HYDROTHERMAL ERUPTIONS - A HAZARD ASSESSMENT

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SUMMARY - Although relatively rare, hydrothermal eruptions do pose a potential hazard to users of geothermal resources. Natural mechanisms that trigger such eruptions include changes in rainfall (as demonstrated at Wairakei) and barometric pressure, earthquakes, and landslides. Eruptions may be indirectly induced by deep pressure drawdown and the creation of a steam zone allowing increased flow of steam to the surface. Although prediction is difficult, mitigation of the hazard may be possible by recognising the factors that increase the risk for a particular thermal area and monitoring *them*. The potential consequences of any man-made impacts on such areas, such as excavation, sealing, flooding, draining, *drilling* or fluid injection, must be carefully considered beforehand.

1.   INTRODUCTION

Hydrothermal eruptions constitute a potential hazard in active geothermal fields. Eruptions are of concern to resource users, tourist operators, developers and land owners. Development proposals involving thermal areas must address the possibility of induced hydrothermal eruptions caused by artificial changes in the shallow hydrology, or by fluid extraction, reinjection, or excavation. This paper reviews the current state of our understanding of the processes that can trigger and promote such eruptions, provides further insight into the physics of these dynamically unstable events, and recommends practical means of monitoring and mitigating the associated hazards.

2.   HISTORICAL OCCURRENCES

Hydrothermal eruptions have occurred in many geothermal fields in New Zealand. Besides historical eye witness accounts, evidence can be found in the form of surface craters and Characteristic hydrothermal eruption breccia deposits. Descriptions of eruption events in the Taupo Volcanic Zone can be found in: Bixley and Browne (1988), Allis (1983, 1984, 1988), Collar and Browne (1985), and Scott and Cody (1982). Prehistoric or historic natural eruptions in New Zealand have occurred at Waimangu, Orakei Korako, Waiotapu, Rotokawa, Whakarewarewa, Tikitere, Atiamuri and Kawerau geothermal fields. Vent sizes range from 5 m to 500 m in diameter and up to 500 m depth. Some natural eruptions, for example in 1973 at Waimangu, occurred with little warning in the form of precursive hydrothermal activity.

More receendly, exploitation of the Wairakei field has been an important factor leading to induced hydrothermal eruptions in the "Craters of the Moon" (or Karapiti) area and in the adjacent Tauhara field (1974 and 1981 "Pony Club" eruptions). These hydrothermal eruptions are thought to have been indirectly caused by a drawdown of deep reservoir fluid pressure, development of a steam zone, and increased flow of steam to the surface (Allis, 1984). Such induced eruptions have typical durations of several hours, but can continue for several days. The ejected material (usually pumice) is of shallow *origin* and travels laterally up to about 100 m from the vent (depending on wind direction and vent geometry).

3.   ERUPTION CAUSES AND MECHANISMS

Although generally infrequent, natural hydrothermal eruptions are characteristic of the normal evolution of high temperature geothermal systems which pass through stages of dynamic instability, causing changes in surface thermal features. Energy considerations show that there is ample stored energy available in typical geothermal *systems* to drive hydrothermal eruptions without requiring any additional heat input, such as from intruding dykes or degassing magma.

Three physical causes have been identified for shallow hydrothermal eruptions (McKibbin, 1989). The first is the formation of a steam zone due to pressure drawdown, with increased steam flow to the Surface groundwater environment where local aquicludes may partially restrict the steam flow (see Figure 1(A)). The second is hydraulic fracturing allowing a release of non-condensable gases to decrease boiling pressures near the surface. The third is a reduction in lithostatic pressure caused by the removal of surface overburden material, allowing explosive boiling of underlying fluids.

At present, it is generally believed that hydrothermal eruptions cannot be reliably predicted, because there are few warning precursors. A hydrothermal system which
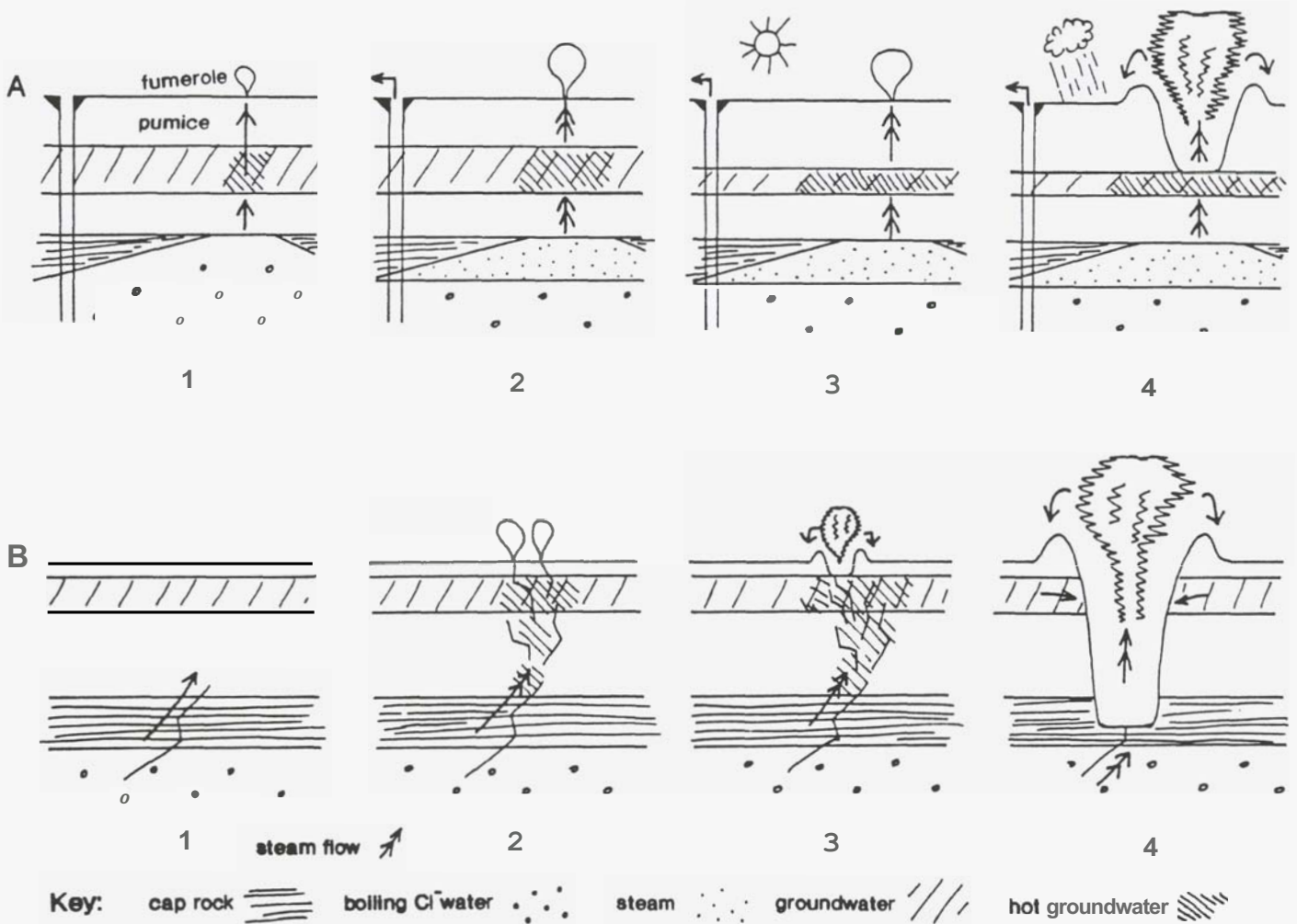
Figure 1: Conceptual models of hydrothermal eruption mechanisms:

(A) Induced steam-zone eruption

1. Pre-exploitation deep boiling aquifer, with **steam** rising through groundwater to a fumarole.
2. Production induced **steam** zone **causes** increasing **steam** flow to the **surface** heating the groundwater.
3. **Low rainfall** allows declining groundwater and shallow heating.
4. High rainfall suppresses **steam**, raising pressure, triggering blowout. **Steam** eruption crater grows to **base** of **shallow** aquifer.

(B) Natural **hydraulic-fracture** eruption.

1. Hydraulic fracture through aquiclude **allows** deep boiling fluids into shallow groundwater.
2. Fracturing propogates to the surface; permeable conduit formed; *steam* emitted.
3. Eruption triggered at the surface from excess *steam flow.*
4. Emption propogates back down through fractured conduit.

vents *steam* to the surface changes gradually to a **point** of instability, and then a random event, such as a barometric pressure low, heavy rainfall, ground slumping or an **earthquake,** may provide the final trigger that sets an eruption off. In this situation, the relationship between cause and effect is difficult to establish. The underlying cause may be the gradually changing hydrothermal venting system, while the immediate **cause** is the perturbation or trigger.

Deep hydrothermal eruptions *are* currently thought to initiate at the Surface rather than "explode" from depth (McKibbin, **1989,** Bixley and **Browne,** 1988). **A** large deep hydrothermal eruption is **considered by** these authors to be the result of evolution of a **shallow** eruption **that has migrated** downwards. The continued ejection of unconsolidated overburden material causes a continued pressure reduction and resultant **flashing** of water at boiling-point-for-depth temperatures. However, studies of epithermal deposits have uncovered many examples of hydrofractured breccia vents deep within ancient (fossil) hydrothermal systems. **Some** of these do not extend all the way to the surface (Lawless **and White,** 1990). The hydrofracturing and brecciation is **caused** by violent upflow of over-pressured boiling fluids and gases. Over-pressuring *can* occur where rising *gas* is locally trapped,

or hydrodynamic pressure gradients exceed hydrostatic because of overlying aquicludes (often self-sealed deposits or lake beds). Hydraulic fracturing may occur when pressures exceed the horizontal stress forces binding the overlying material. These pressures are typically much less than the lithostatic load, and often less than twice the hydrostatic pressure. (There are many examples of induced hydraulic fracture events or micro-earthquakes occurring as a result of over-pressuring from pumped injection into wells). Although hydrothermal hydrofracturing events, originating at depth, do not necessarily result in hydrothermal eruptions, if the fracturing event propagates rapidly to the surface, then it can trigger a shallow emption (see Figure 1(B)). Under favourable conditions of continuing large fluid upflow, the eruption may then migrate back down through the column of hydrofractured material, lifting and ejecting this material as it proceeds. In this way, the hydrofracturing event can both trigger the eruption and also facilitate its growth into a major deep-seated cratering event.

Shallow eruptions may also be considered to be a special case of irregular geyser eruptions, which happen to discharge solids as well as water and steam. The mechanism and dynamics of geyser eruptions have been studied by many authors (eg. Dowden et al. 1991). A simple triggering mechanism in the case of geysers may be the progressive compression of a volume of steam in a chamber, at some tens of meters depth, by water flowing into a tube connecting to the surface. The system ultimately becomes unstable and results in the upwards ejection of fluid from the tube. This process can become cyclic, particularly if there is a continuous supply of steam from below and water from above. A rising steam bubble in a vent of water at boiling point can also trigger an eruption as demonstrated in laboratory models of geysers (Dowden et al. 1991).

Once a shallow hydrothermal eruption has been triggered, overburden material can be lifted and ejected only if the lifting forces (from volumetric expansion of depressurising and flashing water) exceed the lithostatic pressure (weight of the rock). This is much more likely at very shallow depth. The removal of rock further reduces the lithostatic load and allows the eruption to expand and deepen. The eruption will cease when the steam expansion lifting forces drop below the lithostatic pressure, often as falling ejecta is redeposited in the vent, and the supply of boiling water is reduced.

Numerical modelling of the hydrothermal eruption process by McKibbin (1989, 1990) and Bercich and McKibbin (1992) suggests that the flashing front advances down through a near-boiling aquifer at a faster rate than the "erosion" surface, from which rock is ejected, and that both surfaces decelerate with time (assuming uniform porosity and permeability, and boiling-point-for depth temperatures). Modelling also suggests that the vertical velocity of the flashing front is inversely proportional to the flash zone thickness (distance between flash front and

erosion front). Termination of an emption could therefore occur as a result of the redeposition of ejecta back in the vent, which would further thicken the flash zone. Alternatively, if the flash front reaches a layer of rock with negligible porosity (aquiclude) or encounters fluid temperatures below boiling point (for the pressure condition at the flash front), then the eruption will also cease advancing.

Bixley and Browne (1988), discussed induced hydrothermal eruptions associated with the Wairakei development and noted that development of a steam zone did not lead to increased steam pressure beneath the low permeability Huka Formation. The expanding steam zone, however, did lead to an increased flow of steam to shallow levels at Craters of the Moon (Karapiti), which caused shallow steam fissure eruptions. Although these eruptions excavated some impressive craters they did not evolve into large deep hydrothermal eruptions. Similarly, steam breakouts to the surface which occurred at Wairakei wells WK26 and WK204 (rogue bore) created impressive craters, but did not develop into much larger events, probably because the deeper formations immediately underlying the groundwater zone were less permeable, and the surrounding cold groundwater was sufficient to quench upflowing steam. A continuous aquifer of boiling fluids would have allowed the flashing front to propagate down and provide the large volume change necessary to induce a continuing high velocity discharge.

A mechanism for shallow hydrothermal eruptions at Craters of the Moon, was suggested by Allis (1984). He observed that eruptions often appeared to follow a period of heavy rain after a prolonged drought. The proposed mechanism is that a fall in groundwater levels, after a long period of low rainfall, allows steam flow to the surface to increase, thus increasing near-surface temperatures and pressures. Then, a short period (several days or a few weeks) of heavy rain imposes a temporary soil Saturation increase reducing the effective near-surface permeability to steam flow which allows underlying pressures to build up until load pressure is exceeded and a shallow eruption occurs.

This is similar to the mechanism that drives geysers. Alternatively, collapse of crater walls (sloughing) after heavy rain may block steam vents and allow steam pressure to increase. Minor steam eruption events have frequently occurred in March and April after prolonged summer drought conditions, often followed by heavy rainfalls. A similar pattern has been observed elsewhere, for example the Bao Valley eruptions at Tongonan in the Philippines in 1983 followed a period of drought. The "Pony Club" eruptions at Tauhara (Scott and Cody, 1982) also both occurred after long dry spells of several months. In June 1981, eruptions occurred at both Tauhara and Craters of the Moon after several months of below average rainfall followed by 2 weeks of wet weather. Figure 2 shows a chronological record of known steam eruptions at Craters of the Moon and Tauhara (between 1950 and
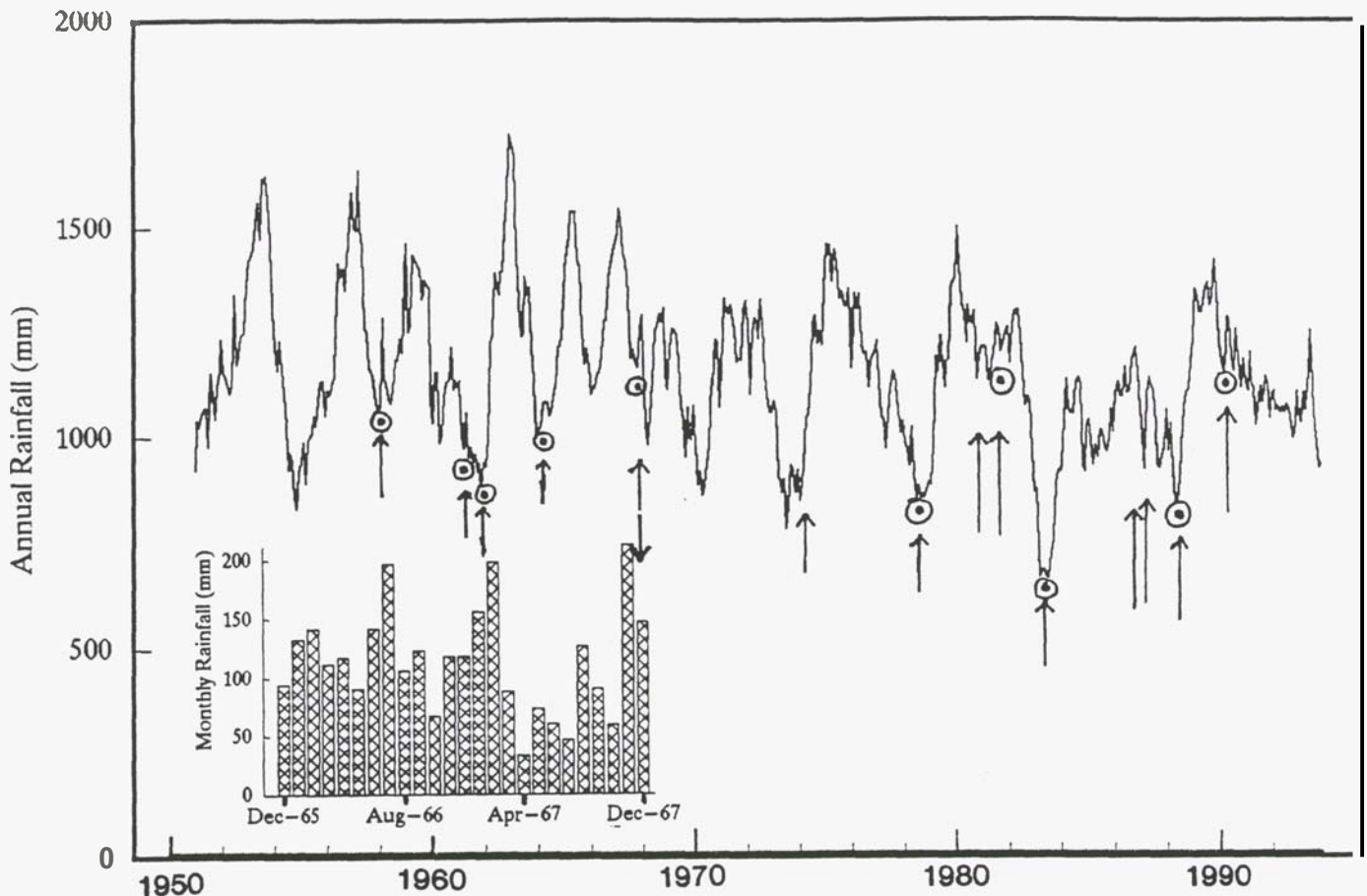
Figure 2: Hydrothermal eruption sequence (arrows) at Craters of the Moon (Wairakei) and Tauhara, plotted with annual rainfall at Taupo (calculated monthly) between 1950 and 1990. Dots above arrows indicate eruptions that occurred during heavy rain following a long *dry* period. Monthly rainfall prior to December 1967 eruption is shown as an inset.

1994) along with annual rainfall at Taupo calculated monthly. The smoothing effect of summing the rainfall for the previous 12 months simulates the long term influence of rainfall on groundwater levels. The majority of recorded eruptions have indeed occurred after long *dry* spells when water levels have dropped significantly. Heavy rain also preceded most eruptions.

Another possible triggering mechanism is the effect of barometric pressure lows causing increased boiling of shallow *steam* heated groundwaters. An increase in *steam* flows from the boiling causes increases in temperature and *steam* pressure in the overlying vadose zone. This effect was observed during a recent ground temperature monitoring study near the "Pony" Club thermal area at Tauhara (Mongillo, 1993).

Other recognised initiating triggers for eruptions include earthquakes (Marler and White, 1975), where a seismic pressure wave propagating through a boiling temperature aquifer may be sufficient to stimulate flashing and initiate ejection of material. Landslides, sometimes caused by heavy rainfall destabilising hydrothermally-altered slopes, have also been known to cause eruptions by the mechanism

of overburden removal. Dench (1988) records such an event that occurred at Wairakei.

4. **HAZARD ASSESSMENT AND MITIGATION**

Developers and local authorities with jurisdiction over thermal areas are often faced with the task of assessing the risk from both natural and induced hydrothermal eruptions to existing and planned facilities. In particular, the likely impact from excavations into, or the sealing over of thermal ground requires consideration.

The implications of the discussion above on occurrences of hydrothermal eruptions and their mechanisms are that the following points should be taken into account when assessing the risk for a particular area:

1. Evidence of previous hydrothermal eruptions. Large, naturally-occurring eruptions can be simply treated by studying return periods and estimating the likelihood of an event during a given time span, analogous to volcanic eruption and earthquake hazard assessments.

2. **Increasing** *steam* flow to the surface **from reservoir pressure** drawdown **and an** expanding steam zone.

3. Vigorous dispersed or superheated **steam** emission, **and** uncompacted low density shallow formations.

4. Near-surface aquifer temperatures close to boiling point for depth.

5. Near-surface aquicludes (eg. silica, cement, clay, or mudstones) confining or deflecting rising **steam and** gas.

6. Fluctuating groundwater levels (e.g. from rainfall variations or draining lakes).

7. Reduction in lithostatic load **from** removal of overburden.

8. Shallow gas pockets, kicks or blowouts during drilling.

Theoretically, the removal of overburden during excavations in thermal ground increases the chances of stimulating hydrothermal eruptions. In practice, however, many such excavations (such **as** waste ponds at drill sites) have been safely completed to depths of many metres in steaming ground Without causing problems. Typically, the hot **ground remains** weakly steaming during excavation, but surface temperatures re-establish rapidly to ambient conditions. A higher **risk** of inducing a **steam** eruption occurs if a vigorously discharging fumarole is excavated or exposed and then incompletely quenched or partially blocked. For such an eruption to expand into a major problem, the upflowing *steam* would **need** to be sufficient to boil laterally inflowing groundwater, which in turn lifts material from the vent by volumetric expansion. Alternatively, if the steaming ground overlies a shallow aquifer of **near** boiling geothermal fluid then a flash front induced by removal of surface lithostatic load could propagate downwards through the aquifer. In such cases, the occurrence of poorly-consolidated high porosity formations (pumice, sand), which *can* easily be lifted during an eruption, increases the hazard.

Confinement of steam flows by construction of cement pads, roading, etc, can result in **a** small increased risk of eruptions if the **steam and** gas pressure is allowed to build up forcing a lateral **flow** to neighbouring discharge areas. Acid condensate from trapped **steam** and gas may also cause local corrosion and soil stability problems. In the majority of such cases, however, **a** new hydrological and thermal equilibrium is rapidly established without any violent eruptions.

Construction of ponds or lakes over thermal ground is generally uneventful if the resulting **mass** of cold water fully quenches any steam discharges. But, **as** with the quenching of discharging geothermal boreholes, the inflow rate of cold water needs to be carefully managed, especially during the early **stages** of flooding. Draining of lakes or **ponds that** cover **pre-existing** steam vents is much more likely to **result** in eruptions. Muffler et al. (1971) suggest that the rapid **draining** of glacially dammed lakes triggered large historic eruptions at Yellowstone. If the heat inflow is sufficient to boil the **reducing** volume of water it may initially geyser **and** then erupt. Such events **are** commonly observed within crater lakes overlying active volcanoes, although these phreatic eruptions are caused by rapid heating **from** intruding degassing magma, at much higher temperatures than conventional **geothermal systems.**

Drilling activities **pose** a significant **risk** of *causing* blowouts or hydrothermal eruptions if chosen *casing* depths **are** inappropriate for the conditions, or if *casing* failures or circulation stoppage **allows** high pressure **steam** to leak into shallow aquifers. Such events have happened at many sites, including Wairakei (Bixley **and Browne, 1988) and** Waiotapu (Dench, **1988),** where **steam** leaks at about **120** m to 180 m depth led to eruption of craters about **30** m to 60 m from the well heads. These events were subsequently controlled by injecting cement slurry into the appropriate shallow **steam** feeding fissure.

Another consideration for geothermal developers is the likelihood of induced eruptions **caused by** selected production/reinjection **strategies.** For example, if large volumes of hot waste water at a temperature above **100°C are** injected (at pressure) into a shallow aquifer, there is a possibility that this water could rise rapidly to the surface, heating the groundwater to **boiling** point, raising pore **pressures,** and inducing eruptions. Deep pressure drawdown in a production **area** *can* create **an** expanding *steam* zone, which may initially allow increased upflow of *steam* to **near** surface groundwater aquifers, **also** causing shallow eruptions.

Although advance prediction of eruptions is difficult, production **and** reinjection schemes *can be* modified to reduce the chances of further induced eruptions if **and** when they are observed. Injection of cooler water into shallow 2-phase zones should have the effect of reducing steam flow to the surface. **This** method is often used **as** a means of controlling **steam** blow-outs on well pads caused by casing failure. If shallow injection of hot water is stimulating eruptions, a control strategy would **be** to throttle or shut down the injection well **and** replace it with **a** deeper well.

Recent studies into the shallow steam-heated groundwater aquifers at Ohaaki have shown that borehole water levels in such aquifers are sometimes highly correlated with barometric pressure. **As** pressures rise, water levels fall, sometimes with barometric efficiencies that approach or even exceed **100%.** This implies the presence of infinitely compressible fluids (presumably pockets of **steam** or gas). Conduits of 2-phase fluids feeding into the perched

aquifers collapse with increased atmospheric pressure, allowing shallow aquifers to periodically drain. Such signs of natural instability in the shallow environment may be a useful means of diagnosing areas that are more prone to hydrothermal eruptions.

5.0 CONCLUSIONS

It is clear from the physical evidence and from modelling studies that the triggering of hydrothermal eruptions and their growth into a size that could be considered hazardous requires a critical combination of conditions. They are therefore relatively rare. However, recognition of the conditions and processes that lead to eruptions can help mitigate any hazard. Prime indicators include the occurrence of vigorously steaming ground and a shallow aquifer at boiling temperatures. The delicate natural balance between heat and mass flow rates in the shallow thermal environment can be upset by a small natural trigger such as abnormal rainfall, pressure changes, landslides and earthquakes, or by a man-made impact event such as excavation, sealing, flooding, draining, drilling or injection. Once an eruption is initiated many influences operate against its continuation to deeper levels, including a declining flash front velocity, infilling eruption material, and a reduction in porosity, permeability or fluid temperature.

Investigation of areas considered prone to hydrothermal eruption risk should concentrate on determining the depth extent and formation porosity of any boiling temperature shallow aquifers. Temperatures of surface ponds should be carefully monitored. Pressures and temperatures of shallow holes should be monitored to help determine if there are any changes in heat flow to the near-surface environment. Monitoring of the relationship between barometric pressure and water level of confined thermal aquifers may indicate the proximity of steam/gas pockets and two-phase feed zones which are potential future eruption sites.

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