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RECENT GEOPHYSICAL EXPLORATION OF THE KAWERAU GEOTHERMAL FIELD, NORTH ISLAND, NEW ZEALAND

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ABSTRACT

Resistivity surveys carried out in 1970 have shown that the Kawerau Geothermal Field has a cross-sectional area of 6 to 10 km^2 at intermediate depths (approximately ½ km). In the light of these surveys, previously published geophysical data have been reinterpreted, and the geological setting and stratigraphy have been re-examined.

Assuming boiling point for depth temperatures to 250°C and a constant 250°C to a depth of 2 km, the field has a minimum stored heat of $3{\cdot}9 \times 10^{18}$ joules above a temperature of 100°C.

Temperature measurements made in wells during the injection of cold water indicate that the best production of hot water comes from andesite at a depth of 750 to 900 m. Because core samples of this andesite have low porosity, the major production is likely to be from fractures in the andesite. The fractures in the andesite are thought to have been caused by recent extrusion of dacite.

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INTRODUCTION

Kawerau Borough lies at an elevation of about 30 metres (m) on the flat land bordering the Tarawera River, approximately 19 kilometres (km) south of the Bay of Plenty and 29 km south-west of Whakatane (Fig. 1). Four km south-east of Kawerau is Mount Edgecumbe, a youthful (less than 10,000 years) volcanic cone that rises to an elevation of 822 m.

In the early 1950's Tasman Pulp and Paper Company started planning the construction of an integrated mill to produce annually some 75,000 tons of newsprint, 90,000 tons of Kraft paper, and 25 million board feet of sawn timber. The existence of thermal activity throughout the Kawerau area suggested that the mill might be located so as to make use of natural steam in the production of paper. Accordingly, geophysical and geological studies (Studt 1952, 1958; Beck 1952; Healy 1951, 1962) were made in the vicinity of the major hot-spring area of the region, Onepu Springs, approximately 2·5 km north of Kawerau. The results of these studies were sufficiently encouraging for the Ministry of Works to carry out an investigational drilling programme in order to evaluate the productivity of the field.

Between August 1952 and November 1955 the Ministry of Works drilled three holes to depth of about ½ km. Testing of these holes demonstrated that production of steam could be obtained from intermediate depths (Table 1). Production drilling was then commenced by a private contractor in April 1956 and by February 1957 an additional 7 holes had been drilled to depths of about 600 m. By the end of 1960 output had dwindled to the

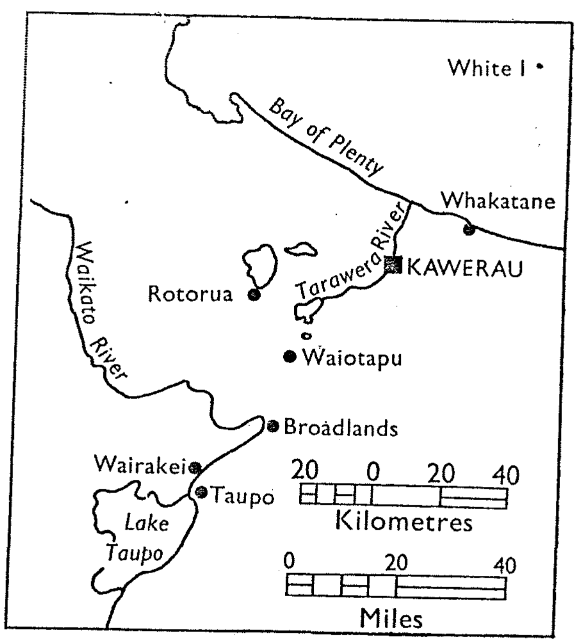


FIG. 1—Location of Kawerau Geothermal Field in Bay of Plenty area, North Island, New Zealand.

extent that holes 7A, 8, 12, and 14 had to be deepened to about 900 m by the Ministry of Works. The resulting increased output was sufficient to meet demands until 1967, when bores 3, 16, and 17 were drilled. The output of these three holes was approximately equivalent to the rest of the field combined (Table 1).

The techniques available in the early geophysical studies (Studt 1952, 1958) did not permit the Kawerau Geothermal Field to be accurately outlined at depth. During the 19 years since the early survey, however, extensive developments have been made in the use of electrical methods in geothermal areas, and far more sensitive equipment is available today than in 1951. Accordingly, electrical surveys of the Kawerau field were made during the 1969–70 field season, in order to determine the extent of the geothermal field at depth and to estimate the amount of stored heat. In this report the results of these electrical surveys are presented, together with a summary of the geology, and a reappraisal of the earlier geophysical work.

GEOLOGIC SETTING

Surface Geology

The Kawerau Geothermal Field lies near the axis of a north-east-trending complex graben that continues north-eastward out to sea to form the White Island Trench and extends south-westward as the Taupo Volcanic Depression (Healy *et al.* 1964). Interpretation of gravity data (Studt 1958, p. 240) indicates that the minimum depth to nonvolcanic basement (presumably greywacke) beneath Kawerau is about 1·5 km. Greywacke is exposed on the surface 12 km east of Kawerau in the Raungaehe Range and 22 km north-west of Kawerau near Otamarakau Valley.

In the vicinity of Kawerau this graben is filled with volcanic rocks and associated sedimentary rocks composed of volcanic detritus. The volcanic rocks are primarily of rhyolitic composition and include flows, tuff breccias, pumice breccias, and ignimbrites. There are a few andesitic rocks (Mt Edgecumbe, Manawahe, Whale Island, and at depth in the Kawerau borefield). Healy (1962, p. 7, section 3) expressed uncertainty concerning the nature

TABLE 1—Kawerau Borefield Data

Date	Production ($kg\ s^{-1}$) Steam	Water	Av. Pressure (Bars gauge)	Av. Maximum Temp. (°c)	Av. Depth (m)	Bores Used
1955	1·9	4·6	8·3	240	460	1, 4
1957	56·6	125·9	8·6	250	600	1, 3, 7A, 8, 10, 11, 12, 13, 14
1961	32·7	100·7	8·6	250	915	7A, 8, 14
1967	68·9	258·3	8·6	255	915	3, 7A, 8, 14, 16, 17

of the bedrock exposed in the young extrusions which form the Onepu Hills (*see* Fig. 5). Specimens from four localities were collected and studied by us. These specimens proved to be flow rocks of dacite composition and not rhyolite. No ignimbrite was identified.

All four specimens from the Onepu Hills are rich in large (1–10 mm) plagioclase phenocrysts, with subordinate quartz phenocrysts. Petrographic study of sample 70Mp13 (from hill 560′) and 70Mp16 (from hill 600′) showed both specimens to be fresh flow rocks containing 20–25% plagioclase phenocrysts (andesine to labradorite), 3–5% quartz phenocrysts, and minor amphibole, pyroxene, biotite, and magnetite. Groundmass material in both specimens is devitrified; 70Mp16 displays conspicuous irregular flow foliation, whereas in 70Mp13 the foliation has been obscured by spherulitic crystallisation of the groundmass. Partial chemical analysis of these specimens by the N.Z. Geological Survey (courtesy of Mr P. R. L. Browne) gave the following results:

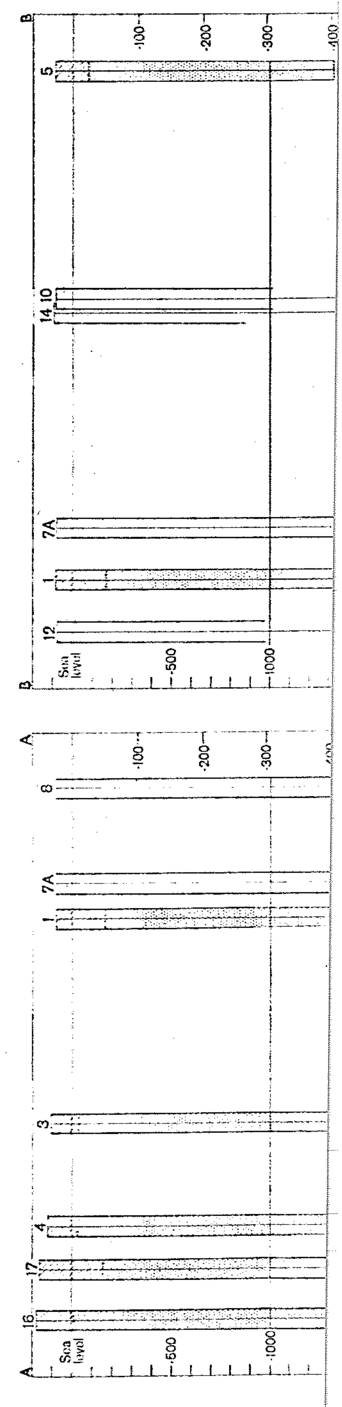
Sample No.	Weight percent	
	K_2O	SiO_2
70Mp13	1·99	70·85
70Mp16	1·86	65·32

Comparison of these figures with the analyses given in Lewis (1968) and Ewart (1966) indicates that the two analysed samples are dacites.

All of the rocks in the Taupo Volcanic Depression except the oldest two ignimbrites are normally magnetised and are convincingly interpreted by Cox (1969) as younger than the 0·7 m.y. Matuyama–Brunhes boundary. Although the nearest outcrop of either of these two reversely magnetised ignimbrites is over 40 miles north of Kawerau, one cannot preclude the presence of reversely magnetised old ignimbrites at depth in the Kawerau area.

The surface geology at Kawerau has been summarised by Healy (1962, pp. 2–3) and depicted on figure 1 of his report. Although geologic relations are tenuous because of the thick, obscuring mantle of Holocene tephra, it appears that these dacite hills are extrusive domes that are younger than all rocks in the area excepting the Holocene tephra. The domes probably were extruded on the ground surface after pushing their way up through the sequence of volcanic and sedimentary rocks that underlie the geothermal area.

Most faults in the Kawerau region strike north-easterly, parallel to the regional structural grain (Healy *et al.* 1964). There is very little expression of faulting around Kawerau except at the borefield, where a linear north-west-facing scarp forming the steep north-west slope of the tephra-covered low ridge just north-west of bores 16 and 17 may represent a fault. In addition, the difference in elevation of the andesite between bore 17 and bore 3 (Fig. 2) may be due to faulting.



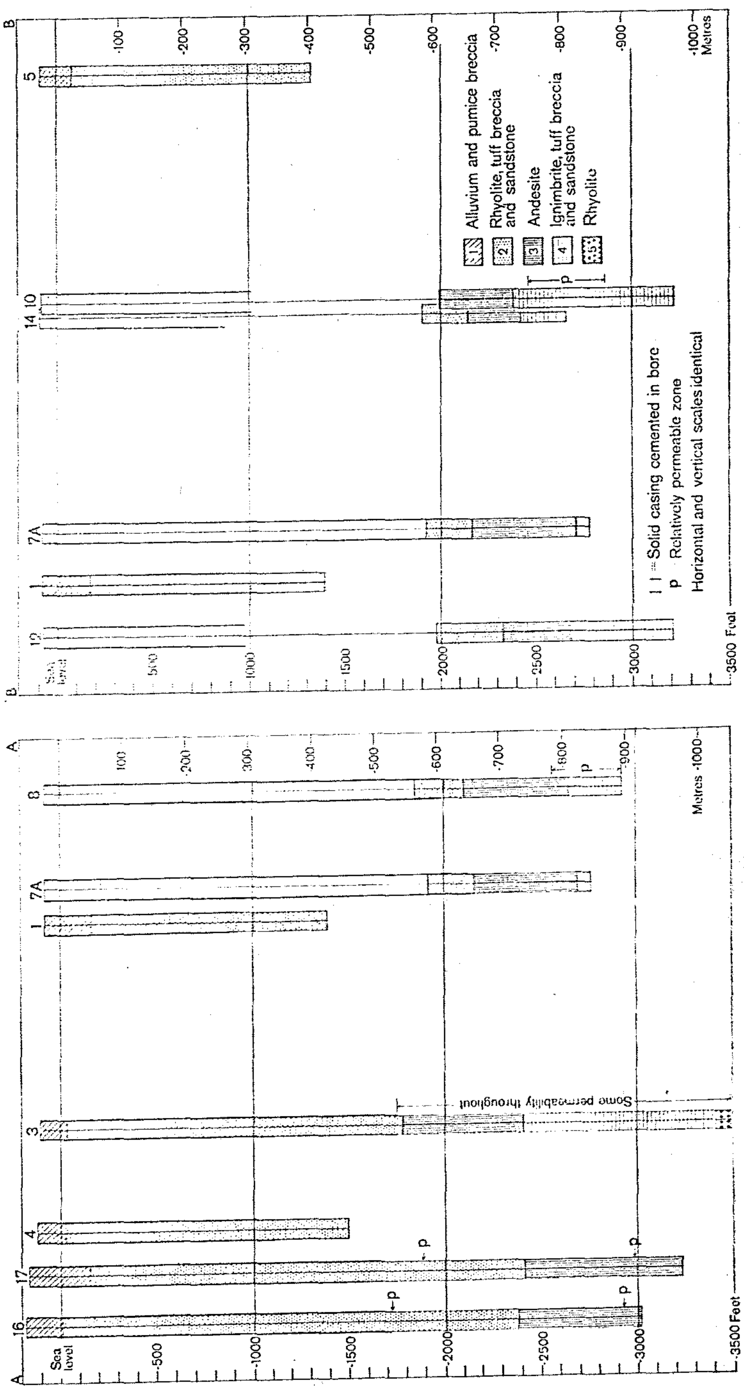


FIG. 2—Generalised geologic section of Kawerau geothermal area. Bores are projected on a vertical plane striking N 52° W through bores 16 and 8 (*see* A–A, Fig. 5) and N 28° E through bores 12 and 5 (*see* B–B, Fig. 5).

Stratigraphy in Bores

The stratigraphic information available in 1962 has been summarised by Healy (1962, pp. 8–9) and by Steiner (1962). Since then, bores 3, 16, and 17 have been drilled and carefully sampled throughout. Cuttings and cores from these bores were logged by J. Healy, and the available stratigraphic data for all the Kawerau bores were summarised by G. W. Grindley in a set of drill logs (written comm. 1970). The generalised geological sections shown in Fig. 2 were prepared by us from these logs, supplemented by additional study of samples and thin sections in the petrology collection of the N.Z. Geological Survey. Samples from bores 2, 9, 11, and 13 are not available (*see* Healy 1962, p. 3)

We have divided the stratigraphic section of the Kawerau borefield into five major units. From top to bottom, these are:

- Unit 1: Alluvium and pumice breccia (45 to 100 m thick).
- Unit 2: Rhyolite, with subordinate tuff breccia, ash, sandstone and siltstone (535 to 720 m thick).
- Unit 3: Andesite (85 to greater than 251 m thick).
- Unit 4: Ignimbrite, with intercalated tuff breccia and sandstone (315 m thick in bore 3).
- Unit 5: Rhyolite (greater than 15 m thick at the bottom of bore 3).

Only Unit 1 outcrops at the surface.

The various rock types in Unit 2 can readily be discriminated in any single bore, but it has not yet been possible to correlate sub-units among the various bores except between bores 16 and 17. This failure is due to (a) poor sampling in the pre-1961 bores, (b) pervasive hydrothermal alteration that has obscured much of the original textures and (c) lateral stratigraphic variation in Unit 2 throughout the borefield. Details of lateral stratigraphic variation are not clear in the older bores, but are evident in bores 16, 17, and 3. In bores 16 and 17 breccias and clastic rocks make up about 40 percent of Unit 2, whereas in bore 3 nearly the entire unit is rhyolite. Furthermore, Unit 2 is considerably thinner and the andesite (unit 3) higher in bore 3 than in bores 16 and 17, suggesting fault movement during the extrusion and deposition of the rocks in Unit 2.

The andesite (Unit 3) is a conspicuous stratigraphic marker readily identified in cuttings or core. It is greenish grey, with conspicuous plagioclase phenocrysts, and is intensely altered. Figures 3 and 4 show that, compared to other rocks of the borefield, the andesite is consistently more dense and less porous.

Unit 4 characterised by the presence of ignimbrite and the absence of rhyolite. Many specimens of ignimbrite and of pumice breccia display glass shards and aligned pumice fragments suggesting emplacement by ash flow; compaction foliation was seen in a few ignimbrite specimens. In bore 10, Unit 4 displays a regular increase in density and a nearly regular decrease in porosity with depth, suggesting increasing compaction and welding of a single ash-flow cooling unit (Ross and Smith 1961). The surface correlative of Unit 4 is not known. Petrographic criteria preclude correlation with the

Matahina Ignimbrite, the prominent ignimbrite exposed on the plateaus to the east and north-west of Kawerau (A. Steiner, quoted in Healy 1962).

Unit 5 was encountered only in bore 3, the deepest bore to date. This rhyolite is characterised by abundant quartz phenocrysts, and the available samples are not intensely altered.

Production Zones

The Kawerau bores have produced from two general levels. The earlier bores produced from breccias and sediments at depths of about 600 m (Healy 1962, p. 5), but falling discharges and temperatures occurred within three years and were attributed by Banwell (1962, p. 1) to invasion of the field by marginal cool water. The bores deepened in 1961 (7A, 8, 12, and 14) and the bores subsequently drilled (3, 16, and 17) produce from a deeper zone (760 m to 910 m).

Temperature runs made during injection of cold water into bores at varying injection rates allow permeable zones to be identified rather precisely. The permeable zones deduced from these temperature runs are indicated on Fig. 2, 3, and 4.

Comparison of temperature data taken at two injection rates in both bore 16 and 17 indicates that the major permeable zone in these bores is the deeper one, in the lower part of the andesite. The most permeable zone in bore 8 appears to be at the base of the andesite and in the immediately underlying ignimbrite. In bore 10, the permeable zone is entirely within the ignimbrite. For bore 3, the water injection temperature runs indicate that there are no well-defined major permeable zones, but that the permeability is rather uniformly distributed in the bore below the casing.

It is perhaps significant that production from the three best Kawerau bores (16, 8, and 17) comes from the andesite, consistently the densest and least porous rock encountered (*see* Fig. 4). This correlation, coupled with the very limited vertical extent of the permeable zones in bores 16 and 17, suggests that the production from these bores is from fissures in the andesite. Apparently for a bore at Kawerau to be a major producer, it must encounter fractures in the andesite or hard ignimbrite, rocks dense enough to support extensive fracture systems. The units which appear to be most porous in hand specimen apparently cannot supply sufficient fluid to the bore to become major production zones. Perhaps these stratigraphic units are not competent enough to allow major fractures to be developed and sustained.

PREVIOUS GEOPHYSICAL INVESTIGATION

Studt (1952, 1958) used a number of geophysical techniques to study the Kawerau area. Perhaps the most informative of these was the gravity survey, which gave a minimum depth of 1·5 km to basement greywacke. In addition the survey defined a local gravity high over an area that includes the present borefield. Studt interpreted this high as due either to a rhyolite intrusion or to densification caused by hydrothermal alteration of the rocks.

Studt's ground magnetic survey of the Kawerau area showed a negative anomaly just to the west of the present borefield. Studt (1958) interpreted the anomaly as caused by the hydrothermal alteration of magnetic minerals to nonmagnetic ones.

Seismic refraction studies at Kawerau (Studt 1958) identified a strongly refracting horizon at a depth of from 60 to 150 m, which apparently correlates with the top of Unit 2 (dominantly rhyolite) of this paper. No consistently deeper refracting horizon could be identified. Seismic refraction methods are of minimal use in this type of geothermal area because the high level of ground noise and high attenuation of the signal make recording difficult, and velocity reversals often prevent the detection of layers deeper than the shallowest high velocity layer.

Several resistivity profiles are given by Studt (1958). The electrode spacing used (30 m and 60 m) gave only a shallow penetration, and the work was hindered by instrumental inadequacies. The apparent resistivity values thus determined are considerably higher than those found in recent years in other New Zealand geothermal areas.

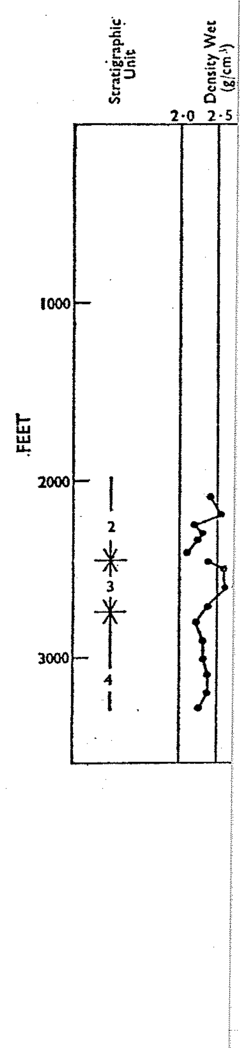
The geophysical investigations reported by Studt (1958) also include temperature data from 24 drillholes in the 30 to 60 m depth range. These data do little to outline the Kawerau field, but are of use when compared with the results of our electromagnetic survey.

Magnetic Survey

The vertical force ground magnetic survey of Studt (1958, fig. 10) is included here in Fig. 5. The two striking features of the magnetic map are the extensive magnetic high in the north-west and the elongated magnetic low trending north-east through the centre of the map. We assume that the magnetic high is caused by buried volcanic material, probably andesite, but any such rocks in the area of the high are obscured by the thick blanket of Rotoiti Breccia and by alluvium (Healy *et al.* 1964). The magnetic low, on the other hand, is probably best explained as partly a peripheral feature complementary to the magnetic high and partly a feature caused by hydrothermal alteration of magnetic materials to nonmagnetic ones.

To illustrate this point, the vertical magnetic field of a magnetic body, similar in area to the magnetic body in the north-west, has been calculated. This body consists of two vertical prisms, one from the surface to 150 m (outlined by the dashed line on Fig. 5) and the other from 150 to 600 m (outlined by the solid line on Fig. 5). The susceptibility used is $25{,}000 \times 10^{-6}$ SI units ($2{,}000 \times 10^{-6}$ cgs units), the average value for New Zealand andesite, and the direction of magnetisation is assumed to be that of the present-day field.

Although these calculations (*see* brown contours, Fig. 5) do not give a perfect fit with the observed magnetic field, they do demonstrate that the shape and magnitude of the measured negative anomaly could be caused by the magnetic high to the north-west. However, Fig. 4 shows that the susceptibilities of the core samples are much lower than expected of unaltered rock, and accordingly part of the magnetic low must be caused



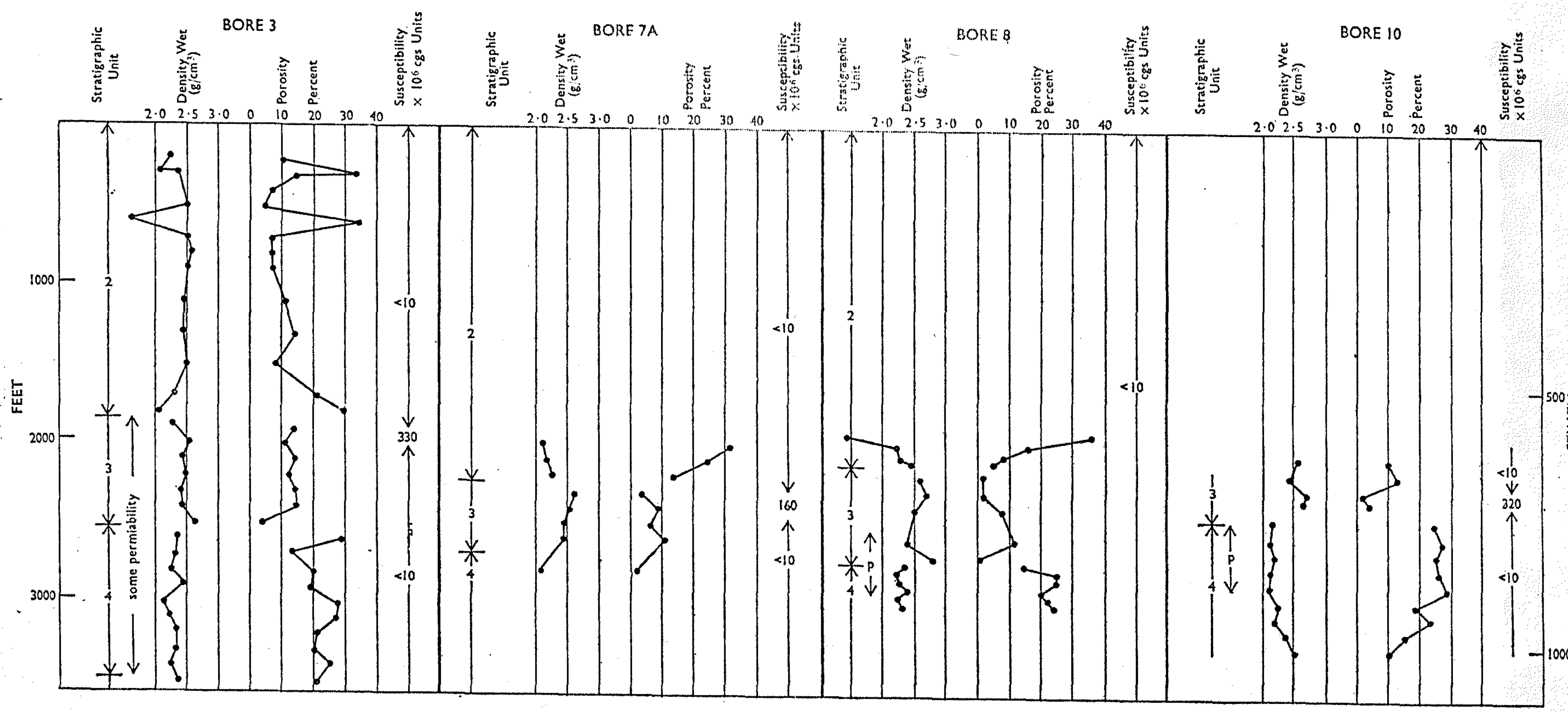


FIG. 3—Graphs showing wet density, porosity, and magnetic susceptibility of cores from Kawerau geothermal bores 3, 7A, 8, and 10.

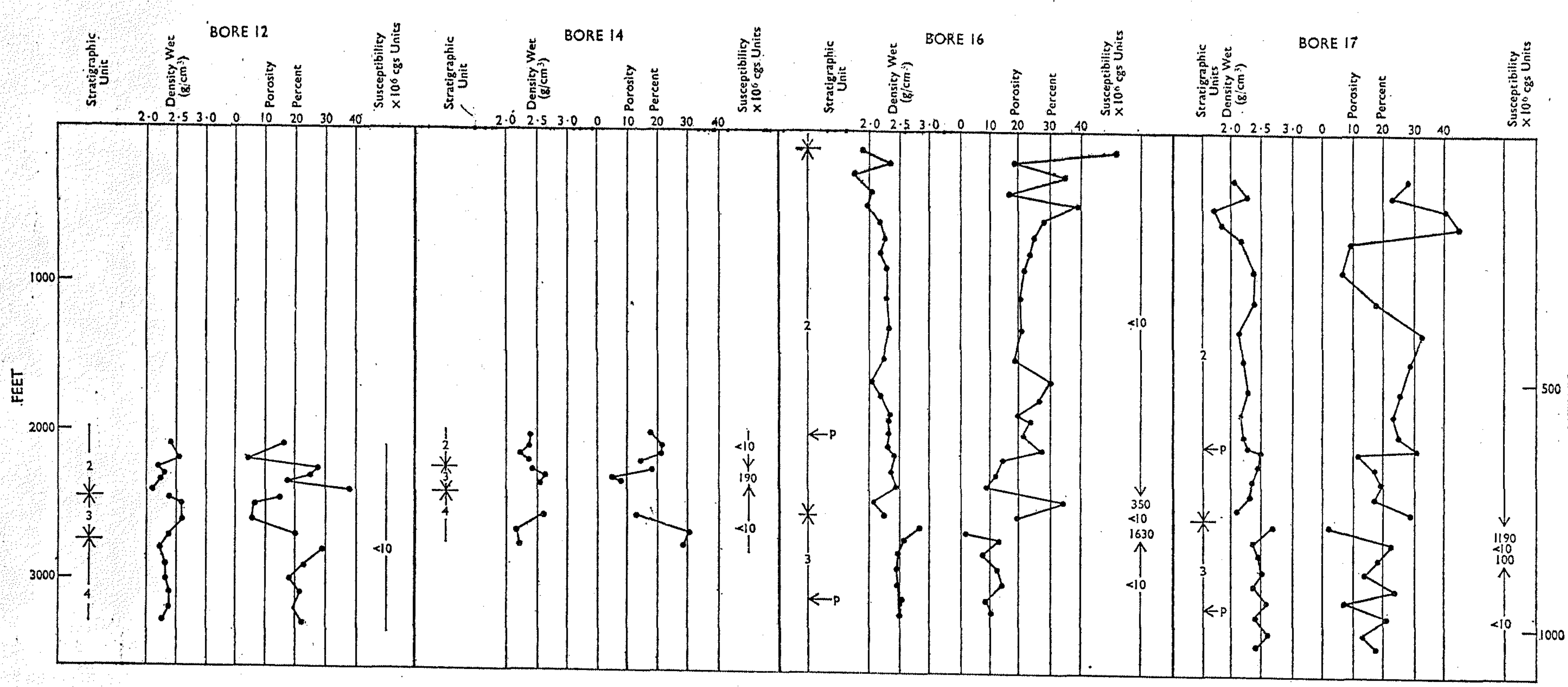


FIG. 4—Graphs showing wet density, porosity, and magnetic susceptibility of cores from Kawerau geothermal bores 12, 14, 16, and 17.

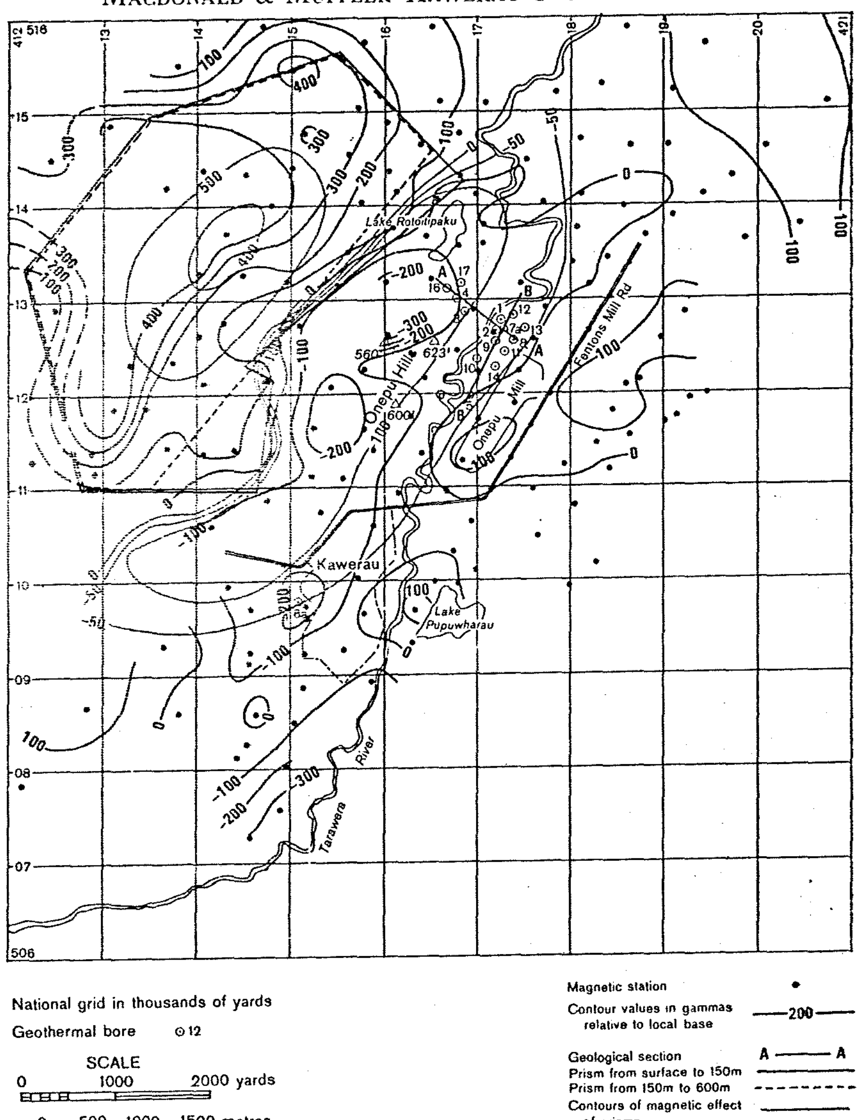


FIG. 5—Vertical force ground magnetic survey of Kawerau geothermal area (after Studt 1958).

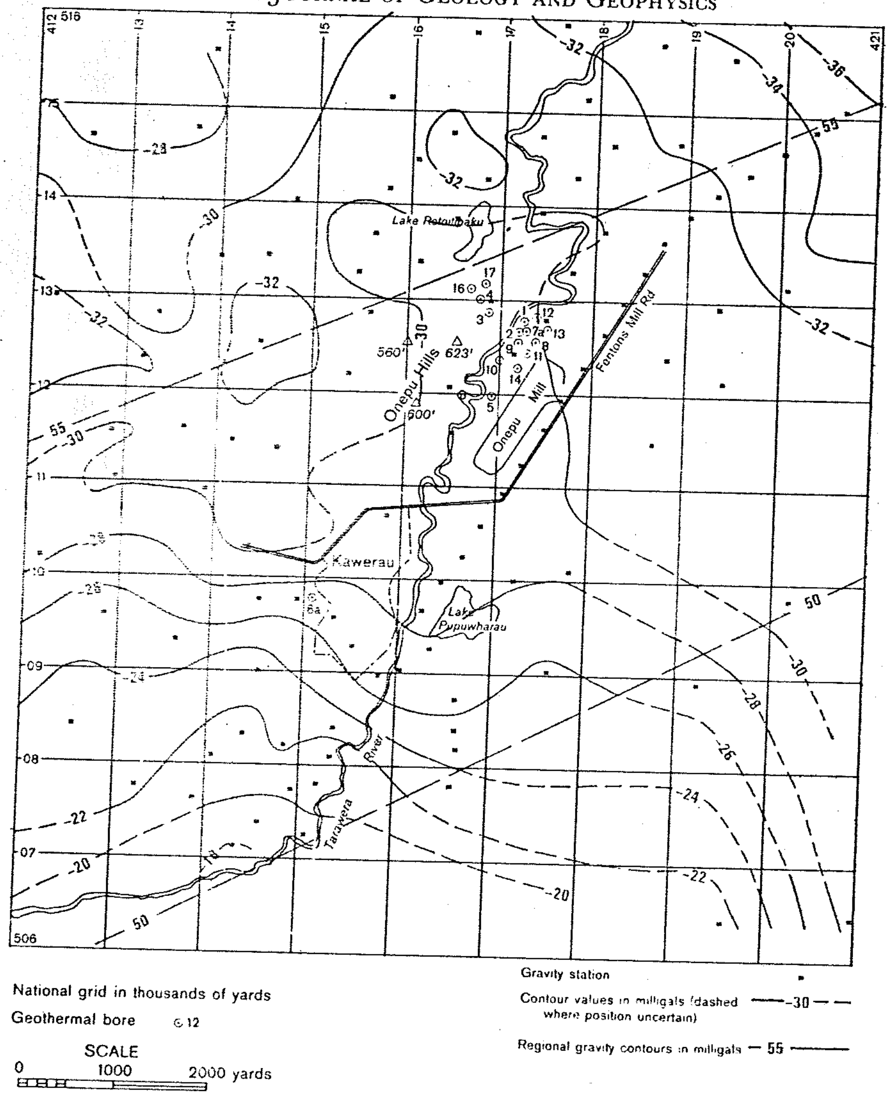


FIG. 6—Residual Bouguer gravity anomalies of Kawerau geothermal area.

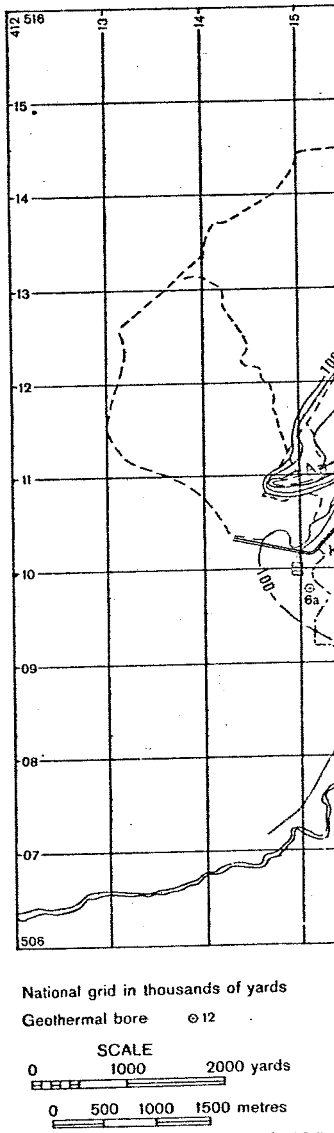


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FIG. 7—Electrom

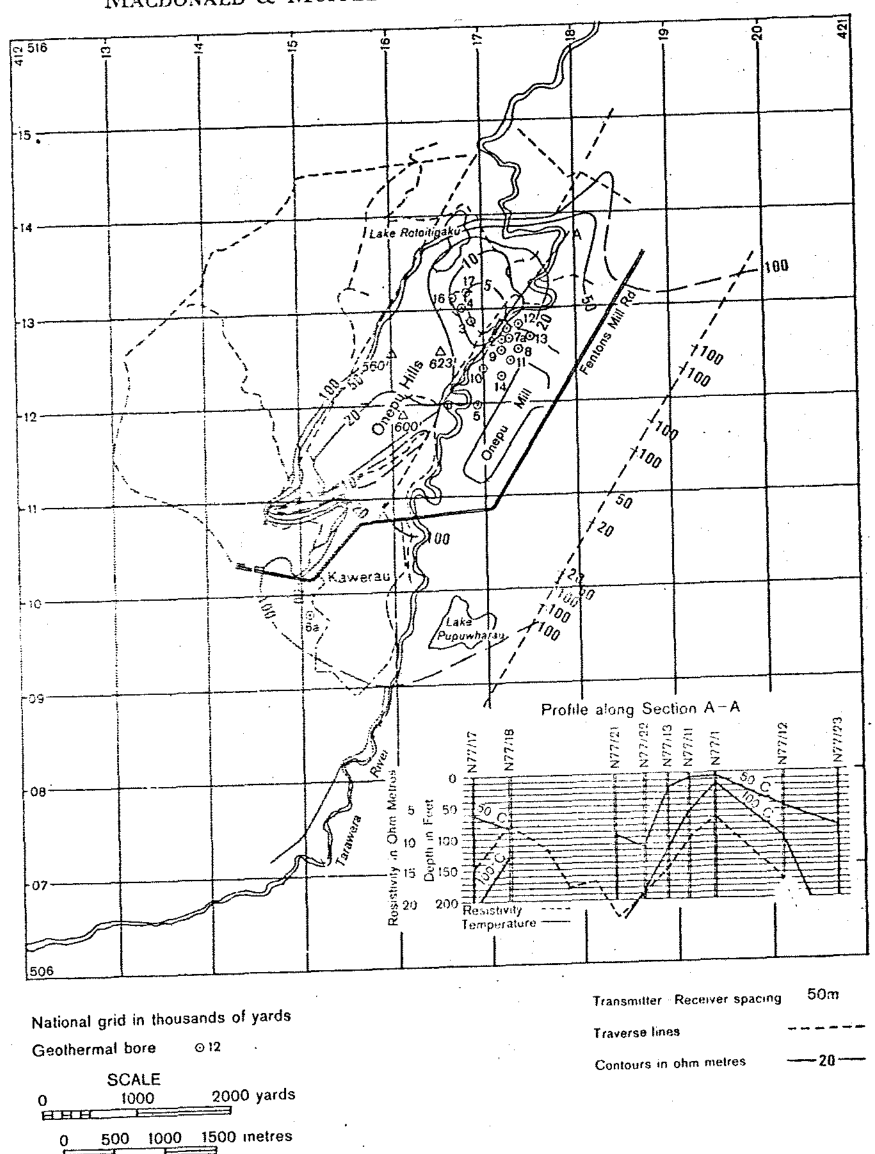

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FIG. 7—Electromagnetic gun survey of Kawerau geothermal area.

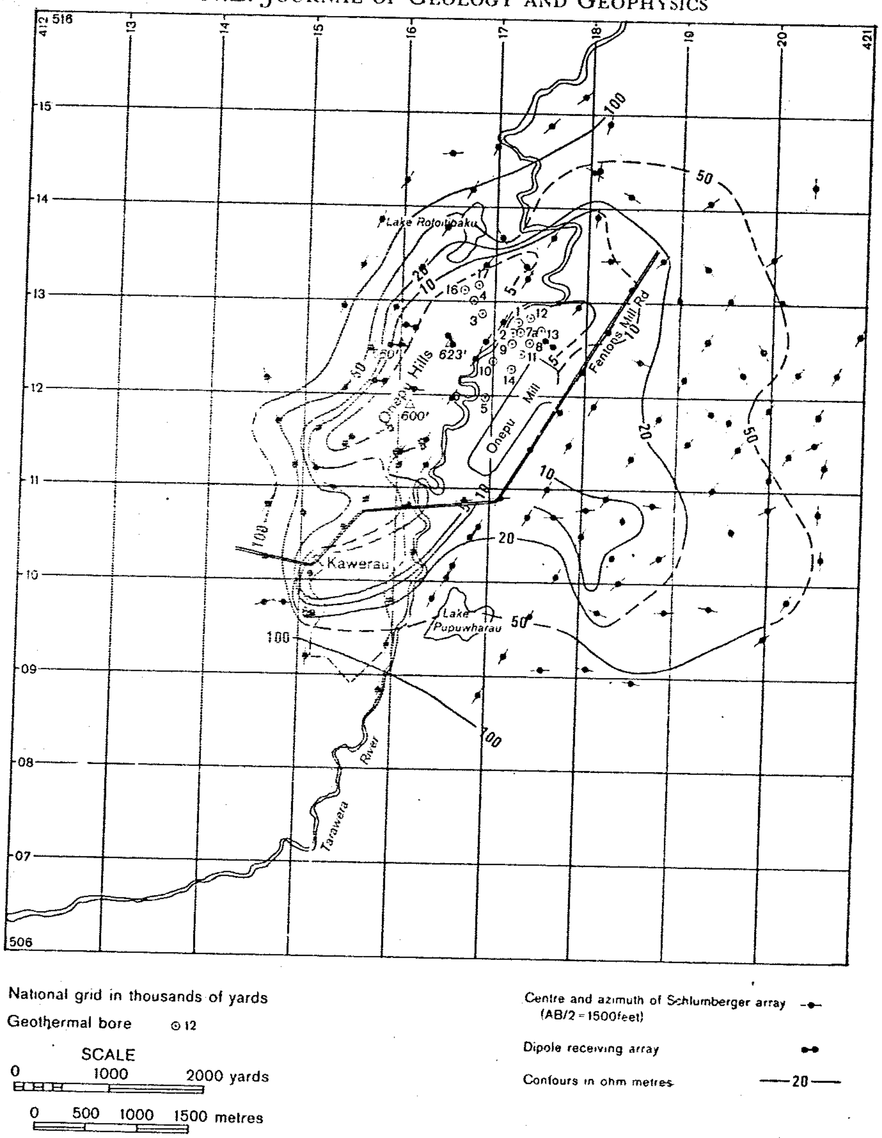

Fig. 8—Apparent resistivity contours of Schlumberger profiling survey (AB/2 = 1,500 ft), Kawerau geothermal area.

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Gravity Survey

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Geophysical

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(3) The amount of interconn
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by hydrothermal alteration of the magnetic minerals to nonmagnetic ones. Hence interpretation of the Kawerau magnetic map is ambiguous, and the magnetic anomalies are of little use in delineating the boundaries of the Kawerau Geothermal Field or in the siting of drillholes.

Gravity Survey

The residual gravity map (Fig. 6) is based on the field data used by Studt (1958) and on 12 additional stations occupied by D. J. Woodward in 1970. The raw field data were reduced using a computer programme (GP–48) that corrects for latitude, elevation, terrain (to 167 km), and earth tides. A density of 2·67 Mg m^{-3} is used in the Bouguer and terrain corrections. The Bouguer anomalies thus calculated were further reduced by subtracting the regional Bouguer anomaly. The regional Bouguer anomaly used is the same as that depicted on fig. 8 of Studt (1958), except 5 mgal has been added to take into account the change of datum from the New Zealand Provisional System to the New Zealand Potsdam System (1959) (Robertson and Reilly 1960).

The residual gravity anomaly map thus produced (Fig. 6) is almost identical to fig. 8 of Studt (1958). A positive anomaly of about 2 mgal is located over the borefield and extends to the south toward Kawerau Borough. Studt (1958, fig. 9) analysed this high by matching the observed anomalies with computed profiles of two-dimensional models, and concluded that the anomaly over the borefield is due to an anomalous mass within the volcanic and sedimentary cover and probably not connected with changes in the basement greywacke surface. Without drillhole data from outside the anomaly we cannot discriminate between Studt's two alternative interpretations: rhyolite intrusion or hydrothermal alteration to denser rock. It should be noted, however, that at the Broadlands geothermal field a similar positive residual anomaly of up to 10 mgal could be resolved into an anomaly of 2 mgal due to the subsurface rhyolite domes and an anomaly of up to 8 mgal due to increased density brought about by hydrothermal alteration of the volcanic overburden (Hochstein and Hunt 1970).

GEOPHYSICAL INVESTIGATIONS IN 1970

The resistivity of ground is primarily dependent on four parameters:

(1) The temperature;
(2) The salinity of the pore water;
(3) The amount of interconnected pores (effective porosity); and,
(4) The amount of minerals of high ion-exchange capacity (mainly clays and zeolites).

Increasing any one of these factors decreases the resistivity. Above 170°C the rate of decrease of resistivity with increasing temperature becomes slight, and above 330°C may even reverse, with resistivity increasing at higher temperatures. Geothermal fields of the hot-water type like Kawerau are characterised by temperatures above 200°C, increased salinity relative to pore water outside the field, and local concentrations of clay and zeolites.

Therefore the resistivity inside such a geothermal field will be lower than the resistivity outside the field.

The spatial distribution of resistivity beneath a measuring point is usually complex and cannot be specified from a single measurement. Consequently, the quantity actually determined in an electrical survey is the "Apparent resistivity", which is the resistivity calculated from Ohm's Law assuming a homogeneous medium. In a layered earth, apparent resistivity can be thought of as a weighted average of the resistivity of the various layers beneath the measuring point.

Resistivities at shallow depths (15 to 45 m) are best investigated by a rapid electromagnetic technique, whereas resistivities at intermediate depths (150 to 1000 m) are most easily studied by direct current methods that use a linear array of four electrodes. Once the boundary of the field is roughly established, greater depths can be investigated by dipole-dipole methods.

Therefore, by using different techniques and geometric factors it is possible to calculate the apparent resistivity within and around a geothermal field at various depths, and thus to develop a three-dimensional picture of the geothermal system.

Electromagnetic Gun Survey

The electromagnetic gun survey (Lumb and Macdonald 1970) is a rapid, inexpensive means of measuring the apparent resistivity of ground at depths of approximately 15 to 45 m. The device consists of a vertical transmitting coil connected by a screen cable to a similar vertical receiving coil, in this survey, 50 m away. The apparent resistivity is calculated from the comparison of the magnetic field detected by the second coil and that of the reference signal fed along the cable.

Apparent resistivity contours of the electromagnetic survey are shown on Fig. 7. The intense electrical interference caused by power lines, fences, etc., east of the Tarawera River precluded use of the electromagnetic gun except along a line 915 m east of Fentons Mill Road.

These results are compared with measured ground temperatures in the insert to Fig. 7. These temperatures are taken from Studt (1958, p. 233) and Studt (1952). Holes with high temperatures along the section correspond to stations with low apparent resistivity. From this comparison one can predict that within the 50 ohm-meter contour, ground temperature will be above normal, and that within the 10 ohm-meter contour temperatures greater than 100°C will be encountered within 50 m of the surface.

DC Resistivity Survey

Measurement of apparent resistivity by DC methods has become a standard technique for outlining geothermal fields (Risk *et al.* 1970; Hatherton *et al.* 1966; Banwell and Macdonald 1965). In the Kawerau survey, spot measurements of apparent resistivity were made using a Schlumberger array, with the current electrodes 914 m apart ($AB/2 = 457$ m) and the potential electrodes 30 m apart ($MN/2 = 15$ m). At additional stations, current electrodes spacings ($AB/2$) up to 915 m were used. At stations with difficult access, such as in the Onepu Hills, Schlumberger arrays could not be used. Dipole-dipole arrays were substituted at 6 stations, using electrode spacings approximately equivalent to the Schlumberger AB/2 = 457 m.

The apparent resistivity values measured with a symmetric Schlumberger array at AB/2 = 457 m probably represent an average of the true resistivities for depths ranging from about 150 to 900 m.

The results of the Schlumberger DC resistivity survey are shown in Fig. 8 as contours of equal apparent resistivity interpolated from the values measured at the data points. The stations along Fentons Mill Road, near the Onepu Mill, and in the town of Kawerau are of low reliability owing to the presence of electrical noise, underground cables, railway tracks, and wire fences.

These resistivity measurements are bulk measurements that are influenced by a hemisphere of ground of radius approximately half the distance between the current electrodes (i.e., 450 m). Therefore, as the electrode system is moved over a vertical boundary between ground of differing resistivity, the measured values will be influenced by the resistivity on both sides of the boundary, and the measured apparent resistivity values will be different from the values on either side of the boundary. Although this boundary will be approximately parallel to the apparent resistivity contours, it need not coincide with any particular contour value.

Figure 9 (derived from Fig. 8), shows the area between the 10 and 20 ohm-metre contours as a shaded band, modified slightly by taking into account the reliability of individual measurements. Where the shaded band is narrow, the boundary of the field should be sharp and well defined; where the shaded zone is wide, the boundary is diffuse. The area of the Kawerau field lies between a minimum of 6 km^2 enclosed by the inner edge of the boundary zone and a maximum of 10 km^2 enclosed by the outer edge.

Ten measurements within the low resistivity area with current electrode half spacings (AB/2) of up to 915 m showed only slight increase in resistivity at the greater spacings. Drilling at Kawerau shows that high temperatures exist to depths of at least 1 km. Both drilling and resistivity measurements in the geothermal fields at Wairakei and Broadlands have shown that these fields have approximately vertical boundaries to depths of at least 2 km. The available evidence indicates that similar consideration apply also at Kawerau.

There are minor variations in the values of apparent resistivity within the resistivity low, with some values as low as 1 ohm-metre. Inasmuch as the salinity of the pore water at depth in the Kawerau field is essentially constant (W. A. J. Mahon, pers. comm. 1971) and the rate of change in resistivity is very small at temperatures greater than 170°c, this change in resistivity within the field is likely to represent either a change in effective porosity or variation in clay and zeolite content.

It is tempting to site drillholes on these areas of very low apparent resistivity with the field. But in the present Kawerau borefield production comes mostly from fissures within the andesite, the rock of lowest hand-specimen porosity. Also, the production level is well below the effective penetration

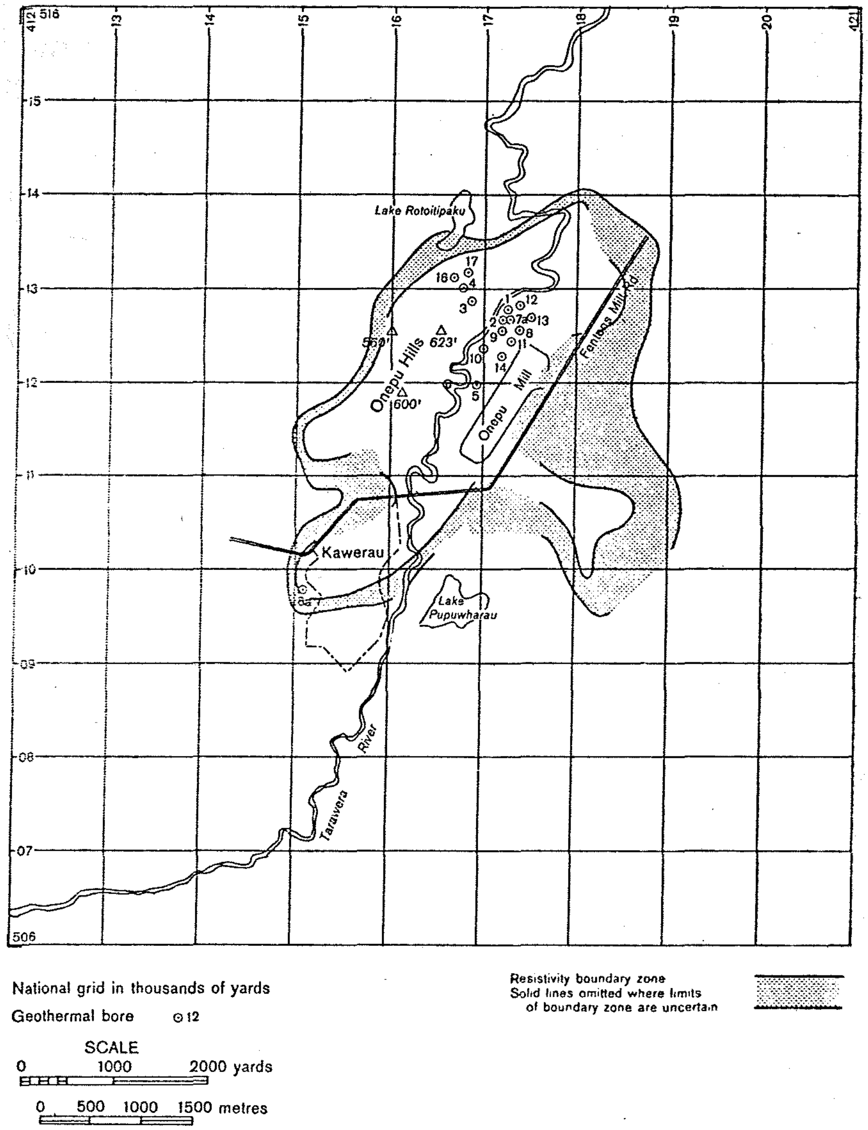

FIG. 9—Resistivity boundary zone derived from Schlumberger profiling survey (AB/2 = 457 m), Kawerau geothermal area.

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inside the resistivity bound
boundary zone, however, dc

Ground Permeability

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But although high temper
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Although there is some
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Unfortunately, there are
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Fissures and fractured
viscous magma as it force
the Tarawera River are
pushed up from depth th
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ENERGY STORED

The minimum total he
a temperature of 100°C

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suggested by the D
(2) the system has a
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(6) the specific heat of
(7) the temperatures a
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depth of the AB/2 = 457 m Schlumberger array. Accordingly, the lows inside the resistivity boundary zone cannot be used to site drillholes. The boundary zone, however, does outline the area of probable production.

Ground Permeability

Within the boundary determined by the DC Schlumberger survey temperature at depth will almost certainly be sufficiently high for industrial use. But although high temperature is a necessary condition for geothermal power production, it is not a sufficient one. Productive bores must intersect zones that are sufficiently permeable for the heat available in the water and rock to be efficiently extracted.

Although there is some debate on the subject, it is becoming increasingly accepted that good geothermal bores are fed from fissures rather than from strata having high intergranular porosity. At Kawerau this certainly seems to be so, for best production is from the andesite, the least porous rock unit in the field (Fig. 4).

Unfortunately, there are as yet no good geophysical techniques for identifying fissured zones within the geothermal field as defined by the resistivity boundary, we therefore must fall back on geological interference. Fissures can be produced by faulting, and the fault pattern can be predicted sometimes, if sufficient surface and drillhole data are available. At Kawerau the evidence for faulting is tenuous (*see* p. 306), and predictions of faults, and hence of related fissures at depth, cannot be made with confidence.

Fissures and fractured ground can also be produced around a body of viscous magma as it forces its way to the surface. The dacite hills west of the Tarawera River are very young extrusions that appear to have been pushed up from depth through the older volcanic and sedimentary rocks of the area. The ground beneath and in the vicinity of the dacite hills is likely to have been extensively fractured during emplacement of the dacite, and consequently, bores drilled on the flanks of the hills within the resistivity boundary are likely to encounter fractured ground.

ENERGY STORED IN THE KAWERAU GEOTHERMAL SYSTEM

The minimum total heat stored in the Kawerau geothermal system above a temperature of 100°C can be calculated from the following assumptions:

(1) The system has a cross-sectional area of between 6 and 10 km^2, as suggested by the DC resistivity survey;
(2) the system has a depth of 2 km (the minimum depth proved by drilling at Wairakei and Broadlands);
(3) the average porosity to a depth of 2 km is 15% (the mean value suggested by the data of Fig. 4);
(4) the dry density of the rock is 2·4 Mg m^{-3};
(5) the specific heat of the rock is 0·83 kJ kg^{-1} $°C^{-1}$;
(6) the specific heat of water is 4·18 kJ kg^{-1} $°C^{-1}$;
(7) the temperatures are at boiling point for all depths until a temperature of 250°C is reached, and the temperatures remain at 250°C to a depth of 2 km.