SURETIMEAT GEOTHERMAL SYSTEM: AN EXAMPLE OF A VOLCANIC GEOTHERMAL SYSTEM

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ABSTRACT

The Suritemeat geothermal system, Vanua Lava, Vanatu (New Hebrides), consists of a major hot spring and fumarole field discharging hot acid water rich in Cl, F, Fe and Al. Water temperatures range up to 120°C a few metres beneath the surface and estimated reservoir temperatures, based on silica concentration, are in excess of 200°C. Minor acid hot springs are found on the N slopes of the volcano and neutral chloride springs flow at lower elevations. Examples of similar systems are found on volcanoes elsewhere and well-described examples are found in Japan and Taiwan. We propose a general model of a volcanic geothermal system in which perched acidic systems are heated by gases rising through the volcano. Deeper, neutral to alkaline chloride hot water systems sit around a zone of conductively heated rock several kilometres below. Seepage from these systems is controlled by local permeability and structure and will usually appear near the base of the volcano. These deep systems are in some, and perhaps most instances, significantly larger than systems found in the summit region of volcanoes.

INTRODUCTION

The New Hebrides island chain contains several active volcanoes, some of which have associated eothermal systems. Most of these have small an8 unimpressive

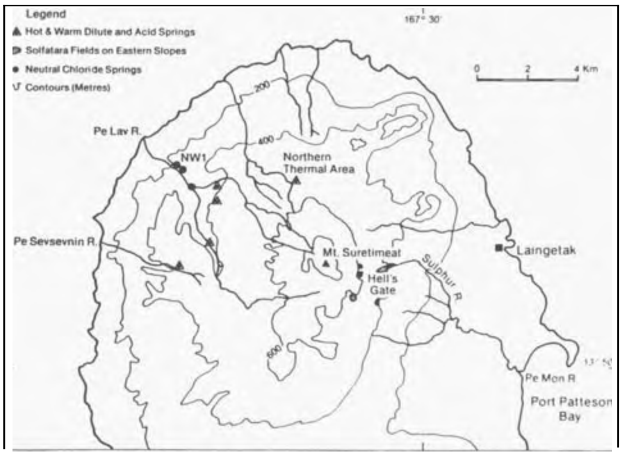

fig. 1 Location of hot springs. Vanua Lava.

discharge features except for the system on the eastern side of Mt. Suretimeat (fig. 1). Here hot springs, fumaroles, and patches of hot or steaming ground cover an area of at least two square kilometres. Our interest goes back to 1974 when R. F. Heming and M. Barsdell made a short reconnaissance and collected samples which turned out to be of acid sulphate water containing significant chlorine, fluorine, iron and aluminum. A more detailed study was made between October 29 and November 7, 1975 (Hochstein & Heming, 1976). Some active discharges were found in 1976 on the northwestern slopes of Suretimeat (Hochstein, 1977).

Suretimeat is the largest and youngest of a number of coalescing composite andesitic volcanoes which form the island of Vanua Lava. The cone is broad, reaches a height of 921 metres and appears to be composed mainly of rubbly porphyritic lavas of basaltic andesite composition with associated scoriaceous beds which are more common higher in the pile. The crater area has the form of a caldera elongated northwestward in which are numerous smaller craters. All are presently inactive. Recent eruptions have probably been hydrothermal explosions and hydrothermal explosion breccias and small lahars are found around the thermal field.

PREVIOUS WORK

Atkin (1868) was the first to describe the discharge features on Suretimeat. He visited Frenchman's Solfataras and the smaller Eastern Crater Solfataras (fig. 2). Detailed descriptions of these areas were later made by Aubert de la Rue (1937). Three small thermal areas, Southeastern, and Southern Crater Solfataras and Whitford's Solfataras have not been described in the literature though the areas are shown on a map by Greenbaum (1974). Small sulphur deposits occur in Frenchman's Solfataras and they were studied by Amstutz (1935). An attempt to mine the sulphur in the early part of this century ended in failure.

HYDROTHERMAL AREAS

The most active of the areas on the eastern side of Suretimeat is *Frenchman's Solfataras* (fig. 2) where numerous hot springs along the bed of the Sulphur River comprise the major discharge. Heat is also discharged as vapour through some powerful fumaroles as well as a diffuse heat loss along a nearly continuous 300 m long strip of weakly steaming ground. Most of the fumaroles occur in the western part of the Solfataras in the vicinity of a narrow gorge called Hell's Gate, while the major hot springs are at the eastern end and along the gorge of the Sulphur River (fig. 2). North of Hell's Gate are a number of ebullient pools, the largest having an area of 12 m^2 and an ebullition height of 0.5 m with a surface temperature of 96°C. A temperature of 98°C was measured in nearby pools and all probably represent quenched fumaroles.

The total heat discharge from Frenchman's Solfataras is between 30 and 40 MW ($7.2 - 9.6 \times 10^6$ cal. $sec.^{-1}$). Most of this is from the fumaroles (15 ± 5 MW). Hot springs at the head of the Sulphur River gorge flow at about 100 litres/sec. and contribute another 10 to 12 MW. Minor evaporative heat loss from hot pools and steaming ground is difficult to estimate but a further 3 MW comes from the pools and about 3.5 MW ± 1 MW from the belt of steaming ground.

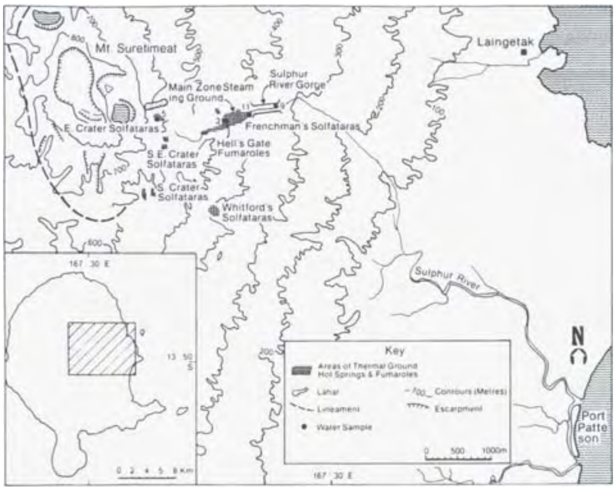

Fig. 2 Hydrothermal features on the eastern slopes of Mt. Suretimeat.

Eastern Crater Solfataras lies in a breached crater (diameter 100 to 150 m) containing weakly steaming ground and a tepid lake with vigorous cold gas discharge. A vigorously boiling pool is the major hydrothermal feature and is a quenched fumarole with a 1 to 1.5 m high ebullition in the centre of a 6 to 7 m diameter pool. Surface temperature in the centre of vigorous boiling was 102°C and 120°C at about 1 m depth. This feature was still discharging steam at the time of Aubert de la Rue's visit. Total heat discharge from this area was about 10 MW, most from the quenched fumarole (7.5 MW) but with a further contribution from hot springs (1.5 MW) and hot ground (1.5 MW).

Other concentrations of thermal activity occur at Southeastern Craters Solfataras consisting mainly of hot springs and fumaroles with a heat output of 5 to 10 MW. Southern Crater and Whitfords Solfataras have not been mapped but from the chemical mass flux into the Sulphur River from these areas a further 40 MW of heat outflow was inferred (Hochstein & Heming, 1976). Another area of acid hot springs occurs on the northern flank of Suretimeat yielding a further 15 MW of discharge.

All of the dominantly fumarolic areas with extensive areas of hot ground occur at elevations of 300 to 600 m. In the gorge of the Sulphur River from 300 m to 250 m A.S.L., are a number of hot springs which discharge a large volume of hot, acidic water into the river. At the mouth of the main gorge (fig. 2) the Sulphur River is a powerful stream flowing at a rate of 500 litres/sec. with a pH of 1.5 at 51°C (heat discharge rate 68 MW). This stream of hot dilute sulphuric acid is one of the most impressive hydrothermal features we know.

Many neutral hot and warm springs are scattered over the *northwest* slopes of the volcano. Those at elevations of 340 to 380 m are not mineralized while the lower springs are neutral chloride waters with temperatures varying between 30° and 70°C. The heat contribution is only a few megawatts.

The entire Suretimeat system covering a minimum area of 50 Km^2 discharges, mainly through hot springs and fumaroles at least 170 MW. If the conductive heat flow over this area is assumed to be a modest 2 HFU then a further 4-5 MW must be added. Hence, the entire system could well be discharging on the order of 200 MW of heat. As many more springs remain hidden on Suretimeat's thickly forested slopes, however this figure is tentative.

CHEMISTRY OF THE FLUIDS

The hot springs of Frenchman's Solfataras and adjacent areas have a very different chemistry to the neutral chloride and dilute waters found on the northwest slopes of the volcano (Table 1). Even within the Frenchman's Solfatara there are significant differences. Most springs are acid (pH 1.4-2.5) and of acid-sulphate or acid-sulphate-chloride type, but concentrations of dissolved constituents vary markedly.

Table 1
Chemistry Of Selected Hot Springs From Suretimeat & Elsewhere

Area	Eastern Crater Solfataras (acid spring)	Frenchman's Solfataras Hell's Gate (acid spring)	Solfataras Eastern End (acid spring)	Sulphur River (acid spring)	Northwestern Slopes (chloride spring)	Tamagawa[1] (acid spring)	Tatun[2] shallow bore
Elevation (M)	580	400	330	300	80	830	95m deep
Na	20	10	144	100	203	114	146
	7 5	5 5	35	32	25	65	58
Mg	18	3		2 5	n d	80	283
Ca		6	120	92		210	
	14	4 8	602	561	nil	158	225
Fe	trace	6	660	447	nil	105	778
SiO_2	250	295	380	326	96	—	419
	216	25	1.345		530	3,240	1,620
So_4		1.650	3.450	2,700	nil	1,330	3,165
	3.3	1 9	44		0 4	120	
B	13	14	50	43	n d	—	46
T°C	90	85	87	80	67	98	161
pH	2 4	1 5	1 4	1 4	6 2	1 2	2 0
Sample No	E5	E3	E11	E9	NW1		(bore 19)

1 Data from Ozawa, et al, 1973, Table 3
2 Data from Chen (1967)

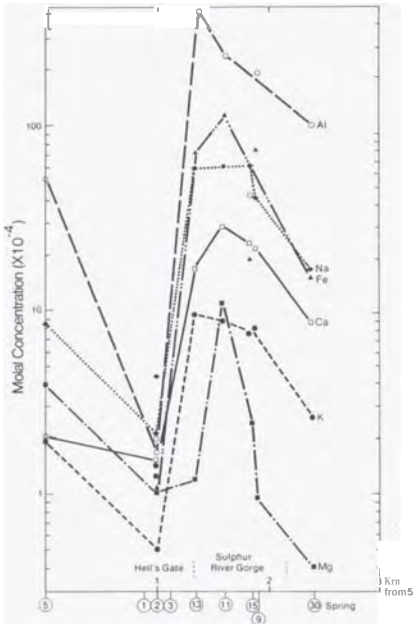

Fig. 3 Variation in cation concentration in the springs of Frenchman's Solfataras. Numbers refer to analyses in Hochstein and Heming (7976).

This variation is well displayed in figure 3. Springs close to Hell's Gate, the centre of fumarolic activity are remarkably dilute compared with other springs downstream which have high concentrations of Al and Fe. Silica concentrations in the springs indicate reservoir temperatures of greater than 200°C.

Acidity in the springs is almost entirely due to free sulphuric acid as shown by the correlation between sulphate and pH. The high concentrations of cations in the springs is due to dissolution of volcanic rocks of the reservoir by these hot, extremely acid waters. Molar ratios of elements such as Na/K and Fe/Al of the basaltic andesites believed to comprise the bulk of Suretimeat are similar to those of the springs. A close correspondence is found between molar concentrations of Na, K, Fe and Al in the rocks and spring waters while Ca and Mg are both depleted in the spring waters relative to the rocks. Lavas in the hydrothermal areas show extreme alteration and are now composed of clay minerals and amorphous silica. Many outcrops still show the well developed porphyritic texture common to the Suretimeat lavas, even though all of the primary minerals have been replaced.

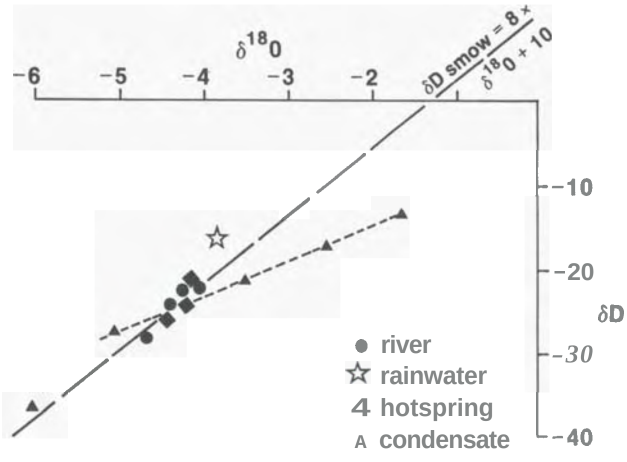

Fig. 4 Oxygen versus deuterium for springs and background waters, Vanua Lava.

Oxygen isotope ratios of samples (fig. 4) show no oxygen shift and the samples are isotopically similar to local rainwater and to four river samples collected from the southeastern and southern parts of Vanua Lava, well away from the thermal areas. Lack of an oxygen shift could be the result of a short residence in the reservoir for the fluid but considering the high salinities of some of the springs it is more likely due to extensive isotopic exchange between the reservoir rocks and circulating water indicating a reservoir with a large water/rock ratio. Condensate samples from the Hell's Gate samples do show a small shift in oxygen and deuterium isotopic composition owing to boiling.

Frenchman's Solfataras geothermal system is interpreted as an acid sulphate reservoir which is heated by volcanic gases containing a high proportion of H_2S which oxidises to H_2SO_4 to give the extreme pH's measured in the springs. Volcanic gases also contribute B and F to the reservoir. While anion chemistry is influenced by volcanic gases, cation concentrations are due to dissolving of much of the reservoir rocks by sulphuric and possibly hydrochloric acid. Variation in the spring chemistry is due to differing reservoir thickness. Volcanic gas exhalations are more concentrated and powerful at Hell's Gate and also at Eastern Craters Solfataras and springs in the vicinity could represent condensate waters.

The acid springs of the northwestern slopes are dilute acid-sulphate waters with much lower dissolved constituents than the springs at Frenchman's Solfataras and these probably represent a weaker manifestation of the Frenchman's Solfataras and adjacent areas. We do not know if these springs tap a common reservoir.

In contrast to the acid springs are the neutral chloride springs along the Pe Lau and Pe Sevsevsin Rivers (Table 1, fig. 1). These have no Fe and Al and lower SiO_2 and Cl than springwaters from Frenchman's. Although estimated reservoir temperatures are moderate (Na-K-Ca = 193°C; quartz cond. = 135°C) it is not clear how much mixing these waters have undergone.

A MODEL OF A VOLCANIC GEOTHERMAL SYSTEM

An early interpretation of Suretimeat, concentrated on the major Frenchman's Solfataras and adjacent areas and regarded the reservoir as a thin "condensate cap" over a zone of rising volcanic gases (Hochstein & Heming, 1975). These gases heated the reservoir on the eastern side of Suretimeat and oxidation of H_2S contributed to its high acidity. The large discharge from this system must require a correspondingly large contribution of meteoric water also. Neutral sodium chloride springs on the lower northwestern slopes are interpreted as the discharge from a deeper reservoir.

Figure 5 is an attempt to explain the major features of the Suretimeat system and is constrained by theoretical and

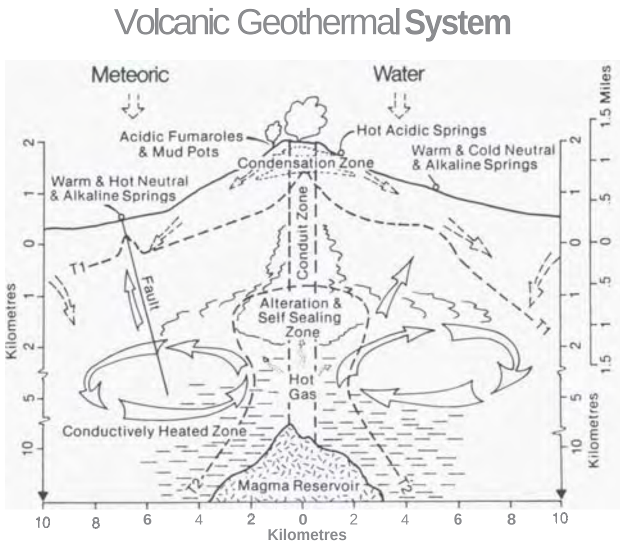

Fig. 5 Suggested model for a volcanic geothermal system.

experimental observations on the hydrothermal circulation associated with cooling magma chambers and attendant mineral zonation (e.g. Norton and Cathles, 1979) and form a general model for volcanic geothermal systems.

The Suretimeat system as described here is contained within the volcanic cone. Hot acid springs flow from relatively small reservoirs high in the volcano which are heated by volcanic gas and fed dominantly by meteoric water falling on the volcano. Deeper in the volcano the reservoirs are near neutral chloride waters which by mixing could provide waters of intermediate or dilute composition which would appear low on the volcano's flanks. These deep systems are heated by contact with magma or its heated country rock envelope. Recharge to the deep system is probably from the lower flanks as recharge through the volcano is restricted by two effects, first a tendency for the volcano to direct groundwater flow outward because of the higher hydraulic conductivity parallel to strata than normal to them, resulting in perching of groundwater. The second influence is a lower permeability in the conduit zone due to alteration of rocks there by fluids charged with volcanic gas.

Suretimeat is an example of a group of hydrothermal systems with a similar distribution of different types of springs around a volcano.

The Tatun volcanic region of Taiwan (Chen, 1967) has similar acid hot springs at higher elevations and neutral sodium chloride springs near sea level. At Hakone volcano, Japan, Oki and Hirano (1974) distinguished between acid sulphate springs associated with solfatara fields on the highest part of the cones of Kamiyama and Komagatake while sodium chloride water is found about 300 m below an active solfatara and finally exits at springs to the east. They present a model consisting of a deep NaCl bicarbonate sulphate water, above which are minor reservoirs, the uppermost discharging acid sulphate water.

Ozawa et al (1973) describe acid hot springs in Japan and divided them into three groups based on their discharge characteristics, cation concentration and associated volcanic gases. They believe that voluminous regular springs with moderately high contents of dissolved salts, such as the springs at Frenchman's solfatara's is formed by fractional dissolution of fumarolic gases into circulating water. Acidity comes from HCl and sulphurous acid which decomposes according to the reaction; $3H_2SO_3 = 2H_2SO_4 + S + H_2O$, and the resulting acid solution dissolves metallic components from the reservoir rocks. This scheme is similar to that proposed at Suretimeat and the concentrated hot springs of the latter system are like acid hot spring waters described from many volcanoes in Japan (Table 1).

The energy discharged by the acid systems is considerable. Oki and Hirano (1974) believe, for example, that approximately 42 MW is discharged from the higher acid sulphate systems of Hakone while about 84 MW flows from the lower neutral sodium chloride springs.

There seems to be no simple relation between the size of the acid sulphate system and the underlying neutral chloride systems. At Frenchman's the acid system is large (> 140 MW/sec.) and the size of the neutral reservoir is unknown. Tamagawa hot spring on Hachimantai volcano of N. Honshu is a discharge feature which rivals the Sulphur River (68 MW) as it flows at a rate of 9.3×10^3 ℓ/min. with a temperature of 98°C and a pH of 1.2 (– 58 MW). Tamagawa is related in some way to the nearby Matsukawa field where acid (pH 3-4) fluids have also been found. Takinoue, 15 Km to the SE is an example of a neutral chloride reservoir.

Acid hydrothermal systems can also be insignificant in comparison to underlying neutral systems. At Yatsugatake, a chain of dormant andesite and dacite volcanoes in central Honshu, the heat discharge from the lower springs is at least 66 MW compared to perhaps 2 MW at most from the higher springs and small fumaroles (Sumi, 1975). Perhaps the relationship reflects the activity or the length of dormancy of the volcano, and consequently the amount of gas and therefore heat supply to the upper, acid reservoir.

CONCLUDING REMARKS

The ability of acid hydrothermal systems to cause intense alteration of the reservoir rocks results in this type of water being a potent mineral-rich solution. Analysis of the Sulphur River shows that it is carrying about 5×10^3 tonnes of Fe, 12×10^3 tonnes of Al and 8.5×10^3 tonnes of SiO_2 into the sea at Port Patteson Bay. The amount of trace metals carried is unknown but from the magnitude of the above figures it can be inferred to be large. It is analogous to the spring waters of Matupi harbour in New Britain, Papua New Guinea where acid mineralized waters discharge from the base of Tavurvur volcano into the sea (Ferguson & Lambert, 1972).

So, as well as the possibility of hydrothermal ore bodies being produced in the deeper reservoir and epithermal ore bodies in the upper part of the volcanic pile, these systems may have the potential to form exhalative ore bodies.

Worldwide there are numerous examples of acid geothermal systems located on the sides of volcanoes where the discharge features are both impressive and voluminous. There remains the possibility however that larger systems, lying at greater depth, are being concealed by groundwater movement on the lower slopes and around the base of the volcano.

ACKNOWLEDGMENTS

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