The Use of Chemical Indicators in the Surveillance of Volcanic Activity Affecting the Crater Lake on Mt Ruapehu, New Zealand

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Abstract

Between January 1966 and December 1973 approximately 100 water samples wert collected from the Crater Lake of Mt Ruapehu. From analyses of the samples, changes in chloride and magnesium concentrations and pH emerged as the most useful indicators for the occurrence of the two major processes associated with eruptive activity: Chloride concentrations vary in response to changes in fumarolic activity, arising from the degassing of magma; rises in magnesium concentrations are due to interaction of lake water with freshly injected, hot andesitic material. Similarly, variations in temperature, pH and the ratio Mg/Cl enable the effects of dilution and evaporation to be considered. The thermal power required to maintain elevated lake temperatures ~ 200 MW during quiet periods, reaching 1000 MW during active periods, is largely transferred by fumarolic steam.

Introduction

The summit crater of Mt Ruapehu, an andesitic volcano in the North Island of New Zealand, normally contains a highly mineralized lake ($> 3\%$ dissolved salts) with surface temperatures varying from below freezing point (PARK, 1887; COWAN, 1927) to 60°C (HEWSON, 1968; LATTER, 1971). Since the beginniing of recorded observations by Europeans, in 1861 (SKEY, 1869), frequent ash eruptions, originating from vents within the Crater Lake, have occurred. In March 1945 mud and ash eruptions heralded a series of events leading to the replacement of the lake by a lava plug dome (BECK, 1951). The sequence culminated on 5 November in the ejection of

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red hot boulders to 500 m above the summit. Activity theen declined and the acid lake started to reform in January 1946. On 24 December 1953 a lahar, caused by the collapse of an ash barrier, flowed down the Whangaehu River and destroyed the Tangiwai railway bridge resulting in heavy loss of life. Since then the N. Z. Railways Department have regularly monitored the pH of the river. Regular sampling and analysis of the Crater Lake waters, commenced in 1966. Subsequently fresh lava is likely to have been injected on at least four occasions: (1) On 2 August 1966 breadcrust bombs of pumiceous andesite were ejected, (2) on 27 April and in early June 1968 eruptions of steam and ash occurred, (3) on 22 June 1969, ash and pumiceous andesite were ejected and lahars flowed down the mountain causing minor damage, and (4) during May to July 1971 ash, mud and bombs were ejected in at least five eruptions.

A bathymetric survey in 1966 (DIBBLE, 1972), showed the lake volume to be $1.03 \times 10^7 \, m^3$, with the diameter of the lake close to 500 m and a maximum depth of around 300 m; 97 % of the lake volume was above the 200 m isobath. In January 1970 one of the present authors (RBG) measured a maximum depth of 78 m, with the lake volume estimated to have decreased to $6 \times 10^6 \, m^3$. This implies that 40 % of the lake volume had been filled in with new material from the 1966, 1968 and 1969 eruptions. Water samples taken from different surface locations and at different depths in the lake show only minor chemical variations: in 1966, samples collected at 25 m intervals down to 200 m showed three percent variations in chloride concentrations and in 1970 samples taken at 0, 40 and 78 m depth contained 11.45, 11.46 and 11.44 g/kg of chloride respectively. These results indicate that the Crater Lake waters are well mixed and largely homogenous throughout.

Trends in the Chemistry of the Lake with Volcanic Activity

Variations in the concentrations of approximately 30 constituents in the Crater Lake water during the 1971 eruptive period were used to investigate the origin of the chemicals dissolved and the factors controlling their concentrations (GIGGENBACH, 1974). Chloride derived mainly from fumarolic HCl, and magnesium from disintegration of magmatic material, are convenient indicators for the occurrence of either of the two most important processes associated with eruptive

activity, degassing and extrusion of magma. The other important indicator, pH, decreases as predominant degassing increases the acidity of the lake waters, and increases when the water reacts with oxidic volcanic material. From variations in temperature and chloride and magnesium concentrations since 1966 (Fig. 1) the following general observations are deduced:
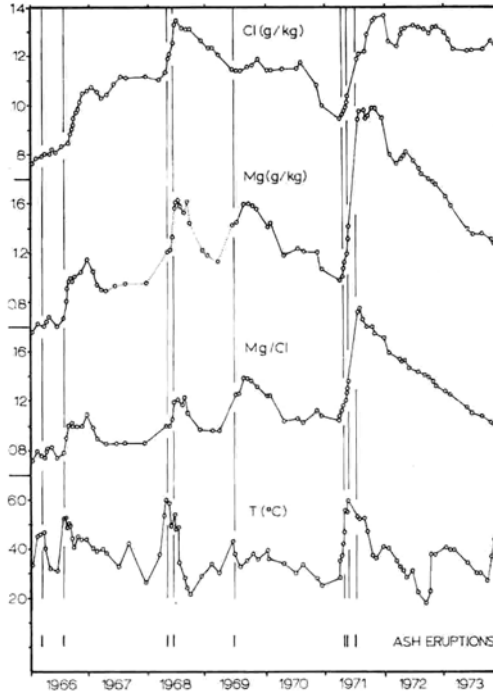

FIG. 1 - The variations in chloride and magnesium concentrations, in the ratio Mg/Cl and temperature from 1966 to 1973. For the period from February 1967 to June 1969 (dotted line) magnesium concentrations were calculated from analytical sodium concentrations by assuming a constant ratio Mg/Na of 1.6.

An increase in lake temperature is usually accompanied by a rise in chloride concentration suggesting a direct relationship between the source of the heat and chloride. With chloride considered to be associated with fumarolic steam injected into the lake, rises in lake temperature can be assumed to be largely due to increased fumarolic activity. The increases in magnesium concentrations also observed during active periods, especially after ash eruptions, indi-

cate strong interaction of lake water with andesitic material at elevated temperatures and would suggest that some heat may be derived from freshly extruded lava.

A complicating factor is that rises in chloride and magnesium appear to reach their peak after the maximum temperature is recorded. This may partly be caused by increased evaporation at these high temperatures; the parallel rises in Mg/Cl, however, suggest that interaction of lake water and extruded material continues for up to several months after the initial injection. A further cause is continued fumarolic activity and, in 1969 and 1971, ash eruptions after the maximum lake temperatures were reached. However, during all periods preceding ash eruptions, the ratio Mg/Cl remained virtually constant for periods of six to twelve months, indicating a reduction in the fumarolic discharge rate and possibly a blockage of conduits. The prolonged constancy in the Mg/Cl ratio can be considered to be an important warning sign for impending ash-eruptions.

The Relationship between Chemistry and Power Input

Variations in lake chemistry and lake temperature are apparently closely related, and a more quantitative correlation can be expected to emerge by comparing the amounts of energy involved in these temperature changes and variations in chloride and magnesium concentrations. In calculating the rate of energy supplied, loss of heat from the lake surface through evaporation and conduction were determined by use of relationships proposed by ROBSON and WILLMORE (1955), SUTTON (1953) and DAWSON (1964).

The area of the lake was taken as 2×10^5 m², and the average air temperature as 0°C at an atmospheric pressure of 550 mm Hg. The resulting relationship

$$P = (0.031 + 0.0135 \, W) \, [196 \, \Delta p + 33 \, (T_2 - T_1)] \, + $$

$$+ \, 4.83 \times 10^{-8} \, (T_2 - T_1) \, M / t$$

allows the calculation of the power, P, (in MW) supplied to the lake over a period of t days, with initial and final temperatures, T_1 and T_2 (in °C). Δp is the difference in vapor pressure of water at the temperature of the lake surface and that of the air (in mm Hg). In

the evaluation of Δp an average lake temperature $(T_2 + T_1)/2$ was used.

Because of the sheltered position of the crater lake an average wind speed, W, of 1 m/sec was assumed; together with the mass of the lake, M, taken to be 10^{10} kg the above expression reduces to

$$P = 8.74\,\Delta p + 1.47\,(T_2 + T_1) + 483\,(T_2 - T_1)/t$$

where the first term represents power lost by evaporation, the second that lost due to conduction and the third, power stored within the lake. According to DIBBLE (1972), for a large lake the factor for
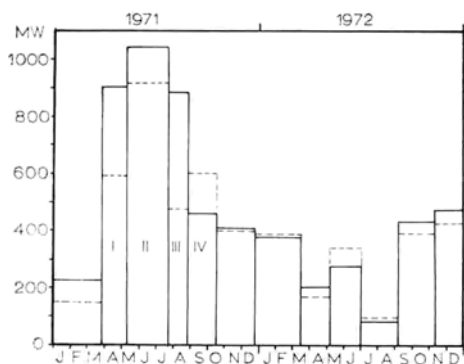

FIG. 2 - Calculated power input into Mt. Ruapehu Crater Lake (solid line) compared to that supplied by fumarolic steam (dashed line) for 1971-1973 (in MW).

wind velocity W (metres/sec) can be changed from 0.0135 W to $0.0033\,W^{0.76}/D^{0.12}$ where D is the diameter of the pool in metres. For Crater Lake $D \approx 500$ metres, changes in wind speed have an insignificant effect on the energy calculation.

The energy equivalent to an increase of 1 mg/kg in chloride concentration was calculated for the period 1972-73. During this time the steady decrease in the Mg/Cl ratio strongly suggests that observed variations in lake temperature were solely due to changes in the rate of injection of fumarolic steam. Magnesium concentrations were used to correct analytical chloride concentrations for evaporation and dilution. The chloride increased from approximately 13500 to 21200 mg/kg (an increase of 7700 mg/kg), and the integrated energy input amounted to 4.7×10^6 MWh. An increase of

1 mg/kg of chloride corresponds to an average injection of 610 MWh. Assuming the enthalpy of the injected steam to be 2660 kJ/kg the amount emitted during the two year period is 6.4×10^9 kg, comparable to the estimated mass of crater lake water, 10^{10} kg. The chloride concentration in the steam injected amounts to approximately 1.2 % by weight or 0.6 mol %, similar to that in high temperature White Island fumaroles of 0.5 to 1.5 mol-% (GIGGENBACH, 1975) and to the 1.12 % by weight calculated for the fluid entering the Green Lake, Raoul Island during the Nov. 1964 eruption (from data taken from WEISSBERG and SARBUTT, 1966).

In Fig. 2 the power input required to maintain the elevated temperatures of the lake water is compared with that likely to have been supplied by injection of fumarolic steam.

Surveillance of Volcanic Activity by Use of Waters Discharged from Crater Lake

The intermittent but frequent discharge of highly acid and mineralized waters through the outlet at the southern end of Crater Lake into the Whangaehu river provides an opportunity to obtain information on the chemistry of Crater Lake without the hazards and inconveniences associated with direct sampling.

Usually overflow is due to input of meltwater and condensing steam exceeding evaporation; on several occasions, however, marked rises in acidity and mineralization of Whangaehu river waters sampled near Tangiwai could be associated with volcanic activity, e.g. the 22 June 1969 eruption led to a drop in pH from around 6.0 to 2.0 and an increase in chloride concentrations from close to zero to 1670 m/kg. A drop in pH from 5.8 on 25 April 1966 to 2.7 on the next day together with the recording of a local earthquake could have signified the occurrence of an otherwise unobserved eruption.

Dilution of the lake discharge with virtually saltfree river water can be expected to have only a small effect on the relative proportions of solute species present. Determination of the ratio Mg/Cl in Whangaehu river samples should provide information on volcanic activity affecting the Crater Lake equivalent to that of samples obtained from the lake itself.

Variations in magnesium concentrations during quiet periods were used to determine the average discharge rate from the southern

outflow over extended periods of time. In Table 1 measured flows are compared with average flows for the intervening periods calculated from the drop in magnesium concentrations. Two values for lake volumes of 6×10^6 m^3 and 10^7 m^3 are given.

TABLE 1 - Comparison of Measured and Calculated Flow Rates (in m³/s).

Date	Measured flow	Calculated flow for a lake volume of	
		6 × 10⁶m³	10 × 10⁶m³
10. 1.73	.15		
		.10	.17
26. 2.73	0.04		
		.03	.05
29. 3.73	.05		
		.07	.12
18. 6.73	.03		
		No overflow	
5. 7.73	.01		
		No overflow	
25. 8.73	0		
		.04	.07
31.10.73	> .10		
		.15	.25
11. 1.73			

The Relationship Between the Chemistry of the Crater Lake and Volcanic Activity During the 1971 Active Period

The onset of the 1971 eruptive period was indicated at the end of March by increased seismic activity. This coincided with the start of a steady increase in the temperature of the lake from 28°, measured on 24 March, to 55° at the beginning of May. From December 1970 to March 1971 decreases in magnesium concentrations correspond to an average monthly dilution rate, by rain snow and melt water, of approximately 3 %. Similar dilution rates are observed for other quiescent periods, e.g. during 1972 and 1973. This value, therefore, was used to correct the analytical values for the effects of dilution during active periods when Mg-concentrations are likely to be affected by water-hot rock interactions.

On the basis of variations in temperature and the values for the three chemical indicators, chloride and magnesium concentrations, and pH, the 1971 active period can be divided into four distinct phases:

Phase I

Lasting from the end of March to the beginning if May, this phase is characterised by a steady and rapid increase in temperature by about 0.7°C/day, corresponding to an average power input of around 900 MW (compare DIBBLE, 1966), more than four times that of the preceding three months. Chloride and magnesium concentrations started to rise significantly, indicating the onset of both increased fumarolic activity and direct lava-water interaction. The rate of supply of fumarolic heat, calculated from the rises in chloride, 600 MW, is insufficient to account for the power required to cause the rapid temperature increases observed. Some heat, therefore, is likely to have been derived from the injected hot andesitic material. With the mass of the lake water taken to be 10^{10} kg, the observed increase of about 130 mg/kg of magnesium during Phase I reflects the addition of 2.9×10^4 kg of magnesium per day, or the disintegration of 1.04×10^6 kg of andesitic material with an average Mg-content of 2.78 %. On the other hand, the amount of freshly intruded lava, with a temperature of around 1000^0 and an assumed heat capacity of 2 kJ kg^{-1} K^{-1} (MATSUO, 1961), required to account for the heat deficit of 300 MW (7200 MWh/day) then is found to be 13.7×10^6 kg/day. Allowing for the heat liberated during crystallisation of this lava mass, however, a considerably smaller amount would be sufficient. As only part of the extruded material is likely to disintegrate completely, the geometric mean of the above two values of 3.8×10^6 kg per day appears to lead to a reasonable estimate of 1.7×10^8 kg of fresh lava injected during Phase I. The values calculated for the power input depend somewhat on wind velocity and on lake volume, neither of which are known accurately. The above estimates, however, give an idea of the magnitudes involved.

The most conspicuous manifestations of volcanic activity during this phase were minor steam eruptions and continuous upwelling in the center of the center of the lake. Assuming asimilar ratio of around 5 for the ratio CO_2/HCl for the fumarolic discharge of Mt Ruapehu as observed for White Island fumaroles (GIGGENBACH, 1975), ca. 7.2×10^5 kg of CO_2 were produced daily during Phase I. This amount corresponds to 5.1×10^5 m^3 of gas at atmospheric temperature and pressure, or 5.1 % of the lake volume. The escape of this volume of gas continuously or in bursts could account in part for the phenomenaassociated with the warming-up phase.

The chemical changes observed during Phase I are likely to reflect the effects of magma rising beneath the lake floor; the relatively small increases in pH and Mg/Cl, however, indicate that the addition of acidic gases due to fumarolic activity and their neutralization by lava-water interaction were more or less in balance.
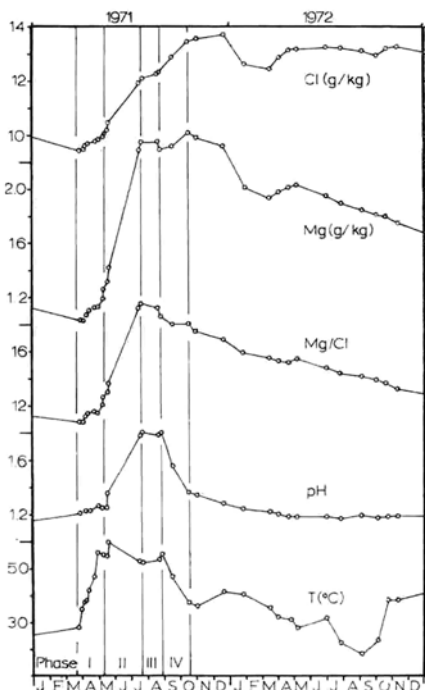

FIG. 3 - Sampling temperatures and values for the chemical indicators Cl, Mg, Mg/Cl and pH, for the Crater Lake on Mt. Ruapehu during the 1971 active period.

Phase II

A marked and steady rise in pH and the Mg/Cl ratio indicated highly increased interaction between water and oxidic, volcanic material throughout the main eruptive phase. For the first major ash eruptions on 8 and 16 May, magnesium analyses before and after the events indicated disintegration of 2.5 and 3.6×10^7 kg respectively. The total volcanic material disintegrated during Phase II was estimated to be approximately 4.7×10^8 kg, 1.8×10^5 m^3 or 1.8 %

of the lake volume. If incomplete disintegration occurred, say 30 % of the extruded material, about 6 % of the lake volume should have been replaced by lava up to the middle of July. Lake temperatures remained largely constant, at approximately 54°, indicating equilibrium between power supplied and dissipated from the lake surface equivalent to approximately 1040 MW.

Phase III

From the end of July to the end of August, temperature, pH and the Mg/Cl ratio remained largely constant, indicating a decline in lava-water interaction and even some slow down in the fumarolic discharge rate as reflected in the low daily increases in chloride of only 1.5×10^5 kg per day as compared to 3.8×10^5 kg per day during phase II. This may have been caused by part of the material extruded onto the lake floor congealing, forming some kind of plug and temporarily impeding the passage of fumarolic gases from deeper levels. The persisting high lake temperatures may have been sustained by heat given off by this cooling and crystallizing lava mass.

Phase IV

During the final phase beginning at the end of August interaction between water and lava can be considered to have ceased. The chloride addition rate, however, of 2.1×10^5 kg/day was relatively high. This continuing addition of acidic gases to the lake caused a reversal in the upward trends in both pH and Mg/Cl, with the former soon reaching its usual value of around 1.2, and the latter continuing to decrease through 1972 and 1973.

Similar sequences of phases, when increases in temperature were accompanied by rises in both chloride and magnesium, can be recognised for the eruptive periods of 1966, 1968 and 1969. However, in the 1969 ash eruption, the most violent event in the 1966-1973 period, a large rise in the Mg concentrations, was accompanied by only minor, very short term increases in temperature and chloride (Fig. 1). This suggests that interaction of lake water with volcanic material was largely restricted to leaching of high temperature andesitic material during the eruption itself. On the other hand, the rapid increase

in temperature in October 1972 was due only to increased injection of fumarolic steam, as magnesium concentrations continued to drop at an average 3 % dilution rate.

A reversal in the downward trends of both chloride and magnesium concentration, which could have been mistaken to indicate an increase in activity, occurred in April 1972. The continuing steady drop in the Mg/Cl ratio and temperature, however, suggested that the apparent rises were due to the preceding samples being diluted by the presence of excess melt water in the sampled surface layers of the lake during a period of maximum melt water run-off.

A survey of chemical analyses of waters from the Crater Lake on Taal (Philippines) suggested a similar relationship between lake chemistry and volcanic activity. Between November 29, 1968 and January 24, 1969 the acidity increased considerably to drop again to below its former value by February 28 1969. A marked increase in the number of volcanic quakes occurred in late January 1969 (ALCARAZ, 1969). This suggests an increase in fumarolic activity followed by magma movement and subsequent leaching of the lava by acidic lake water.

Acknowledgements

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