent thermal fluid, namely Wairakei, Tiwi and Ahuachapan. All have suffered large pressure declines within the liquid zone of their reservoirs (> 10 bars). It is probably not coincidental that post-exploitation hydrothermal eruptions have occurred at all three. At least partial reinjection of spent thermal fluid is now being practised at all of them.

3.3 Preventing Eruptions

If shallow monitor wells start to record dangerously high steam pressures, then it may be possible to vent the steam. An alternative approach is to inject cool or cold water to prevent steam from accumulating (Lawless and Menzies, 2000).

It may be possible to prevent eruptions by flooding the site to raise the hydrostatic pressures. This method was used in an unsuccessful attempt to stop the eruption of well WK 204 at Wairakei (Thompson, 1976). It was also done at Tokaanu, New Zealand, where the tailrace from a hydro-electric power station comprises an artificial pond located and designed to suppress eruptions from a thermal area there.

4. CONCLUDING REMARKS

Hydrothermal eruptions do not all require a field-wide cap or cover rock which allows reservoir pressures to exceed those of lithostatic or the tensile strength of this rock (though they can occur this way). Rather, they most commonly occur in water-dominated reservoirs with water nearly at its boiling temperature, so that any local de-pressurisation permits it to boil.

In both cases, water flashes to steam and a flashing front descends into the reservoir. Energy for boiling comes principally fiom the fluid, although heating by wallrocks may also contribute. The large specific volume change of water when it boils provides the mechanism for the steam thus generated to brecciate and eject the reservoir rocks so that a zone of rock brecciation accompanies the descending flashing front.

The implication of this mechanism is that there is no simple "rule of thumb" for predicting the occurrence of hydrothermal eruptions. If one were to require an absolute guarantee that a hydrothermal eruption will not occur within a certain area (before, say it was inhabited or exploited), then all systems with boiling point for depth conditions within the upper few hundred metres would have to be avoided. In practical terms such a criterion would be unrealistically conservative. It would preclude habitation in much of Rotorua and Taupo, for example.

A more pragmatic approach is to recognise that the type of small, frequent eruptions which results from the "top-down" mechanism are of limited lateral extent, and to establish suitable buffer zones around sites of current or past activity.

The larger, magmatic- or tectonic–related events are sufficiently infrequent that their occurrence can be approached in a similar way to the prediction of volcanic eruptions. In most cases they will be sufficiently infrequent that the probability of occurrence during the duration of any human activity or occupation is low.

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