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## **Analogue modeling of instabilities in crater lake hydrothermal systems**

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### ***Abstract***

We carried out analogue experiments on two-phase boiling systems, using a porous vertical cylinder, saturated with water. The base of the cylinder was heated, and the top was cooled, as in a natural hydrothermal system. Previous work had shown that once the two-phase zone reached a certain level, thermal instabilities would develop. We made measurements of the acoustic energy related to boiling, and we found that high levels of acoustic noise were associated with the part of the cycle in which there was upwards water movement. We repeated our experiments with a cooling water tank at the top of the system, representing a crater lake. This showed that periodic thermal instabilities still developed in this situation.

We then compared our analogue measurements to two natural systems known to exhibit periodic behavior. There is good agreement between the variations seen in our model, and the variations seen at Inferno Crater Lake in the Waimangu Geothermal area, New Zealand, whose level cycles by nearly 10 meters, with a typical period of 38 days. Particularly notable is how in both systems high levels of acoustic noise are associated with rising water level. The much larger Ruapehu Crater Lake, also in

New Zealand, cycled with a period of several months to a year for over a decade prior to the 1995 eruption. Strong acoustic and seismic energy usually occurred just before the lake temperature started to rise. This suggests a slightly different model, in which the increasing two-phase flow zone triggers more general convection once it reaches the base of the lake.

## **1) Introduction**

Active crater lakes produce some specific volcanic hazards, including potential explosive contact between magma and water, discharge of the gas dissolved in the water, seepage of toxic fluids and the sudden draining of the water contained in the lake, with the risk of lahars.

A crater lake is a unique window that offers an insight into the way hydrothermal systems work and how they interact with magmatic sources. The monitoring of the physical parameters of a crater lake provides a way to quantify the integrated heat and mass flow from a volcano. Those volcanic crater lakes that are associated with hydrothermal systems will collect heat, liquid and gas from the underlying volcano.

Some crater lakes show temperature or level cycles, including the one at Ruapehu volcano and lakes in the Waimangu hydrothermal area located in the Taupo Volcanic Zone (New Zealand). Both have cycles that include rapid temperature increases ('heating phases'), which are generally not related to any magmatic activity. The study of this periodic behavior can lead us to understand how some hydrothermal systems can be intrinsically unstable. In this paper, we describe an analogue experiment, which aims to understand how boiling instabilities in porous media operate within these unstable hydrothermal systems.

If there is a volcanic crater lake above a hydrothermal system, this establishes a single-phase liquid reservoir at the top of the system. Hence, the shallower part of the hydrothermal system, just below the lake, can be seen as a porous or fractured medium saturated with liquid which is globally in a single phase liquid state, i.e. below the saturation temperature. However, it is quite common in crater lakes to observe that boiling occurs in some localized small areas. At the bottom of these hydrothermal systems, the fluids are likely to be in a single-phase vapor due to the high temperature of the gas coming from the magma (Hurst et al., 1991; Christenson and Wood, 1993). Above this dry vapor layer, there may be a two-phase layer or direct contact with the single-phase liquid layer above.

Schubert and Straus (1980) have studied the stability of a saturated single-phase liquid zone lying over a saturated single-phase vapor zone in a porous medium. Their calculation was revisited by Dominiak (2000) who showed, contrary to the results of Schubert and Straus, that this superposition is unstable whatever the permeability of the medium. Moreover, a two-phase layer is always present between the single-phase vapor layer and the single-phase liquid layer. This two-phase zone contains water and brine at saturation temperature, and exchanges latent heat at the bottom and top boundaries. These three layers constitute a heat pipe system (Udell, 1985), as deduced by Hurst et al., (1991) to be present at Ruapehu Crater Lake based on calculations of the effective enthalpy. The temperature profiles are linear in the liquid and dry vapor zones. In the two-phase zone, the temperature is nearly constant and the heat is transferred by convective counter-currents of rising steam and descending condensate. This layered configuration of liquid over steam induces a Rayleigh-Taylor gravitational instability (Schubert and Straus, 1980). The temperature increase with depth in the two-phase and liquid zones creates a natural convective instability while the viscosity difference between liquid and steam leads to a Saffman-Taylor instability in the two-phase zone (Chuoque and Van Meurs, 1959). Furthermore, the growth or decrease of the two-phase zone generates a convective flow in the liquid saturated layer,

which potentially causes another thermoconvective instability (Stemmelen et al., 1992). The aim of this paper is to study the effects of heat pipe instability by analogue modeling and to compare the results with some observations of Waimangu and Ruapehu crater lakes, both located in the Taupo Volcanic Zone of New Zealand.

## ***2 - Analogue experiment***

### **2.1 – Previous experiments on boiling instability in porous media**

Three-dimensional analogue experiments on boiling in porous media have been conducted by Sondergeld and Turcotte (1977) on a large water saturated sandbox heated from below and cooled from above. They observed the development of a two-phase water-steam zone after the boiling temperature was reached at the bottom. Because of the large size of the sandbox, this two-phase layer showed a non-planar interface with the liquid layer located above. For a higher heat flux, they observed the formation of a dry steam layer below the two-phase zone. Bau and Torrance (1982) used a cylindrical column with the same boundary temperature conditions, and observed temperature oscillations in the overlying liquid saturated layer when the two-phase zone depth exceeded a critical value. Stemmelen (1991) measured both temperature and saturation in a porous cylinder and observed stratification into three layers. For higher heat fluxes, instabilities of the front between the two-phase region and the liquid one were observed and periodic water flows were recorded through the permeable upper surface of the column. Like Stemmelen (1991), Fitzgerald and Woods (1997), also observed oscillations and both concluded that these oscillations were the result of a gravitational (or bulk compressive) instability, with thermal conduction in the liquid saturated zone as the restoring mechanism, which led to the period of oscillation  $T$  being proportional to  $h^2$  where  $h$  is the thickness of this layer. Dominiak

(2000) conducted several experiments with various heights of liquid saturated layer and also observed a good correlation between  $T$  and  $h^2$ .

## 2.2 - Description of the analogue acoustic experiment

Our aim was to extend previous analogue studies on boiling in porous media with two different experiments. The first experiment aimed to check if thermal instabilities were accompanied by noticeable acoustic activity. In the second analogue experiment, we imposed a new boundary condition at the top by adding a liquid reservoir instead of a constant temperature condition, in order to match crater lake systems.

A sketch diagram of the experiment is presented in Figure 1a. The porous medium of height  $H = 10$  cm is constituted of glass beads embedded in a vertical Pyrex tube of internal diameter  $D = 6.6$  cm. The diameter of the glass beads ranges from 150 to 250 micrometers, and was chosen in conformity with previous studies (Stemmelen et al., 1992; Dominiak, 2000) to correspond to unsteady periodic states. This column is heated from below by a thermostatic plate. A hollow cooling plate made of brass is present at the top of the bed, with its temperature maintained constant by circulating water. This plate is perforated to allow free liquid water flow and is pressed downward to prevent fluidization of the porous bed. The Pyrex tube is covered by glass wool for insulation. Several thermocouples are inserted vertically in the porous medium at different depths, so the acoustic signal can be compared with the temperature changes. The water level is measured by a piezometric sensor set in the liquid layer above the cooling plate. To detect the acoustic signal emitted from the boiling porous medium, a Brüel & Kjær 8103 hydrophone is suspended in the water layer above the cooling plate, without any mechanical contact to the tube. The signal from the hydrophone is high-pass filtered with a cut-off frequency of 500 Hz, then amplified. In order to monitor the spectral content of the signal, we sample the acoustic

signal at a frequency of 20,000 Hz. An accelerometer type 4378 from Brüel & Kjær, with a flat frequency response up to 7,000 Hz, is mounted on the Pyrex tube. The signal from the accelerometer is also high-pass filtered with a cut-off frequency of 500 Hz, then amplified. The rms. acceleration  $a_{\text{rms}}$  is recorded continuously during experiments.

### 2.3 - Acoustic experiment with fixed temperature

The porous medium is saturated with distilled water prior to the experiment. The heater plate is progressively heated to reach a temperature which ranges between 130 and 200°C in order to obtain an unsteady periodic state. We observe that the water is progressively pushed out of the porous medium, and when the overlying water layer reaches several centimeters above the perforated plate, the water level, temperature and the acoustic level start to display periodic changes. An example of temporal variations of water level and acceleration is presented in Figure 2a. In Figure 2b, we have plotted the acceleration  $a_{\text{rms}}$  as a function of the water level velocity  $v$  (the derivative of the overlying water level), and we can see that the acoustic level is stable when the level velocity  $v$  is negative and increases when the level is rising.

This shows that the acceleration amplitude  $a_{\text{rms}}$  clearly increases during the water upflow and is at a background level during the recession stage. The probable sources of sound during the upflow phase could be the cavitation of bubbles due to sub-cooled boiling, the breaking of liquid bridges between the beads and microscopic movement of glass beads. (Subcooled boiling is local boiling before the bulk of the liquid reaches boiling temperature, so the gas bubbles will collapse soon after they form.) All of these impulsive sources contribute to the acoustic energy, and excite the porous column in a wide range of frequencies. The fact that there is no increase of the acoustic level during the downflow part of the cycle means the transfer of fluid is not an efficient acoustic source in the porous medium.

After Leet (1988), the root mean square wave acceleration (or velocity) created by a boiling source at a distance  $r$  is proportional to  $\left(\frac{V_{steam}}{r}\right)^{1/2}$ , where  $V_{steam}$  is the volume rate of steam production. In our experiment, when the interface between the liquid layer and the two-phase layer is stable, the steam production is almost constant at a level  $V_0$ . When this interface is rising, there is a greater production of steam, and the liquid is pushed out of the porous column at a rate  $V_{out}$ .

If we assume that the total steam production  $V_{steam}$  is approximately  $V_{out} + V_0$ , i.e. that the mean saturation of the two-phase zone is kept constant, the acoustic *rms* acceleration  $a_{rms}$  will be proportional to  $(V_{out} + V_0)^{1/2}$  and thus to  $(1 + kv)^{1/2}$ , where  $v$  is the rise velocity and  $k$  a constant. The solid line on Figure 2b shows that a relationship of this form does give a reasonable fit to the observed acoustic signal, although there are some unexplained outliers.

The spectral content of the acoustic signal, as given by the accelerometer and the hydrophone measurements in the overlying water, has a peak around 1000 Hz, suggesting there is a resonator in the system. As observed in steamflood sites (Lumley, 1997), there is a strong impedance contrast between liquid and steam zones, due to a large seismic velocity decrease, up to 40 %, in the steam area compared to the liquid saturated area. This impedance contrast and the high attenuation in the steam layer make the liquid saturated layer a good candidate for an acoustic resonator which is excited by boiling at its base. In some experiments with the hydrophone, several peaks are clearly present, and some of these peaks shifted 30% higher in frequency during a heating phase. This suggests the characteristic length of the resonator is decreasing when the water level is high. This is consistent with the resonator being the top water-saturated porous layer, which is the only layer whose size is reduced during the heating phase and the water rise. The observed change in frequency corresponds



approximately to the change of  $h$ , the height of the liquid saturated layer. In some cases, however, no spectral structure with fundamental and harmonics was present, and the peak frequency was almost constant during the cycle. The reason for the presence or absence of harmonics and frequency shift was not clarified, but could be due to the shape of the surface that separates the liquid and two-phase zones, which was sometimes nearly planar and could then have been a more efficient resonator.

## 2.4 - Simulation of boiling beneath crater lake

In this experiment, we change the thermal boundary conditions to fit the conditions that prevail on a crater lake; instead of a fixed temperature at the top of the porous medium, we place a large volume of water whose surface temperature is allowed to vary freely (Figure 1b). The tank surface is subject to thermal exchange with the surroundings by convection and radiation, as at a crater lake. The Pyrex tube was changed to a Teflon one, because of its lower thermal conductivity and so we could easily insert horizontal thermocouples through the tube. We replaced the cooling plate by a sifter to prevent vertical movement of glass beads and placed the tube beneath a water tank, whose area is about 100 times larger than the area of the porous column. It should be noted that the Ruapehu Crater Lake presents approximately the same ratio (100:1) between the surface area of the lake and of the north vent which is its main heat supply. The aim of the experiment is to see if the new boundary conditions can still induce periodic thermal instabilities.

The results of this experiment show that the behavior of the system with water tank is similar to the one with a fixed temperature at the top. We observe unsteady periodic states, with periodic variations of temperature, both of the water in the tank and inside the porous medium. We present in Figure 3 typical variations of temperature and pressure in the tank. It should be noted that sometimes the oscillations stop, as shown previously by Bau and Torrance (1982) and Dominiak (2000), then restart several

minutes later. The period of the cycle has a stable mean value during an experiment lasting several hours, but individual cycle lengths varied by up to 30 %.

### ***3 - Application to Inferno Crater Lake, Waimangu hydrothermal area, New-Zealand***

#### **3.1 – Cyclic hydrothermal activity at Inferno Crater Lake, Waimangu.**

Waimangu is a major geothermal field in the Taupo Volcanic Zone, located in the North Island of New Zealand (Figure 4). Most of the present day features were created by the 1886 Tarawera rift eruption, when a number of new active vents appeared along a southwest-northeast trend. Two of these vents now contain Inferno Crater Lake and Frying Pan Lake (Figure 5). Inferno Crater Lake has always shown periodic water level variations. Between 1900 and 1904, when the nearby Waimangu Geyser was active, Inferno Crater Lake activity was affected by this geyser, with a cycle of about 36 hours. Frying Pan Lake formed after an eruption from Frying Pan Flat in 1917 (Lloyd and Keam, 1965). At present, the mean cycle length, between two water level minima in Inferno Crater Lake, is about 37.7 days  $\pm$  9.7 days (Scott, 1992b, 1994), and variations in Frying Pan Lake follow a related cycle.

Four distinct stages are recognized within the Inferno level cycle (Scott, 1992b, 1994); (1) an initial water rise of about 5 meters, (2) a period of oscillating but rising water level, (3) an overflow and (4) a recession stage when the water falls 8 meters. During a cycle, the lake water temperature shows a very good correlation with water level. We present water level and water temperature variations for the year 1972 in Figure 6.

In Waimangu as in many geothermal systems (Kieffer, 1984), the fluids at depth create a

background of seismic noise. There is a remarkable variation of the seismic noise amplitude during the water level cycle of Inferno Crater Lake (Tosha et al., 1996). During the phases in which the water is rising and overflowing, the seismic amplitude increases to 10 times the background level, then falls abruptly when the water level starts to decrease (Figure 7). It should be noted that this seismicity pattern is fundamentally different to the one recorded in Old Faithful Geyser (Kedar et al., 1996). In Waimangu, there are few discrete seismic events, about 50 during a cycle, and there seems to be no correlation between earthquake occurrence and cyclic change of the lake water level (Tosha et al., 1994). At Old Faithful Geyser, the seismic activity is composed of many discrete events, up to 100 per minute, whose rate of occurrence and amplitude get stronger as the eruption cycle progresses. The seismic signal in Waimangu is more a continuous noise, with increasing amplitude during a cycle, while the signal in Old Faithful Geyser is composed of discrete events, due to the collapse of steam bubbles (Kieffer, 1984).

### 3.2 – Model of Inferno Crater Lake

The results of the tank model are in good agreement with the Inferno Crater Lake observations. In both cases we observe periodic changes of water level and water temperature with a good correlation between these two signals. The seismic noise level observed at Inferno is high during the water level rise and overflow, and very low in the recession stage (Stanton, 1978; Tosha et al., 1996). These observations are also in good agreement with the results of our model, where the acoustic level is higher than background levels only during upflow periods. At Inferno, the seismic level increases during the cycle (McLeod, 1990; Tosha et al., 1996). In stage 1, the peak seismicity (about  $1.5 \mu\text{m.s}^{-1}$ ) corresponds to a rate of increase of lake volume of up to  $2000 \text{ m}^3$  per day. In stage 2, periods of high seismic level ( $3.5 - 5.5 \mu\text{m.s}^{-1}$ ) correspond to times when the level is rising with volume changes

between 4000 and 6000 m<sup>3</sup> per day. The highest seismic velocity occurs in stage 3 ( $> 5\mu\text{m.s}^{-1}$ ) where the average volume change is about 6200 m<sup>3</sup> per day. The ratio  $\text{flow rate}/(\text{seismic level})^2$ , which our model suggests should be proportional to the distance  $r$  to the source, decreases by a factor of 3.6 between stage 1 and stage 3. At present, the location and the extension of the seismic sources are not known, so a precise seismic survey around Waimangu Lakes is needed to define the movement of the boiling interface versus time.

By drawing up the mass and energy balance of Inferno Crater Lake, McLeod (1990) calculated the enthalpy of the incoming lake fluid during a cycle, which represents the ratio  $Q_f/M_f$  where  $Q_f$  is the vented energy, and  $M_f$  the vented mass. He found that the enthalpy slightly changes during a cycle, with a mean value oscillating between 500 and 1000 kJ.kg<sup>-1</sup>. These results show that the fluid consists mainly of hot water rather than steam which would have given a value of enthalpy three times greater. They also confirm that the steam content of the fluids entering the vent does not change very much during a cycle. The slight increase of enthalpy during a cycle can best be explained by an increase in temperature of the input fluid, which comes from a conducting liquid layer with a temperature gradient, and has a deeper origin with time. The pulsating regime during stage 2, has the same input enthalpy as the main cycle, and appears to be a secondary instability at a smaller temporal and spatial scale.

We will now study in more detail the enthalpy variations and the thermal balance of the lake, and see how the model can explain the relations between Inferno and Frying Pan lakes, and the changes of cycle period with time. It was observed that the level fluctuations of Inferno Crater Lake and the discharge of Frying Pan Lake displayed an interrelated cycle of 38 days (Scott, 1992b). The minimum level of Inferno Crater Lake is close to the level of Frying Pan Lake, the maximum level is about 9 meters higher. The fact that the temperature of Frying Pan Lake also responds to the 38 days cycle but

is not in phase with Inferno Crater Lake temperature indicates there is not a direct hydraulic connection between the two lakes. Moreover, if we compare these two signals, it appears that only the long period components are in common, the short period fluctuations are not transmitted from one lake to another. The area around the old Waimangu geyser site, which is located between Inferno and Frying Pan lakes (Figure 5) also has cyclic deformation changes (Otway, 1976), with a vertical displacement of about 2.3 mm at the center of the site. The time lag between the ground level minimum at Waimangu geyser site and the water level minimum in Inferno Lake is about 8 days with a horizontal separation of 200 meters. The time lag observed between the levels of Frying Pan Lake and Inferno Crater Lake (Scott, 1992b) is about 17 days, for a horizontal distance of 400 meters between the two lakes (center to center). The corresponding velocities of perturbation are the same for both systems, about 25 meters per day, if we assume a horizontal path. All these observations seem consistent with a process of pressure diffusion in the compressible two-phase zone of the hydrothermal system. We can estimate the hydraulic diffusivity inside the hydrothermal system, by using the relationship giving the diffusion velocity  $v$  of a periodic perturbation of period  $T$  (Carslaw and Jaeger, 1959), in an infinite medium of diffusivity  $\kappa$ :  $v = \sqrt{\frac{4\pi\kappa}{T}}$ . Taking the horizontal velocity of 25 meters per day as a minimum velocity, we obtain a minimum diffusivity of about  $2 \cdot 10^{-2} \text{ m}^2 \cdot \text{s}^{-1}$ , or  $1900 \text{ m}^2 \cdot \text{day}^{-1}$ . The soil consists of volcanic deposits, some of which are only 100 years old from the Waimangu geyser. The common value of diffusivity used for densely packed sand or clayey sand lies between  $10^{-3}$  and  $10^{-2} \text{ m}^2 \cdot \text{s}^{-1}$  (Domenico and Schwartz, 1998). The higher observed diffusivity value may indicate the recent material is still loosely packed, or represent enhanced diffusion in the direction of the recent volcanic fault lines.

The two lakes and the geyser appear to be part of a single hydrothermal system, oriented SW-NE as suggested by the crater location and the topography, with a two-phase reservoir which operates as a heat pipe quite close to Inferno crater. This reservoir would generate instability in Inferno Crater Lake

and a related pressure and temperature pulse in Frying Pan Lake. A single hydrothermal system is in agreement with the observations made by Scott (1992a) who observed a constant state for the total combined annual vented mass, energy and enthalpy of the two lakes. The apparent inverse relationship between the discharge of Frying Pan Lake and the water level in Inferno, can be seen as a coincidence due to the distance between the two lakes that induces a phase difference of about half a cycle.

The lake level record since 1971 (Scott, 1992a, 1994) shows that the hydrothermal system is subject to perturbations. The period of the cycle can change as observed between 1977 (8 cycles per year) and 1978 (12 cycles per year) and sometimes the periodic activity can stop as occurred for several months during 1990. The period  $T$  as described by the 1-D model should depend, among other things, on the thickness of the liquid saturated layer  $h$ . If only conduction occurs in the liquid layer, Fourier's law of heat conduction  $q = -k.grad(T)$  implies that the height of the liquid saturated layer, and hence  $T$ , will change with thermal boundary conditions, i.e. the temperature at the lake surface and the heat flux  $q$  at the base (Figure 8a). The 1972 benchmark appears as a year when the period of the oscillation seems to have been affected by the surface temperature, with an inverse correlation between the period and the annual air temperature (Figure 8b). It should be noted that only a few years during the period 1971 to 1991 show this inverse correlation. Other parameters can change the period of oscillation, such as the basal flow or the hydraulic conditions in the pipe, which depends on the amount of water recharge to the system. As seen in the analogue model, the single cycle duration can change by 30 %, so some of the observed variations in Inferno are inherent instabilities of the system.

### 3.3 – Scaling Relationships

In this section, we look for an appropriate scaling parameter to compare the analogue experiment with the observations at Inferno Crater Lake. The restoring mechanism after instability develops is the

thermal conduction in the liquid saturated zone (Stemmelen, 1992, Fitzgerald and Woods, 1997, Dominiak, 2000), which suggests the dimensionless parameter  $P = \frac{T_c \tau}{h^2}$ ,  $h$  and  $\tau$  being respectively the height and the thermal diffusivity of the liquid saturated porous medium, and  $T_c$  the period of the cycle. Values of diffusivity  $\tau$  in liquid saturated layer for the glass beads in the experiment and for the volcanic sediments in the vents are likely to be similar.

In Inferno Crater Lake, the large (10 metre) lake level changes and the speed of the recession stage, which looks like a gravitational collapse of the overlying liquid-saturated layer, suggest that the instability is gravitational rather than convective (Ramesh and Torrance, 1990). Such a gravitational instability, unlike convective instabilities such as liquid fingering, has no characteristic scale of its own, so we should expect the relationship between the two systems to give a constant value for  $P$ , in other words  $T_c \propto h^2$  to obtain an order of magnitude of the liquid-saturated layer thickness  $h$  for Inferno. Taking a layer thickness of 10 cm and a cycle period of 10 minutes for the analogue experiments, the thickness at Inferno with its 38-day cycle should be 74 times larger, i.e. about 7.5 meters. It is reasonable that this thickness value can be smaller than the lake level range (10m), because the volume of expelled water originates from the whole aquifer at Waimangu hydrothermal system, as well as water resulting from de-saturation processes in the two-phase layer during the rising level phase (Dominiak, 2000). This reasonable agreement supports our assumption that our analogue model exhibits the same instability process that is at work around the Inferno Crater Lake.

#### ***4 - Application to the Ruapehu Crater Lake, New-Zealand***

##### **4.1 - Activity of Ruapehu hydrothermal system**

Mt Ruapehu is an active andesitic stratovolcano located at the southern end of the Taupo Volcanic Zone on the North Island of New-Zealand (Figure 4). Before the 1995-1996 series of major eruptions, a crater lake (Ruapehu Crater Lake) filled the crater and was overflowing the southern crater rim by a narrow channel. At the level of the outflow, the surface area was estimated to be  $2.10^5 \text{ m}^2$ , and the volume was  $7.5 \cdot 10^6 \text{ m}^3$ . The maximum depth recorded during bathymetric surveys before the last eruptions was about 170 meters. This lake permanently received mass, energy and chemical flows from a hydrothermal system, mainly discharging through the North Vent. Regular observations of water temperature, outflow rate and water chemistry have been made at approximately monthly intervals since 1965 (Hurst et al., 1991). From December 1993 to June 1995, a datalogger recorded Crater Lake temperature and hydro acoustic levels in the lake at a 2 hours interval (Hurst and Vandemeulebrouck, 1996). Observations of the lake temperature and chemistry since about 1980 have shown a form of cyclic heating and cooling, with a cycle period ranging from six months to more than one year. During the heating part of the cycle, the water temperature could rise by up to  $1^\circ\text{C}/\text{day}$  and reach up to  $60^\circ\text{C}$ , but this did not lead to any significant eruption. The thermal power input to Crater Lake, was calculated by Hurst and Dibble (1981) and later by Hurst et al. (1991) from the changes in stored energy of the lake after allowing the effects of surface cooling. Typical values of the thermal power input were about 400 MW during a heating phase, and about 100 MW at other times.

During the 1971-1996 period, the relations between recorded seismicity and volcanic activity at Ruapehu depended on the style and scale of eruptions (Sherburn et al., 1999). Therefore, although every heating phase was accompanied by tremor emission (Dibble, 1974; Sherburn et al., 1999), volcano-tectonic earthquakes were not usually observed. The heating phases are thus not the result of hydro-fracturing at depth, as observed in Poas (Rowe and al, 1992) and in Kelut crater lakes (Lesage and Surono, 1995, Vandemeulebrouck et al., 2000) but appear to be a change of flow regime in an open



hydrothermal system. Tremor observed on Ruapehu generally had one or two sharp frequency peaks, and a normal dominant frequency between 1.8 and 2.3 Hz with very little second harmonic energy (Hurst and Sherburn, 1993). A spectral peak around 6-7 Hz has been observed since 1993, and was attributed to a shallow source near the lake (Sherburn et al., 1999). From 1985 to 1988, a shift from 2Hz to 3Hz of the tremor peak frequency was observed during heating phases and was attributed to additional heat input to the lake (Sherburn and Hurst, 1988).

The power of hydroacoustic signals from the lake water was measured continuously from December 1993 to June 1995 (Hurst and Vandemeulebrouck, 1996). The two first heating phases in 1994 were both preceded by strong acoustic signals, with most energy being recorded in the 2Hz frequency band (Figure 9). Only a moderate level of acoustic signals was recorded in November 1994, just before the third heating phase started. Very strong acoustic signals were recorded during May 1995, one month before a small eruption on 29 June 1995. Ruapehu finally produced a substantial eruption starting in September 1995, which resulted in the complete disappearance of its crater lake.

#### 4.2 Model of Ruapehu Crater Lake

Heat balance models, as calculated by Hurst et al. (1991), showed that only a heat pipe at depth can generate the elevated power, up to 600 MW, observed in Ruapehu Crater Lake. To transfer such power, the vent should consist of very permeable material, saturated with fluids. In a normal state, it seems likely that the shallower part of the vent, just below the lake bottom, is saturated with single-phase liquid because of the low temperature lake water at its upper surface. This assumption was confirmed by hydroacoustic noise measurements in the North Vent in 1991 (Vandemeulebrouck et al., 1994), which showed low acoustic levels in the audio frequency bands. These bands correspond to the sound produced by steam bubble collapse in the lake. The observed low acoustic level shows that during a

period of low to moderate heat input, steam input is quite small and that almost the entire heat input is carried by hot water, rather than by steam. The upper part of the vent can thus be seen as a liquid saturated layer, with some small areas of boiling. Based on chemical analyses, Christenson and Wood (1993) argued that there was strong evidence of boiling occurring deeper within the vent and the development of highly concentrated fluids. These authors agreed with Hurst et al. (1991) on the existence of a heat pipe and they explained the observed increase in Mg and Cl in the lake during heating phases and eruptions by the expulsion into the lake of previously formed brine fluids. The structure of our model thus seems consistent with these observations.

In their study on heat source of Ruapehu Crater Lake, Hurst et al. (1991) observed several episodes of lake outflow increase during eruptions (1966, 1969) and heating phases (1968, 1971, 1975, 1980, 1982). These overflows were followed by lake level decreases, up to 5m below the outlet, at the time of lake cooling. Two phenomena can be the source of level changes: the thermal expansion of water, and water/steam exchange between the hydrothermal system and the lake. For lake water cooling from 60°C to 30°C, the specific volume change at normal pressure is about –1%. As the Ruapehu lake volume was estimated by Hurst et al. (1991) to be  $7.5 \times 10^6 \text{ m}^3$  and its surface  $2 \times 10^5 \text{ m}^2$ , the level change due to the thermal contraction of the lake is about – 0.375 meter, which is one order of magnitude below the level drop observed during 1966 and 1985. The thermal expansion is thus not responsible for the observed lake level changes. The alternative, as suggested by Dibble (1974), is that steam pushes out liquid water during a heating phase and steam is replaced by liquid during cooling, which amounts to a displacement of the interface between liquid layer and two-phase layer, as in our model.

At Ruapehu Crater Lake, the duration of the tremor episode before a heating phase is very short, just a few days, compared with the duration of the heating phase, that lasts a number of months. This differs from our analogue model, where the two durations are the same, and could be explained by the small

height of the liquid saturated layer in the vent. The rise of the boiling interface stops when it reaches the top of the vent near the lake water, and the seismic noise in the vent returns to the background level. We suggest that upflow in the North vent triggers convection on a larger scale, including the lake itself and the layers at the lake bottom, which appear as a fluidized bed during sampling. The existence of convection outside the North Vent was deduced by Christenson (2000) from the chemical analyses of lake water. If the origin of the thermal instability is convective (Ramesh and Torrance, 1990), i.e. in a liquid-dominated two-phase zone, the characteristic length  $h$  should include all the parts of the system that can convect, and will be much larger than the upper part of the North Vent. As the characteristic size  $h$  is larger, the cycle period should be longer, which implies that the characteristic length of the resonator differs from the size of the unstable zone, and the durations of the acoustic and thermal cycles are so much different. Before the Ruapehu 1995-1996 eruptions, it was difficult to evaluate the flow into the Crater Lake, because the lake was generally overflowing at the outlet, and there was not any flow monitoring. At present, the lake level is well below the outlet one, and we are endeavoring to monitor the lake level, temperature and the hydro-acoustic noise, in order to get a better understanding of the lake processes.

The main differences between Inferno and Ruapehu crater lakes are the different size of the hydrothermal systems which implies different input thermal power and cycle period, and the lack of interaction with a magmatic system in the case of Inferno. The non stationary heat flux and gas flow at the base of the Ruapehu heat pipe produces a very variable cycle time, compared to Inferno which has a comparatively constant period.

## **5 - Conclusion**

We have extended previous analogue models of two-phase boiling systems, firstly by recording

acoustic signals associated with the periodic instabilities that developed. Strong acoustic signals occurred only when an increasing volume of steam was pushing the steam-water interface upwards, suggesting that the acoustic source was associated with boiling, as in Leet (1988). We also found that periodic instability still occurred when the upper boundary was changed from a constant temperature plate to a water tank representing a crater lake. This instability whose nature seems to be rather gravitational than purely convective exists even if the heat power and the thermal boundary conditions are maintained constant.

The temperature and level changes in Inferno Crater Lake (Waimangu) show regular variations very similar to those of the analogue model. It also is a clear example of seismic energy produced by the movement of hydrothermal fluids, and again the seismicity varies with the rate at which water is pushed up from the two-phase system. Ruapehu Crater Lake also has quasi-periodic temperature variations, but the acoustic episodes are very short compared to the heating phases, which could indicate a more complex system than a 1-D heat pipe with impermeable boundaries.

Our main conclusion is that the hydrothermal systems at Ruapehu and Waimangu can produce their own intrinsic instabilities without any changes in their underlying magmatic systems. This phenomenon may also occur at other volcanoes that are capped by a hydrothermal system. For volcano monitoring, it is crucial to be able to discriminate such hydrothermal instabilities from ones of magmatic origin. Studies on how hydrothermal systems work and respond to external forcing should be pursued to reach that goal. Finally, we need to improve our current observations of volcano crater lakes, if we want to be able to identify when the magmatic bodies are starting to change, as opposed to instabilities that only affect the hydrothermal system above the magma.

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## Figure captions

Figure 1: Sketch diagram of the analogue experiments: (a) acoustic experiment with fixed temperature, with the aspect ratio conserved; (b) simulation of boiling beneath a crater lake. The water tank size is not to scale.

Figure 2: An example of periodic instabilities observed in the analogue experiment : (a) temporal variations of level of the overlying water layer and rms acceleration level. (b) Corresponding rms acceleration level  $a_{rms}$  as a function of velocity  $v$  of the overlying water level. The solid line fit corresponds to a function  $a_{rms} = cst$  for negative velocities (water level decrease), and to a function  $a_{rms} = c(1 + kv)^{1/2}$  for positive velocities (water level rise), where  $c$  and  $k$  are constants.

Figure 3: Temperature and hydrostatic pressure (in arbitrary units) transients observed in the water tank.

Figure 4: Map of the North Island of New-Zealand showing the location of Mt Ruapehu and Waimangu hydrothermal site, and the approximate boundaries of Taupo Volcanic Zone (solid line).

Figure 5: Location of Inferno Crater Lake, Frying Pan Lake and Old Geyser site at Waimangu, New Zealand.

Figure 6: Inferno Crater Lake level and temperature observed in 1972 (courtesy of Brad Scott, IGNS).

Figure 7: An example of seismic level (grey) and lake level relative to overflow level (solid line) observed at Inferno Crater Lake during a cycle. Adapted from McLeod (1990).

Figure 8: (a) Analogue experiment: Cycle period  $T_C$  for different values of cooling temperature at the top of the column (b) Cycle length and air temperature observed at Inferno Crater Lake in 1972: the solid line with triangles represents the cycle length of Inferno lake level, the dashed line with circles the monthly averaged air temperature in Rotorua.

Figure 9: Observations at Ruapehu Crater Lake from December 1, 1993 to June 26, 1995: (a) Lake surface temperature ( $^{\circ}\text{C}$ ), (b) acoustic pressure level ( $\text{Pa}/\sqrt{\text{Hz}}$ ) recorded by sensors in the lake; (c) volcanic tremor level ( $\mu\text{m/s}$ ) recorded at Dome Shelter seismometer. Due to a range problem in the acquisition system, temperature values above  $47.5^{\circ}\text{C}$  were off scale.

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