THE GEOPHYSICAL STRUCTURE OF THE BROADLANDS-OHAAKI GEOTHERMAL FIELD (NZ); A CASE HISTORY OF EXPLORATION.

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Introduction

During the past decades most of the known hot-water geothermal systems in the Taupo Volcanic Zone (TVZ) have been explored by geophysical techniques. The Broadlands-Ohaaki geothermal field, located on the eastern margin of the TVZ, is one of the thermal systems ($\approx$25 km^2) delineated by these surveys. An electric plant (105 MW) is presently being constructed to exploit the reservoir.

The extent of the Broadlands-Ohaaki field was first outlined by resistivity measurements in 1965 (Risk et al., 1977). Between 1968 and 1970 detailed seismic refraction, gravity and magnetic surveys were undertaken to determine detailed structural features within the field (Hochstein and Hunt, 1970). Analysis of seismic refraction measurements (about 50 line km) was restricted to short segments (<3.0 km) of reversed travel-time distance profiles and only shallow structures (<500 m) could be mapped with confidence. Local gravity data corrected for regional effects show residual highs up to 100 μN/kg (10 mgal) within the geothermal field. These anomalies were qualitatively interpreted by Hochstein and Hunt in terms of densification of porous reservoir rocks caused by thermal alteration and mineral deposition.

Since 1970 stratigraphic and rock property data from 25 additional wells have become available and the acquisition of 26 km of common-mid-point seismic reflection data in 1984 has provided better correlation of the volcanic stratigraphy and established a more accurate velocity model for the geothermal field. In addition, the use of efficient ray tracing techniques allowed a more comprehensive analysis of refraction data including modelling of unreversed travel-time curves. More detailed knowledge of the geometry of the major stratigraphic horizons was obtained from a reinterpretation of the residual gravity data. A low level airborne magnetic survey was also completed in 1984. The location of seismic and gravity data profiles across the field is shown in Figure 2. Seismic, gravity and magnetic interpretation section for one of the 10 profiles is displayed in Figure 1 (profile B-B').

Seismic refraction data

The analysis of the 1966-68 refraction data was restricted to short segments with reversed travel-time data. The lateral variation in velocity necessitated tedious trial and error modification of initial velocity models which were correlated with stratigraphic information from a few drill holes. The time consuming nature of this procedure meant that only shallow structures including the top of the Ohaaki Rhyolite (velocity 2.3-2.5 km/s) and Broadlands Dacite (velocity 3.3 km/s) could be mapped with confidence (see Figure 1a). An upper near-surface refractor of velocity 0.4-1.2 km/s was observed over the whole area which is underlain by a refractor with a velocity of

1.5-1.9 km/s. On profile B-B' arrivals from a refractor of velocity >3.5 km/s were tentatively interpreted as signal from deeper welded ignimbrites.

Recently a reinterpretation of all refraction data has been attempted (Henrys, 1987 and shown in Figure 1b) using accurate static corrections and having the advantage of efficient ray tracing algorithm plus stratigraphic information from 42 wells. For the first time more than one refractor could be recognised and could be traced over longer horizontal distances (compare Figure 1a and 1b). Longer offset travel times (>3.0 km) were modelled as arrivals from the top of the Rautawiri Breccia and Rangitaiki Ignimbrite. Furthermore, modelling of unreversed travel-time curves identified a number of horizons (velocity range 2.2-2.8 km/s) below the Ohaaki Rhyolite that can be correlated with the producing Waiora Formation.

Seismic reflection data

During October and November, 1984, six common-mid-point seismic reflection lines (26 km in total) were recorded using the New Zealand Department of Scientific and Industrial Research (D.S.I.R.), Geophysics Division, 48-channel system (Sercel HR 338). The orientation of the profiles, shown in Figure 2, was chosen to be either parallel or perpendicular to the dip of the greywacke basement and correspond closely to a number of previously recorded seismic refraction lines (Hochstein and Hunt, 1970). The aim of this study was to test the application of modern reflection techniques to the mapping of subsurface structures of the Broadlands-Ohaaki geothermal field.

While seismic reflection data present an important new source of geophysical information for the understanding of the geothermal field, the quality of data is severely degraded by low-frequency noise and only a few coherent reflectors could be accurately identified. The top and bottom of the Ohaaki Rhyolite account for the major reflecting horizons with occasional less strong reflectors from the top of the Rangitaiki Ignimbrite (Figure 1b). However, even strong reflectors are not coherent across any single profile and the top of the rhyolite and dacite flows may show up with strong reflections at one part of the profile, but elsewhere with weak or no reflections.

Gravity data

There are about 700 gravity stations in the vicinity of the Broadlands-Ohaaki geothermal field mostly established during 1966-67. Residual Bouguer anomalies (mean error ±5.0 μN/kg) corrected for regional effects (Stern, 1979) are shown for profile B-B' in Figure 1c. In previous interpretations of local residual anomalies (MacDonald and Hatherton, 1968; Hochstein and Hunt, 1970) the effect of the concealed northwest dipping basement was reduced by assuming a smooth sub-surface topography. Subtracting the basement effect produced 2nd order residual gravity anomalies which were inferred to be caused entirely by mass inhomogeneities within the volcanic rocks. Isolated residual gravity highs (+100 mN/kg) were interpreted to be caused by densification of rocks within the geothermal field. Since 1970 density measurements of cores and stratigraphic information from 25 new wells have become available (Wood, 1983; DSIR Geophysics Division files) which allow a more detailed analysis of residual gravity data.

Using constraints imposed by borehole information, interpretation of seismic refraction and reflection data, and measured density contrasts between stratigraphic units, a reinterpretation of gravity anomalies over the Broadlands-Ohaaki field in terms of $2^1/2$ dimensional structures (Rasmussen and Pedersen, 1979) was attempted for 4 east-west and 2 south-north profiles (profile B-B' is shown in Figure 1c). The detailed interpretation models allow the compilation of a structural contour map of the basement and the construction of isopach maps of the producing formations (Waiora Formation and Rautawiri Breccia), and the major concealed rhyolites and dacite domes.

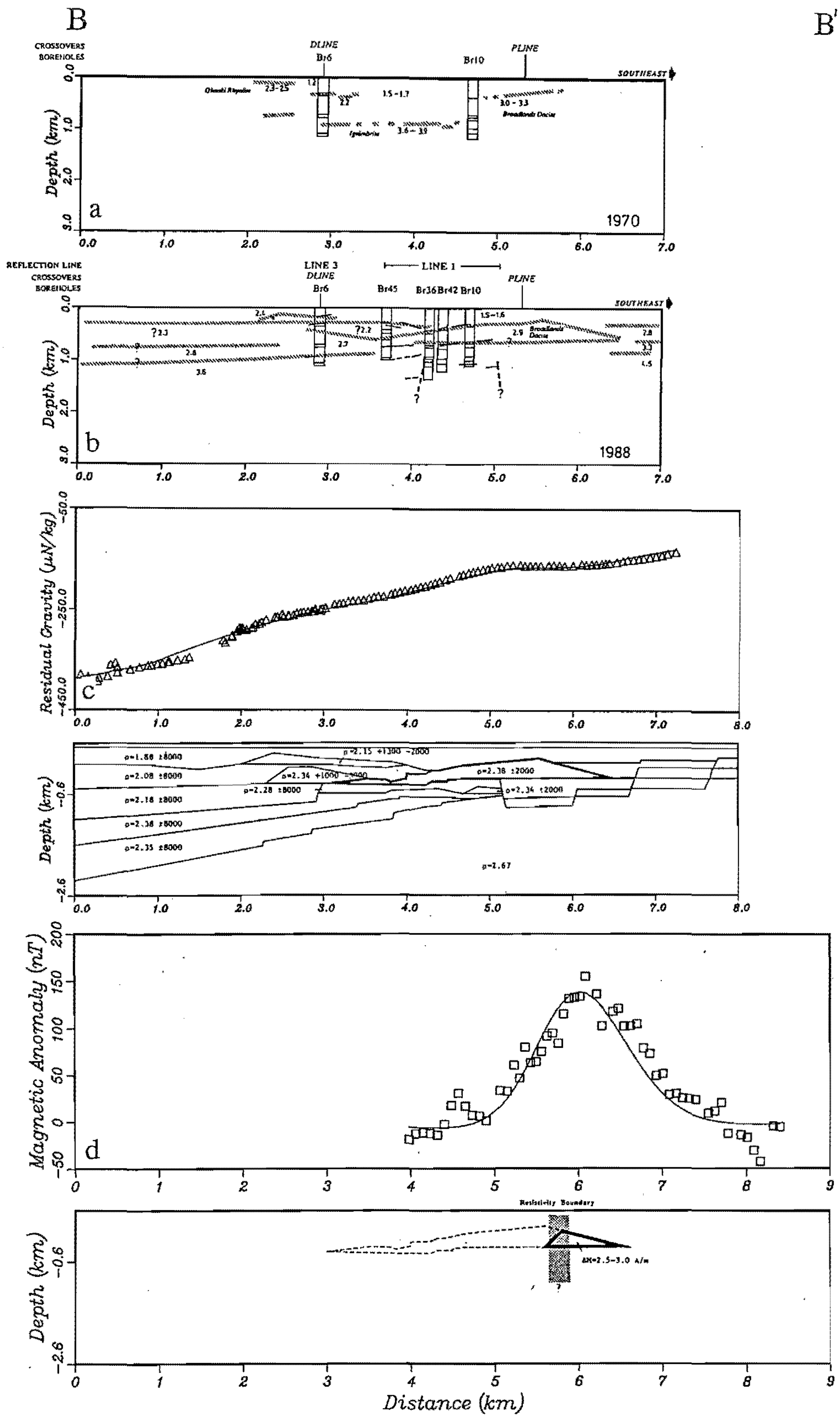
The best defined volcanic unit is the Broadlands Dacite (Figure 2). Isopachs indicate that the Dacite unit is a large dome shaped body with the base covering about 16 km^2 and a maximum thickness of 600 m; i.e. it is similar in size and thickness to the Tauhara Dacite dome cropping out near Lake Taupo. The large number of external constraints defining this body indicate that the uncertainties in isopach contours to be ±50 m. Combined gravity and magnetic modelling of this body (Figure 1d) indicate that within the geothermal field the dacite is wholly or partially demagnetised. The observed 120 nT positive magnetic anomaly can be modelled as the remaining wedge of magnetised dacite that extends beyond the eastern margin of the resistivity boundary and having a magnetisation contrast of 2.5-3.0 A/m with respect to surrounding volcanic rocks.

Conclusions

This paper has shown that an integrated analysis of seismic reflection and refraction data and of gravity and magnetic anomalies can give a very detailed picture of a hot-water reservoir. The structures elucidated in this study do no not effect the siting of future production wells, since production drilling is nearly complete. Although, it is likely that the structural details outlined will supply additional information for assessment of productivity and monitoring.

This study has completed the geophysical exploration of the Broadlands-Ohaaki geothermal field started 20 years ago. Together with detailed geological and geochemical studies this field now represents one of the best studied hot-water reservoir in the world.

Figure 1. Composite interpretation sections of profile B-B'. **(a)**; Interpretation of seismic refraction data up till 1970. **(b)**; Interpretation of seismic refraction and reflection data till 1988. Stratigraphic logs of intersecting boreholes are taken from Browne (1971) and Wood (1983). Refraction horizons are displayed in the diagonal line type together with refractor velocity. Major seismic reflections (1984 survey) are shown by heavy lines in (b). The position of possible fault structures interpreted from reflection data are shown by broken lines. **(c)**; Observed, computed Bouguer anomalies, and interpreted section. Observed gravity values are shown by Δ symbol. The solid line is the computed Bouguer anomaly at station height. Figures in the section denote wet density (in Mg/m^3) of rocks and the strike length of each body (in m) (+ values give lateral extent into the plane of the section. **(d)**; Observed, computed magnetic anomalies, and interpreted cross section. Observed magnetic values are shown by • symbol. The continuous solid line is the computed 3 D magnetic anomaly corresponding to the dacite body outlined in the thick line type. Figures in the section denote the magnetisation contrast. The vertical resistivity boundary is shown by the stippled pattern.


B
B'
CROSSOVERS
BOREHOLES
DLINE
Br6
Br10
PLINE
SOUTHEAST
Depth (km)
a
1970
REFLECTION LINE
LINE 3
LINE 1
Br45
Br36Br42 Br10
b
1988
Residual Gravity (μN/kg)
c
Magnetic Anomaly (nT)
d
Resistivity Boundary
Distance (km)

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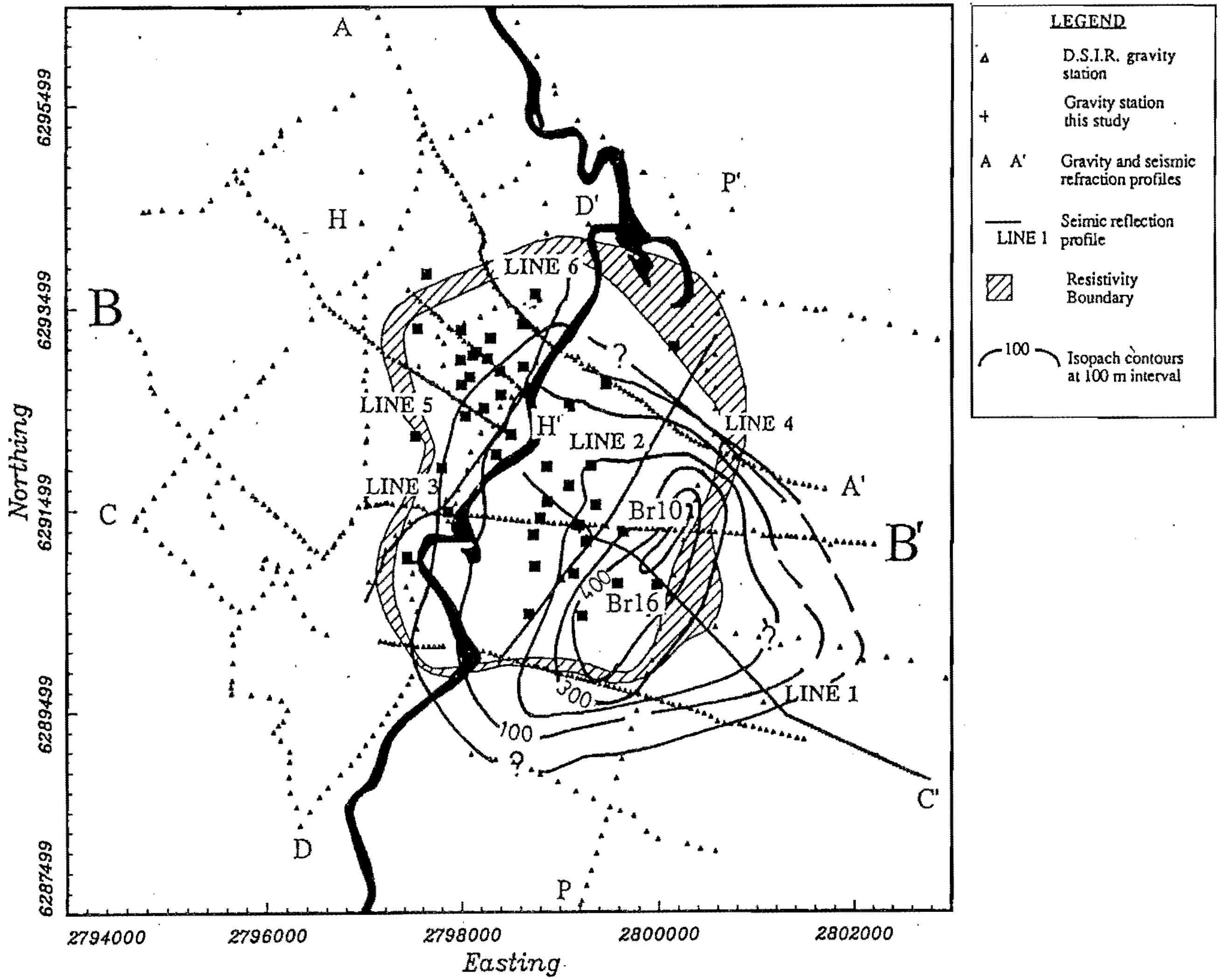

Figure 2. Isopachs of the Broadlands Dacite determined from interpretation of seismic and gravity data. Contours are in metres and are dashed where inferred. the resistivity boundary is from Risk et al. (1977).