Proceedings 18th NZ Geothermal Workshop 1996

SEISMOLOGICAL AND SELF-POTENTIAL SURVEYS AT INFERNO CRATER LAKE, WAIMANGU GEOTHERMAL FIELD

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SUMMARY - A short term micro-seismic survey and self-potential (SP) measurements were performed in **1994** and **1996** around Inferno Crater Lake, Waimangu Geothermal Field, to increase our understanding of the hydrothermal dynamics associated with the water level change at the lake. Seismic survey with five seismometers around the lake revealed that the acoustic noises were concordant with rising water levels in Inferno Crater Lake and the overflow, being strongest during the period of oscillating water level and overflow. No significant seismic signatures were recorded during water level recessions. SP measurements were made along four survey lines in Waimangu Geothermal Field and repeat SP surveys were carried out eight times along the footpath in Waimangu Valley. Terrain-related potentials are dominant along the most survey lines though positive SP anomalies are observed near Inferno Crater Lake and Waimangu Geyser. Remarkable SP changes with time were also found among the repeat SP surveys near Waimangu Geyser, which is probably caused by the change of subsurface condition.

1. INTRODUCTION

Waimangu is a major and well known geothermal field in Taupo Volcanic Zone (Hunt et al., **1994)** and was affected on **10** June **1886** by the eruption of nearby Mt. Tarawera (Simmons et al., **1993).** The eruption created several craters including Inferno Crater, which is filled with water at present. Inferno Crater Lake has shown water level variations since at least **1901,** when it was affected by activity of Waimangu Geyser, which was active between **1900** and **1904.** Present surface hydrothermal activity is dominated by Inferno Crater and nearby Frying Pan lakes (Fig. 1), which display interrelated cyclic changes (Scott **1992, 1994).**

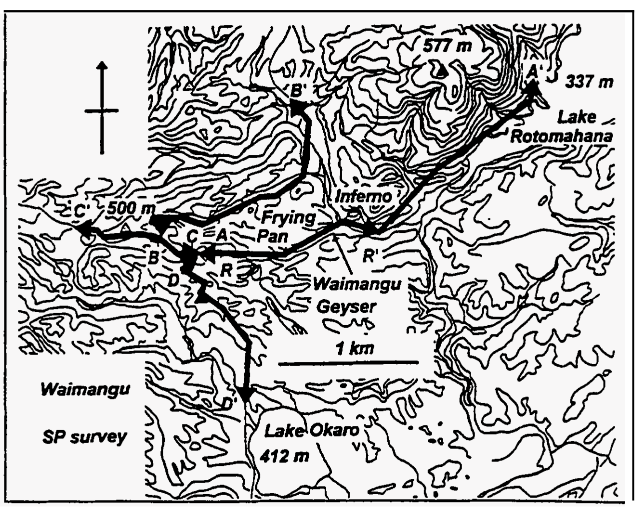

Fig. 1 Map showing Inferno Crater and Frying Pan lakes with locations of SP survey lines.

Several experiments have been made to examine a correlation between the water level change in Inferno Crater Lake and seismic noise. **A** preliminary study at Inferno Crater Lake during 1974-75 showed a positive correlation between the water level change and seismic output (Scott,1976). There was a high level of seismic noise present during the **rise of** waterlevel and the main overflow. We have carried out several seismic surveys around Inferno Crater Lake. The first survey was performed in **1993,** focusing on microearthquake activity and the second in **1994** investigated the characteristics of the seismic noise.

A self-potential (SP) survey is conducted by mapping the natural time-invariant electric field at the earth's surface. In recent years, the SP method has attracted increasing interest in geothermal prospecting and engineering geophysics. Among the various mechanisms which can cause SP, the most important appear to be electrokinetic (streaming) potentials arising from underground fluid flow (e.g., Ishido et al., **1990;** Hochstein et al., **1990).** However, no SP survey was made in the Waimangu Geothermal field prior to **1996.**

We report here results of SP and microseismic surveys, designed to obtain seismic and SP output associated with the movement of fluids which occurs during the cyclic variations of water level in Inferno Crater Lake, in an attempt to increase our understanding of the mechanisms behind the cyclic variations.

2. INFERNO CRATER LAKE

The first recorded large scale cyclic variations at Waimangu were of the Waimangu Geyser, with a cycle of about **36** hours. Variations of the water level at Inferno Crater Lake, which are now seen as a cyclic and inverse relationship between the water level of Inferno Crater Lake and the discharge of Frying Pan Lake are the dominant cyclicity observed at Waimangu. The mean cycle length, between the water level minima, is **37.7 ± 9.7** days and four distinct stages are recognised within the cycle (Scott **1992, 1994;** Fig. **2):** (1) an initial water level rise, (2) a period of oscillating but rising water level, **(3)** an overflow and **(4)** a recession stage.

The initial seismic noise recordings at Inferno Crater (Scott 1976) demonstrated that there was a high level of seismic noise present during the rising phase of each oscillation in Stage 2 and during the main overflow (Stage 3). Stanton (1978) carried out a more detailed study of the characteristics of the acoustic noise in Inferno Crater Lake and qualified the positive relationship between the rise of water level and a strong acoustic noise signal. However, the seismometers he used had low sensitivity and the measured frequency spectra showed no consistent characteristics.

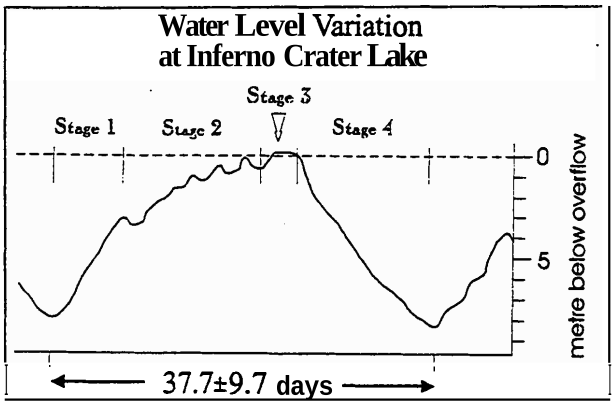

Fig. 2. Plot of water level changes at Inferno Crater Lake showing the 4 stages.

Leigh (1985) made a similar survey using a four-element, directional seismic array with 1 Hz seismometers; his data show that the dominant frequency was within the range 5-10Hz. Cross correlation analysis revealed the acoustic noise to come from the centre of Inferno Crater Lake. However, there was no significant variation with time in the power spectrum and power of acoustic noise during his three day survey.

Tosha et al. (1994) reported the results of the first micro-seismic survey designed to obtain information about the style of microearthquake activity. Microearthquakes happen frequently in the Waimangu Geothermal field area. No correlation between occurrence of these microearthquakes and water level change in Inferno Crater Lake has been observed. The interrelated cyclic variations between Frying Pan and Inferno Crater lakes are restricted to a small volume of geothermal fluid in a restricted area adjacent to Inferno Crater. The pressure perturbations associated with this fluid do not produce any discrete microearthquakes.

The cyclic and inverse relationship between the water level of Inferno Crater Lake and the discharge of Frying Pan Lake respectively is a characteristic of the hydrothermal phenomenon in Waimangu Geothermal field. We under took experiments using the SP method has an opportunity to reveal more about the underground fluid flows associated with this cyclicity.

3. METHODS AND INSTRUMENTS

3.1 Seismic Survey

Five vertical-component seismometers with 1 Hz resonant frequency (Mark Product L-4C) were used in the seismic survey. In the first part of this survey four vertical-component seismometers were placed at the same survey points as those in the previous survey (Tosha et al 1994). One seismometer (WMGO) was placed close to the outlet of Inferno Crater Lake, two seismometers (WMG1,WMG2) were placed on ridges in the south-east and north-west, and the fourth one (WMG3) was installed between Inferno Crater and Frying Pan lakes. The fifth sensor (WMG4) was placed about 100m north from WMG2 (Fig. 3). Each seismometer was buried in a shallow hole (< 1m depth) to get good contact with surrounding rocks. The horizontal distance between the seismometers was typically about 100m, and the greatest elevation difference between WMG4 (on the north ridge) and **WMGO** (outlet) was about 50 m. The resultant configuration was expected to give a good resolution of the signal travel path in the northeast-southwest direction, but not so good in the northwest-southeast

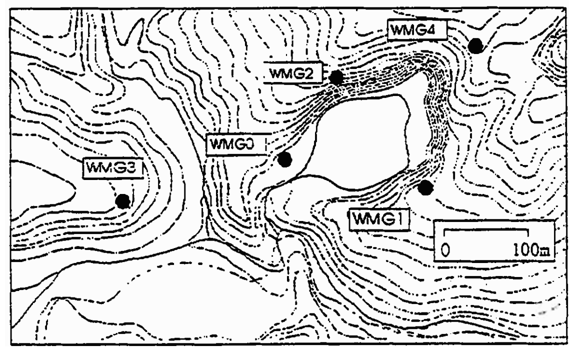

Fig. 3. Simplified topography map of Inferno Crater Lake showing relative locations of the seismometers used during the survey.

Two **EARSS** digital recorders fitted with 40 MB harddisks were used to record the data during the survey in 1994. Seismic signals were transmitted to the recorders via wire lines without amplifiers. **As** one of the objectives of this survey **was** to record wave forms, an internal timer was used to switch on preset recording windows. Event trigger mode was also enabled. **As** **EARSS** has no function to synchronise the internal clocks between two units it was necessary to branch the seismic signal at **WMGO** to each recorder, hence, enabling us to synchronise data from each recorders. Data were downloaded to a personal computer and archived on MO disks.

The internal timer in each **EARSS** recorder was set to record for 160 seconds, every two hours during the first 8 weeks, and for 20 or 30 seconds every **30** minutes during the later part of the experiment. **A** continuous digital record is not possible unless the storage capacity of the recorder is significantly increased. The recording frequency was 100Hz. Operation of the network commenced on 18 September and continued until 14 December 1994 with several breaks, due primarily to power supply failures.

3.2 Self-potential Surveys

Self-potential **(SP)** measurements were made with silver-silver chloride non-polarizing electrodes (Ishido et al., 1992) and a high-impedance (10^9 Ω) voltmeter. We used "leapfrog" survey configuration in which a dipole of fixed length (100 m) is stepped along the survey line, alternating the leading and following electrodes. The measurements along survey lines **AA'**, BB', CC' and DD' shown in Fig. 1 were carried out on February 14, 20, 20 and 21, respectively in 1996. All measurements are relative to point A.

Repeat self-potential measurements were carried out eight times during February 14 through March 25,1996 along survey line RR' (a part of **AA'**, see Fig. 1). This survey line starts from 200 m west of "Tearooms" and passes by Frying Pan Lake, Waimangu Geyser and Inferno Crater and ends at "**Bus** Stop #1".

Continuous recording of SP was carried out around the IGNS observation hut near Inferno Crater Lake from February 15 through April 1, 1996. Electric potential differences over three dipoles (of 10 to 30 m length) were monitored using $Pb\text{-}PbCl_2$ electrodes and digital data loggers (sampling interval was set *5* minutes). Soil moisture change and precipitation were also monitored.

4. RESULTS AND DISCUSSION

4.1 Level of seismic noise

Previous studies of seismic noise (Scott, 1976; Stanton, 1978) reported strong seismic noise ($>3\mu m\ sec^{-1}$) during the water level rises in the oscillation stage (Stage 2) and during the overflow (Stage 3).The levels of seismic noise measured during this survey are similar to those reported in the previous studies. Though the seismic noise exceeded 3 $\mu m\ sec^{-1}$, they did not trigger the digital recorders during the survey by Tosha et al.(1994). As the trigger algorithm requires a rapid increase in the signal amplitude, it is possible that we could not get triggers as the amplitude of the seismic noise increases very gradually during the water level. During this survey we used the internal timer to ensure regular data capture every hour or every 30 minutes. To analyses the mean amplitude the first 30 seconds for each record was integrated.

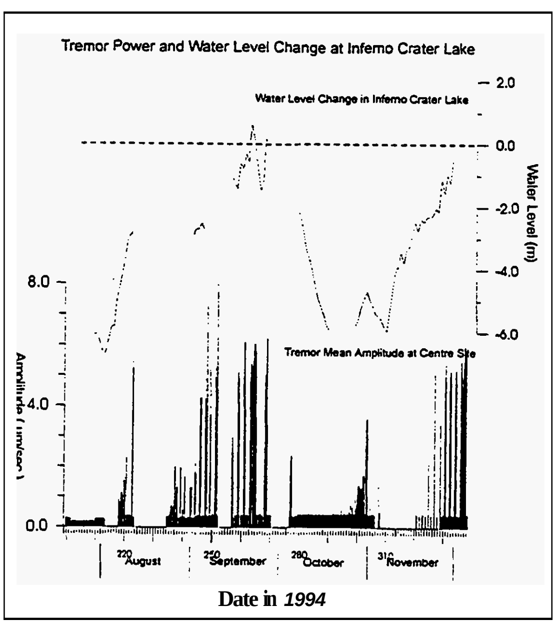

Fig. 4. Plot of mean signal amplitude at WMG0 (vertical component) and water level of Inferno Crater Lake

The results of these analyses are shown in Fig. 4 where the mean amplitude of seismic noise as measured at **WMGO** and the water level variations in Inferno Crater Lake are shown; unfortunately records are not complete. The figure shows two distinct levels of seismic noise signal, those less than 0.5 $\mu m\ sec^{-1}$ and stronger ones ranging from 3 to over 6 $\mu m\ sec^{-1}$.

Weaker signals predominate during two periods, from 18 July to 3 August (days 199-213) and 3-28 October (days 277-299). During these times the water level in Inferno Crater Lake was receding (Stage 4). High levels of seismic noise (3.5-5.5 $\mu m\ sec^{-1}$) were recorded from 12 August to 26 September (days 223-269) and 23 November to 14 December (days 324-339) during Stage 2 when the water level was rising. Stage 1 of the cycle is represented by records from 6-9 August and 27-31 October when the seismic noise signal climbs out of the background signal at about 0.4 $\mu m\ sec^{-1}$ and gradually rises to about 2 $\mu m\ sec^{-1}$ (Fig. 4). Stage 3, the overflow, is represented by recordings on 22-24 September (days 263-265) and 3-6 December (days 336-339) when the signal levels are persistently above 5 $\mu m\ sec^{-1}$.

The level of seismic noise in Stage 1 (0.5-2 $\mu m\ sec^{-1}$) is higher than that in Stage 4 (0.3-0.4 $\mu m\ sec^{-1}$), but is lower than the signal which accompanies a water level rise in Stage 2 (2-6 $\mu m\ sec^{-1}$) and the overflow (Stage 3) when the signal level is typically < *5* $\mu m\ sec^{-1}$. One of the characteristics of the stronger signals in Stage 2 is that they occur pulsatory, whereas in Stage 3 they are continuous. This pulsatory nature is no so apparent early in Stage 2, becoming more regular through the Stage. The interval between the commencement of strong noise is 42-44.5 hours and duration 9-10.5 hours. This periodic noise seems to suggest that there is a single driving force associated with the water and temperature rise seen in the lake.

4.2 Frequency of seismic noise

To examine the relative wave forms at each recording site we have taken a representative 30 second sample from each of the stages in the Inferno Crater Lake cycle and calculated the power spectrum at each stage. In Fig. *5* the power spectra at **WMGO** are shown for successive five sets of records in a two-hours interval. During Stage 1 sites **WMGO** produce signals with dominant frequencies of 9 and 6 Hz. During stage 2 the resultant spectra are similar to that in Stage 1 but the power of 9 Hz signals are much stronger. In Stage 3 the spectra at WMGO is narrower and the dominant signal is around 7 Hz. In Stage 4 the power level is 1-2 orders of magnitude less than in other stages and the power spectra become much broader. The 6 Hz signals are dominant during all the stages of the water level change at WMGO. The 6 Hz signal is not concordant with the hydrothermal movements at Inferno Crater Lake and is probably caused by the resonance between seismometer and the surrounding soils or the response of the recorder. This requires more detailed analyses which is beyond the scope of this report.

4.3 Self-potential Distribution

SP profiles along the survey lines AA', BB'. CC' and DD' are shown in Fig. *6*. As shown in the figure, terrain-related potentials (see Fig. 1 for topography) are dominant the along survey lines of BB', CC' and DD' and a part of AA' southwest of Frying Pan Lake. SP decreases about 5 mV as elevation increases 1 m. The 5 mV/m value is quite large, as terrain-related SP usually ranges from 0.1 mV/m to 1 mV/m. However, if the water table is shallow and closely follows the ground surface and the subsurface electrical resistivity is not so low, a SP decrease of 5 mV would be expected to result from an elevation increase of **1** m through electrokinetic coupling (Ishido, **1989).** (Survey lines BB', CC' and DD' are located outside of the very low resistivity zone shown in Fig. 5 of Bibby et al.'s paper, **1994.)**

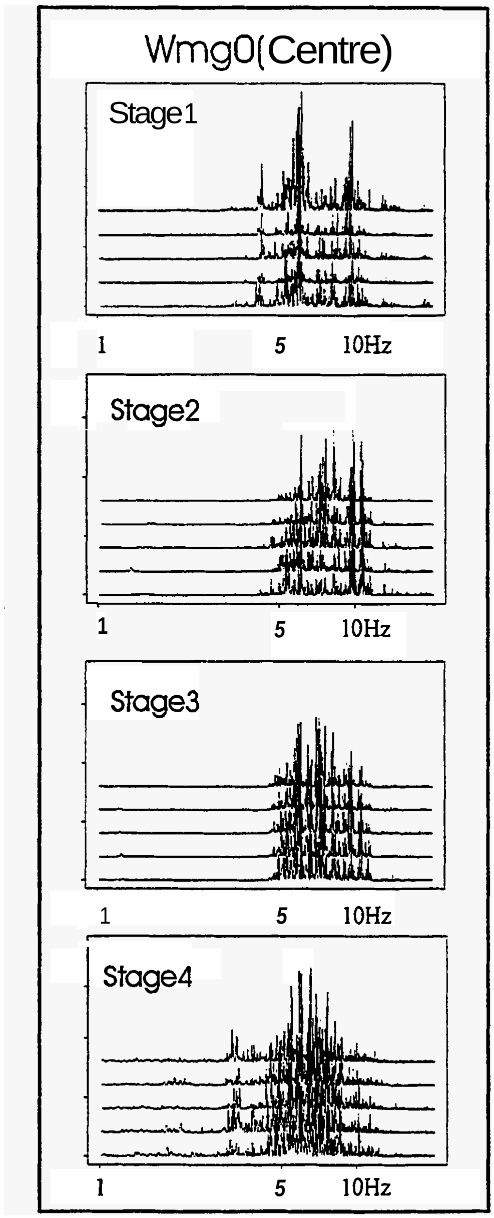

Fig. 5. Plot of power spectra at the centre site (WMG0) during Stage 1 through Stage 4 of the Inferno Crater Lake cycle.

No terrain-related potentials are seen along survey line AA' east of Frying Pan lake. This part of the survey line runs through the areas of hydrothermal upflows. The lack of terrain-related potential is due to no groundwater flowing from higher to lower elevations taking place. **As** seen in Fig. 2, (although the elevation becomes higher) SP increases as approaching Inferno Crater and Waimangu Geyser from the eastern end of the survey line near the shore of lake Rotomahana. This positive anomaly of relatively large spatial extent **is** probably caused by the hydrothermal upflows through electrokinetic coupling (see e.g. Ishido, **1981**; Ishido, **1989).** The magnitude of this anomaly is not so large in comparison with the terrain-related anomalies. This is thought due to a deeper location of current sources (producing **SP)** and lower electrical resisivities in the thermal area.

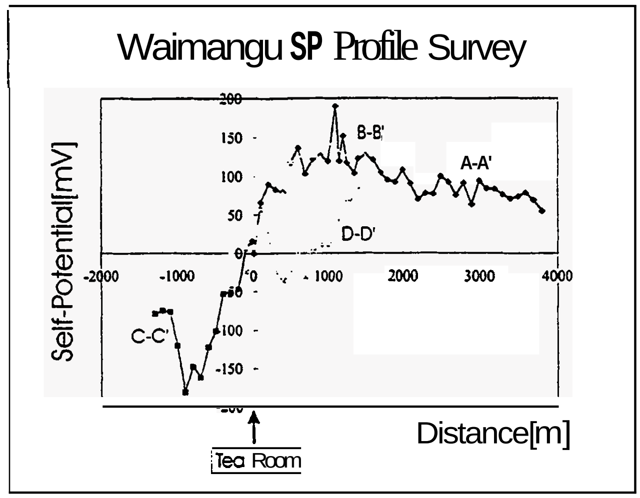

Fig. 6. SP profile along the survey lines shown in Fig. 1.

As seen in Fig. 6, a positive SP anomaly of short spatial extent is presently centred at the old Waimangu Geyser site. This is probably caused by localised subsurface upflow. The depth of the current source producing the anomaly is estimated several tens of meters based upon the spatial extent of the anomaly. Since thermal waters of Waimangu Valley have neutral pH (except Inferno Crater Lake) and relatively low salt concentrations (Simmons et al., **1994),** the coupling coefficient of electrokinetic effects is expected quite large (Ishido and Mizutani, **1981),** so thermal upflows can produce substantial **SP** anomaly on the ground surface.

4.4 SP Changes

The results of repeat SP surveys along line RR' are shown in Fig. 7. The profile is referred to a point near "bus road". Noticeable SP changes were found near Waimangu Geyser. The predominant positive SP anomaly observed at the first survey **(14** February) almost disappeared at the third survey (26 February), then recovered at the fifth survey (5 March) and disappeared again at the seventh survey **(18** March). This fluctuations are probably caused by changes in subsurface conditions such as changes in the rate of the upflow mentioned in the previous section or changes in electrical resistivity which may be induced by vapour-saturation changes at shallow depths **.**

4.5 SP Monitoring at Inferno Crater

The results of SP continuous recording near **WMG0** are shown in Fig. **8. All** SP records show clear changes corresponding to rainfalls. However, it is difficult to explain other SP changes, especially those which appear on record SP-2.

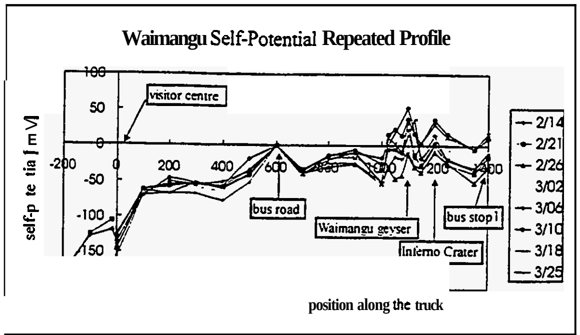

Fig. 7. Results of SP surveys repeated along the footpath in the Waimangu Valley

Soil moisture recorded at about 50 cm depth by an electronic sensor is plotted in unit of mV. The values 1200 and 1060 mV roughly correspond to water saturation of 10 and 30 %, respectively. The results show diurnal moisture changes: water saturation decreased during day times. It is noticed that the amplitude of the decrease became small after rainfalls. Although the magnitude of such diurnal change in soil moisture is thought to differ from point to point even in a small area, no significant diurnal changes in SP were observed.

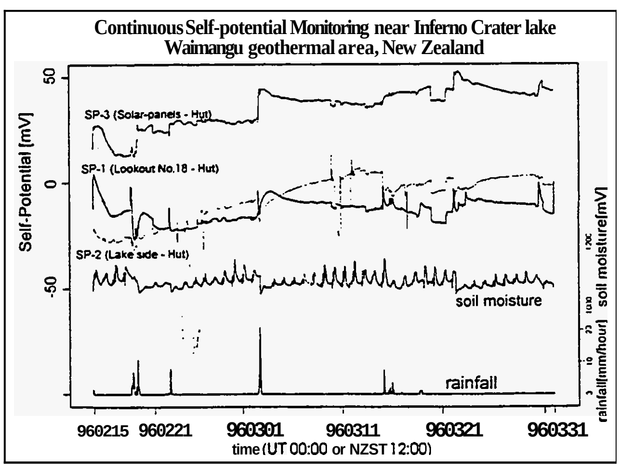

Fig.8 Plots of continuous SP recording near Inferno Crater Lake. Shown are also soil moisture change and precipitation

5. CONCLUDING REMARKS

Seismic survey shows that there is a continuous background signal that produces a consistent 5 Hz seismic signal at all sites, with an amplitude of about 0.3-0.4μm sec^{-1}. This is particularly clear during Stage **4** as the water level is falling in Inferno Crater Lake. During the rising water level phases of Stages 1 and 2 there is a significant increase in the amplitude of the recorded signals (2-5 μm sec^{-1}) and the dominant frequency also changes to around 9 Hz, except at site WMG4 where it remains at 5 Hz. The strongest signals are recorded during Stage 3 but the power spectra remain similar to those observed in. Stages 1 and 2. The signal source is probably closer to WMGO and 3 than to the other sites. More detailed studies of the coherence of the wave forms may give more detail on this.

Further field surveys are required to clarify the nature of SP fluctuations taking place near Waimangu Geyser. In addition to more carefully designed repeat surveys, continuous recording of the anomaly is desirable using "long length" dipoles (one electrode of each dipole is set near the anomaly and the other one is set at remote "stable" point). Numerical modeling of SP has been undertaken recently. A "postprocessor" developed by Ishido and Pritchett (1996) allows us to calculate space/time distributions of electrokinetic potentials resulting from histories of underground conditions (pressure, temperature, flowrate etc.) being computed by a multi-phase, multi-component, but unsteady multidimensional geothermal reservoir simulation. It seems quite promising to apply this technique to hydrological modeling of the Waimangu geothermal system.

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