Proc. 12th New Zealand Geothermal Workshop 1990

SELF-POTENTIAL SURVEYS OF THE MOKAI AND ROTOKAWA HIGH TEMPERATURE FIELDS (NZ)

M.P. Hochstein[1] I.D. Mayhew[2] R.A. Villarosa[3]

[1]Geothermal Institute, University of Auckland,
[2]Hydrological Section, Auckland Regional Council, Auckland
[3]Geothermal Division, PNOC-EDC, Manila, Philippines

ABSTRACT

Self-potential (SP) surveys of the Mokai and Rotokawa geothermal fields (Taupo Volcanic Zone) show the existence of a large (>3 km) wavelength positive (200 to 300 mV) SP anomaly that coincides with the lateral extent of the reservoir. At Rotokawa, the anomaly reaches a maximum over the upflow centre in the southern part of the prospect. At Mokai, the anomaly is depressed in level by terrain-induced streaming potentials. These disturbing effects were recognized by expressing the observed data with respect to a reference potential near the Waikato River, the hydrological sink for all groundwater flow in both prospects. Thermal SP effects cannot be separated from terrain-induced streaming potentials.

Introduction

Self-potential (SP) anomalies can be observed over most high temperature geothermal prospects. Both positive and negative potentials with short (<0.3 km) and long (>1 km) wavelengths have been observed. The magnitude of many anomalies are of the order of a few hundred millivolts (mV); anomalous high values (up to +3V) have been observed in the Puna Field (Hawaii). A short summary of the method has been given by Goldstein (1988).

The SP anomalies can be classified by the following parameters:

- dominant wavelength,
- polarity (with respect to an undisturbed reference potential outside the prospect),
- magnitude (in mV),
- resistivity structure and hydrological setting of prospect.

In moderate or steep terrain, areas with an undisturbed reference potential are difficult to find. A common problem of older SP surveys has been that the surveyed area was too small. It appears now that only surveys covering areas greater than 50 km^2 produce representative SP patterns. SP surveys of about 20 high temperature prospects have been published covering prospects in the US, Mexico, Japan, the Azores, Greece, and Italy. Two groups can clearly be distinguished:

(a) prospects with dominantly positive long wavelength anomalies over the reservoir, and
(b) prospects with a long wavelength dipolar anomaly.

There is a small third group with rather indistinct or irregular anomaly patterns.

Examples of the first group are a prospect in the Yellowstone Park (Zhody et al., 1973). where the geothermal SP phenomenon was first noticed, several Hawaiian Rift prospects (Zablocki, 1976), the Pico Alto Caldera (Azores) prospect (Anderson et al., 1982), the Coso prospect in California (Brophy and Waff, 1986), and several prospects in Japan (Ishido et al., 1990). In the second group are the prospects of Cerro Prieto in Mexico (Fitterman and Corwin, 1982), and the East Mesa prospect in California (Corwin et al., 1981).

Where SP surveys of unexploited systems were repeated, the anomalies were found to be reproducible (Corwin and Hoover. 1979; Ishido et al., 1990). Changes in SP anomalies over exploited high temperature systems have also been observed (Kikuchi et al., 1988; Goldstein and Alvarez, 1989).

The SP effect associated with high temperature systems is related to transfer of electrical charges caused by fluid movement. This involves some charge separation, probably by interface polarization which is enhanced by the presence of clay minerals; charge separation increases with temperature. In a cold groundwater setting, the driving force is the normal hydraulic gradient; in high temperature systems it is buoyancy (convection). Any charge transfer is associated with a natural current field which produces an elecmc field at the surface proportional to the average resistivity. The SP effect of charge transfer in cold groundwater settings has been called "streaming potential". In this paper, this effect is called "cold streaming potential". The SP effect over high temperature systems is also a streaming potential associated with hot fluids. Both effects can occur together.

The streaming potential has also been called electrokinetic potential, and the effect of increasing charge separation at higher temperatures has been called thermo-electric coupling (Corwin and Hoover. 1979). In high temperature systems both mechanisms operate together.

With respect to a surface reference electrode near a regional hydraulic sink, the cold streaming potential at a field electrode over higher terrain is always negative (see Fig. 1), upflow of cold water (producing well) produces a positive SP anomaly (Corwin and Hoover, 1979).

Little is known about SP anomalies of NZ high and low temperature systems. Between 1982 and 1989, students and staff of the Geothermal Institute made various SP surveys over two high temperature systems in the Taupo Volcanic Zone (Mokai and Rotokawa prospects). The results of these surveys are presented in this paper.

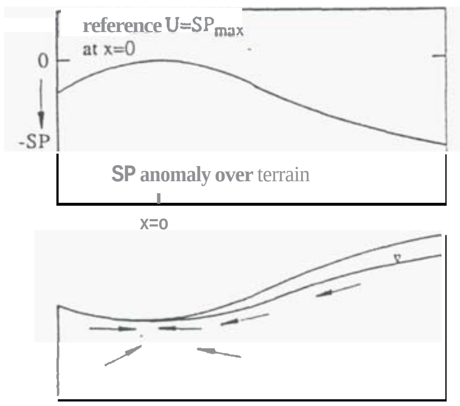

Fig. 1: Terrain-induced streaming potential with respect to a reference electrode near the hydrological sink (bottom of valley).

Instrumentation and field procedure (high temperature systems)

To obtain reproducible results we used a 4- (5-) point leapfrog array which allows for multiple measurements (see Fig. 2). Selected noise-free $Cu/CuSO_4$ unpolarized electrodes (unpolarized "pots") were used (potential difference between any pair in an electrolytic bath was <1 mV). The separation between the electrodes was usually 500 m; four segments of twin cables were used. All surveys started outside the outer resistivity boundary of each prospect. The electrodes were placed 0.4 m below the surface and were kept shaded.

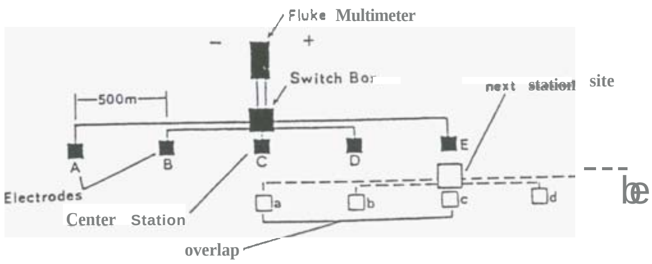

Fig. 2: Field set-up of SP surveys described in this paper.

Using a suitable switch box, 10 potentials were measured with the five-point array shown in Fig. 2, namely, V_{AB}, V_{AC}, V_{AD}, V_{AE}; V_{BC}, V_{BD}, V_{BE}; V_{CD}, V_{CE} and V_{DE}. The potentials were measured with a digital voltmeter (10MΩ input impedance). After completion, the centre station was moved to the next site and the redundant cable segments and non-polarizing electrodes were moved to the front (see Fig. 2). The potential difference between any adjacent station was therefore determined by a set of 5 independent readings. All electrodes settled within 15 minutes. Repeat readings the next day showed that potentials were reproducible within ±10 mV.

The arrangement shown in Fig. 2 was used for the Rotokawa survey. For the SP survey of the Mokai prospect we used a four-point electrode array (i.e. electrode E in Fig. 2 was not employed); in this case a set of 3 independent readings were obtained, but progress was reduced as the centre station was advanced by only one cable length each time. During the Mokai survey, telluric potentials were monitored along a fixed array in the centre of the survey area. However, the self-checking addition of potential differences over small distances did not require any reduction of telluric potentials. No telluric monitoring station was used for the Rotokawa survey.

Averaging of the data sets produced almost noise-free potential differences. The quality of the surveys can be assessed from the closure errors of various loops when adding the potential differences. At Mokai the closure error was of the order of 5 mV for a loop 23 km in length; at Rotokawa, closure errors were 3 mV and 17 mV for 11 km and 18 km loops respectively. One 3 km-long segment of the Rotokawa survey was re-measured one year later; the reproducibility at stations near active discharge features at Lake Rotokawa was poor (±30 mV); over cold ground the reproducibility was good (±10 mV).

It appears that the multiple array leapfrog method used during our surveys produces an almost noise-free data set. This is an improvement on older surveys, as the single roving electrode array used in these often produced noisy data (refer to repeat surveys described in, for example, Corwin and Hoover, 1979).

Results (Mokai SP survey)

This survey was made in September 1982 (Mayhew, 1982). The SP anomalies are shown as a contoured map in Fig. 3a; the data are plotted with respect to an inferred zero reference potential at the regional hydraulic sink, the Waikato River (upper part of Fig. 3a). For comparison, the apparent resistivity map of the area is shown in Fig. 3b (taken from Bibby et al., 1981); the likely extent of the deeper hot water reservoir is enclosed by a hatched boundary. The pattern in Fig. 3a does not show any clear positive SP anomaly associated with the reservoir although the SP contour pattern is rather smooth over the area of interest.

The picture changes if the observed SP data are plotted versus topography. A section 18 km long, almost N-S trending, is shown in Fig. 4 (for locality see Fig. 3a). This figure shows that the SP data are controlled by topography, since the SP data contain a cold streaming potential which probably is proportional to the hydraulic gradient where horizontal flow is maximal. The profile in Fig. 4 is almost parallel to the regional groundwater flow; in addition, there is some deeper lateral outflow of thermal water from the Mokai Field. Terrain-induced streaming potentials have been described in the literature. Corwin and Hoover (1979) found a streaming potential of about –500 mV for the lower slopes of Adagak Volcano in Alaska over an elevation difference of 300 m, which is of the same order as the SP values in the first 5 km in Fig. 4 where a change in level of about 140 m produces a streaming potential of about -250 mV. The data cannot be directly compared since the magnitude of SP values is also affected by the mean resistivity of the overburden.

If one explains the first part of the SP profile in Fig. 4 in terms of a streaming potential, one can give a qualitative interpretation of the remaining part of the profile. For this, we recall that, for an increasing hydraulic gradient in an upstream direction, the streaming potential becomes increasingly negative (see Fig. 1) if measured with reference to an electrode close to the regional hydraulic sink - here, the Waikato River. The largest negative potential should therefore occur on top of the catchment divide (profile km 19.5 in Fig. 4). Unfortunately, the survey was not extended up to the divide; however, at an elevation of 640 m (km 17.7). negative potentials of -550 to –700 mV were measured.

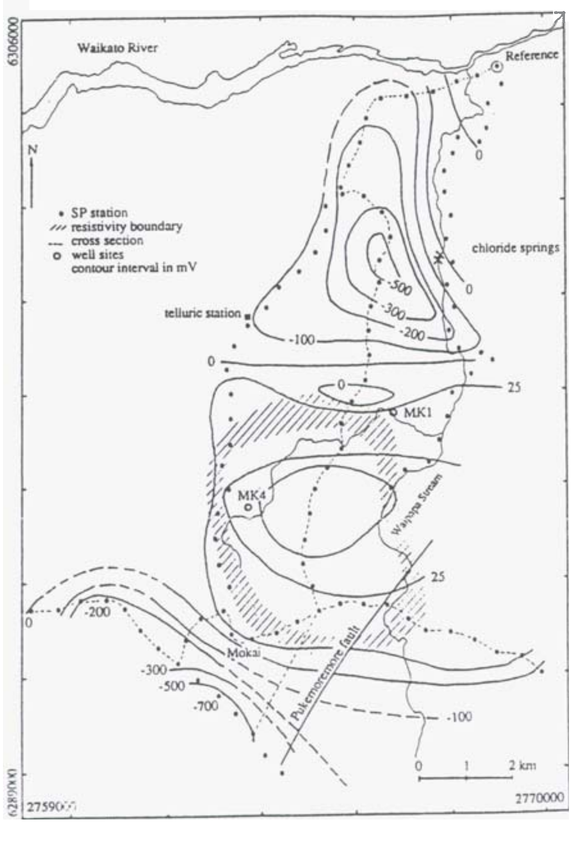

Fig. 3a: SP anomaly map of Mokai Geothermal Field (contour values in mV).

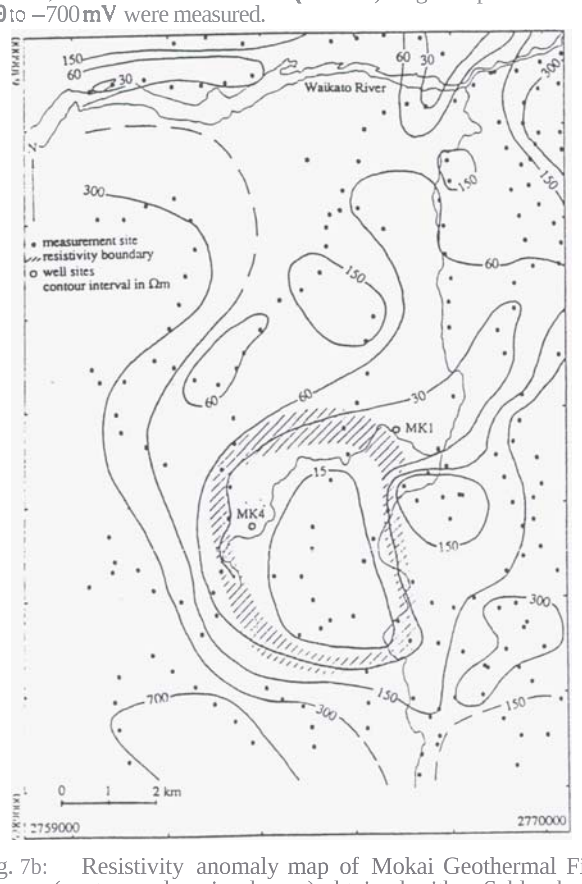

Fig. 7b: Resistivity anomaly map of Mokai Geothermal Field (contour values in ohm-m) obtained with a Schlumberger array with AB/2 = 1200 m.

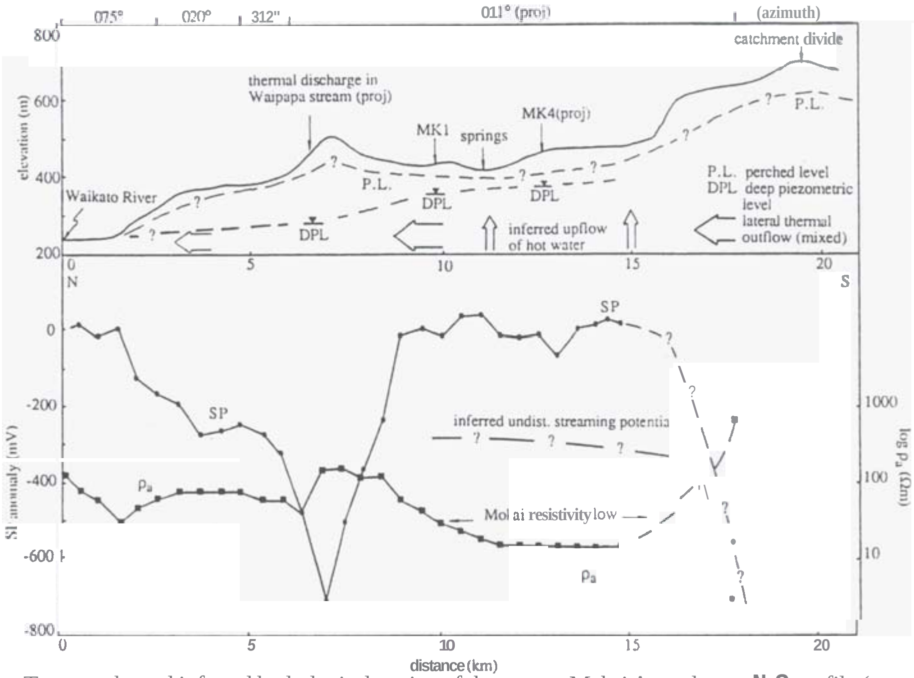

Fig. 4: Topography and inferred hydrological setting of the grater Mokai Area along a N-S profile (upper part) Observed SP values and apparent resistivity AB/2 = 1200 m along the same profile (lower part); for location of profile see Fig. 3a.

Not much is known about the regional hydraulic setting of the Mokai area. A piezomemc level of +350 m was observed in well MK1 which lies at the N margin of the Mokai Field. Cold springs and slightly steam-heated water are discharged in a local valley at profile km 11 (Fig. 4) at an elevation of 420 m, pointing to a perched water table in the area. An inferred perched water table is shown in Fig. 4, based on the level of a few cold springs projected onto the profile. Temperature data in well MK1 indicate a horizontal outflow at a level between 200 and 270 m. In the Waipapa stream at profile km 6.5 (proj.), deeper thermal water is discharged at an elevation of *280* m; this defines the deep piezometric level at this point.

If one extrapolates the streaming potential between 0 and 5 km in the section of Fig 4, one can postulate that beneath the ridge at profile km 7 the undisturbed potential is probably about –300 mV. Changes in the hydraulic gradient of the perched and deep water tables beneath the ridge, together with a marked increase in resistivity, probably explain the "terrain effect" of this ridge. If the undisturbed streaming potential beneath the Mokai Field was also about –300 mV, the thermal SP effect caused by upflow of thermal waters would be about +300 mV (Fig. 4). Hence, the whole of the Mokai Field would be associated with a broad, positive SP anomaly. Since the undisturbed, terrain-induced streaming potential cannot be defined exactly, the magnitude of this thermal SP effect cannot be assessed with certainty.

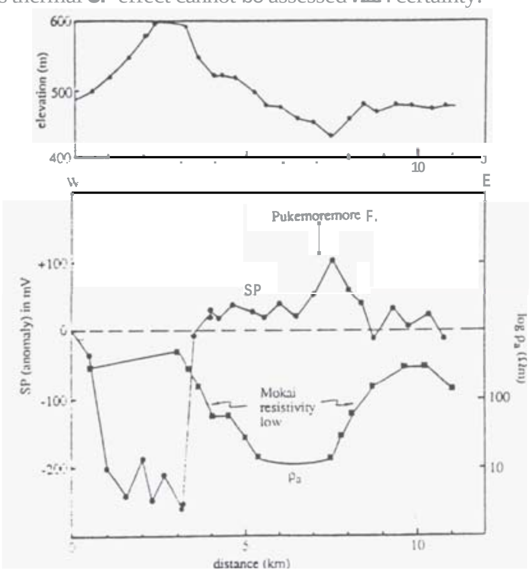

Fig. 5: Topography of Mokai area along an E-W profile (upper part). Observed SP values and apparent resistivity (AB/2 = 1200 m) along the same profile (lower part): for location of profile see Fig. 3a.

Terrain-induced streaming potentials can also be recognized in an E-W profile (Fig. 5) which runs approximately perpendicular to the regional hydraulic gradient. A broad ridge between profile km 1 to 4 shows up with a negative (–250 mV) potential. A local positive SP value of +100 mV near the Pukemoremore Fault may be associated with the fault, the local valley at profile km 7.5, or both features.

The absolute SP values in Fig. 5 indicate another problem: if the "undisturbed" regional streaming potential over the Mokai Field were –300 mV, as postulated from data in Fig. 4, one would expect that the outer points in the SP curve in Fig. 5 would also reach this "undisturbed level". However, data in Fig. 5 indicate a level of about ±0 mV for the outermost stations. It appears, therefore, that without any detailed knowledge of the actual hydrological setting, terrain-induced streaming potentials cannot be reduced. Hence, in steeper terrain, the terrain-induced SP effect cannot be separated from the SP effect associated with thermal upflows (or downflows).

Results (Rotokawa SP survey)

The Rotokawa Survey was made in September 1988 (Villarosa, 1988) and incorporates an earlier survey made by Geothermal Diploma students in 1987; the area south of Lake Rotokawa was re-surveyed in August 1989.

The hydrological setting of the Rotokawa prospect is quite different from that of the Mokai prospect, the terrain being flatter. At Rotokawa, the Waikato River flows through the prospect; hence, it can be expected that an SP profile along the river would reflect data which are not greatly affected by terrain-induced (cold) streaming potentials. The observed SP pattern shown in Fig. 6, however, indicates that, with reference to an assumed undisturbed potential at the outer eastern edge of the field, the potentid at the western edge is still positive (about +100 to 120 mV).

A well-defined positive anomaly (+230 mV maximum) occurs 0.5 km to the N of Lake Rotokawa in an area with significant surface discharge (steam and acid condensates). The SP data along a N-S profile are plotted in Fig. 7, together with an inferred temperature section (using data from Krupp and Seward, 1987); the section indicates that the centre of the positive SP anomaly coincides with an upflow centre of hot fluids. The resistivity data (at AB/2 = 1000 m) shown in Fig. 7 were taken from a map published by Geophysics Division. DSIR (1985). The Rotokawa SP anomaly appears to be a *good* example of a "hot streaming potential" anomaly.

The thermal SP effect is reduced over the slopes of the Oruahineawe Rhyolite Dome and also over higher terrain lying 2 km to the east of the Dome (see Fig. 6). In the east, the SP values decrease locally by about 150 mV per 100 m elevation with reference to stations near the river: this is similar to the SP change with elevation observed near the Waikato River at Mokai (Fig. 4). The apparent indentation of the SP contour pattern near the NW boundary of the Mokai Field (Fig. 6) is, therefore, the effect of terrain-induced streaming potentials.

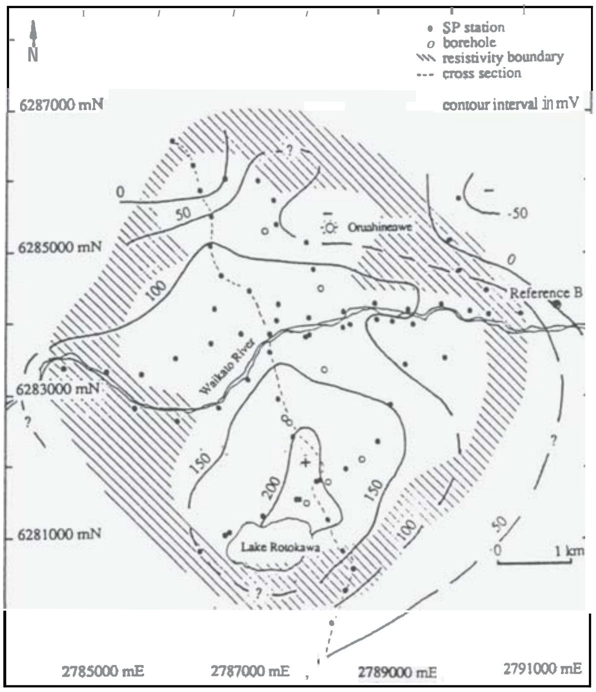

Fig. 6: SP anomaly map of Rotokawa Geothermal Field (contour values in mV).

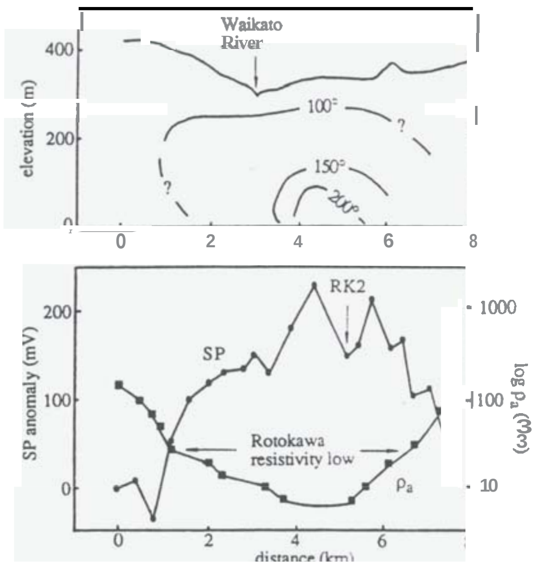

Fig. 7: Observed SP values along a NNW-SSE trending profile across the Rotokawa Field; for location of profile see Fig. 6. Topography and inferred temperatures of section down to sea level (upper part).
Observed SP values and apparent resistivities (AB/2=1000m) along the same profile (lower pan).

Discussion of results

The SP surveys of the Mokai and Rotokawa geothermal prospects have shown that both reservoirs are associated with a positive, large wavelength SP anomaly. At Mokai, this anomaly is distorted by terrain-induced streaming potentials; at Rotokawa the terrain effect appears to be small. The peak of the SP anomaly coincides here with the upflow centre of thermal fluids.

The effect of terrain-induced streaming potentials can be recognized if SP anomalies are plotted with reference to a station near a regional groundwater sink (Waikato River in both surveys). These potentials cannot be separated from potentials induced by thexmal upflows. In both prospects, potentials at higher terrain outside the reservoir appear to cancel in part the terrain-induced streaming potentials, although we know too little about whether the reference potentials used in our surveys are representative "undisturbed" potentials. Other, similar surveys appear to be affected by the same problem.

The study shows that, before any quantitative interpretation of the "thermal SP effect" can be attempted, one has to look at the reduction of terrain-induced SP effects. Although theoretical studies of the thermal SP effect are advanced (Ishido et al., 1990), similar studies of the terrain-induced effects are lacking. If the terrain-induced effects could be reduced, the residual "thermal SP effect" should contain important information for the numerical modelling of geothermal reservoirs in their natural (and exploited) state.

Acknowledgements

The multiple SP leapfrog array was proposed by G. Caldwell (now Geophysics Division, DSIR, Wellington), who also assisted during the Mokai survey. Dr S Henrys (now at Rice University, USA) assisted with the Rotokawa Survey. Dr G.L. Scott (Geothermal Institute) draughted most of the figures.

References:

Anderson, E., Ussher, G., Tearney, K. (1982): Geophysical survey of the Pico Alto geothermal prospect, Terceira Island, Azores. Proc. Pacific Geoth. Conf. 1982 (4th NZ Geoth. Workshop), Univ. of Aucklkand, 385-390.

Bibby, H.M., Dawson, G.B., Rayner, H.H., Stagpoole, V.M., Graham, D.J. (1981): Geophysical investigations of the Mokai Geothermal Field. DSIR Geophys. Div. Report 184, Wellington, NZ, 41 pp.

Brophy, P., Waff, H., (1986): Self-potential gradients, Coso Geothermal Field,, California. Trans. Geoth. Res. Council 10, 211-216.

Corwin, R.F., De Moully, G.T., Harding, R.S., Morrison, H.F. (1981): Interpretation of self-potential sounding results from the East Mesa geothermal field, California. Journ. Geophys. Res. 86, 1841-1848.

Corwin, R.F., Hoover, D.B. (1979): The self-potential method in geothermal exploration. Geouhvsics 44, 226-235.

Fitterman, D.V., Corwin, R.F. (1982): Inversion of self-potential data from the Cerro Prieto geothermal field, Mexico. Geophysics 47, 938-945.

Geophysics Division (DSIR) (1985): Sheet U17 - Wairakei: Electrical resistivity map of New Zealand 1:50 000. Nominal Schlumberger array spacing 1000 m. Department of Scientific and Industrial Research, Wellington, NZ.

Goldstein, N.E. (1988): Subregional and detailed exploration for geothermal-hydrothermal resources. Geotherm. Science and Technology, 1, 374-379.

Goldstein, N.E., Alvarez, J. (1989): Self-potential changes at the Cerro Prieto Geothermal Field. Lawrence Berkeley Lab. Report LBL-26948, Berkeley, Calif., 9 pp.

Ishido, T., Kikuchi, T., Sugihara, M. (1990): Mapping thermally driven upflows by the self-potential method. Geophysical Monograph 47, IUGG, 151-158.

Kikuchi, T., Sugihara, M., Ishido, T. (1988): Self-potential changes induced by geothermal fluid production. Proc. Int. Svmp. on Both. Energy 1988, Geoth. Res. Soc. of Japan, 75-77.

Krupp, R.E., Seward, T.M. (1987): The Rotokawa geothermal system, NZ: an active epithermal gold-depositing environment. Economic Geology 82, 1109-1129.

Mayhew, I.D. (1982): Field investigation of self-potential at the Mokai geothermal field, New Zealand. Geothermal Institute Project Report No. 82.11, Library, Univ. of Auckland, 45 pp.

Zhody, A.A., Anderson, L.A., Muffler. L.J.P. (1973): Resistivity, self-potential and induced polarization surveys over a vapor-dominated geothermal system. Geophysics 38, 1130-1144.

Zablocki, C.J. (1976): Mapping thermal anomalies on an active volcano by the self-potential method, Kilauea, Hawaii. Proc. 2nd UN Symp. on Development and Use of Geothermal Resources, San Francisco, US Govt Printing Office, vol. 2, 1299-1309.