GEOPHYSICAL METHODS FOR SHALLOW GEOTHERMAL EXPLORATION AND ASSESSMENT OF SUSTAINABLE RESOURCE UTILISATION - AN EXAMPLE FROM AWAKEN, WHAKATANE

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SUMMARY - Recent geophysical measurements, including Bouguer gravity, gradient-array resistivity (using an adaptation of the tensor bipole-dipole method), supported by a vertical electrical sounding, are used to construct a conceptual model of the low-temperature geothermal system at Awakeri Hot Springs. Historical discharge temperatures and flow rates of the hot springs and bores are compared with recent data to draw conclusions about the probable sustainable rate of abstraction. Geochemical and geological information are also integrated with these geophysical and hydrological data to produce an assessment of the resource that can assist with future well siting and resource management.

1.0 INTRODUCTION

Awakeri Hot Springs and campground are located 3 km southwest of Awakeri (originally a railway station) along State Highway 30 between Kawerau and Whakatane, New Zealand. Early DSIR records (Aug 1945) show that three springs at Awakeri, two natural and one excavated, had temperatures between 56" and 60°C, with daily variations of about 1°C. Collectively they discharged about 2.3 Vs, representing a natural heat output of 0.4 MW (thermal). Swimming baths were constructed partly over an excavated spring, and on 16/08/1960, the temperature measured in this spring (with the baths emptied) was 64.5°C. Black algae were also noted in the spring channel and when decayed, these deposited a black silty sludge. This 'excavated' spring was sealed when the bathing pool was reconstructed in the 1970s. The large bathing pool was also reconstructed after the Edgecumbe earthquake in 1987, which caused local ground deformation and damage.

On 23/10/1963, samples were taken from the excavated spring and two adjacent drill holes (B1&B4) and chemically analysed. The results (from Glover, 1968) are shown in Table 1. These indicated the presence of weakly-mineralised, neutral, chloride-bicarbonate water. A low CVB ratio of 4.3 indicates the influence of underlying greywacke.

Geothermometer temperatures, as indicated by the chemical ratios and silica content, are relatively low, and typical of tectonic springs. They do not indicate the presence of a high temperature geothermal system, such as at nearby Kawerau. The origin of the hot waters is therefore inferred to be from deep circulation of meteoric groundwater along a major basement fault.

The geology of the Awakeri Springs area consists of greywacke basement (down faulted to the northwest, and exposed at Raungaehe Range to the east), overlain locally by > 50 m of Matahina Ignimbrite and sediments forming the Rangitaiki Plain. Bore M4 reached greywacke basement at 64m depth, but M1 did not reach basement at 104m maximum depth. A major NE trending basement fault, bounding the Whakatane Graben, is thought to be located near the main highway adjacent to Awakeri springs, based on limited drillhole and seismic evidence. Modriniak (1945) interpreted these data to indicate a displacement of greywacke basement from 66m to 183m. Hot water probably ascends this fault, then into horizontal aquifers beneath the ignimbrite, and finally up to the surface on another local fault penetrating the Matahina Ignimbrite. Modriniak also identified a narrow magnetic low coinciding with the Awakeri hot spring.

Table **1.** Chemistry of Awakeri waters 23/10/1963.

Sample #	**1273A**	**1973B**	**1271**
Sample **location**	Spring	**B4**	**B1**
Temperature °C	**58**	**70**	**69**
pH	8.35	8.35	8.25
Cl mg/kg	38	40	39
Na mg/kg	110	110	110
K mgkg	1.5	1.5	1.5
F mg/kg	4	4	4
SO_4 mg/kg	13	4	8
HBO_2 mg/kg	11	11	11.3
SiO_2 mg/kg	63	63	64
NH_3 mg/kg	0.2	0.2	0.1
CO_2 mg/kg	171	173	172
H_2S mg/kg	1	4	4

2.0 DRILLHOLE DATA

M1 and M4 boreholes were drilled in the 1940s (see figure 1 from NZGS 1974). They were located 340 m north and 150 m east of the hot spring. M1 produced a small flow of 49°C waters at 80 m, and M4 produced an artesian flow of 0.5 l/s of 48 °C at 55m. These bores indicated the likely 500m lateral extent of a hot water aquifer within permeable sediments at depths of 50 to 80m. M2 and M3 were abandoned, and M1 and M4 are no longer accessible.

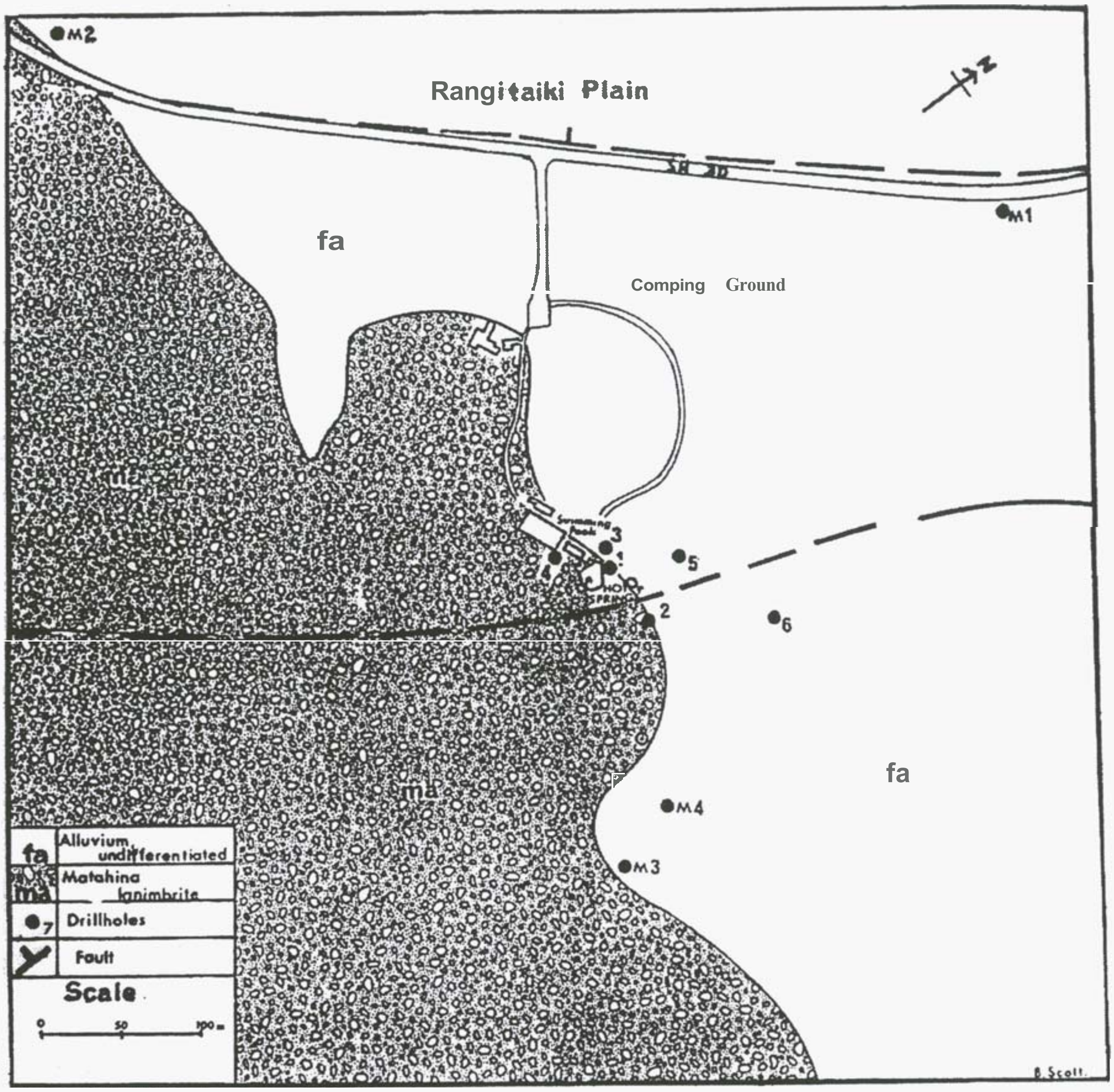

Figure 1. Early sketch map of Awakeri Springs and bores (fi-om NZGS, 1974)

Subsequent Awakeri holes were drilled closer to the springs (Figure 1, labelled 1 to 6). They produced hot water fi-om near the base of, and beneath, the Matahina Ignimbrite at temperatures between 56°C and 70°C (**NZGS,** 1974). The highest temperatures occurred closest to the hot spring but the greatest **flows** were obtained from the more distant holes. In 1972, the available **flow** of hot water **from** all sources was 3.03 *Vs*. With the drilling of holes B5 and B6 in September and October 1973 the potential yield increased. By 1974, the total artesian discharge of hot water fkom all sources (springs and bores) was about 5 *Vs* representing a total heat output **of** about **1** MW (thermal) relative to 12°C ambient temperature.

B4 is the deepest bore at 98m but did not reach greywacke basement. Only one new bore (B7) has been added since those shown on the 1974 map and this is located adjacent to B6 (which ceased discharge). Boreholes presently **in** use include B1, B2 and **B7.** B3 to B6 were abandoned. B2 was deepened to 51m and flows about **2.3 l/s;** B7 is 73 m deep, cased **to** 19 m and flows about **3** *Vs*.

3.0 RECENT FLOW RATE AND TEMPERATURE DATA

From measurements made on 6/12/2001, during a typical operating day, the following water flows and temperatures at Awakeri were recorded:

1) Pukaahu Spring: T = 56°C, outflow=1.0 l/s into a sump.
2) Children's pool: T = 37.3°C, 0.125 l/s into sump.
3) Main pool: T = **37.5°C,** 1.29 l/s outlet to drain.
4) Spa pool: T = 43°C, 0.45 l/s outlet to drain.
5) Under floor heating: T = 53.3°C, 0.182 l/s to drain.
6) Heat exchanger, when all flow was temporarily discharged to drains: T = 53°C, 3.8 **l/s** at drain.
7) Holding tank before spa pools (bore water): T = 56°C.
8) NE boundary drain (behind borehole **7):** T = 24.7°C (ambient air temperature = 22.6°C).

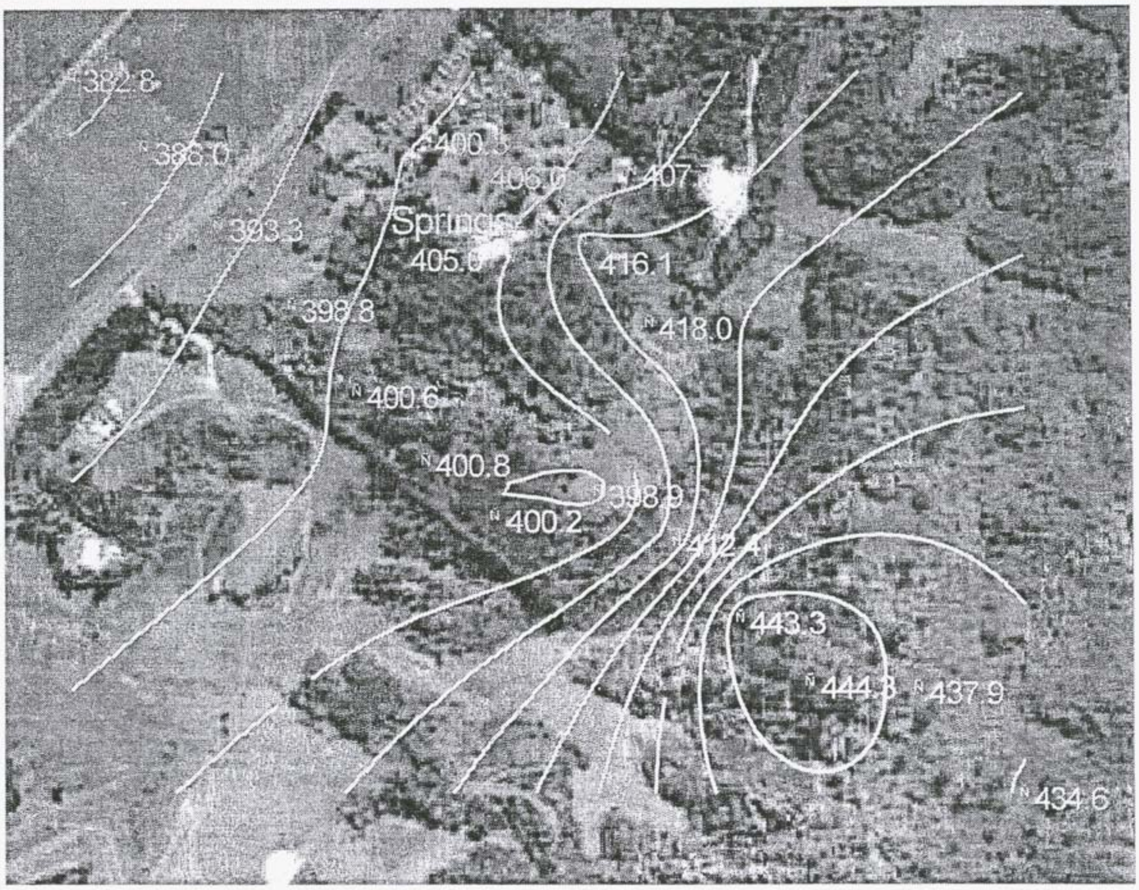

Figure 2. Aerial photo of Awakeri Springs, with an overlay of Bouguer gravity anomaly contours and values. The photo is oriented north and the width is 1.05 km. Faults are inferred to coincide with steep gravity gradients. A NE trending fault is apparently displaced by a cross fault

The combined typical discharge during the day from all spring and pool outlets amounts to 3.05 l/s (0.42 MW thermal). This can increase by up to 3.8 **l/s** (0.65 MW thermal) if the heat exchanger is fully open and discharged to the drain. The heat exchanger is normally only used at night, at less than 50% capacity, to maintain pool temperatures. So an average total flow rate over 24 hours is about 4 ±1 l/s, and about 0.5 to 0.6 MW thermal, depending on seasonal demand.

The present-day total discharge flows are usually less than the estimated 1974 flows (5 l/s, 1 MW thermal), and slightly more than the earliest natural spring discharge measurements of about 2.3 **l/s** and 0.4 MW thermal.

4.0 SUSTAINABLE EXTRACTION RATE

The temperature of the discharging natural springs does not appear to have changed significantly with time (58° – **Aug.** 1945, ***58"*** – Oct. 1963, 56" – Dec. 2001). In December 2001, Pukaahu Spring was discharging about 1.0 l/s, compared to the earliest recorded combined spring flowrate of 2.3 l/s.

The present day total discharge of heat fiom the spring and bore-fed pools is slightly more than the pre-development natural heat discharge from the springs. Discharge from the natural springs apparently declined when some wells initially came into production (NZGS, 1974), and it was thought that there was some initial pressure interference between neighbouring bores B1 and B2. However, there has been no subsequent evidence of long term decline in output or temperature that would indicate that the resource is being depleted. Effects on groundwater are also negligible. The bores and spring still **flow** under artesian pressure, despite many decades of utilisation. Warm (25°) groundwater still discharges into surrounding drains, such as the northeast boundary drain.

Therefore, it is concluded that the Awakeri Hot Springs operation is currently extracting and utilising hot water in a long-term sustainable manner.

5.0 BOUGUER GRAVITY

A gravity survey was designed to locate local evidence for subsurface density changes that could be attributed to basement-displacing faults. Greywacke basement has a density of about 2670 kg/m^3 and overlying volcanic and sedimentary formations have densities of 2150 kg/m^3 or less. Bouguer gravity anomaly values were calculated from gravity measurements made at 22 sites near Awakeri on 6/2/2002. Sites were located along a **NW-SE** profile and near boreholes (Figure 2). Elevations were determined using phase-processed differential GPS data (10 minute files) at *6* sites where satellite coverage was possible, and using 3 Baromec barometers elsewhere (average of 10 repeats at each site). The two methods gave consistent elevations to within 0.6m across a range of 10m to 230m. We used the Wairakei-based (La Coste-and-Romberg) gravity meter, and a local base was established on the front step of motel E. This was later tied into the NZ primary gravity network. Terrain corrections were calculated from field estimates out to zone D, from the topographic map to zone **H,** and from the GNS Terrain program for the remaining zones.

The results are shown as a contour map of Bouguer values (Figure 2). As expected, the map shows a gradient of increasing gravity across the edge of the Whakatane Graben, reflecting the change in density from low density graben infill material to higher density greywacke basement. The slope of the gravity change indicates a steeply-sloping basement interface. However, the contours indicate that the basement surface is not simply a planar feature along a major NE trending graben fault. It appears to be displaced in the vicinity of the Awakeri hot springs, possibly by a cross-fault. Therefore, it is likely that the locus of the springs is controlled by the junction of a NE trending basement fault and a cross-fault.

6.0 RESISTIVITY

Tensor resistivity gradient measurements along three profile lines and a vertical electrical sounding were conducted in the vicinity of the Awakeri hot springs to investigate the local resistivity structure. The gradient resistivities were measured using a novel adaptation of the multiple-source tensor bipole-dipole method used to investigate the deep resistivity structure of many geothermal fields in the Taupo Volcanic Zone. Here, we established three pairs of current electrodes surrounding the area of interest (approximately 0.2 km^2) and measured vector electric fields (as a function of the three current orientations) with orthogonal arrays at 20m spacing along a total of 1.2 line-km of traverse. The locations and orientations of these profile lines were constrained by access routes **through** and around the camping ground next to the spring and swimming pool. Figure 3 shows a map of the resistivity profile lines. The nominal maximum probing depth (AB/2 equivalent) for these resistivity data is about 300m at the centre of the lines but reduces to about 100-150m at the **ends** of the lines. This is greater than the borehole depths (50-100m), but the effective average penetration depth should be similar (50-150m).

The results, as shown in Figures **4** to *6* for current dipoles **A** to C, show that resistivities in the vicinity of the spring and the productive bores are consistently low (about 15 ohm-m). Values increase to about 40 ohm-m to the SE between bores B2 and **M4,** probably revealing a lateral boundary in this direction (ignoring possible changing penetration depth effects). The strongest contrast is observed in the data fiom current dipoles **A** and C which are oriented across the resistivity change. **A** higher resistivity boundary is also observed to the NW, with values rising fiom about 15 (+-5) ohm-m to values of 40 to 70 ohm-m on the three lines. The changes are relatively smooth probably indicating gradational changes in thermal clay alteration and temperature. The zone of anomalously low resistivity forms a narrow NE trending zone, approximately 80 m wide by at least 200m long, that encompasses the existing bores B2 to B7, and extends a short distance **SW** of the swimming pool.

Evidence of anisotropic resistivity structure is also revealed by the angle deflections, or differences between measured electric field direction and computed current direction (assuming isotropic half-space). ***An*** example is given in Figure **7.** Changes in angle deflection along the profiles amount to as much as **30** degrees, particularly when the current orientation is oblique to the NE trending low resistivity anomaly. Current is channelled into this anomaly causing orientation deflections of opposite sign inside and outside the low resistivity structure. This effect is also observed in the elliptical representation of the resistivity tensor, with the major axis of the resistivity ellipse oriented along the low resistivity linear structure when inside it, but oriented perpendicular to the structure when the site is located outside it.

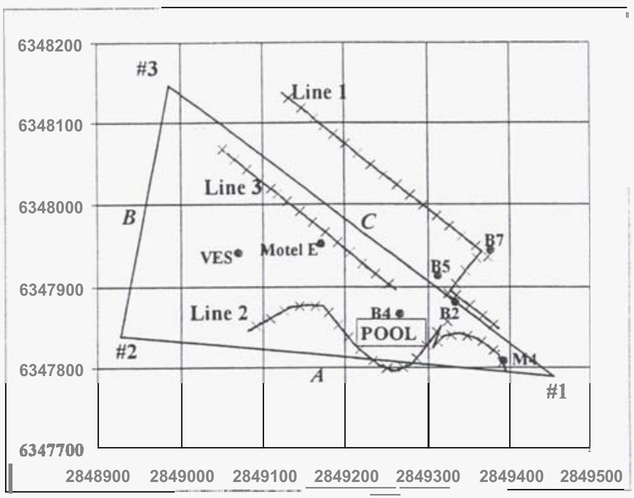

Fig **3.** Location map of resistivity profiles near the Awakeri hot spring and pool. Three profile lines were traversed using vector electric field measurements for **3** current dipoles (A,B,C). VES is a vertical electrical sounding. Selected bores are also shown (B2-B7).

To determine resistivity changes with depth, a Schlumberger resistivity sounding **(VES),** using AB/2 spacings of 2m to 200m, was conducted in the field **between** the main highway **and** the office (see Figure **3).** Gradient array measurements at this site reveal resistivities of **46** to **60** ohm-m for equivalent AB/2 spacings **of 216** to **285m,** consistent with the VES value at AB/2 of 200m of **45** ohm-m. The orientation of the sounding was parallel to the road (NE). The results were interpreted in terms of a sequentially layered resistivity structure, as follows:

R (ohm-m):	350	59	32	90	40	?
Thickness (m):	0.4	5	66	110		

The lowest resistivity layer (**66m** of **32** ohm-m) is caused by Matahina ignimbrite containing some dilute thermal water and weak clay alteration. The higher resistivity layer may be caused by the sedimentary sequence underlying Matahina ignimbrite. The value of the deepest resistivity layer is poorly constrained because of limited data at these depths.

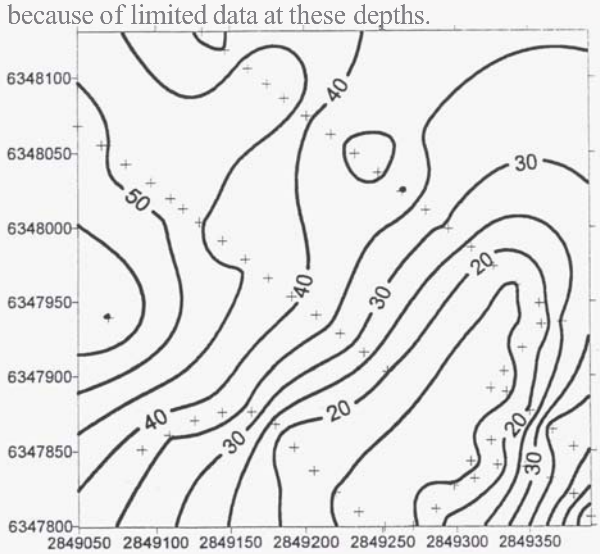

Figure. **4.** Resistivity contours (ohm-m)-current dipole **A** (E-W). See figure **3** for profile line locations.

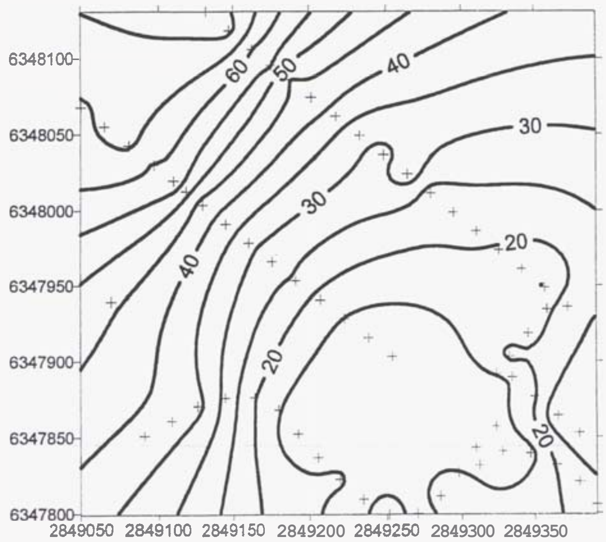

Figure **5**. Resistivity contours - dipole **B** *(N-S).*

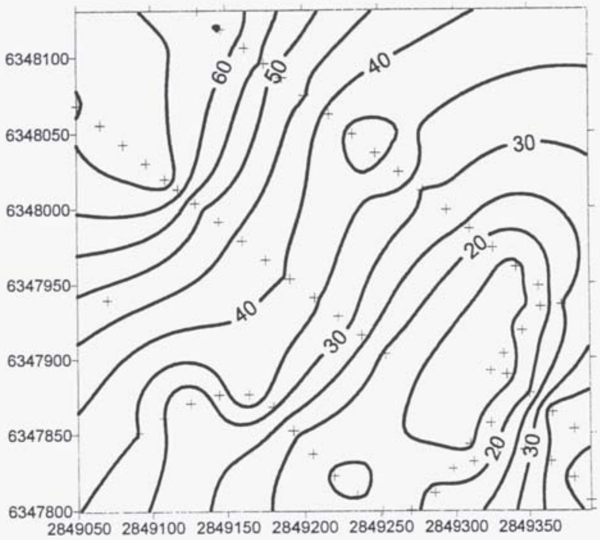

Figure *6*. Resistivity contours - dipole C **(NW-SE).**

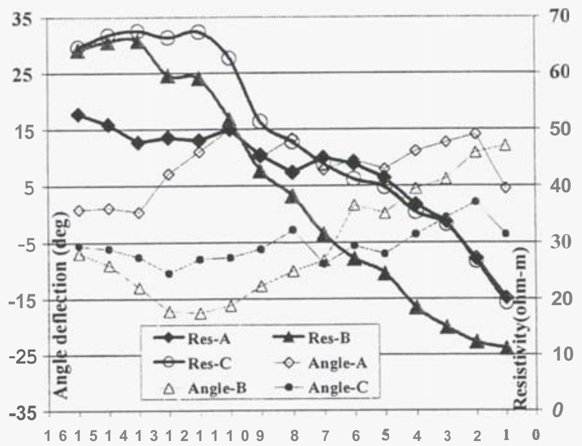

Figure **7.** Resistivities and angle deflections along Profile **3 (NW** to **SE,** 20m intervals) using current dipoles A, B, and C. These show decreasing resistivities closer to the hot spring, and angle deflections characteristic of a 200m wide boundary.

7.0 CONCLUSIONS

From an integration of the geochemical, geological, hydrological and recent geophysical information from around Awakeri Hot Springs, it is concluded that this area consists of a limited geothermal resource at shallow depth, fed by a hot fluid upflow of tectonic origin. The resistivity data outlines a narrow zone about 80m wide by at least 200m long of about 15 ohm-m caused by the primary effects (mostly hydrothermal clay alteration) of the **60 °C** upflow. Resistivity and gravity results (Figure **8)** suggest that the upflow may be focussed on an intersection of a major NE-trending graben-bounding fault and a cross fault that has also displaced the greywacke basement.

Anecdotal evidence for the presence of active fault movement aligning with the resistivity low at Awakeri (and the fault mapped in figure 1) was given by a long term resident of the camp who recalled observing ground cracking (along the centre of the resistivity low) during the Edgecumbe earthquake in **1987.** Some horizontal dispersion of the hot upflow occurs in permeable horizons of the Matahina Ignimbrite and sediments overlying greywacke basement, but these lateral flows progressively cool with groundwater dilution (to about 50 °C, about **150-200m** fiom the upflow).

The Awakeri Hot Springs operation is currently extracting and utilising hot water in a long-term sustainable manner. It is recommended that any future replacement wells be drilled into the narrow, fault-controlled zone of low resistivity where most of the existing boreholes are located.

This case study shows how integrated exploration and assessment of a low temperature geothermal resource can assist with sustainable resource management, including future well siting, and extraction strategy.

8.0 ACKNOWLEDGEMENTS

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9.0 REFERENCES

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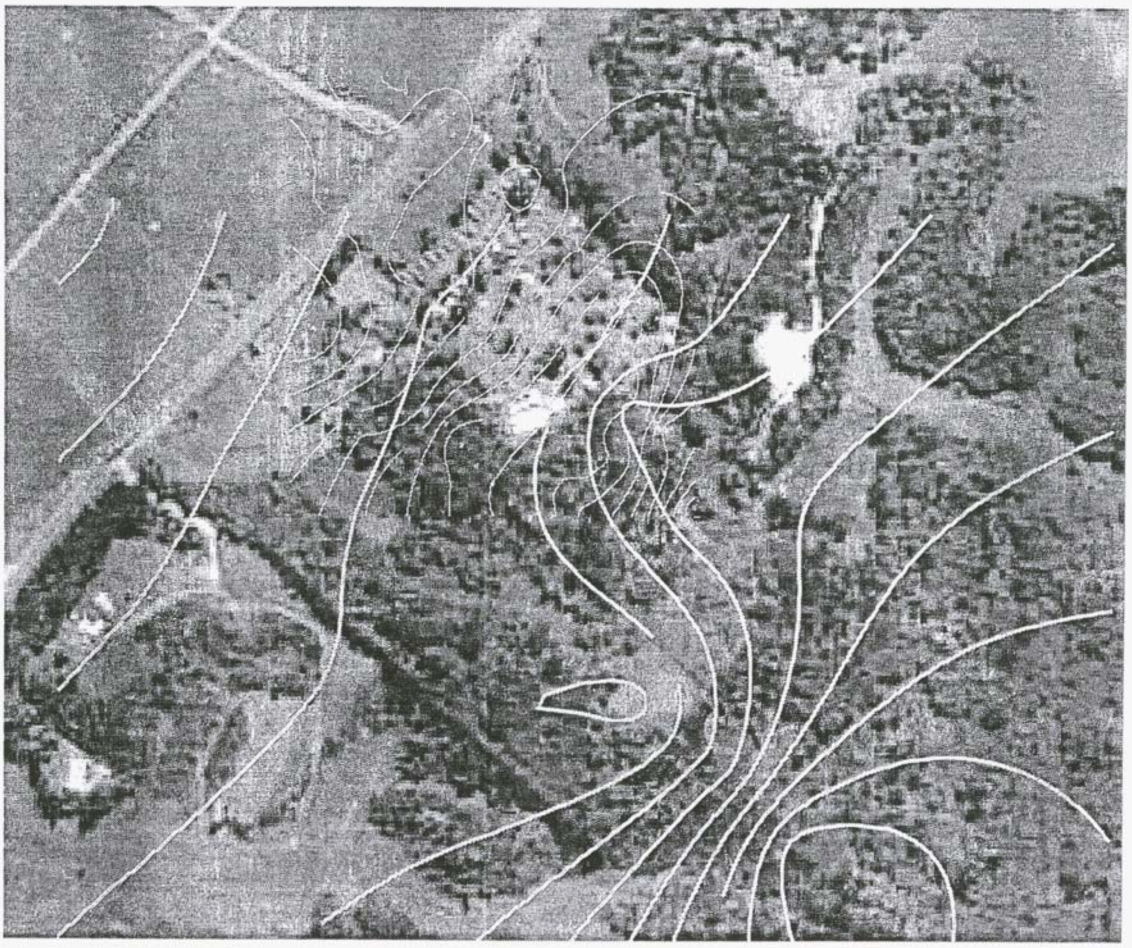

Figure **8** . Aerial photo of Awakeri Hot Springs overlain by contour maps of resistivity (dipole A from figure **4)** and Bouguer gravity (from figure 2) showing the coincidence of the linear low resistivity feature and the steeper gravity gradient implying the presence of a basement displacing fault.