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GEOPHYSICAL STRUCTURE AND DENSIFICATIO
LAYERS IN THE BROADLANDS-OHAAKI FIELD (

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ABSTRACT

Isopach maps of the main lithostratigraphic units of the Broadlands-Ohaaki geothermal field have been constructed from integrated geophysical models and well logs. Hot fluids are produced mainly from two pyroclastic flows which exhibit moderate permeability within a small (3 km^2), elongated area in the centre of the field. Significant densification of the rocks in both layers within this small area is described. In the upper layer (Waiora Formation), densification is associated with mineral deposition (mainly quartz); in the deeper layer (Rautawiri Breccia), densification is probably due to compaction by explosive, natural hydraulic fracturing. Ancient hydrothermal eruptions affected the top layer. A model is proposed which links the various phenomena, assuming that later fracturing was confined to the small area with hydrothermal eruptions which coincide with the area affected by densification and enclosing most of the productive wells.

Introduction

Production of two-phase fluids from the Broadlands-Ohaaki geothermal field comes mainly from two producing layers in the reservoir, namely the Waiora Formation at a mean depth of about 5 0 m and the Rautawiri Breccia at a mean depth of 800 m. Although both layers are extensive, and coherent within and outside the field, productive wells appear to be confined to a strip approximately 1 km wide, covering an area of about 3 km^2 in the centre of the field. This strip trends NW and is roughly defined by the 250°C contour at about 1000 m depth (see Fig. 1). Although the two layers have been encountered elsewhere in the hot reservoir (~12 km2 at 0.5 km depth), as defined by the resistivity boundary shown in Fig. 1, no significant production outside the permeable strip has yet been found.

From geological mapping and lithostratigraphic studies it is known that all major faults within the reservoir are NE-trending normal or transcurrent faults which follow the trend of the shear belt of the Taupo Volcanic Zone (Grindley and Browne, 1976; Wang and Hedenquist, 1981). The question arises: how can the locally enhanced permeability of the two producing layers be explained, and what process caused the apparent NW trend when all permeable vertical features show a NE trend?

A retrofitting study of geophysical anomalies over the Broadlands-Ohaaki Field was undertaken in 1984 after production drilling had been completed (Henrys, 1987). For the study, all relevant information From earlier (1976-70) geophysical surveys was used, together with results from detailed seismic reflection and airborne magnetic surveys undertaken in 1984 and drillhole data from 42 exploration and production wells. The seismic reflection survey (12-fold CMP) showed that incoherent reflections from concealed Quaternary extrusions and pyroclastic flows could be obtained down to about 1 km depth; these data, together with re-interpreted older seismic refraction data, gravity data and tie-in data to wells, can be used to define the gross structure of major lithostratigraphic units inside and outside the geothermal reservoir. Preliminary findings have been presented (Henrys, 1988), and a more detailed account will become available soon (Henrys and Hochstein, in press).
Implications of the study relating to the history of geophysical exploration of the Broadlands-Ohaaki Field are discussed in another paper presented at this Workshop (Hunt, 1989).

The new interpretation models allow the construction of isopach maps of the two main producing layers inside the field and across its boundary. Because representative rock parameters (Whitford and Lumb, 1975) and petrological descriptions (Browne, 1971, 1973; Wood, 1983) are also available, we attempted to find out what causes locally enhanced permeability within the two producing layers.

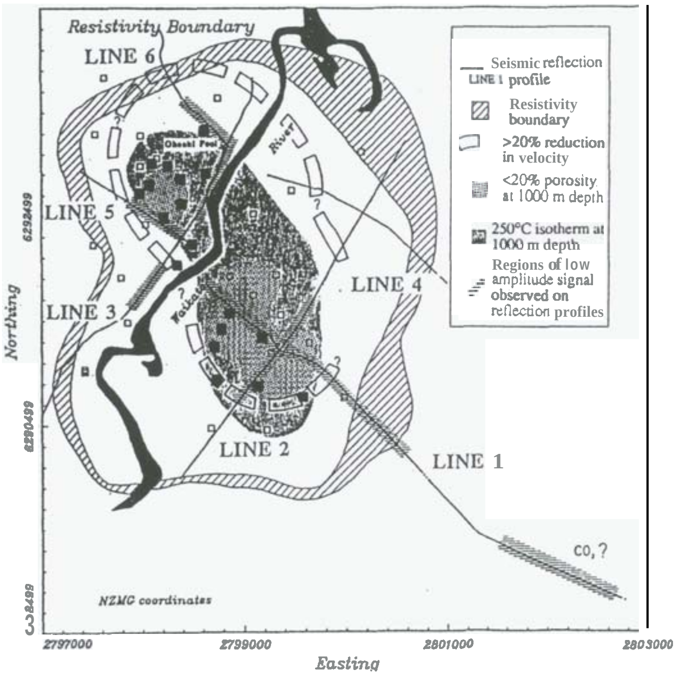

Fig. 1: Map (from Henrys, 1987) of the Broadlands-Ohaaki geothermal field showing the NW-trending pattern of high temperature isotherms at 1 km depth and the lateral extent of densification of reservoir rocks (also at 1 km depth). Production wells are showb by solid squares.

Isopach map of Waiora Formation and Rautawiri Breccia unit

The isopach maps of the Waiora Formation and Rautawiri Breccia layer are shown in Figs 2 and 3 respectively. Both units are pyroclastic flows probably made up of several smaller flow units which can no longer be distinguished because of intense thermal alteration and mineral deposition. The Waiora Formation is made up by a pumiceous lapilli tuff with originally low quartz content; the Rautawiri Breccia consists of lithic and lapilli tuffs.

The Waiora Formation is overlain by a thin (usually less than 50 m thick) lacustrine layer which, in turn, is overlain by the Ohaaki Rhyolite extrusions which cover about 10 km^2 of the Broadlands-Ohaaki Field; this rhyolite is absent in a small SE comer of the field. The Ohaaki Rhyolite/lacustrine layer contact is an important seismic interface which can be recognized in most seismic reflection profiles. Inside the productive field, the Rautawiri Breccia unit is associated with a small seismic velocity inversion ($v_p \approx 2.5$ km/s at 800 m depth); it is underlain both inside and outside the field by the denser welded Rangitaiki Ignimbrite where the interval velocity (v_p) increases to about 3.3 – 3.5 km/s. The Rautawiri Breccia / Rangitaiki Ignimbrite interface is the deepest reflector in the reflection section but can also be recognized from refracted amvals. Thus one interface for each of the two producing horizons is well known; using stratigraphic logs and gravity models, the isopach maps shown in Figs. 2 and 3 could be constructed.

The isopach contours in Fig. 2 show that the Waiora Formation attains a minimum thickness of 100-200 m inside the field; the unit increases in thickness to the west and to the north outside the field (maximum thickness about 400 m). It rests on the flat flanks of the concealed Broadlands Dacite extrusion over most of the field (except in the NW); the formation is therefore sandwiched between the almost level bottom

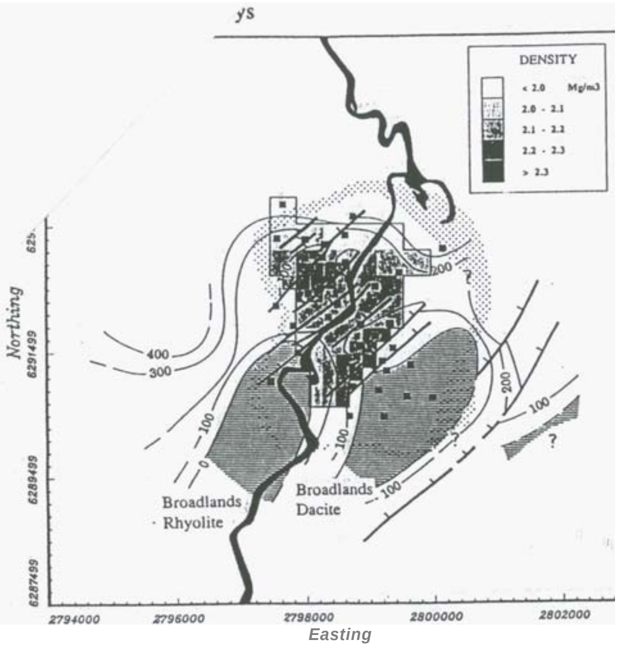

Fig. 2: Isopachs of the Waiora Formation compiled from integrated seismic and gravity interpretation models as well as litho-logical logs from all wells. Contours are in metres and dashed where uncertain. The lateral distribution of saturated density (core measure-ments) is shown by a box pattern. Wells are shown as small solid squares.

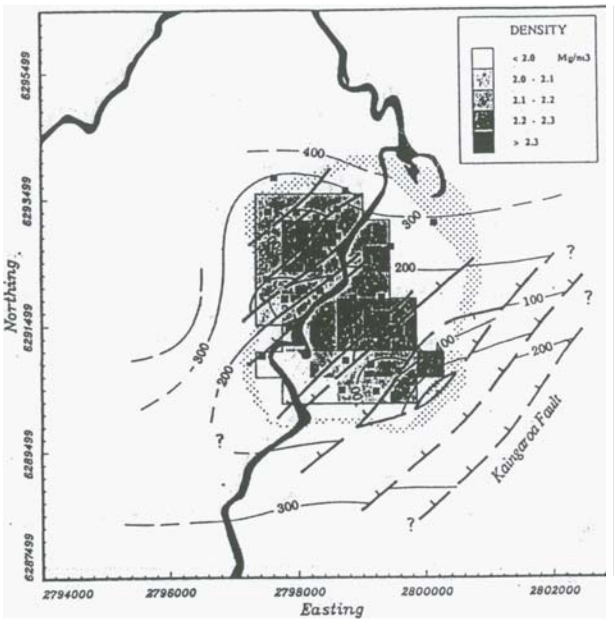

Fig. 3: Isopachs of the Rautawiri Breccia; for details see caption of Fig. 2.

of the Ohaaki Rhyolite and the top of the Broadlands Dacite Dome extrusion. The higher-standing parts of the Broadlands Dacite and of a third extrusion, the Broadlands Rhyolite flow (see Fig. 2), are not covered by the Waiora Formation. These two extrusions reflect high-standing terrain at the time the Waiora Formation was deposited. The Broadlands Rhyolite flow represents a flow tongue which infilled a broad, NNE-trending depression; the source of this flow lies outside the field (Henrys and van Dijck, 1987). From seismic evidence, the Waiora Formation appears to be less than 200 m thick to the east of the geothermal field where it terminates at NE-SW trending fault scarps. Although a number of NE-striking normal faults cut through the Waiora Formation, their throw is small (usually c 30 m); then is no evidence of cross faulting. The isopach map shown in Fig. 2 contains no information that explains the NW-trending, localized high permeability structure (see Fig. 1).

The isopach map of the Rautawiri Breccia (Fig. 3) shows a similar pattern; its thickness appears to be greater (up to 400 m) outside the field in the N part (but also in the SE corner) than anywhere else inside where the flow is about 150-300 m thick. The thickness of the Rautawiri Breccia, however, differs locally more than that of the Waiora Formation. Near BR 27 on the SE bank, it attains a minimum thickness of ≤100 m, whereas in the SE comer beneath well BR 16 it reaches a thickness greater than 500 m, probably associated with a structurally-controlled depression beneath BR 16. The top of the Rautawiri Breccia was probably eroded just to the west and beneath the Waikato River; this erosional depression was infilled by the northern flow tongue of the Broadlands Rhyolite flow (see Fig. 2). Normal, NE-striking faults also cut the Rautawiri Breccia unit although the vertical throw at the Rautawiri Breccia/Rangitaiki interface is usually < 50 m. A few of these faults show up with diffraction patterns in the seismic reflection section. Again, the isopach map shown in Fig. 3 contains no information which can explain the localized high permeability structure within this unit. No evidence of cross faulting, postulated by Wang and Hedenquist (1981), was found.

Densification pattern of the producing layers

The phenomenon that the saturated density of reservoir rocks of the Broadlands-Ohaaki Field increases generally with the intensity and rank of alteration had already been noticed when density measure-ments of cores from the first nine exploration wells became available (Hochstein and Hunt, 1970). Henrys (1987) analyzed the saturated density of all major lithostratigraphic units using data from 42 wells, and found evidence that significant lateral changes in density exist, especially in the Waiora Formation (based on 79 samples) and the Rautawiri Breccia (using 137 samples). Other, but smaller, lateral changes in density were also found for the Ohaaki Rhyolite and the Broadlands Dacite. For the interpretation of gravity anomalies it was impartant to quantify these lateral changes. For gravity modelling, the densities indicated by the box patterns shown in Figs 2 and 3 were used. These patterns indicate that there are two centres of densifi-cation within tach producing layer, namely, one somewhere near BR 8 in the NW part and another broader centre near BR 36 in the SE part of the field. The densification pattern for the Rautawiri Breccia covers almost half of the field (see Fig. 3); it also reflects a broad NW trend. The densification pattern for the Waiora Formation is more localized. Some radial symmetry with respect to the two centres listed above is indicated. To display the densification pattern in a line drawing, saturated density and porosity of the Waiora Formation and the Rautawiri Breccia have been plotted in Figs 4a,b versus radial distance for the NW centre (i.e. near BR 8). It can be seen that the density of both formations increases from about 1.9 to 2.0 x 10^3 kg/m^3 in colder (non-productive) wells to about 2.4 x 10^3 kg/m^3 close to the centre where productive wells are clustered, the porosity decreases from about 0.4 to less than 0.1. The shaded area with respect to a porosity of 0.4 indicates the decrease in pore volume. A similar pattern is indicated for the SW centre (i.e. centre near BR 36). Most of the values shown in Figs 4a, b represent the mean of several cores; since density measurements of porous rocks can contain a systematic error (i.e. if cores are not fully saturated), we only used data for which the particle (i.e. matrix) density lies within the range of 2.55 to 2.70 x 10^3 kg/m^3. Allowing for the thickness of each formation, one can evaluate numerically the total reduction in pore volume for each formation (about 25 E6 m^3 for the Waiora Formation and ≥ 50 E6 m^3 for the Rautawiri Breccia).

There are two possible mechanisms which can cause densification, namely:

(i) enhanced mineral deposition, and
(ii) local compaction.

Browne (1973) studied the mineralization of most of the wells in the Broadlands-Ohaaki area (BR 2-BR 25) and found that quartz, adularia, albite, chlorite, and calcite are the most abundant replacement and deposition minerals. There is some indication of greater quartz abundance in the Waiora Formation (av. 50%), whereas quartz appears to be less abundant in the Rautawiri Breccia (av. 35%); primary and secondary quartz were not quantified separately. As for calcite, there is some indication that this mineral is slightly more abundant in the Rautawiri Breccia than in the Waiora Formation; calcite rarely accounts for more than 5% of the total volume of minerals (values of 1 to 3% occur throughout most wells).

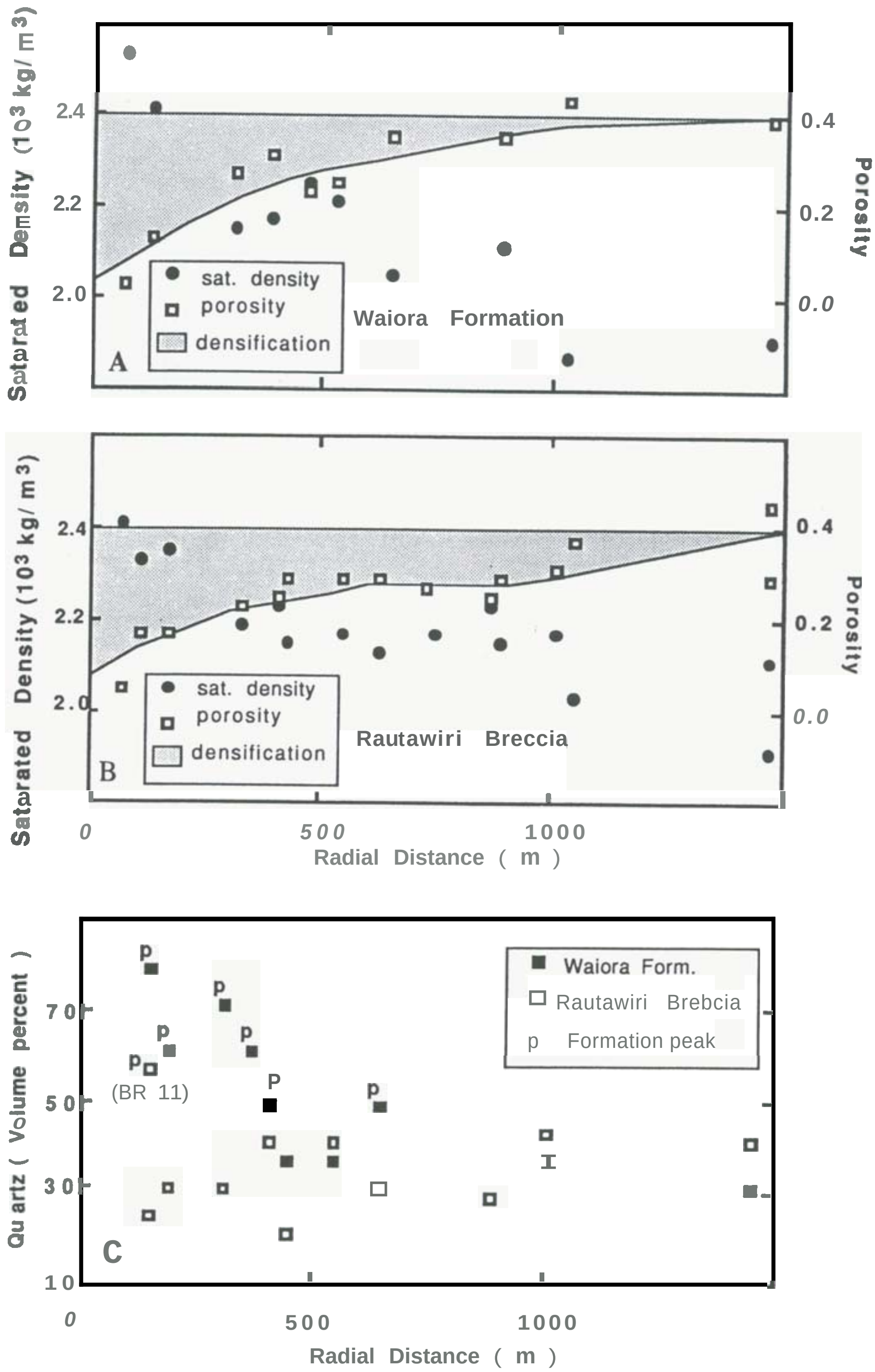

Fig. 4: Saturated density, porosity and quartz content of cores from the Waiora Formation and the Rautawiri Breccia. The values are plotted by assuming a radial symmetry for the densification pattern with respect to the NW centre (see Figs 2 and 3; coordinates of centre: 285 775 E 615 575 N).

A. Saturated density (10^3 kg/m^3) and porosity of cores from the Waiora Formation; values are the mean of several cores for each well. Lateral extent of densification is shown by a shaded pattern, taking as reference line a mean porosity of 0.4 for the same rocks in colder wells.

B. Saturated density and porosity of cores from the Rautawiri Breccia.

C. Quartz content of cores from the Waiora Formation and the Rautawiri Breccia. Values are the mean of all samples for each well and are based on semiquantitative XRD and infrared analyses (Browne, 1973).

If the average volume percent of quartz is plotted versus radial distance (Fig. 4c), one finds that quartz values are higher in the Waiora Formation nearer to the NW centre than further away; most wells with high quartz values also show a quartz peak for the formation. A different setting is indicated for the Rautawiri Breccia where quartz values do not increase towards the NW centre, with the exception of one well (BR 11) where quartz reaches 60%; it is possible that quartz is even slightly depleted in wells near the densified centre. Considering the small number of cores taken from each layer, it is remarkable that these "spot" data can be used to recognize such patterns. The data in Fig. 4c indicate that densification by mineral deposition probably occurred in the Waiora Formation but that a different mechanism of densification affected the Rautawiri Breccia. There were insufficient data to check whether significant quartz concentrations occur in the same layers near the SE centre.

The results in Fig. 4c encouraged us to check whether any correlation exists between densification and well output (i.e. gross permeability). As parameter for densification we used the normalized porosity ($\Delta\phi/\phi$), assuming that the average porosity of both formations far away from the productive centres is 0.4. No correlation exists for wells with feed points in the Rautawiri Breccia; for those with feed points in the Waiora Formation, the value of $\Delta\phi/\phi$ was within the range of 0 to 0.2 for non-productive wells but showed a large scatter of 0.35 to 0.9 for wells with outputs > 200 t/h (with the exception of BR 20).

Whatever mechanism is the cause of densification, the denser rocks within both layers contribute significantly to the positive residual gravity anomaly over the field which encloses both centres of densification (Hochstein and Hunt, 1970).

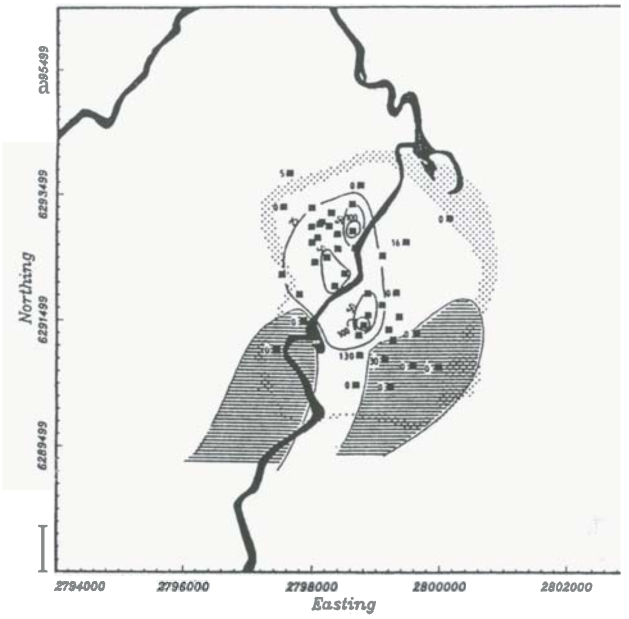

Fig. 5. Isopach map of the siltstone layer lying on top of the Waiora Formation. The high standing volcanic domes and extrusions at the time when the siltstones were deposited are shown by shading; "O" indicates absence of this layer. For other details see caption of Fig. 2.

Natural hydrofracturing of producing layers

Grindley and Browne (1976) already recognized that significant hydraulic fracturing has occurred in both producing layers; the brecciated nature of the deeper layer was used to describe it as a "breccia". Grindley and Browne postulated that hydraulic fracturing is associated with the development of high pore pressures in existing fractures and that explosive fracturing occurs when the fluid pressure exceeds the confining pressure or the Strength of the rocks. Such pressure build-up could develop if the layer is covered by an impermeable layer or overburden.

Occurrence of ancient hydrothermal eruptions

A layer of bedded lacustrine siltstone and mudstones with inferred low permeability lies on top of the Waiora Formation; the layer is covered, in turn, for most of the field by the Ohaaki Rhyolite. The bottom could not be detected by seismic methods. To check whether there is any structural relationship between this layer and the densification pattern of the Waiora Formation, an isopach map of the lacustrine layer was constructed (Fig. 5) which is based on stratigraphic logs. The map shows that the layer only extends as far as the denser part of the Waiora Formation; some crater-like structures are also indicated, where the thickness increases sharply. The layer is absent on top of the Broadlands Rhyolite and over the high-standing parts of the Broadlands Rhyolite (see Fig. 2), with the exception of BR 27 where 30 m-thick lacustrine sediments occur. The isopach contour pattern in Fig. 5 indicates that this layer probably reflects the infill of a series of smaller, deep depressions and a broader depression which could constitute a sequence of coalescing hydrothermal eruption craters. An accumulation of young, coalescing hydrothermal eruption craters has, for example, been described by Muffler et al. (1971) for Yellowstone (U.S.).

A siltstone layer also covers the top of the Rautawiri Breccia, mainly beneath the western part of the field. Information from lithostratigraphic logs, however, is not sufficient to construct an isopach map for this lower siltstone layer. Irregular changes in thickness were noted for a few wells (BR 8, for example, where the layer reaches a thickness of 110 m, although elsewhere the layer is usually less than 50 m thick). Clear evidence for the hypothesis of ancient hydrothermal eruptions is not yet available. As will be shown in the following paragraph, the assumption that ancient hydrothermal eruptions occurred at Broadlands makes it possible to establish some linkage between all phenomena discussed so far.

Possible linkage between the phenomena of densification, mineral deposition, hydraulic fracturing and hydrothermal eruptions

Let us first consider the following setting:

(1) Tectonic deformation during the last 10^6 yr has always been significant in the Broadlands area, which forms part of the inferred Taupo Volcanic zone shear belt; this deformation is marked by shear and separative movement. Resistance against shear deformation is low in NE direction; that in NW direction is high. As a result, a squence of NE-trending faults have developed, the older (deeper) ones show en echelon pattern (Henrys, 1987) but conjugate faults did not develop. Originally, the natural permeability of all pyroclastic flows and volcanic extrusions deposited in the Broadlands area during the last 10^6 yr was very low. Subsequent tectonic deformation enhanced the vertical permeability and allowed some upflow of hot water. The Broadlands system already existed when the pyroclastic flows of the Waiora Formation were deposited.

If this setting is similar to the historical setting, linkage between the various phenomena described in this paper can be established by postulating the following mechanisms:

(2) A sequence of widespread hydrothermal eruptions at the top of the Waiora Formation, which was then the free surface, caused a local reduction in strength of both layers; the fracturing penetrated down to the Rautawiri Breccia and triggered hydraulic fracturing. The first deposition of minerals occurred in the Waiora Formation but probably scaled the fractures. Without further fracturing, deposition of minerals and densification would not have continued.

(3) Even with mineral deposition, the strength of the rocks shattered by hydrothermal eruptions would still have been low. Tectonic deformation probably led to further fracturing, especially in areas affected by hydrothermal eruptions; localized conjugate shear fractures could also have developed, and hydraulic fracturing continued. The Ohaaki Rhyolites covered the Waiora Formation and the siltstone layer; a lake formed, and up to 350 m-thick lake sediments (Huka Falls sediments) were deposited (Henrys and Hochstein, in press) and covered the high-standing Broadlands Dacite Dome and the Ohaaki Rhyolite flow. The vertical permeability of the thick lake sediments was always low; hot water only ascends now from the top of the Waiora Formation via young faults which cut the extrusions.

The key argument for this scenario is that hydraulic fracturing and fracturing induced by secular tectonic deformation has always been concentrated in parts of the field where the strength of the rocks was initially reduced by ancient hydrothermal eruptions. Such local fracturing has continued until recently and might explain the somewhat grater permeability of these layers, as shown by the high output of wells. Densification of the productive layers, however, probably involved two mechanisms: repetitive stresses associated with hydraulic fracturing in the Rautawiri Breccia and dominantly mineral deposition in the Waiora Formation.

Summary

Lithostratigraphic logs of wells and integrated geophysical interpretation models can be used to construct isopach maps of major lithostratigraphic units of the Broadlands-Ohaaki Field. These maps contain no information that can be used to explain the enhanced permeability pattern of a small area (about 3 km^2) within the field where productive wells are located.

Most of the presently-produced hot fluids enter the wells through localized feed points which occur in two productive layers, the Waiora Formation and the Rautawiri Breccia. Density data from cores and gravity anomalies show that the pore volume of both layers has been reduced significantly in the small area with productive wells. Densification also occurs in extrusions lying on top of the Waiora Formation but is less significant. Petrological data indicate that densification in the Waiora Formation is associated with mineral deposition whereas for the Rautawiri Breccia another mechanism is indicated. An isopach map of the siltstone layer on top of the Waiora Formation points to the occurrence of hydrothermal eruptions; this layer extends laterally as far as the densified formations.

A model is presented which links the various phenomena using as a starting point an inferred reduction in the strength of both layers induced by a sequence of ancient hydrothermal eruptions affecting the top of the Waiora Formation. It is also assumed that later fracturing (hydraulic fracturing and fracturing induced by regional tectonic deformation) was confined mainly to the area which had been affected by hydrothermal eruptions.

Acknowledgements

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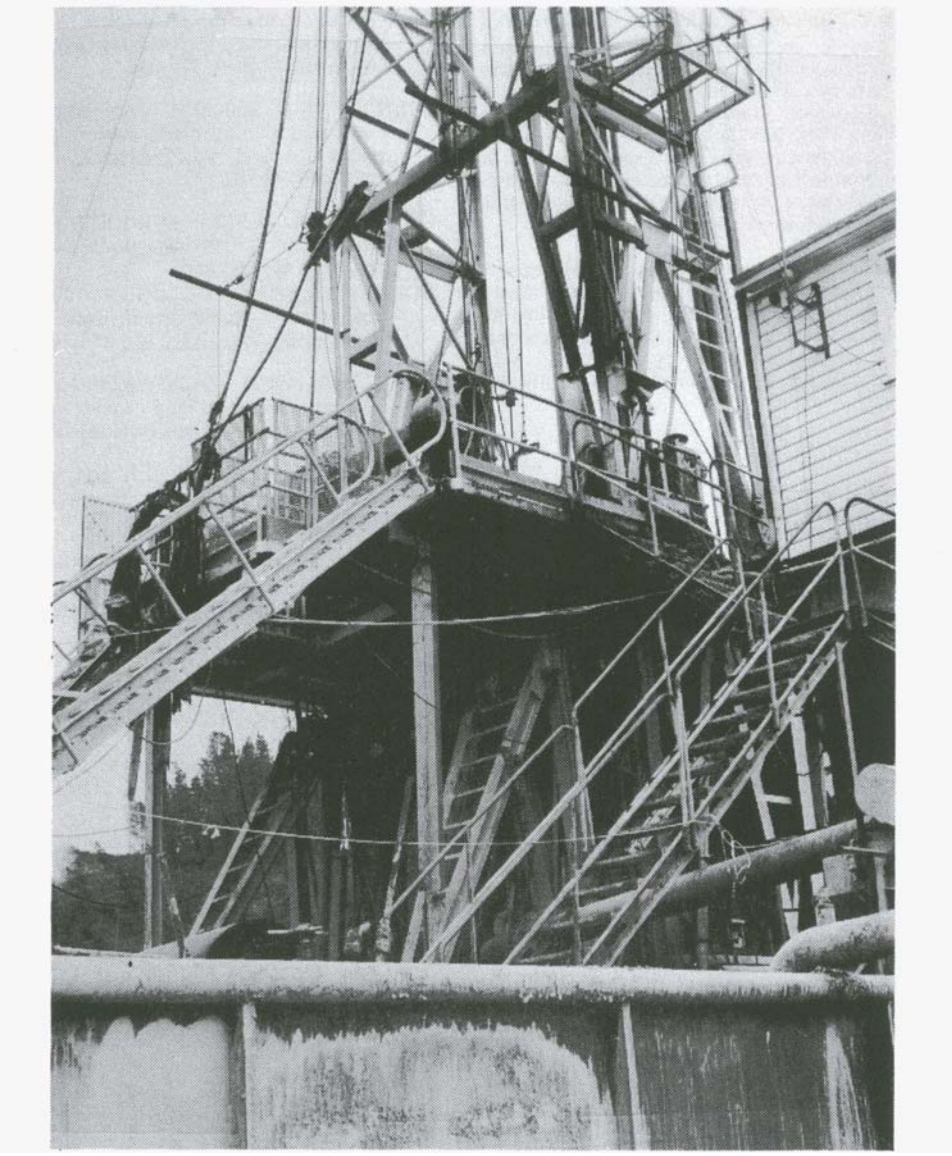

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