ALTERNATIVE BOUNDARY CONCEPTS FOR GEOTHERMAL FIELDS

P.F. BIXLEY

Geothermal Resource Engineer, ECNZ, Wairakei, NZ

SUMMARY - The basic tool used to outline the subsurface extent of liquid dominated geothermal fields in the Taupo Volcanic Zone has been various forms of resistivity mapping. Boundary zones derived using this method have been shown to consistently outline the areas of hot geothermal resource down to the depths so far explored and these geophysical boundaries have become the commonly accepted "field boundaries". As a geothermal exploration programme proceeds, a better understanding of the sub-surface conditions gradually unfolds, and boundaries derived using other scientific disciplines can be defined. Today, any geothermal development is likely to require reinjection of separated water and condensate. In order to properly assess the potential effects of a field development on the environment - subsurface and surface - alternative types of boundary need to be recognised. This paper compares some different boundary types, using resistivity, geology, geochemistry, permeability and temperature characteristics.

1. INTRODUCTION

In the geothermal environment of the Taupo Volcanic Zone, the use of resistivity methods has proven to be successful for delineating hot geothermal resources. In terms of locating successful production zones (ie good permeability), the boundaries drawn using electrical survey methods are somewhat optimistic, and may extend up to 1 km outside the limit of successful production wells (drilled to < 1500 m depth).

For geothermal development today in New Zealand, many more factors other than production must be taken into account when formulating a field development concept. After the high temperature production zone has been located, an area for reinjection of used fluids must be found and the potential effects of the production-injection operations evaluated. The Resource Management Act requires that potential effects on the "environment" are assessed: This is the total environment - including the hot resource itself, surrounding cooler aquifers, any surface features and the atmosphere. Effects may be thermal, chemical, pressure or biological changes. To make a complete assessment of the possible effects of both production and reinjection we need to have a much broader appreciation of the concepts of boundaries, the nature of inter-connections between different parts of a geothermal field and between the field and surrounding aquifers.

2. CONCEPTS OF LIQUID-DOMINATED GEOTHERMAL FIELDS

In this discussion, the geothermal "field" is considered as that part of the resource that can be accessed by drilling - ie down to 3-4 km. Conceptually, geothermal fields may be considered as bodies of hot fluids that are surrounded by and in intimate contact with cold water (figure 1). In the natural (undisturbed) state, the higher temperature of the geothermal body is maintained by a continuing input/recharge of heat and mass to balance that lost around the field margins and at or near the ground surface. From a hydrological point of view a physical boundary is not essential as the buoyancy of the hot fluid relative to the surrounding colder fluids allows the formation of a stable rising plume of hot fluids above the heat source that eventually reaches the ground surface to dissipate any excess heat and mass (Alternatively the heat and mass can be dissipated via shallow outflow structures).

Any change in pressures due to fluid withdrawal or injection will affect the various fluids flowing along the natural flow paths which link the deep hot fluid with the cooler fluids surrounding the field and with manifestations of the geothermal energy at the ground surface. Some flow paths will be zones of enhanced permeability such as faults. Other significant "flow paths" such as hydrological boundary zones may have poor permeability and act as barriers to fluid movement. Because these lower permeability boundary zones have very large cross-sectional areas, although the permeability is small, the cumulative fluid flow across a boundary zone may still be significant.

Most of the geothermal fields in New Zealand have only been explored to relatively shallow depths. Of 150 wells drilled at Wairakei only three are deeper than 1600 m. At Ohaaki, two wells out of 50 are deeper than 1600 m. The bulk of the wells in these fields were completed before 1980.

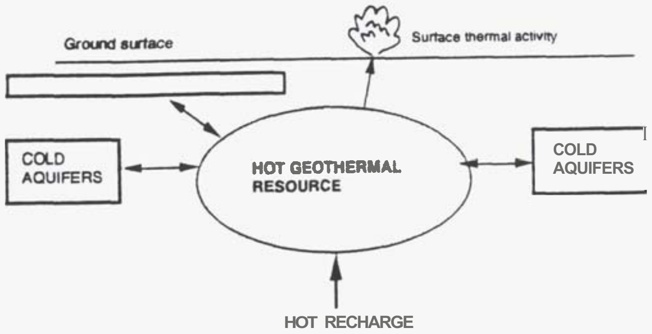

Figure 1 - Conceptual model of a liquid geothermal field showing the main hydrological elements.

For fields explored more recently in New Zealand, the investigation wells have been drilled to 2.5 - 3 km depth. Rotokawa is the best explored "deep" field with 4 wells deeper than 2 km and 4 shallower wells. Our understanding of the deeper structures and paths of recharge fluids into geothermal fields in the Taupo Volcanic Zone is limited by the depth and locations of the existing exploration wells, and the conceptual ideas for the deeper parts of these fields relies on the limited deep exploration in the Taupo Volcanic Zone together with experience from other countries.

3. BOUNDARIES

Geothermal fields are three-dimensional structures and boundaries (if present) may be present at the top and bottom as well as at the sides of the fields. Even in the undisturbed state these properties may vary with time by processes such as re-activation of faulting or by hydraulic fracturing (Grindley and Browne, 1975). Boundaries displaying different characteristics will be found in different locations around the field. Redeposition of minerals associated with the flow of hot fluids through the ground results in changes in the host rock properties and causes a contrast in the rock and fluid properties "inside" and "outside" the field.

Geophysical boundaries as defined by resistivity methods have been shown to provide a good indication of the general area where high temperatures may be encountered at depth (Risk 1984). But to answer more detailed questions about the location of productive zones and fluid interactions between the geothermal reservoir and the surrounding environment, additional information is needed.

The definition of a boundary lies largely in the eye of the beholder - as there are many different scientific and engineering disciplines involved in exploring and assessing geothermal resources, there are many different concepts of what a boundary "really" is. Geophysical measurements are usually the first used to delineate a field and boundaries based on these measurements often remain the definitive field boundary, long after other information is available. The different types of boundary are often related and may result from some geological feature - eg faults or change of rock type - or they may be caused through alteration of the original rock through action of the geothermal fluids. However they will not often be located in the same place - laterally or vertically.

4. EXAMPLES OF DIFFERENT BOUNDARY TYPES

Several geothermal fields in the TVZ have now been explored in detail by various scientific methods and by drilling and testing of wells. The results of this work has shown a fairly consistent pattern. The general field structure found is as shown in figure 2, a section across the Rotokawa field.

4.1 Rotokawa

The resistivity structure at Rotokawa is known from DSIR surveys made in 1984-85 (Geothermal Developments and Investments, 1988), with a boundary zone corresponding with depths of about 600 metres below ground surface. Eight exploration wells have been completed, with four wells in the 2-3 km depth range. These wells have proven a productive zone below 1500 metres depth with temperatures more than 300°C. A section through the deep wells from the centre of the field, towards the north is shown on figure 2.

It is not clear from the section, but in the central part of the field the wells typically show an initial very steep temperature profile down to 300 metres, then a small inversion, followed by another steep increase into the high temperature productive part of the resource. The most northerly well, RK8, although hot at the bottom (about 280°C) found little permeability and is non-productive. Thus the northern extent of permeability/production (to the depths explored) appears to be located near RK6. Based on the present well information the bulk of any production would come from within the Rotokawa Andesite below about 1500 m depth. The resistivity boundary refers to about 600 m depth and is separated from the productive formations by about 1000 m of poorly permeable rock.

At Rotokawa there may be some concern that the relatively shallow resistivity boundary definition may not properly reflect the pattern of good permeability and production which lies at much greater depth. There is also little information available about the shallower hydrology and how this may relate to the resistivity pattern.

4.2 Ohaaki

The shallow part of the Ohaaki field is the best delineated geothermal area in New Zealand. Nearly 50 wells have been drilled in an area of about 10 km^2. As mentioned above, the bulk of the wells are about 1200 m deep and only two of them are deeper than 2 km. The resistivity structure has also been investigated in some detail (Risk et al, 1977). Wheras at Rotokawa the potential production zone and the effective depth of penetration of the resistivity surveys differ by 1000 m or so, at Ohaaki the average production depths and the resistivity penetration depths are comparable.

The bulk of the production at Ohaaki is obtained from 400-1000 metres depth and the resistivity boundary zone is considered to represent depths between the surface and 1000 m (Risk et al 1977). The resistivity boundary and "production" boundary (270°C isotherm at 600 metres depth) is plotted on figure 3. The resistivity boundary clearly outlines the production zone, but there is an annulus about 1 km wide between the production and resistivity boundary zones. A similar pattern between the proven productive area and the resistivity boundary zone is found at Wairakei.

A cross section for the eastern part of the field is plotted on figure 4. This shows the relationship of the resistivity, underground temperatures and production zone delineated by drilling.

Where there are no effects from shallow outflow structures, the isotherms around typical Taupo Volcanic Zone fields slope away from the central part of the resource at about 45° (figs 2 and 3). Around the edges of the field there may be temperature reversals in association with horizontal outflows of hot geothermal water - this is usually found within 600 m of the ground surface.

4.3 Lateral Outflow Structures

Figure 5 shows a section through the shallow outflows which extend southward from the Ohaaki field. The chemistry of these outflows is low chloride, high bicarbonate water. As part of the investigation programme for reinjection, extensive interference tests were carried on in this part of the field about 1980 (McGuinness 1984). This testing indicated that the fluids in the outflow structures were not communicating with the high chloride fluids found in the central part of 'the field. There is an obvious strong geological control on the outflow, with one zone confined within the Huka formation sediments and another within the top of the Broadlands Rhyolite below the Huka formation sediments.

In retrospect, the combination of chemistry and pressure data from wells in this area had already conclusively demonstrated that at least down to 1000 metres depth, there was no significant coupling with the high-chloride fluids in the central part of the field. However the interference data was invaluable to show that these geothermally-contaminated aquifers were extremely permeable and extensive (to the south outside the resistivity boundary) and would be suitable for reinjection. The geophysical data shown by Henrys (1987) confirms that the rhyolite structures controlling the shallow outflows to the south of the field extend for several kilometers southward along the Waikato River alignment.

4.5 Reinjection

Reinjection of separated water and steam condensate is an integral part of the steamfield design in any field being developed today. Thus when evaluating the impacts of a development proposal, both reinjection and production effects must be taken into account - not only the impact of reinjection on production, but also its potential impacts on surrounding colder aquifers. For most liquid fields the reinjection system design is a water disposal problem, with the primary objective to minimise the chances of reinjected fluid returning to the production zone. Having reliable information about the hydrological boundaries is essential to evaluating the reinjection system performance. As shown by the Ohaaki example, there may be good hydrological connections across the field boundary defined by resistivity data and careful investigation may be required to reliably predict effects of using this type of aquifer.

4.6 Slanting Upflow

While slanting/lateral flows of geothermal fluids are common in other countries, this type of structure does not seem to be well represented in Taupo Volcanic Zone. This impression may be partly due to the depth of exploration wells being somewhat less than that has been common elsewhere, and through not having appropriate topography. On present information, the Mokai field is an exception, where isotopic data and well temperature profiles indicates a strong lateral flow . Where a slanting upflow from depth is expected there would be a corresponding greater offset between the field boundaries derived from shallow penetrating geophysical methods and the subsurface conditions later found by exploration drilling.

4.7 Conclusion

Resistivity data provides a good guide to the location of hot geothermal resources. However as more data becomes available from drilling and testing wells the definition of the field boundary and inter-connections with adjacent aquifers should be reviewed in order that the full area where potential effects of production and reinjection operations can be identified.

5. REFERENCES

Geothermal Developments and Investments Ltd (1986). *Evidence presented in support of Water Right Application to the Waikato Regional Council.*

Grindley, G.W.G. and Browne P.R.L. (1976). Structural and hydrological factors controlling the permeabilities of some hot-water geothermal fields. *Proc UN Symposium on the Development and Utilisation of Geothermal Resources* pp 377-386.

Hedenquist, J.W. (1990). The thermal and geochemical structure of the Broadlands-Ohaaki geothermal system, New Zealand. *Geothennics* V19/2 pp 151-185.

Henrys, S. (1987). Structure of the Broadlands-Ohaaki geothermal field (New Zealand) based on interpretation of seismic and gravity data. *PhD Thesis, Auckland University*.

McGuinness, M.J. (1984). Ohaaki Rhyolite interference tests. DSIR *Applied Mathematics Department Report 288.*

Nairn, I.A. (1986). *Report to Waikato Regional Council.*

Risk, G.F. (1984). Electrical resistivity Survey of the Wairakei Geothermal Field. *Proc 6th NZ Geothermal Workshop*, p 123-128.

Risk, G.F., Groth, M.J., Rayner, H.H., Dawson, G.B., Bibby, H.M., MacDonald, W.J.P. and Hewson, C.A.Y. (1977). The resistivity boundary of the Broadlands geothermal field. *DSIR Geophysics Division Report No 123.*

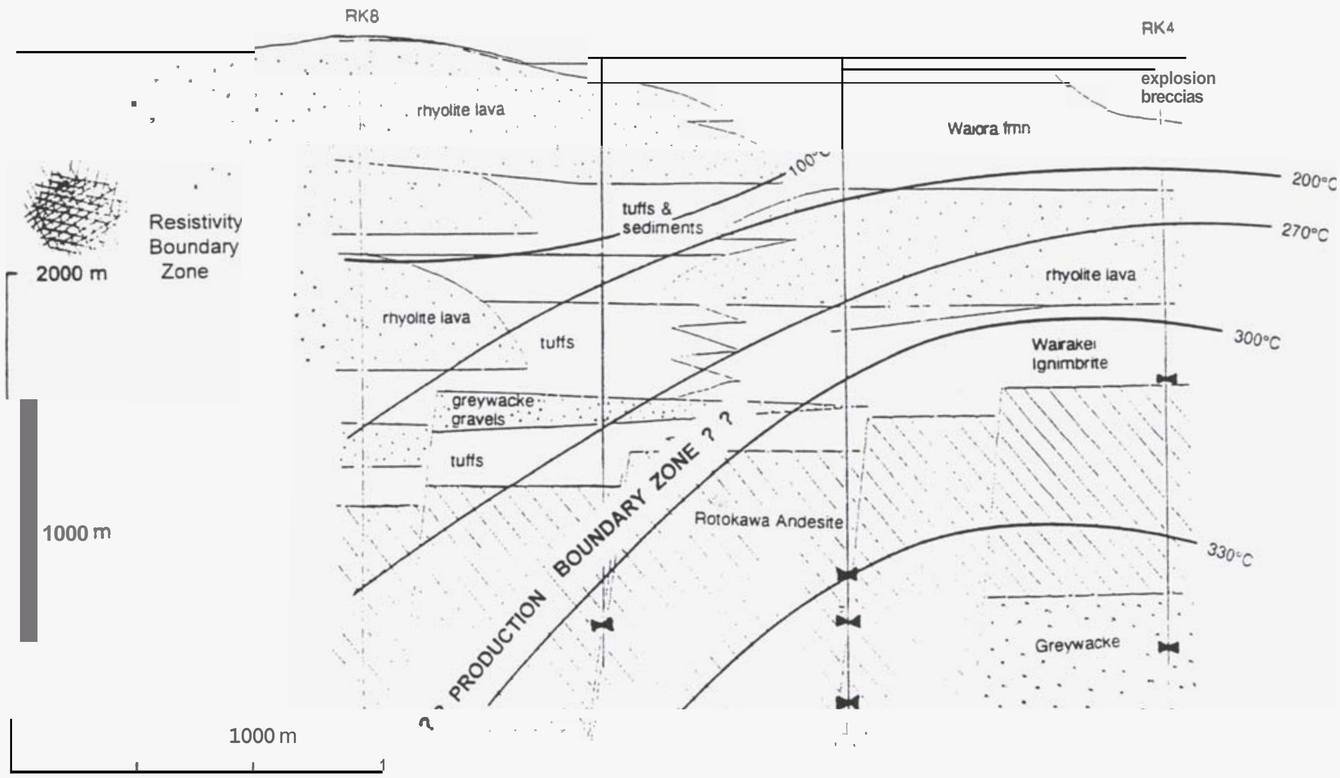

Figure 2 - Simplified cross section of the northern part of the Rotokawa field (Geology after Nairn, 1986). Horizontal and vertical scales equal. The northern resistivity boundary lies about 1 km north from RK8.

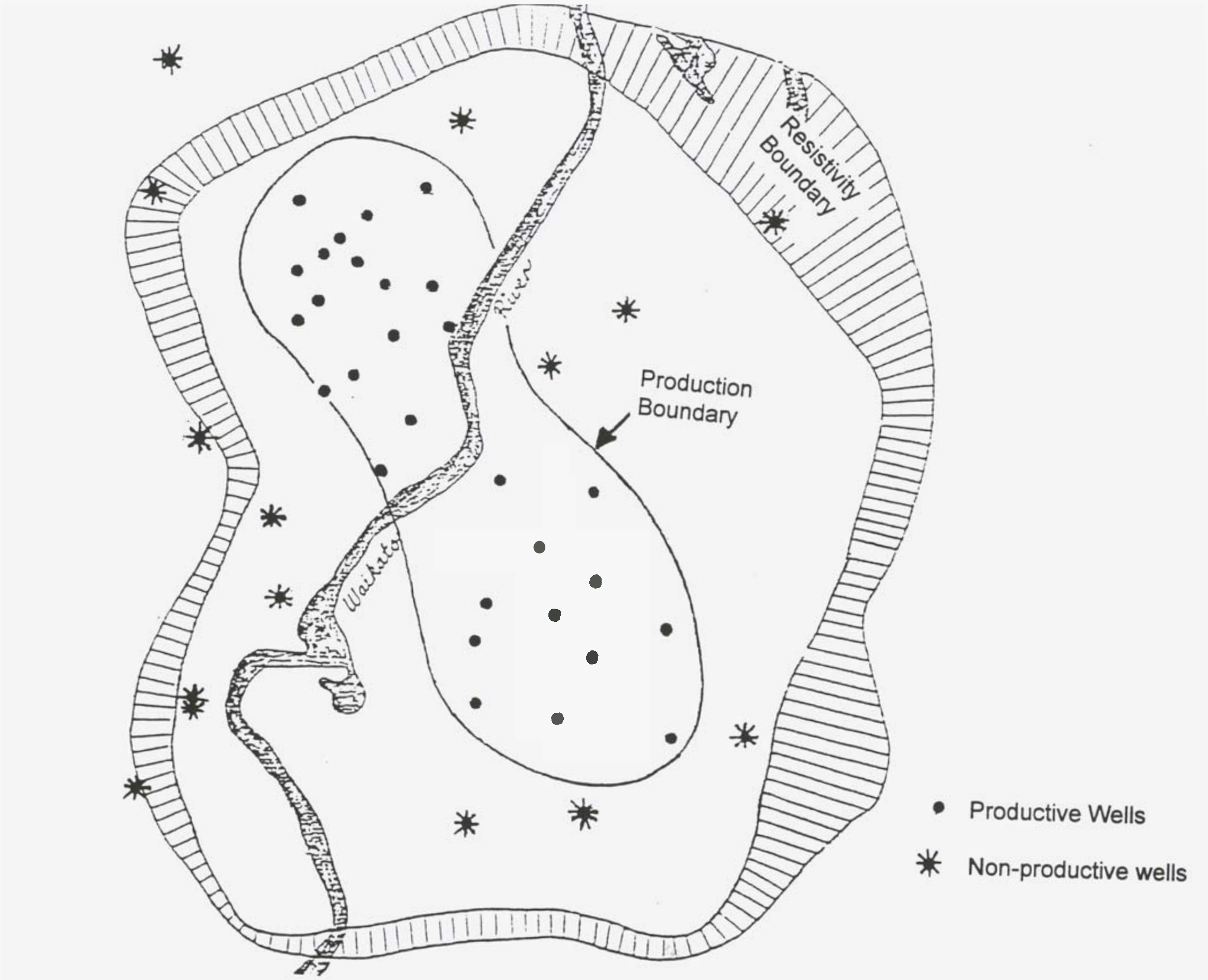

Figure 3 - Ohaaki geothermal field showing the resistivity boundary and the hot productive part of the field proven by drilling. At Ohaaki the depth of penetration of the resistivity surveys and the production depths are similar, whereas at Rotokawa the production depth is more than 1000 m below the boundary zone defined by resistivity. The production "boundary" has been chosen as the 270°C isotherm at 900 m depth, as this contour encloses all the successful production wells.

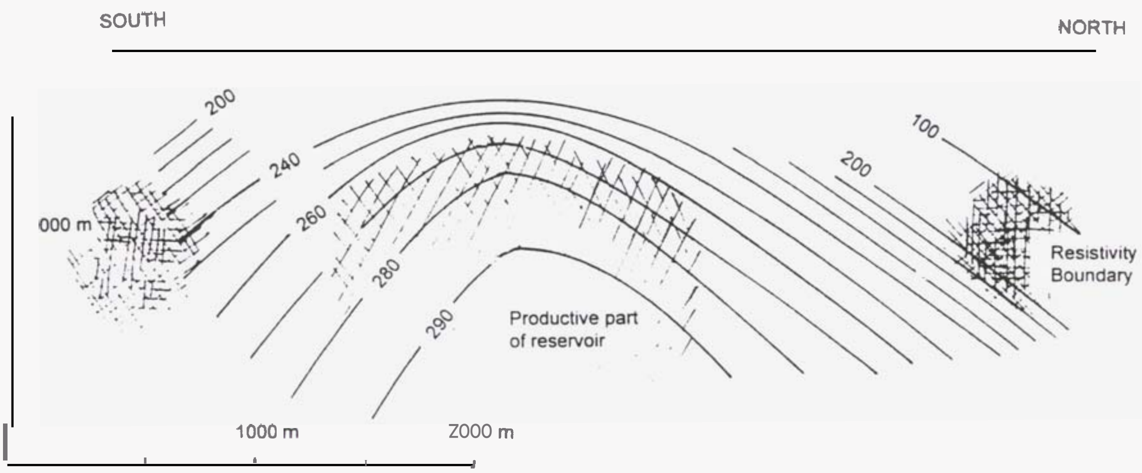

Figure 4 - NE-SW section across the eastern part of the Ohaaki field, showing the relationship between temperatures, production and the resistivity boundary.

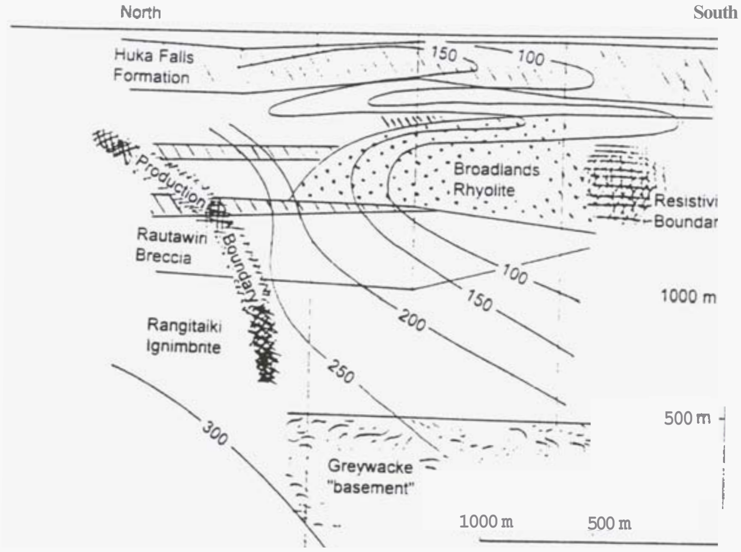

Figure 5 - Idealised cross section extending south from the productive wells in the western part of the Ohaaki field. This shows the shallow flow structure controlled by geology in the part of the field. Temperatures indicate outflows are present within the Huka sediments at 100-150 m depth and in the upper part of the Broadlands Rhyolite at about 300 m depth. More detailed temperature data shows a small inversion at the bottom of the Broadlands Rhyolite, indicating a possible inflow of cooler water here. This section is oblique to the field boundary defined by resistivity which lies about 500 m to the west of the section line and would intersect about well M9. Interference tests have demonstrated good connections between the deeper parts of well 34 and the production zone (34 is hot but not productive) and no connection between well completed into the Ohaaki rhyolite southwards from well 13 and the production zone or wells completed to the same depths above the production zone.