CALORIMETRY AND HYDROTHERMAL ERUPTIONS, WAIMANGU HYDROTHERMAL FIELD, 1971-1990

Bradley J. Scott
Institute of Geological & Nuclear Sciences, Rotorua, N.Z.

SUMMARY

Application of mass and energy balance equations for a water body allow the vented mass and energy of the two crater lakes at Waimangu to be calculated. The ratio of vented energy to vented mass is the enthalpy of the fluid entering the lake. At Frying Pan Lake the mean annual mass discharged is 121 x 10^5 kg and energy 8.87 x 10^{12} J. The mean annual enthalpy is 749 $\pm$ 19 kJ kg^{-1} representing a vent temperature of 177°C. At Inferno Crater Lake the mean annual vented mass is 50.6 x 10^5 kg and energy 4.1 x 10^{12} J. The average annual enthalpy is 1197 $\pm$ 117 kJ kg^{-1}. During the 19 year monitoring period examined, seven hydrothermal disturbances have occurred within the Waimangu hydrothermal system; some were subtle while others were catastrophic producing large surface changes. The long term trends indicate the total heat flow from Waimangu has stabilised to the physical conditions created by the 1886 volcanic eruption. This stable signature also indicates a steady state in processes associated with Tarawera Volcanic Complex.

INTRODUCTION

Surface hydrothermal activity at Waimangu is associated with the southwestern end of a 17 km-long en echelon fracture formed on 10 June 1886 by the Tarawera Rift eruption (Nairn and Cole 1981). Mass and energy balance equations which derive the mass and energy of the vented fluids are examined and applied to the 1971-1990 data set, and also to calculate the fluid enthalpy. Changes in the vented mass, energy and enthalpy are discussed in conjunction with known hydrothermal events defining the long term behaviour of the Waimangu hydrothermal system.

CALORIMETRY CALCULATIONS

The enthalpy of the deep fluid feeding a hydrothermal lake can be determined from the application of the laws of energy and mass conservation. In the case of a hydrothermal lake, the primary source of energy and mass is the fluid entering via submerged springs. To determine the vented energy, contributions from various extraneous energy sources, and sinks, are identified and removed from the nett calculated change in energy stored in the lake during a given interval. The residue is the vented energy. Application of a mass balance equation determines the mass of fluid being vented into a lake. The ratio of vented energy (Q_v) to vented mass (M_v) is the enthalpy (H_v) of the fluid entering the lake:

$$H_{fv} = \frac{Q_v}{M_v}$$

At Waimangu the calorimetry of both Frying Pan (Wilson, 1981) and Inferno Crater lakes (McLeod, 1983, 1992) have been studied. These studies examined and determined the relative magnitudes of the individual components of the mass and energy balance equations. These were re-examined and applied to daily instrumental records from 1971 to 1990 by Scott (1991).

In the case of both lakes, the mass gained from peripheral springs and precipitation, and lost by seepage are small and can be ignored. Therefore the mass entering the lake from the vent(s) is: $m_v = \Delta m_{lake} + (m_d + m_e)$
where:

m_v	=	input of steam and water from the vent(s)
Δm_{lake}	=	increase/decrease in lake mass
m_d	=	surface discharge (overflow or volume change)
m_e	=	mass evaporated

The largest component for Frying Pan Lake is the discharged mass (m_d), while at Inferno Crater Lake the increase/decrease in mass associated with water level change (Δm_{lake}) is.

The law of conservation of energy states that if no work is done on or by a system, the increase in the stored energy of the system is equal to incoming energy less outgoing energy. For a lake with varying volume of water at varying temperature the total incoming energy via the vent(s) Q_v is:

$$Q_v = Q_e + Q_a + Q_c + \Delta Q - Q_r$$

where:

Q_e = energy lost by evaporation
Q_a = nett advected energy
Q_c = energy lost by conduction
ΔQ = increase in the stored energy of the lake
Q_r = nett radiated energy received

In the case of Frying Pan Lake the energy used for evaporation (Q_e) is the largest component, while at Inferno Crater Lake the nett increase in stored energy (ΔQ) is.

LONG TERM TRENDS

The mass and energy balance equations have been applied to the post 1971 daily records from Frying Pan and Inferno Crater lakes in an attempt to define the state of the Waimangu hydrothermal system in the longer term. However such an operation produces high frequency signals in the data plots. To overcome this, mean annual data are used in this presentation.

Frying Pan Lake

The mean annual vented mass has ranged from 134.0 x 10^5 kg in 1973 to 109.1 x 10^5 kg in 1983. A persistent decline is apparent from 1973 to 1983, remaining steady 1983-1988, and rising 1989-1990 (Fig.1). This trend correlates well with rainfall trends. The vented energy also displays a similar trend, although the decline is interrupted between 1977 and 1981, before reaching a low in 1983, rising again to 1986, falling in 1987 and then rising again (Fig.1). The mean annual vented energy has ranged from 10.16 x 10^{12} J in 1973 to 7.97 x 10^{12} J in 1983, with a mean of 8.87 ± 0.54 x 10^{12} J for the 19 years of record.

The long term enthalpy trend displays arise with time (Fig.1). A peak in 1973 reflecting the Trinity Terrace eruption (Lloyd & Keam, 1974), followed by a decline to 1977, sharp rise in 1978 then a steady rise through to 1981. This is followed by a fall in 1982-83 and then another peak in 1986 and a sharp decline in 1987 (Fig.1). A simple 6 year cycle is apparent in this data. The mean annual enthalpy has ranged from 1152 to 702 kJ kg^{-1} with a mean of 749 ± 19 kJ kg^{-1} for the 1972-1990 period.

Inferno Crater

The mean annual vented mass (Fig.2) has ranged from 30.8 x 10^5 kg in 1973 to 79.5 x 10^5 kg in 1980, averaging 50.6 ± 14.4 x 10^5 kg (1971-1990). A significant increase is apparent in 1975, followed by a sharp decline to a steady level 1977-1979. Sharply rising in 1980, then declining to 1984, with a minor peak in 1985, before declining to a low in 1988-1989. A sharp rise occurs in 1990 (Fig.3).

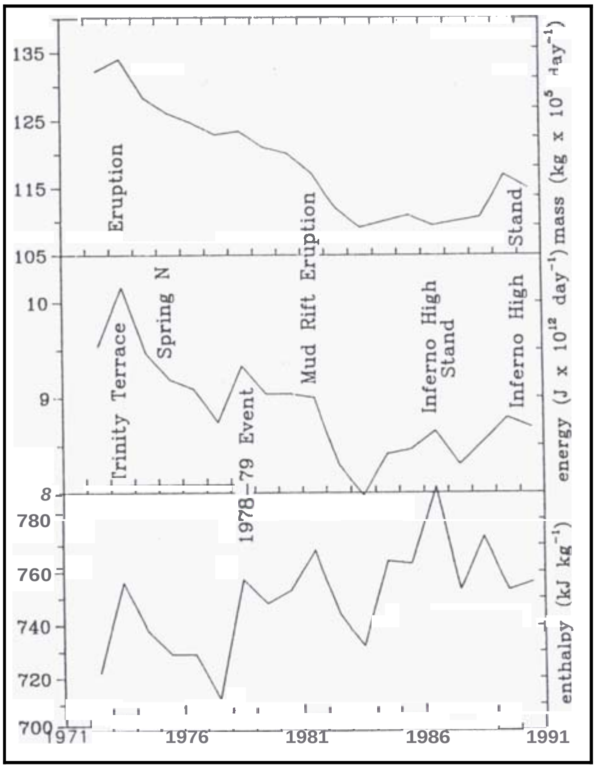

Figure 1: Time series plots of annual vented mass, energy and enthalpy for Frying Pan Lake 1971-1990.

The annual vented energy from Inferno Crater Lake has ranged from 2.4 x 10^{12} J in 1973 to 5.9 x 10^{12} J in 1980, averaging 4.09 ± 0.93 x 10^{12} J. Declining to 1973, the energy rose sharply in 1974 to peak in 1975 before declining 1976-1977. It then oscillated high-low-high, to a high in 1980, followed by a long term decline to 1989 except for a minor peak in 1985 (Fig.2). In contrast the enthalpy is relatively constant except for a broad high 1973-1981 with two prominent peaks, one being strongly correlated with the 1978-1979 Raupo Pond/Inferno Crater Lake hydrothermal disturbance (Keam, 1979). A sharp rise is apparent 1990. These variations are discussed below in relation to known hydrothermal disturbances. The average annual enthalpy is 1097 ± 117 kJ kg^{-1}, having ranged from 910 to 1471 kJ kg^{-1}.

The mean annual enthalpy of Frying Pan Lake (749 kJ kg^{-1}) indicates a minimum temperature of 177°C in the hydrothermal system below this feature, while the Inferno result (1097 kJ kg^{-1}) represents 274°C. Keywood (1991) examined a range of geothermometers and estimated subsurface temperatures from near boiling discharging features in Echo Crater at 200-240°C, and Inferno Crater Lake at 198-270°C. These results are in general agreement. Application of enthalpy-chloride models produces a deep parent fluid of enthalpy 1160 kJ kg^{-1} with a chloride content of 540 mg/kg (Keywood, 1991).

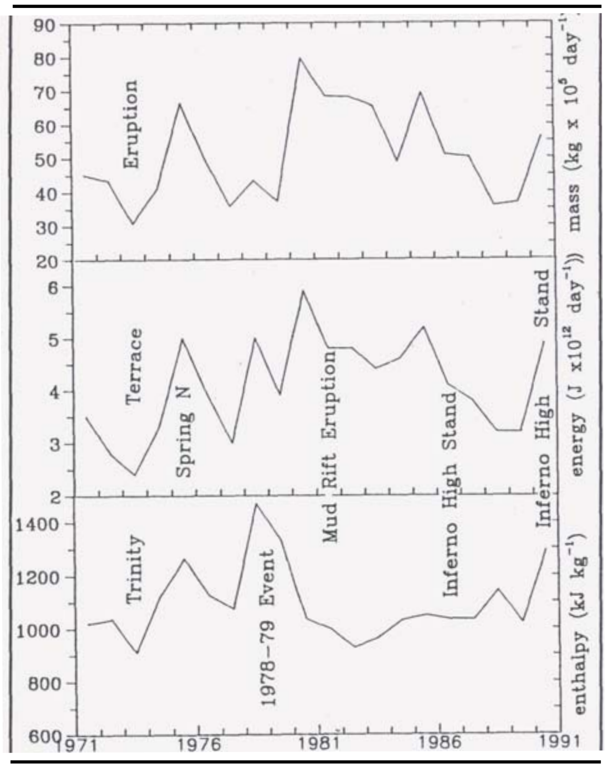

Figure 2: Time series plot of annual vented mass, energy and enthalpy for Inferno Crater Lake 1971-1990.

HYDROTHERMAL DISTURBANCES

Since instrumental monitoring commenced in 1971 several hydrothermal disturbances have occurred at Waiinangu. Some such as the 1973 Trinity Terrace eruption were catastrophic creating large changes, while others were subtle and caused abnormal behaviour in only one of the lakes. Each of these are described in detail by Scott (1991) and summarised below.

Trinity Terrace Eruption

On 22 February 1973 a hydrothermal eruption occurred within Echo Crater at Trinity Terrace. The eruption continued for at least 15 minutes and 970 ± 150 m^3 of country rock was ejected. Frying Pan Lake was increased in area by 285 ± 15 m^2 as a result of the explosions (Lloyd & Keam, 1974).

Spring N

In late May 1975 changes to the hydrothermal activity at Waimangu Geyser site in northeastern Echo Crater were noted. A boiling spring (Spring N) developed into a geyser and vegetation showed signs of heat stress and other springs dried up. Detailed ground temperature measurements, precise levelling, and chemical monitoring were conducted. The tail end of an elevated temperature and ground surface went was recorded, but no eruption eventuated.

1978-1979 Raupo Pond-Inferno Crater Lake

During the night of 23 February 1978 a hydrothermal event occurred at Raupo Pond Crater and Inferno Crater Lake (Keam, 1979). The Mud Rift was in eruption and a new depression of about 600 m^3 volume formed in Inferno Crater Lake. Although this event is discrete, irregular activity continued over the next seven months.

1981 Mud Rift eruption

In May 1981 eruptions at Raupo Pond Crater created two small craters and destroyed the Mud Rift (Scott 1982, Scott & Lloyd 1982).

1986 Inferno High Stand

Following an apparently normal rise in January 1986, the water level of Inferno Crater Lake remained above -2.28 m for 67 days, and overflowed at least nine times. During March conditions became very stable with overflows every 77 ± 4.4 hours, lasting for 8.1 ± 3.2 hours, and discharging 1.40 ± 0.09 x 10^6 litres. Following this unprecedented sustained high stand, water level receded normally to -9.75 m.

1990 Inferno High Stand, Part One

Following a failed cycle in December 1989, several large oscillations were apparent on the next rise to overflow in early February 1990. Once near overflow level Inferno Crater Lake stood high for about 160 days, except for a minor recession in late May to -3.63 m. During this high stand at least 50 overflows occurred and a considerable volume of mud was deposited in the crater. The flows lasted 9.0 ± 5.8 hours and discharged 2.4 ± 1.5 x 10^6 litres each.

1990 High Stand, Part Two

Following an overflow in November 1990 the lake only receded 1.78 m before re-establishing another prolonged high stand and accompanying minor overflows, which lasted until January 1991. Nine flows lasting 7.1 ± 0.9 hours, occurred every 60.2 ± 17.3 hours. The average discharge volume was 1.86 ± 0.34 x 10^6 iitres.

In contrast with the 1986 high stand there is a significant increase in the vented mass and energy associated with the 1990 events. At Frying Pan Lake increases are apparent in the year before but small declines are registered in 1990 (Figs 1,2).

DISCUSSION

Monitoring the two largest surface discharging features at Waimangu since 1971 has shown that the hydrothermal system is dynamic and responds to short and long term perturbations. These have ranged from hydrothermal eruptions preceded by only minor surface changes to long term climatic trends such as rainfall. An unusual aspect of the hydrothermal activity is its cyclic nature, centred on an 8 m water level fluctuation of Inferno Crater Lake over 38 days, and an inverse discharge variation from Frying Pan Lake of 20.2 litres sec^{-1}.

A conspicuous feature of the longer term trends at Waimangu is the apparent switching of activity between the two lakes (Figs 1,2). This type of phenomena has repeatedly been observed in detailed geyser observations at Yellowstone National Park, where total heat flow from a group of vents remain constant but the focus of activity shifts between vents in the group (Straser 1989, Scott-Bryan, 1989). The term exchange of function is given to this behaviour.

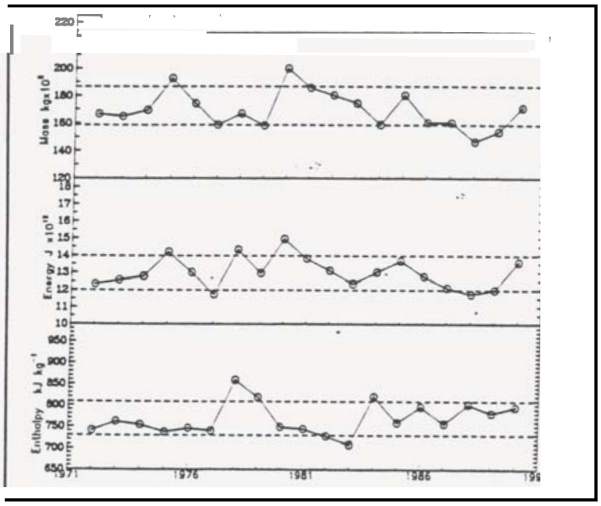

Figure 3: Plots of total annual vented mass, energy and enthalpy for 1971-1990.

To examine this concept using the 1971-1990 Waimangu data set the vented mass and energy values for both lakes have been combined, and fluid enthalpy calculated in an attempt to define the long term total discharge of the Waimangu hydrothermal system (Fig.3). The near constant state for the total discharge, compared with the variations of the individual features (Figs 2,3) is conclusive evidence for the exchange of function phenomena operating in the plumbing of these lakes.

SUMMARY

It is difficult to envisage the switching mechanism which has redirected the deep fluids between the two lakes, but the mass, energy and fluid enthalpy data strongly indicate some form of function exchange occurring. Possible scenarios could include the formation of steam blockages in critical passages which inhibit or stop the flow of fluids via that route, or the ingress of lower enthalpy fluid preventing bubble growth in part of the system.

In conclusion the data presented here on the Waimangu hydrothermal system show it to be relatively stable in the longer term while supporting dynamic short-term exchange of function between the 2 large crater lakes. In terms of volcanic hazard assessment of the Tarawera Volcanic Complex and the Rotomahana area, the data show that the heat flow from depth is relatively stable, indicating that the system has stabilised with respect to the new hydrothermal and hydrological conditions created by the 1886 volcanic eruption. This monitoring programme appears as a useful volcano surveillance tool. Major deviation of outflow conditions defined here could herald future volcanicity, while minor deviation would relate to near surface hydrothermal events.

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