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HORIZONTAL FLOW IN HYDROTHERMAL SYSTEMS

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ABSTRACT

D.c. resistivity measurements and drill hole data have shown the existence of extensive horizontal flows of hot water which originates within certain hydrothermal systems in Chile and New Zealand. The geological and hydrological conditions which favour such flows are discussed.

INTRODUCTION

Hypotheses concerning hydrothermal systems have for many years been governed by concepts undergoing evolution as fresh data have come to light during exploration of geothermal fields and extraction of geothermal energy. As most large fields described so far are located in regions of Quaternary volcanism a magmatic heat source was generally favoured, with transport of heat upwards by magmatic steam (e.g. Allen and Day, 1935; Grange, 1937; White and Brannock, 1950; Healy, 1956; Banwell, 1957). When isotope chemistry was applied to geothermal hydrology the evidence for magmatic steam receded (e.g. Craig *et al.*, 1956), and it became accepted that geothermal systems contain almost exclusively non-magmatic water. This inference was further strengthened by studies in New Zealand which showed that the mineral content of most thermal waters can be derived simply by the solvent action of hot groundwater passing through the rocks (Mahon, 1967).

Two concepts inherent in most of the earlier discussions of hydrothermal systems have remained unmodified, namely the magmatic source of the heat, and the almost vertical passage of hot water to the surface. Heat is considered to be transferred from a

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magmatic source by conduction, and thence to the surface by upward movement of groundwater that has circulated deeply through the heated zone. Models were developed of convection cells, located above magma chambers and delivering the heated groundwater to thermal springs at the surface, creating the concept of the thermal areas marking the tops of almost vertical columns of hot water. A steep thermal gradient at the base of each column is required to obtain sufficient heat flow, so convecting magma in the underlying chamber was introduced to maintain the heat supply (e.g. Grindley, 1960; Banwell, 1963; Healy, 1964; White, 1968). As it was inferred that the ascending thermal water selectively followed vertical permeable zones, fault fractures were sought as preferred sites for production wells (e.g. Grindley, 1965).

That there is still some reservation about isolated heat sources, and that some mechanism for concentrating heat flow from large areas would be preferable, has been fully discussed by White (1968). Neither did the various models proposed account adequately for the major temperature reversals encountered in many geothermal fields. Horizontal movements of hot water within the systems over distances of the order of the radius of each column only were envisaged. The influence of regional and intermediate-depth groundwater movement in the uppermost 1–2 km has been a neglected factor in geothermal studies, and owing to lack of reliable piezometric and permeability data inside and outside hydrothermal systems, the models referred to above were largely speculative as far as the hydrology was concerned. A model based on the hydrology of large basins has been proposed by Healy (1970) to account for the concentration of higher-than-average crustal heat flow into a central discharge area by centripetal horizontal movement of groundwater at depth. So far this has been applied theoretically only to a hypothetical hydrothermal system in that type of hydrological setting. The aim of this paper is to draw attention to the horizontal component of hot water movement now demonstrated to be an important factor in some hydrothermal fields.

In the following, the lateral extent of thermal fluids at depth is mainly inferred from d.c. resistivity measurements made with either central or non-central linear arrays, i.e. Schlumberger or dipole arrays. The resistivity of rocks at depth in hydrothermal areas is brought about by electrolytic conduction through hot saline water and conduction through hydrated alteration minerals (clays). Hence, rocks containing hot saline fluids exhibit low resistivities and can be outlined by resistivity measurements at the surface (see, for example, Risk *et al.*, 1970).

Northern Chile

Recent exploration of geothermal fields in northern Chile as part of a United Nations Development Project undertaken with the Chilean Government has produced direct evidence for large horizontal flows of hot saline water. Beneath the Andean volcanoes east of the El Tatio geothermal field (22° 21′ S; 68° 01.5′ W) a series of Upper Tertiary and Quaternary volcanic formations rest on a relatively impermeable Cretaceous shale basement, and extend west covering a north–south-trending ridge with a core of the basement shale. This provides a barrier to the regional westward flow of the groundwater through the volcanic formations. The hot saline water comes from an as-yet-undefined source beneath one of the volcanoes. Within the area drilled, the hot water flows horizontally to the north-west with a small upward vertical component. Some of the hot water rises to the surface in a discharge area within the Tatio Basin, which lies between the source and the tectonic barrier range.

The extent of the hot saline water is outlined in Figs. 1 and 2 by the low apparent resistivity contours derived from a resistivity survey (Schlumberger array) with a nominal depth penetration of 0.5 km and from dipole surveys with a nominal depth penetration of more than 1 km. Both maps show also the location of the drilled wells and of the discharge areas containing fumaroles and hot springs, many of which are boiling. The horizontal flow pattern is manifested by the occurrence of a temperature maximum in the wells shown in Fig. 3. The section has been compiled from drill hole data which clearly show the existence of a horizontal hot water flow for a distance of 5 km, though from geophysical data it can be inferred that horizontal flows over a distance of 15 km or more occur.

Most of the hot water flows through an ignimbrite formation, and colder water moves west through an overlying dacite layer where it is heated by mixing with hot water and probably also by steam rising from the ignimbrite aquifer. Inflows of colder water from the east are indicated in Figs. 1 and 2 by high-resistivity indentations in the low-resistivity contours, and zones of mixing by the broader bands of intermediate resistivity. The flows tend to converge as they approach the discharge area, and part of the hot water flows further north beyond the Tatio Basin towards a gorge which cuts the north–south basement ridge. Within the section shown in

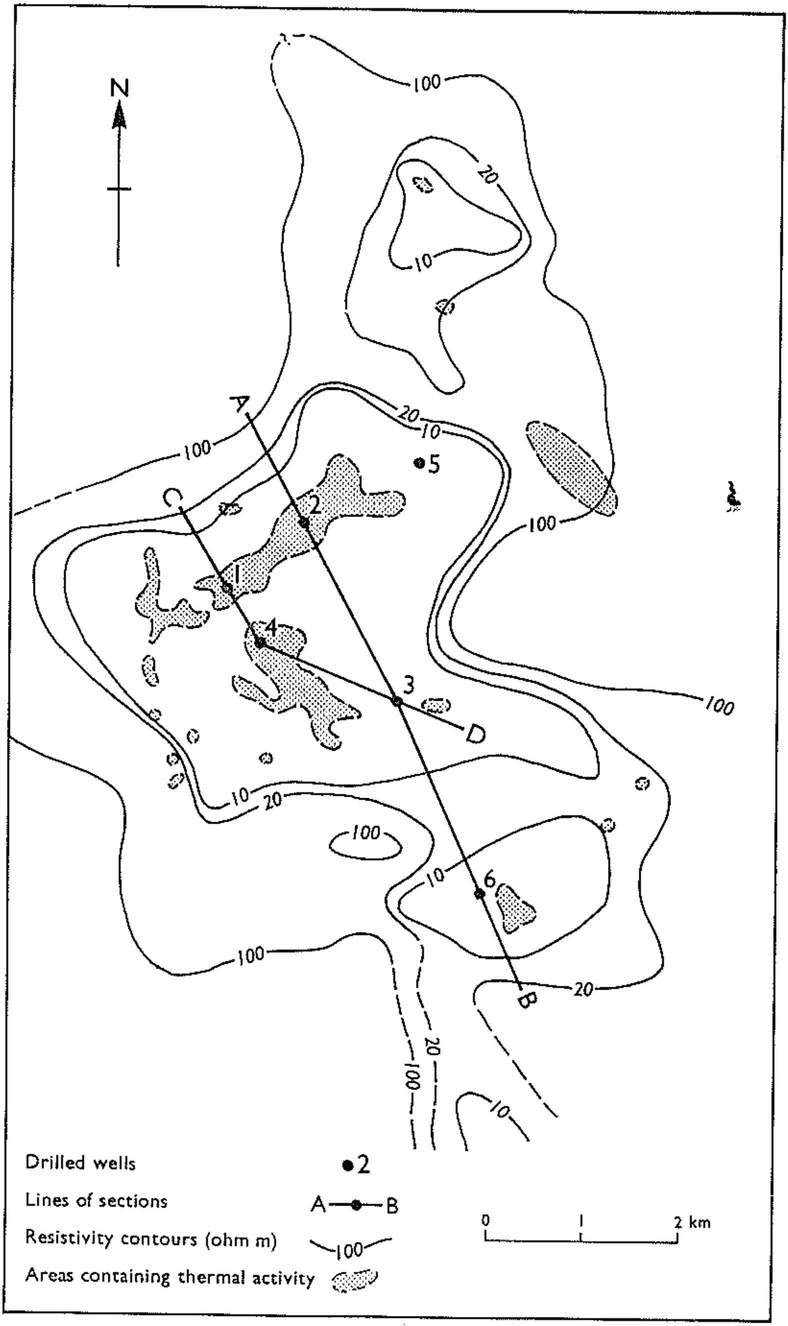


FIG. 1 — Map of apparent resistivity from Schlumberger measurements, El Tatio, Chile. The depth of penetration is 0.5 km (nominal). The boundary between hot and cold water lies somewhere between the 20 and 100 ohm m contours.

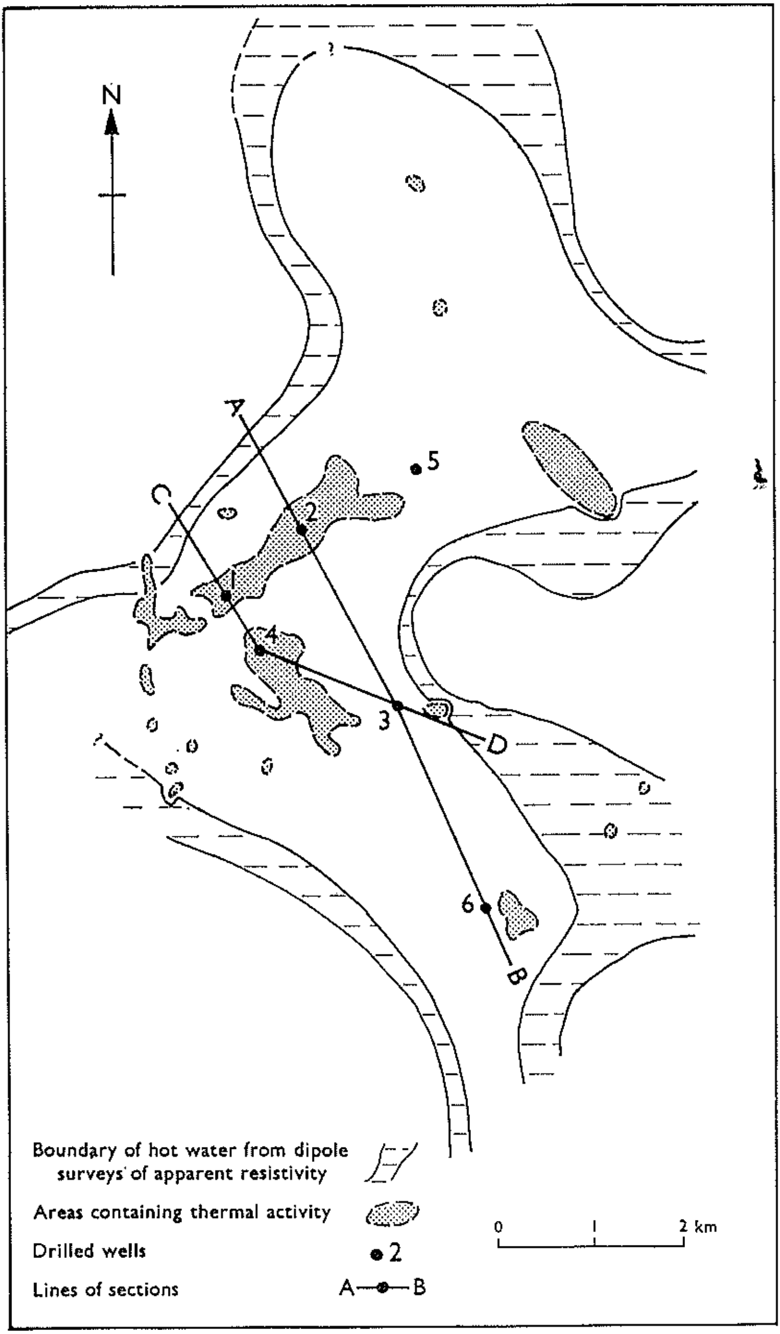
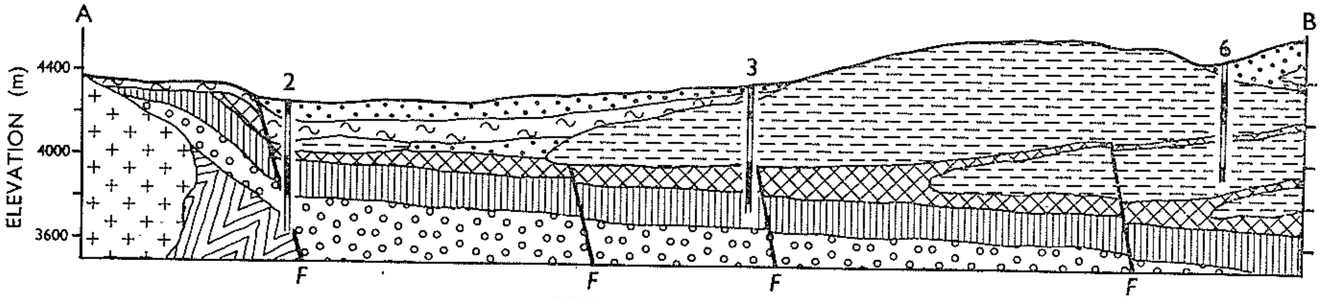
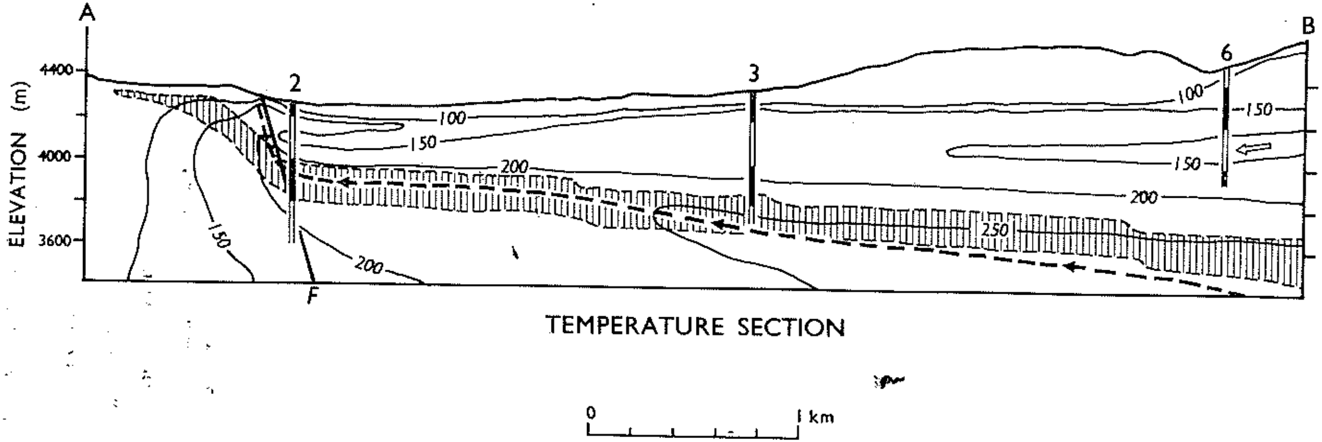


FIG. 2 — Map of apparent resistivity from dipole measurements, El Tatio, Chile. The nominal depth penetration is greater than 1 km.



GEOLOGICAL SECTION



TEMPERATURE SECTION

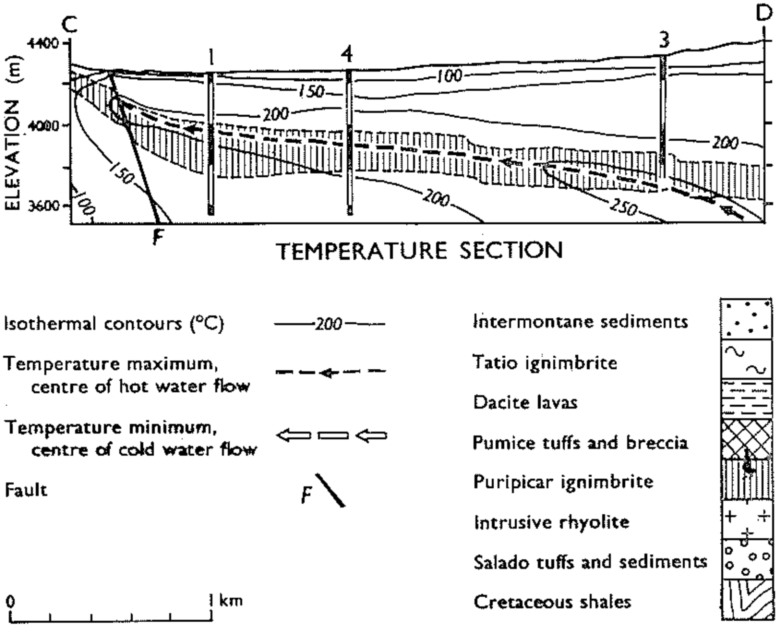


FIG. 3 (*above and opposite*) — Geological and temperature profiles of the El Tatio geothermal field, Chile.

Fig. 3 the temperature decreases laterally in the ignimbrite by about 10–15 degC/km and downwards by 50–100 degC/km.

A similar pattern involving horizontal flows of hot saline water to areas of thermal springs has been inferred also from resistivity measurements at Puchuldiza, another geothermal field 350 km north of El Tatio. The pattern appears particularly applicable to large volcano complexes that have undergone extensive hydrothermal alteration in the centre, and beneath or around which high heat flow presumably remains. The hydrological model suggests that wells for the production of hot water and steam should be sited as near to the source as possible, consistent with the economic factors involved.

New Zealand

The existence of extensive horizontal flows of thermal fluids in the two areas in Chile led us to investigate the possibility of such flows also occurring in other places. In New Zealand, resistivity surveys have been widely made in parts of the central volcanic district of the North Island where most of the New Zealand hydrothermal fields are located (Hatherton *et al.*, 1966) and where the hot waters appear to rise more or less vertically. However, in the Waiotapu–Reporoa valley (38° 20′ S; 176° 22′ E) an elongated pattern of low apparent resistivity (Fig. 4) suggests the existence of a significant horizontal flow of hot saline water. Although fewer resistivity measurements have been made here than in the Chilean fields, and the depth of effective penetration was hardly more than 0.6 km, evidence to support the horizontal flow comes from temperature measurements in wells drilled at Waiotapu and Reporoa, 6 km apart (Fig. 5), namely Waiotapu No. 7 and Reporoa No. 1. The hot water comes from an unknown source near Waiotapu or farther north-east, and flows south-south-west towards Reporoa and the Waikato River valley, which is the main drainage channel for the entire district south of Waiotapu. Between Reporoa and the Waikato River are a number of thermal springs at isolated localities, but all have lower temperatures than those at Waiotapu. Data from wells No. 7 at Waiotapu and No. 1 at Reporoa (Fig. 5) indicate that the horizontal decrease in temperature at 1 km depth between the two localities is about 10 degC/km, and at Reporoa the negative thermal gradient below the maximum temperature of 234°C at 1 km depth is about 50 degC/km. These values are comparable with those found in Chile.

In the Reporoa well there are two temperature maxima separated by a zone of slightly lower temperature marking an inflow of colder water. North of the well is an indentation in the 10 ohm m and 20 ohm m contours bounding the western side of the low-resistivity strip (see Fig. 4), thus indicating where the colder flow enters the strip. In the well the upper maximum temperature occurs in rhyolite lava, and the lower temperature maximum in the top of a pumiceous tuff layer.

HORIZONTAL FLOW AND PERMEABILITY

Horizontal flows tend to be related to rock permeabilities, but it has been noted in Chile that whereas the ignimbrite through which the hot water moves is of the welded type which normally possesses high permeability because of well-developed joints, significant permeability was in fact encountered only at the level of the hottest water. Some joints had been sealed by deposition of iron oxides before the geothermal system developed, but the others above and below the hot zone have since become filled by silica and, more rarely, calcium carbonate. Silica was found also in joints in cores taken above the level of maximum temperature in the Reporoa well.

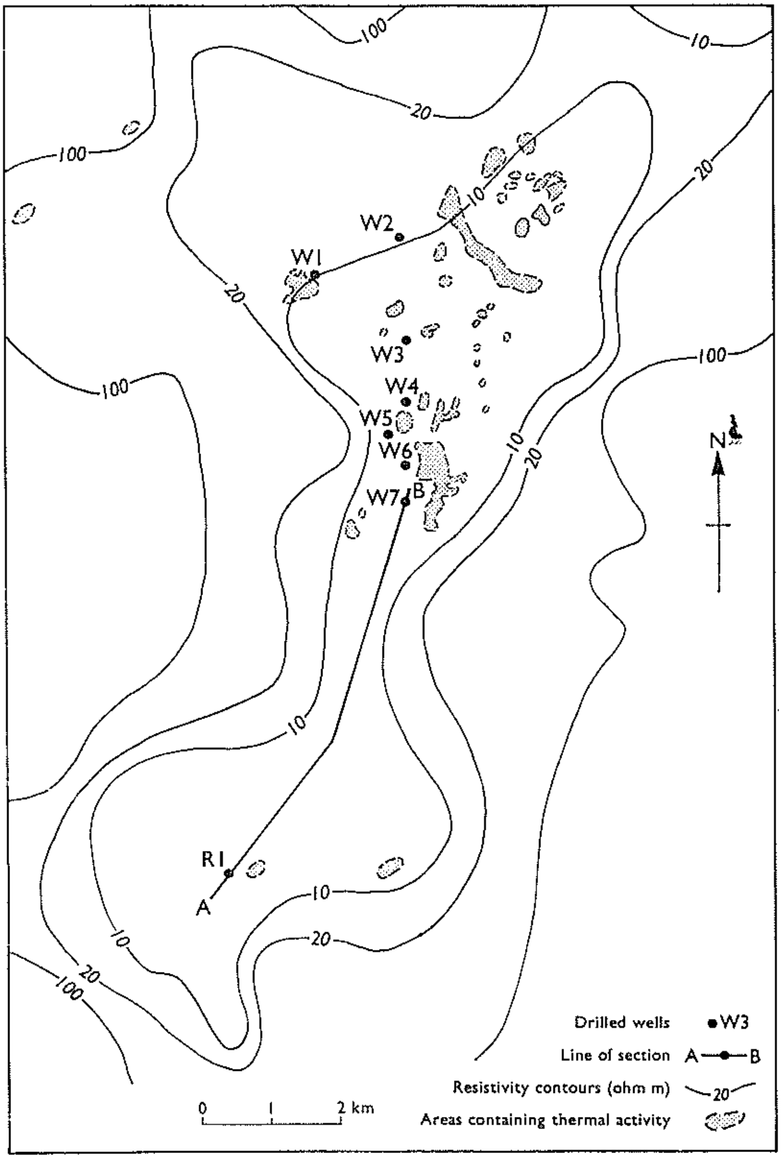


FIG. 4 — Map of apparent resistivity in the Waiotapu–Reporoa area, New Zealand. The depth of penetration is 0.61 km (nominal). The boundary between hot and cold water lies somewhere near the 20 ohm m contour.

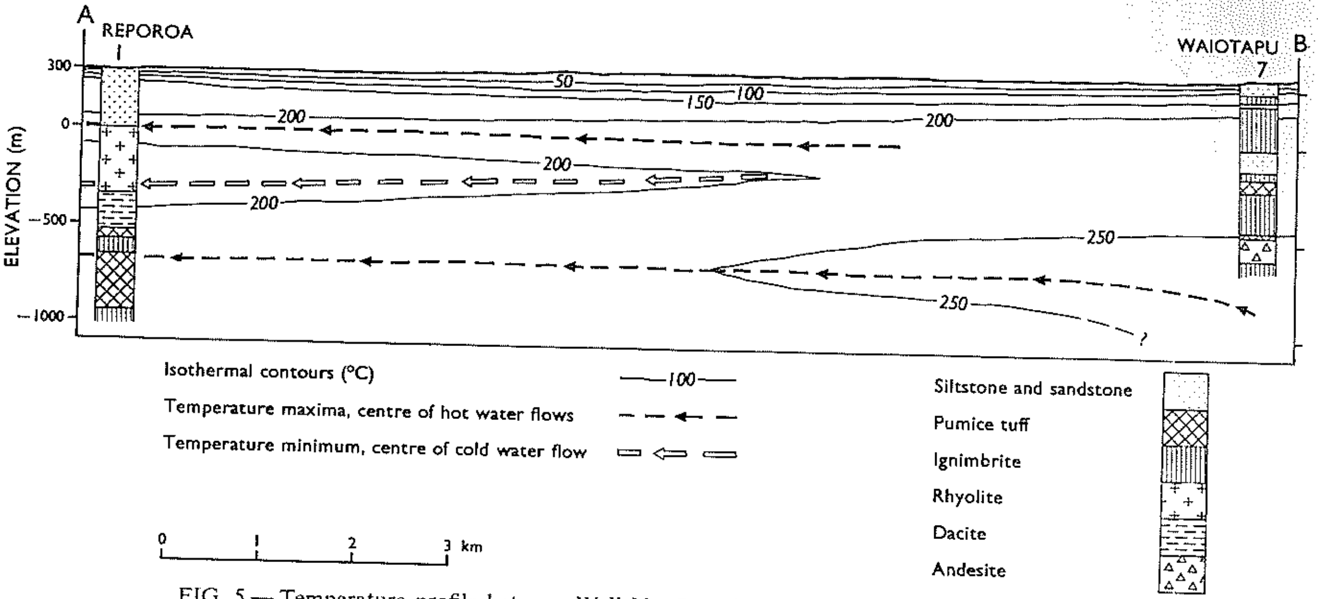


FIG. 5 — Temperature profile between Well No. 7, and Well No. 1, Reporoa, New Zealand.

It is inferred from these data that where horizontal flow occurs, the flow pattern becomes established initially by the controlling factors of permeability and hydraulic potential, but the hot saline water, which is usually saturated with silica, deposits silica above and below the hottest part of the flow owing to loss of heat by conduction. In this way the hot-water flow tends to become isolated from the colder water above and below and a conductive thermal gradient develops above and below the hot-water aquifer. It follows that to seek vertical fault fractures in such a location as sites for production wells will prove negative unless these fractures carry hot water from the horizontal flow directly upwards towards the hot springs at the surface and remain unsealed. It is therefore more profitable to search laterally across the hot-water flow for the zone of maximum permeability.

SUMMARY OF RESULTS

In some geothermal fields extensive horizontal flows of hot water may occur where hot water is generated in or enters an area through which the local or regional flow of groundwater is largely horizontal. The hot water may interfinger with cold-water flows, but will tend to become sealed off by deposition of silica. The existence of horizontal flow may be deduced by relating systematic resistivity measurements outlining the margins of low-resistivity areas created by the presence of hot saline fluids to inferred geological and hydrological conditions. Recognition of a field of this type is an important factor in siting production wells.

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