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POSSIBLE CAUSES OF HYDROTHERMAL ERUPTIONS

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SUMMARY – Small hydrothermal eruptions occur in New Zealand every few years and there is evidence of very large ones in the past. There is no clear distinction between these, phreatic eruptions and phreatomagmatic eruptions because the detailed mechanics of these events is not clearly understood. Literature on natural explosions, explosions in engineering plant and the results of exploding a buried charge are reviewed and 3 physical processes that could be the cause of hydrothermal eruptions are identified. The collapse (condensation) of a steam zone offers the best explanation for small hydrothermal eruptions.

1. INTRODUCTION

Small hydrothermal eruptions occur in New Zealand every few years; the most recent one occurred in September 2002, and they have occurred at Orakei Korako and Rotorua (Kuirau Park) in the last few years. There are many NZ examples of craters from large hydrothermal eruptions that occurred pre-recorded history. Hydrothermal eruptions have attracted a good deal of attention internationally but their cause is not understood. They occur in areas where the ground is generally hot and there is surface discharge of heat; there is sufficient thermal energy available to account for the mechanical work expended in forming the crater. It is impossible to contemplate the fundamental causes of hydrothermal eruptions without also considering phreatic and phreatomagmatic eruptions. The physical process or processes that give rise to any of these types of eruption are not understood and the terminology used in the literature is less than precise, see for example the review of terminology provided by Ollier (1974) and Browne and Lawless (2001). The words phreatic and phreatomagmatic are used to convey the notion that high temperature heat sources are involved, without and with magma, respectively.

Hydrothermal eruptions *start* suddenly, so it is reasonable to *ask* whether they can be classified as explosions. Surprisingly, given humanity's interest in creating them, explosions are only loosely defined as a sudden physical or chemical change of state of a mass accompanied by a release of energy. It is sometimes stated that the release must be rapid enough to produce a pressure wave; in air an explosion is audible, but the definition does not allow a distinction to be drawn between explosions and weak sound waves. Explosions that create damage produce shock waves, which are strong pressure waves with a very sharp front. However the pressure waves from an underground explosion may attenuate at the surface and be inaudible; there is no evidence of a bang from all hydrothermal eruptions, but they could nevertheless originate as an underground explosion by the release of energy at a rate that in air would produce shock waves. It appears acceptable therefore to consider that a hydrothermal eruption might be regarded as an explosion, and this was important in directing this review.

It is also a characteristic of hydrothermal eruptions that they last for minutes or hours, whereas other forms of explosion are over in milliseconds. Given that hydrothermal eruptions occur in geothermally active areas, it is not difficult to conceive of a crater, once formed, discharging water and steam like a geothermal well. It is the initiation of the eruption that is the puzzle, not its longevity.

2. LITERATURE ON HYDROTHERMAL AND PHREATIC ERUPTIONS

Including the literature on both phreatic eruptions and hydrothermal eruptions, publications fall into two categories, those that catalogue and analyse the results of eruptions and their precursors from a strictly geological point of view, and those that address the process. Some papers deal with both.

Barberi et al (1992) report on 132 historical phreatic eruptions, of which they found that the majority (1 15) were not followed by eruptions of magmatic material. They observed that the products were fall deposits (ash, mud and blocks) within a few hundred metres of the crater, but that in rare cases blocks were thrown 1.5km. They quote an 1888 Bandai eruption as being the biggest non-magmatic eruption in recorded history, and describe it as a "blast" throwing an estimated 1.3-1.5 km^3 of material over an area of 13 km^2 and killing 461 people. The main objective of their work was to decide whether there were consistent precursors to eruptions, and they concluded that the most consistent precursor was an earth tremor occurring up to a few hours before the event.

Browne and Lawless (2001) review New Zealand hydrothermal eruptions in detail, and note that numerous small relatively shallow eruptions have occurred in historic times but that much larger events involving depths of 450m occurred over the last few thousand years. The largest of these, at Rotokawa, deposited material over a radius of 2km. In discussing depth they note that the events may *start* in the top few metres and through time form a deep crater. They appear to favour the process starting with the failure of a localised layer of strong material, in locations where the water is near to boiling. They explain how such layers could be produced. They note that the explosion breccia is "milled" during the process (ie has the sharp comers rubbed off), before falling back into the crater. The implication is of high rate of change of kinetic energy of the debris. They provide an extensive literature list.

Germanovich and Lowell (1995) consider a phreatic eruption (one involving water and heat from magma, but no magma itself) resulting from cracks propagated following heat transfer from shallow magmatic intrusions. The paper includes significant analysis of structural failure of the rock.

Several aspects of hydrothermal eruptions have been investigated by McKibbin and colleagues, see for example McKibbin (1996)

All authors on this general topic in the earth science literature recognised that there is sufficient energy in the hot ground to account for the release. Those who have attempted analysis have applied conventional thermodynamic processes. By conventional is meant the consideration of energy release between two end states, with flashing of water to steam and with conventional transfer of heat to mechanical work by a "Pdv" process that is independent of rate. However the reports of actual events and geological evidence show that there must be more sophisticated processes involved, at least in those eruptions that are very large or very sudden. The possible excess pressure that could occur in the steady state at depths of a few metres is only a few bars abs., and it is difficult to see how this could produce even a small explosion. What is required is some physical process to amplify or focus the energy release, and this leads to an examination of rapid transients. Hence it is appropriate to examine man-made explosions and explosions in man-made equipment. In man-made equipment the geometry and material properties are well defined. This is a distinct advantage in the detailed analysis of events, compared to geological environments.

3. TYPES OF EXPLOSION

It is convenient here to define four types of explosive event, namely:-

1. failure of a vessel containing high pressure fluid
2. chemical explosions (TNT, gelignite, etc)
3. homogenous nucleation
4. collapse of a vapour bubble

This list focuses on explosions involving fluids and excludes events such as failure of a metal rod in tension, which releases energy at a high enough rate to produce a bang and might therefore be considered an explosion.

The first in the list differs from the rest, which involve release of energy by phase change; containment failure might involve phase change, but it is not a primary requirement.

Examples of category 1 are the over-pressuring of gas cylinders and pipes, which causes them to fail by splitting longitudinally. The release may create a shock wave, depending on the fluid and its pressure.

Chemical explosions, category 2, have received a great deal of attention. Since they are used to make holes in the ground, empirical methods are available to relate crater size to soil type and the type and weight of explosives. They produce a crater very like that of a hydrothermal eruption – Fig 1, taken from Henrych (1979).

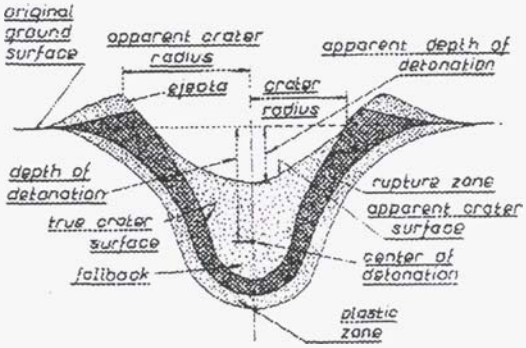

Fig 1 Crater produced by chemical explosion in soil, from Henrych (1979)

Examples of category 3, homogenous nucleation, are more difficult to demonstrate explicitly because other processes may take place simultaneously. Explosions caused by molten metals coming into contact with water are thought to originate from this physical process and have been investigated in the last two decades, particularly in connection with the safety of nuclear reactors. They are generally termed steam explosions. The energy release may be as great as a chemical explosion, and there are examples of extensive damage, eg a whole aluminium factory being destroyed as a result of an explosion arising in a continuous casting plant in which molten aluminium is discharged into water. Volcanic eruptions such as Krakatoa are thought to be of this type, as recognised by Blander (1979). It is fair to say that this type of explosion presented the same problem to engineers as hydrothermal eruptions to geologists – for a long time there was no clear idea of how so much energy could appear as mechanical work in such a short time. This type of steam explosion used to be termed a BLEVE (Boiling Liquid Expanding Vapour Explosion), but this term now has a wider meaning and includes the failure of pressure vessels containing flammable liquids at high pressure, such as LPG, which ignite to create fireballs (AIChE,1994).

Finally there is a class of explosions resulting from the collapse of a vapour bubble, category 4. The damage from these can be significant but is much less than in steam explosions. Examples are the failure of individual pipelines and valves rather than complete plant (Wilkinson and Dartnell, 1980). A spherical vapour bubble in pure liquid condenses by contracting inwards. The rate of condensation is high enough for the surrounding liquid to accelerate inwards to produce a point source of very high pressure.

4. CRATER FORMATION BY A CHEMICAL EXPLOSION

Hydrothermal eruptions form craters with a particular shape, as do chemical explosions, so it is worth examining the latter. A chemical explosion results from a rapid change of phase- from solid to gas. The change occurs in a narrow front radiating out from the source at very high speed as a detonation wave. Pressure waves normally travel at sonic speed (by definition) but with chemical explosives the detonation wave travels an order of magnitude faster, depending on the type of explosive. Henrych (1979) gives the detonation wavespeed in nitroglycerine as 8,000m/s, fast enough for the whole explosive to have reacted before the gas begins to expand. The detonation wave is a shock wave in which the conditions at the wavefront accelerate the phase change and reinforce the wave. The explosion of a charge buried in the earth may therefore be considered to start as a bubble of very hot, high pressure gas from which radiates a shock wave through the surrounding soil. Fig 2 is taken from Henrych (1979) who explains that the shock wave travels faster than the gas bubble expands, reaches the surface and reflects back as a pressure reduction wave (a rarefaction shock wave). The reflected wave reaches the bubble after it has expanded and has the effect of changing its expansion from spherical to an expansion towards the surface. The gas expansion goes on to form a "cupola" of the soil, which eventually bursts, the fragments spread out and some fall back into the crater to form an apparent crater surface, partly refilling the hole formed (see Fig 1). The various stages are shown in Fig 2. Henrych explains that the material initially thrown upwards is overtaken by material thrown by the rarefaction wave, serving to shatter the former material (cf the "milling" described by Browne and Lawless (2001)).

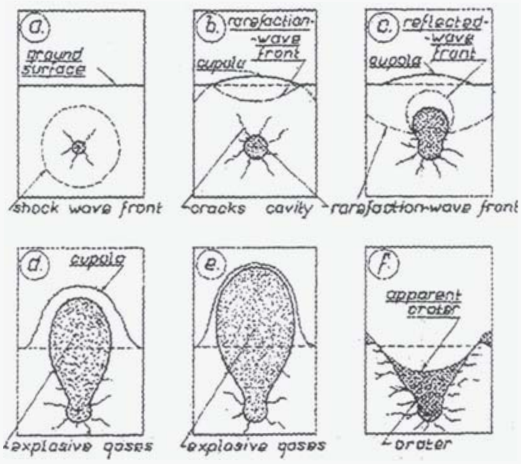

Fig **2** – Explosion process from a buried chemical explosive, from Henrych (1979)

5. PHYSICAL PROCESSES THAT PRODUCE NATURAL EXPLOSIONS AND THEIR APPLICATION TO HYDROTHERMAL ERUPTIONS

The analysis of chemical explosions reveals that speed of energy release and resulting shock waves are vital to the explosive process. We must now examine the circumstances in which explosion types 2,3 and **4** of the list in **3** above provide these features, and then consider whether the same circumstances can arise in geothermal areas.

5.1 Containment failure

Whilst containers are usually man-made, competent rock can constitute a containment wall.

Failure of a container of (non-inflammable) gas at high pressure is known to produce shock waves under some circumstances, as judged by blast damage. This blast is probably a function of rate of failure and internal pressure, eg there are reports of the neck of a gas cylinder being broken and resulting damage being due only to the cylinder acting as a projectile, whereas where cylinders split there is blast damage. The energy source is the compressive energy of the gas and the strain energy in the steel cylinder. Steel pressure vessels can be safely tested using pressurised water, to avoid blast, so it is clear that the contribution of the cylinder's strain energy to the total is not important, although it must influence the fracturing process – in simple terms it will pull the two parts aside. The usual cylinder pressure for common gases such as N_2 is in the order of 160 bars, so the rapid opening of the split will presumably result in a positive pressure shock wave moving out into the surrounding air, plus a rarefaction shock wave entering the cylinder and rebounding off the opposite wall as a positive pressure wave to follow the first shock wave out into the surroundings. It is not necessary to postulate a detonation wave, nor is there any chemical or physical process that might fit this description. However there is a report (AIChE, 1994) of a liquid CO_2 storage tank at only 8 bars abs and -15°C projecting fragments 360m and creating a blast. The flashing of liquid to vapour must therefore have played an important part. Failure of a layer of rock and flashing of water to steam is suggested by Browne and Lawless (2001) as a possible cause of hydrothermal eruptions. Comparing this with the CO_2 cylinder explosion, the enthalpy change from saturated liquid to saturated vapour ("latent heat") for C02 at 8 bars abs is only about ¼ of that of water, so the energy released is less than with water. The velocity of sound in liquid CO_2 and water are similar, but in gaseous CO_2 is half that in steam, so that shock waves would be more readily created by mechanical movement in the gas. Energy release by flashing water to steam is available at geothermal sites, but only at relatively low pressure, probably only 1-2 bars above atmospheric bearing in mind that eruptions start at only a few metres depth, even taking into account that the sinter might be overlain by wet (heavy) clays.

Altogether, there are too many imponderables and some laboratory experiments are required to make progress to find out whether simple containment failure is a contender for creating hydrothermal eruptions. A container filled with water saturated material typical of hydrothermal eruption fine debris and fitted with a bursting disk could be heated to above 100°C and then the disk burst deliberately. The reaction force of the vessel on its mounting could be measured and a parametric study carried out.

5.2 Homogenous nucleation

The change from saturated liquid to saturated vapour starts at nucleation sites. Water boiled at atmospheric pressure in a vessel by heating over a flame or electric element changes phase at nucleation sites in the walls of the vessel. The pattern of bubble growth is well understood and the nucleation sites in steel pipes or lutchen pans are scratches in the surface. Nucleation takes place at a few tens of °C above saturation temperature at most, and at less than 10°C in water at atmospheric pressure in kitchen pans. Poor nucleation sites are those that require a higher temperature in the liquid to initiate the phase change; laboratory chemists provide nucleation sites in smooth glass vessels to avoid "bumping", which is a more sudden phase change that results from the liquid being slightly superheated. The release of energy causes a pressure wave.

In the absence of any surface to provide nucleation sites, the phase change occurs at locations in the liquid where the increased molecular motion allows the molecules to be far enough apart to begin to behave as a gas. There is a homogenous nucleation temperature for every liquid and solution. This can be most easily measured by suspending a drop of the liquid or solution in another, immiscible liquid with a higher boiling point. The drop has no nucleation sites other than those that occur naturally within its molecular structure. The classical theory was developed by Volmer (1939), Skripov (1974) and others, and was reviewed by Blander (1979). A detailed description of classical measurements of the homogenous nucleation temperature or limit of superheat is given by Forest and Ward (1977), who investigated the effect of the liquid containing gas in solution.

For pure water, the homogenous nucleation temperature is of the order of 300°C. The energy released by the spontaneous nucleation of water with this degree of superheat is large and shock waves can be created. In the last two decades, many experiments have been carried out in which drops of molten metal are allowed to fall into liquid water. The molten metal provides no nucleation sites for the water, but delivers a high heat flux so that the water in contact with the drop becomes superheated. Significant explosive effects have been measured. Progress in understanding "steam explosions" has been reviewed by Fletcher and Theophanous (1994). This review makes it quite clear that several physical processes are involved, of which homogenous nucleation is only one. Various processes are envisaged to provide the greatest energy exchange between the water and the molten material. The review notes the experimental work of Stanmore and Desai (1993) in an investigation of explosions resulting from ash from coal-fired power station boilers falling into the water-filled ash hopper beneath the boilers. Pulverised coal was supplied to the boiler and the ash had a particle size ranging from 4 to 30μm. The ash particles were partly sintered as a result of the high temperature environment. Stanmore and Desai concluded that loose ash or highly fused lumps do not cause explosions, whereas lightly sintered ash does. This work may be relevant to an understanding of hydrothermal eruptions because, according to Meade (1964) this range of ash particle size is within the range of clayey sediments. Furthermore, Meade quotes montmorillonites as holding an order of magnitude more water than illite, and finally, clay particles are entirely wettable. That these facts are relevant to hydrothermal eruptions is speculative only at present – the temperature of the ash is much higher than that at the site of a small hydrothermal eruption.

5.3 Collapse of steam zones

The work by Wilkinson and Dartnell (1980) includes a study of the failure of a valve at Fiddlers Ferry power station, UK, in which the author was involved. Steam condensate in fossil fuelled power stations is pumped to a tank (deaerator) above the boiler. The tank is held at condenser pressure and the condensate is boiled to drive off dissolved gases. The water then descends a vertical height of 35 m to the feed pump, passing through a valve and strainer on the way. If the turbine trips the condenser pressure rises, and so does the deaerator pressure, and the deaerator water temperature is subject to variation. The cause of the explosion was deduced to be a steam bubble that formed by the flashing of hot water and became trapped in the bonnet of the valve and/or the strainer, subsequently collapsing when the pressure increased or the temperature of the surrounding water decreased. The relevant point is that the hydrostatic head of water was of order 2.5 bars abs, much closer to pressures that might be found under confining layers in geothermal ground at a few metres depth, yet the result was a burst cast iron valve, Wilkinson and Dartnell estimate that a 40 bar pressure wave was required to burst the valve. It seems conceivable therefore that bubble collapse could provide a pressure wave sufficient to fracture a thin layer of rock and produce the smaller hydrothermal eruptions observed in recent times in New Zealand.

6. DISCUSSION

It seems quite likely that the full range of physical processes, categories **1,3** and **4** above can occur in natural explosions associated with volcanism and geothermal heat. Blander's (1979) analysis of magma explosions resulting from homogenous nucleation is convincing.

In carrying out the work that led to this review it was at first thought that the presence of dissolved gas in the water could perhaps reduce the homogenous nucleation temperature sufficiently to bring it within the range of temperatures that might occur in shallow steaming ground. However a reworking of Forest and Ward's (1977) calculations shows that the reduction in homogenous nucleation temperature due to CO_2 dissolved in water is negligibly small. The reduction is surface tension dependent. Forest and Ward used nitrogen dissolved in ethyl-ether, which has a very much lower surface tension than water. It is possible that clays such as montmorillonite could exhibit some extra release of energy on the flashing of water contained in the clay, but there is no evidence of such an effect. The high pressures produced by steam bubble collapse reported by Wilkinson and Dartnell (1980) offer the best possibility of creating high pressures in near-surface geothermal conditions. The common precursor to hydrothermal eruptions that Barberi et al (1992) found was an earth tremor. This could produce flashing in water near saturation temperature, which would produce no eruption but would leave a steam zone. One can envisage such a small zone beneath a confining layer collapsing against the layer with the momentum of the following water fracturing the layer, and with remnants of the wave continuing on upwards. The pressure wave would rebound into the water beneath as a rarefaction wave, causing enhanced flashing to help drive the overlying soil upwards. The presence of dissolved non-condensable gas would reduce the pressure rise due to the bubble collapse; the water in power stations is particularly free of dissolved gas, leading to higher pressures at the centre of a collapsing bubble. This is a factor against bubble collapse as a strong explosion creator in geothermal situations, however a pressure rise much less than the 40 bar quoted by Wilkinson and Dartnell (1980) would produce a small eruption. Therefore failure of a confining layer caused by a steam zone collapse appears to be the most likely mechanism for producing the small hydrothermal eruptions observed recently in New Zealand. This proposed mechanism would be amenable to laboratory experimentation, which is necessary to make more progress.

7. CONCLUSIONS

A review of various physical processes that can cause explosions, and a review of chemical explosions and their craters suggests that the smaller hydrothermal eruptions are likely to be weak explosions caused by the collapse of a steam bubble, possibly beneath a thin confining layer of competent rock.

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