Proc. 10th New Zealand Geothermal Workshop 1988

HYDROTHERMAL ERUPTION POTENTIAL IN GEOTHERMAL DEVELOPMENT

P.F. Bixley[1] and P.R.L. Browne[2]

[1] Consultant, PO Box 1414, Taupo, New Zealand
[2] Geothermal Institute, University of Auckland, Private Bag, Auckland, New Zealand

ABSTRACT

Hydrothermal eruptions are typical features of the Taupo Volcanic Zone high temperature geothermal fields. In the undisturbed systems, major deep-seated eruptions, originating as deep as 400 metres below ground surface can be expected every few thousand years, while small shallow focus events occur years apart. It is proposed that these shallow focus "eruptions" are in fact initiation events which can develop into the major deep-seated type of eruption where reservoir rock and fluid properties are favourable. While the probability of the small shallow focus events may be increased by field exploitation, the factors favouring deep-seated eruptions are reduced. However, as hydrothermal eruptions are characteristic of high temperature fields, their destructive potential should be considered in any development proposal.

INTRODUCTION

One of the potential problems identified in some recent geothermal development proposals has been the threat of hydrothermal eruptions (Marshall, 1987): These commonly occur during the natural evolution of high temperature geothermal systems, and have been induced in some exploited reservoirs. Indeed there seem to be a range of related styles of eruption extending from geysers through to major deep-seated activity. In this paper we briefly describe the different types, consider the relationships between them and propose that their eruption mechanisms and occurrences are related.

NATURAL HYDROTHERMAL ERUPTIONS IN THE TAUPO VOLCANIC ZONE

Over the past few years, detailed geological mapping and occasional observation in the Taupo Volcanic Zone have shown that hydrothermal eruptions are common and typical features of the high temperature geothermal systems characteristic of this area. Their magnitude can vary from minor events originating a few metres below ground surface to massive, deep-seated eruptions that produce several million cubic metres of ejecta from depths as great as 400 metres.

Prehistoric

There have been many prehistoric eruptions at several New Zealand fields: At Kawerau 14,500 and 9,000 years ago (Nairn and Solia, 1980); at Whakarewarewa about 42,000 years ago (Lloyd, 1975); at least four times in several locations at Orakeikorako during an eight thousand year period; Waiotapu, where eruptions occurred more than 13,450 years ago and at least five probably more violent ones about 900 years ago (Hedenquist and Henley), 1985; Also at Upper Atiamuri about 14,000 years ago and at Tikitere (Browne and Lloyd, 1986). At Rotokawa there have been at least eight and probably as many as thirteen large eruptions (Collar, 1985; Collar and Browne 1985); seven of these probably occurred 11-20,000 years ago, am three from 9,000 to 9,700 years ago; other Rotokawa eruptions occurred about 6,000, 4,500 and 3,700 years ago. The prehistoric eruptions are recognised only from the deposits ejected and there must have been many eruptions of which no geologic record survives or whose deposits have yet to be interpreted correctly. In many places, e.g. Kawerau and Rotokawa, the ancient craters have been filled in and can only be located by mapping the ejected deposits. These large magnitude eruptions produced vents from 50 to 250 metres in diameter and deposits that cover 5 to 10 km^2, with thicknesses close to the vent of up to 15 metres, but thinning to less than 2 metres at 1 km distance; ejected blocks may be 1-2 metres in diameter but their size decreases sharply away from their vents.

Historic

The eruptions that produced the initial craters in the Waimangu area in 1886 were phreatomagmatic and not hydrothermal in character. Nevertheless there were later hydrothermal eruptions at this field in 1915, 1917,1924 and 1973; further, the Waimangu 'geyser* which erupted between 1901 and 1904 showed many of the features characteristic of hydrothermal eruptions.

The Waimangu eruption of February 22, 1973 has been studied in detail (Lloyd and Keam, 1974). Although very small, it erupted through a lake and lasted for at least 15 minutes. Ejecta fell over approximately 3,000m2 to a maximum thickness of 0.45m, and deposits extended to 12m above Frying Pan Lake. Undoubtedly most of the ejecta fell back into the lake but the erupted volume is calculated as $970 \pm 150 m^3$.

Lloyd and Keam (1974) concluded that the the depth of disruption extended some 90m below the lake level which itself is not more than 30m deep.

Precursors to this eruption were slight. About five weeks before the event two small springs appeared at the then lake edge and boiling muddy water splashed up to 0.5m above the springs; nearby 50mm diameter stones were dislodged from the enlarging vents. Other new springs appeared, some boiling and turbulent, but it is claimed that on-land activity ceased, being replaced by that offshore where the gas discharge increased.

Changes in thermal activity in active geothermal fields are common occurrences and it is only with hindsight that these events were recognised as precursors to the February 23 eruption. Lloyd and Keam suggest that the eruption was caused by a higher permeability path being created in the rocks below the lake. This change was expressed at the surface by increased thermal activity a few weeks prior to the eruption.

At least one hydrothermal eruption occurred at the Ngatamariki field in 1948 (R.F. Keam cited in Browne and Lloyd, 1986), and periodic eruptions of Crater Lake, Ruapehu, have a hydrothermal style (Naim et al, 1979) although strictly speaking they are phreatomagmatic.

General Lessons from Natural Hydrothermal Eruptions

Some natural hydrothermal eruptions have surprisingly deep focal depths. At Waiotapu, eruptions ejected material material derived from at least 350m depth and at Kawerau from at least 200m. The smaller 1973 eruption at Waimangu by contrast, had a focal depth of only 90m (Hedenquist and Henley, 1985; Nairn and Solia, 1980; Lloyd and Keam, 1979).

The ejected material typically consists of very poorly sorted, angular blocks of fine-grained reservoir rock, much of it hydrothermally altered; a great deal of steam, water and mud are also ejected. The greater proportion of material falls back into the funnel-shaped craters and a sizable volume of "ejecta" probably never ascends above the crater lip. The size of the crater vents differs greatly. The Kawerau eruption craters may have been as much as 500m in diameter (Nairn and Solia, 1980) while those at Waiotapu ranged from 60m to perhaps as wide as 250m.

INDUCED HYDROTHERMAL ERUPTIONS

There have been several small hydrothermal eruptions at Whakarewarewa in recent years and several larger ones in the Taupo district resulting from the manipulation of geothermal resources.

Eruptions occurred at the Tauhara field in 1974 and 1981 (the latter described by Scott and Cody, 1982). Allis (1979, 1984, 1986) gives an account of at least 20 hydrothermal eruptions that have taken place in the "Craters of the Moon" area (Wairakei field) in the last 20 years. One eruption occurred earlier this year leaving a crater 10m in diameter. These induced eruptions were of short duration (hours at the most) and shallow focus (a few metres); ejected material travelled only 100m or so from the vent although the blast may be directed (e.g. Tauhara 1981). Their genesis can be explained as a result of shallow hydrology changes with an increased steam flow from the deep reservoir due to exploitation-induced boiling.

In some cases climatological factors alone may be sufficient to induce a shallow eruption - for example a combination of low rainfall lowering groundwater levels in a shallow aquifer, already at boiling point-for-depth conditions and a sudden lowering of atmospheric pressure. These shallow eruptions appear to be confined to areas of steam-heated ground where the heat flow is already high. The area affected by the eruption is small, a few hundred square metres at most, and engineering solutions can be applied to remedy damage.

MAN-MADE ERUPTIONS

During the early development of the Wairakei geothermal field, well drilling and casing problems resulted in several eruptions of geothermal fluid through the formation adjacent to wells. A brief review of the conditions leading up to these events provides an insight into the requirements necessary to initiate a natural hydrothermal eruption.

Well WK26 was completed to 559m with 219mm diameter casing to 454m, in November 1953. The well heated to about 250°C and was extensively discharged and tested: Discharge enthalpy was consistently about 1100 kJ/kg, indicating a small steam or two-phase contribution in addition to the major liquid feed. In January 1958 the well was shut in for maintenance and a casing caliper survey showed a small "pit" at a depth of 180m. The well was serviced and put back on to production. In July 1959 the well was shut for a Master Valve change: At this time a shut wellhead pressure of 34 bg (gas) was measured. In August 1959 downhole "go-devil" surveys indicated a severe casing problem at 179m, near the base of the Huka Falls Formation mudstones. Temperature profiles measured during cold water injection showed that the total injected water flow was being lost through the casing, at 179m and subsequent lead impression blocks proved a major casing break here. Over the next few months the well was variously discharged, shut and quenched several times due to problems with the wellhead equipment. The shut-in wellhead pressure was variable at 32-35 bg (saturated vapour).

In March 1960 a workover was underway when a fumarole formed about 60 metres from the wellhead; then a major eruption occurred, covering the wellsite with a 2 metres thickness of debris. Vigorous activity (mainly fumarolic, interspersed with eruptions) continued until December 1960 when a relief well was drilled to intercept the feed zone in well 26, and cement placed to seal off the flow. The surface activity began to decline almost immediately this had been achieved.

The pressure data indicates that the formation at 180m depth was exposed to pressures as high as 34 bar briefly, and 32 bar for an extended period. Although the timing is a little uncertain, it appears that at least 6 months elapsed between the time the major casing break appeared and the surface effects became apparent.

At well WK204 (The "Rogue Bore"), blowout problems occurred during drilling. The 300mm diameter anchor casing had been cemented to 122m, within the base of the Huka Falls Formation sediments. After drilling on, major circulation losses occurred at 350 and 370m. At the latter depth circulation was stopped while tripping out of the hole. Four hours after stopping circulation the well came under pressure, and seven hours later a jet of steam erupted 30m away from the wellhead. This subsequently developed into a discharge of "dry'Vsaturated (?) steam initially via the formation outside the wellbore, then later via the well casing.

Analysis of data from nearby wells indicates that WK204 had intercepted one (or more) highly permeable fissure, filled with vapour at 22-23 bg. As soon as circulation was stopped this pressure was applied almost immediately to the host formation at 122m depth.

In both the WK26 and WK204 blowouts, Bolton (1961) ascribes one of the prime factors to be a poor cement seal in the casing annulus, thus providing a high permeability path for reservoir fluids to reach the surface. Reviewing the likely pressures that were applied to the formation at the casing shoe, it appears that in both cases the overburden pressure was closely approached, or exceeded, and this initiated the blowout. Robertson (1984) gives the physical properties for fresh core material from the Huka Formation: Average porosities from this study are 50-60% and wet density of 1.4-1.8 g/cm3 .

There are some other examples in the Wairakei field where pressures about midway between local hydrostatic and lithostatic have been applied at the casing shoe without a blowout occurring. In these cases it seems that the Huka Falls Formation mudstones here provide the extra strength necessary to avoid a blowout.

The examples of blowouts may also give a clue to the time needed for an eruption to develop. In neither case was the blowout a catastrophic, instantaneous event; rather, eruption developed over a period of time sufficient to allow personnel and equipment to be removed from the danger zone.

ERUPTION MECHANISM

Although there are large differences in the eruption styles described above, it is likely that there is a continuum between them which may perhaps even extend to include features such as geysers.

The man-made events indicate that down to moderate depths (200m), an eruption may commence if the fluid pressure can build up to the lithostatic pressure alone. If these events were, in fact, precursors to "full scale" hydrothermal eruptions, why did they not then develop into the real thing? In the case of WK26 the feeding fissure was cemented off before the eruption became totally out of control. For WK204, the eruption was initiated from a vapour-filled formation, which was not supported directly below by an extensive boiling-point reservoir: The permeability of the feeding fractures was sufficiently high that drawdown of the vapour zone was not great enough to produce fluid from the underlying liquid immediately. Later when cooler liquid was drawn in to the discharge this did not have sufficient energy to maintain and enlarge the eruption which then died.

While the shallow-focussed eruptions have occurred very frequently, on the scale of years apart within a single field, the deep-seated, large eruptions are much less common - from the Rotokawa and Waiotapu data these are in the order of hundreds or thousands of years apart. The long time intervals indicate that something extra is needed to ionduce major eruptions. Several mechanisms have been suggested:

- accumulation of non-condensable gases in near-vertical fissures,
- reduction in fluid pressures due to draining of lakes overlying a geothermal system,
- increase of fluid pressures within the geothermal system due to chemical sealing of outflow channels,
- seismic activity.

Hedenquist and Henley(1985) suggest that accumulation of non-condensable gases in mineral sealed near-vertical fissures can provide the fluid over-pressure necessary to initiate an eruption. As observed by Collar (1985), this mechanism requires the fissure to act as a cased (ie leak-free) well. For formations whose porosity is commonly 30-50%, this seems unlikely. More than 200 deep geothermal wells (and maybe over 1000 shallow wells - less than 100m deep) have been drilled in the Taupo Volcanic Zone. As far as the present authors are aware none of these wells have encountered the over-pressured gas conditions necessary to support this mechanism.

Another mechanism has been reduction in hydrostatic pressure due to draining of lakes overlying a geothermal system (Muffler et al, 1971). Throughout the Taupo Volcanic Zone, Huka Falls Formation type mudstones are in many geothermal fields. These deposits were laid down in shallow lakes similar to those present today. Sudden draining of these lakes could have provided an initiation mechanism, although there is presently no recognised field evidence for such activity.

Increasing fluid pressure within the reservoir due to field-wide sealing by mineral deposition has also been suggested; while there is unquestionably considerable redistribution of mass within geothermal systems by chemical means, there is no evidence of such field-wide sealing of outflow channels in the Taupo Volcanic Zone. In none of these geothermal systems does the pressure gradient in the undisturbed (pre-exploitation) reservoir exceed boiling point from ground surface (allowing for the dynamic pressure gradient).

Input of seismic energy seems to be the most likely mechanism to initiate an eruption. During many major earthquakes both cold water and geothermal aquifers become stimulated to higher levels of activity; in the 1987 Edgecumbe earthquake, one geothermal well at Kawerau that had remained open for several years as a water level monitor commenced discharging. In association with the 1886 Tarawera eruption there was a dramatic increase in geyser activity in Rotorua (Keam, 1988). There are many other examples.

As suggested by Hedenquist and Henley (1985), the eruption mechanism should be considered as a sequence: initiation; eruption; post-eruption (this latter mineral deposition stage is not considered further here). In this context the induced and man-made eruptions described above and the possible "eruption" mechanisms are initiation events. Whether such events develop into a full scale eruption will depend on the geologic and fluid conditions in their immediate vicinity. Conditions favourable to sustaining an eruption include high porosity with limited or poor permeability; the formation should contain liquid at boiling temperature. Unfavorable conditions are low porosity, highly permeable rock, vapour-dominated or with liquid well below boiling temperature.

Where favourable conditions occur in the immediate vicinity of an initiation event, pressure reduction in the fractures, with consequent boiling within rock pores can propagate a wave of hydraulic fracturing into the rock matrix. Where a fault or fracture allows deeper penetration of the pressure wave the disruption can rapidly propagate to great depth. Energy to support the eruption is provided by die boiling pore water within the rock matrix.

If insufficient energy is available the eruption will cease prematurely: This can result where there is low porosity, low temperature liquid, or vapour-filled pores. If permeability is too great the "eruption" moves toward geyser-type activity where large amounts of fluid are discharged with comparatively little erosion of channel walls (eg WK204). Permeability improvement by the eruption itself may result in subsequent geyser activity.

At Rotokawa and Waiotapu the major hydrothermal eruption centres are coincident with fault traces. This association indicates that the faults are likely to provide vertical paths of limited permeability necessary for an eruption to propagate to great depth.. If seismic energy can trigger the initial boiling, with simultaneous opening of the flow path, the eruption would soon become self perpetuating with rapid erosion of the flow channel.

RESERVOIR CHANGES WITH EXPLOITATION

From the early stages of development at Wairakei, when it became obvious that boiling and the formation of a vapour-dominated zone was occurring, there was concern that vapour pressures at the top of the reservoir would increase. Special shallow wells were drilled to monitor the development of the vapour zone.

Detailed examination of the pressure data over the period of initial boiling and rapid liquid pressure decline indicates that vapour pressures did not increase at any level in the reservoir. Where a well intercepted a boiling zone, the initial vapour pressure developed at the saturation temperature at that level, and subsequently decreased slowly.

There is some superficial evidence of pressure increase of several bars in the higher temperature western Wairakei wells, but closer examination shows that the true vapour pressures, reflecting formation conditions did not increase.

For the vapour pressure to increase beneath the overlying Huka Falls Formation "caprock" at Wairakei would require the existence of vertical, highly permeable (open?) fissures, analogous to wells. As there is no evidence of any pressure increase, perhaps this indicates that such features are not present either?

Lessons from the measured vapour pressure changes at Wairakei are:

- Where a vapour zone develops, the pressure does not increase above the liquid pressure present at that level prior to field exploitation. Thus the vapour zone pressures will not initiate an eruption by exceeding lithostatic pressure below the caprock.

- The development of a vapour zone will result in an increase in vertical steam flow, and this is likely to result in an increase in small shallow focus "eruptions". These are unlikely to develop into deep-seated eruptions as they are steam-heated events.

DISCUSSION

The hydrothermal eruption initiation/propagation sequence described above may assist in our understanding of several related features in geothermal systems. Permeability enhancement by hydraulic fracturing can be explained without requiring an increase in overall reservoir pressures. Here an inverse argument is used. The fracture is enlarged by a sudden pressure reduction in the primary permeable feature (ie fractures), then the pressure difference between the matrix pores and this provides the energy to propagate the fracture by implosion and brecciation of the matrix. Rock mass is actually removed from the fractured zone. Here the hydraulic fracturing process occurs only where appropriate rock and fluid properties are present and the fracture may develop horizontally or vertically depending on the presence of these characteristics.

As these eruptions have been common to most of the Taupo Volcanic Zone high temperature geothermal fields during the last 20,000 years, there is no reason to believe that they were rarer in the past. If this is true, such events may be critical to developing the vertical permeability structure of such geothermal systems. If we consider that eruptions occur with a minimum frequency of once every 10,000 years, then a system such as Wairakei with a life of say 300,000 years would have experienced 30 major hydrothermal eruptions: The accompanying effects on the permeability structure of the system would be significant. While faults may be important features in the structure, permeability enhancement by hydrothermal eruption may in fact dominate. It is interesting to note that tracer tests indicate that faults (as mapped on the surface) are equally important as flow barriers as fluid conductors.

Since hydrothermal eruptions are typical features of high temperature active geothermal fields, it follows that their destruction potential should be considered as part of any exploitation proposal. The hydrothermal eruption history of a field should be specifically investigated by mapping the distribution of the eruption products and determining their chronology.

Hydrothermal eruptions are evidence of a dynamic, evolving geothermal system; there is a suggestion that they occur most frequently during the early growth of a field (e.g. at Waimangu) but become rarer as the field approaches maturity. Most geothermal fields are closely associated with active volcanic features. The seismic activity associated with any volcanic eruption could induce a hydrothermal eruption and this possibility should also be considered in risk assessment; similarly injection of magmatic gases in association with nearby volcanic eruption could also trigger hydrothermal eruptions such as those which occurred at Waiotapu about 900 years ago (Hedenquist and Henley, 1985).

ACKNOWLEDGEMENT

The authors acknowledge the permission of Electricorp Production for use of data pertaining to the Wairakei geothermal field; we thank J.W. Hedenquist and R.G. Allis for their helpful comments.

REFERENCES

Allis, R. G. 1979: Thermal History of the Karapiti area, Wairakei. DSIR Geophysics Division Report 137, 38p.

Allis, R. G. 1984: The 9 April, 1983 steam eruption of Craters of the Moon thermal area, Wairakei. DSIR Geophysics Div Rep 196, 25p.

Allis, R. G. 1986: Physical effects of expoitation of Wairakei geothermal field, Field Tour guide, Taupo volcanic Zone, New Zealand Geological Survey Record 11,166-169.

Bolton, R. S. 1961: The prevention of blowouts and other aspects of safety in geothermal steam drilling. UN Conference on new sources of energy, V3 Geothermal Energy, UN New York, 1964.

Browne, P. R. L. and Lloyd, E. F. 1986: Water dominated geothermal systems and associated mineralisation. New Zealand Geological Survey Record 11, 145-212.

Collar, R. J. 1985: Hydrothermal Eruptions in the Rotokawa Geothermal System Taupo Volcanic Zone. Geothermal Institute, Auckland University, Report GIR 014, 97p.

Collar, R. J, and Browne P. R. L. 1985: Hydrothermal eruptions at the rotokawa geothermal field, Taupo Volcanic Zone, New Zealand. Proceedings 7th New Zealand Geothermal Workshop, 171-175.

Hedenquist, J. W. and Henley, R. W. 1985: Hydrothermal eruptions in the Waiotapu geothermal system, New Zealand: Their origin, associated breccias, and relation to precious metal mineralisation. Economic Geology 80,1640-1668.

Keam, R. F. 1988: Tarawera: The Volcanic Eruption of 10 June, 1886. R.F. Keam (publisher, Auckland).

Lloyd, E. F. 1972: Geology and hot springs of Orakeikorako. New Zealand Geological Survey Bulletin 85,164p.

Lloyd, E. F. 1975: Geology of Whakarewarewa hot springs, New Zealand Geological Survey Report, DSIR Information Series No 111, 24p.

Lloyd, E. F. and Keam, R.F. 1974: Trinity terrace hydrothermal eruption, Waimangu, New Zealand. NZ Journ. of Science, 16:511-528.

Marshall T.W, 1987: Rotokawa geothermal field: Reservoir assessment and development impacts. Waikato Valley Authority technical report 1987/3.

Muffler, L. P. J., White, D. E. and Truesdell, A. H. 1971: Hydrothermal explosion craters in Yellowstone National Park. Bull of Geol Soc Am, 82: 723-740.

Nairn, I. A. and Solia, W., 1980: Late Quaternary hydrothermal explosion breccias of Kawerau geothermal field, New Zealand. Bull Volcanique, 43, 1-13.

Robertson, A. 1984: Analysis of subsurface compaction and subsidence at Wairakei geothermal field, New Zealand. MSc thesis, Geology Department, Auckland University, 123p.

Scott, B. J. and Cody, A. D. 1982: The 20 June 1981 hydrothermal explosion at Tauhara geothermal field, Taupo. NZ Geol Survey Report 103, 32p.