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A THREE DIMENSIONAL MODEL OF THE DISTRIBUTION OF HYDROTHERMAL ALTERATION MINERALS WITHIN THE BROADLANDS-OHAAKI GEOTHERMAL FIELD

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Abstract

Plan view maps depict temperature, geology and alteration mineralogy at three levels (100 m, 400 m, 750 m) below ground surface within the Broadlands-Ohaaki geothermal field. The distribution of adularia-illite-calcite-pyrite and montmorillonite-calcite-siderite-kaolinite mineral assemblages are spatially and genetically related to the position of two main fluid types, chloride and CO_2-rich steam-heated waters, respectively. In addition, the dismbution of temperature sensitive clay minerals (montmorillonite, illite/montmorillonite, illite) closely parallels the patterns of isotherms. For both active and extinct geothermal settings, alteration mineralogy supplies information regarding fluid temperature, pH and permeability which is useful for interpreting the paleohydrology.

Introduction

The Broadlands-Ohaaki geothermal field has been the subject of a numerous alteration studies most of which were directed towards the deep parts (>800 m) of its reservoir (e.g. Browne and Ellis, 1970; Browne, 1972; Eslinger and Savin, 1973; Blattner, 1975; Lonker et al., 1990). Although petrographic descriptions of drill core from 40 wells exist (Browne, 1971; Wood, 1983), less attention has been paid towards understanding the low temperature (100°-250° C) alteration regime in the shallow and marginal portions of the field. From an epithermal perspective, it is in this region where gold mineralisation commonly occurs (e.g. Hedenquist and Henley, 1985), and indeed, gold deposited in well head pipework and the Ohaaki Pool (Weissberg, 1969; Brown, 1986). A recent geochemical model (Hedenquist and Stewart, 1985; Hedenquist, 1990) describing the evolutionary ties and interactions between ascending chloride waters and marginal CO_2-rich waters now allows correlation between alteration mineralogy and fluid types.

As part of a project investigating hydrothermal processes in the epithermal environment, plans, or horizontal slices, depicting alteration mineralogy, temperature distribution and lithology were drawn for several depths. These maps relate alteration patterns with stratigraphy, temperature and hydrology and extend the thermal and geochemical structural model for the field described by Hedenquist (1990).

Geology and alteration: A 3-D model of Broadlands-Ohaaki

Maps showing isotherms, geology and alteration are depicted in Figures 1, 2 and 3, for the 100 m, 400 m and 750 m depth levels, respectively. Temperature data for all wells were obtained from Lee-Joe and O' Sullivan (1986), and boiling temperatures were determined from the curves by Sutton and McNabb (1977). The stratigraphy and alteration are based upon petrographic core descriptions (Browne, 1971; Wood, 1983) and XRD studies of cuttings. Alteration patterns depict hydrothermal mineral dismbutions of clays, carbonates and pyrite, although in places these overlap. The positions of natural, structurally controlled fluid conduits are not well known as contacts are located from cuttings; hence, faults with small displacements are not recognisable. Structures shown are based on gravity and seismic interpretations (Henrys, 1987) and surface geology (Grindley and Browne, 1968).

Fluid types

Two main fluid types exist at Broadlands-Ohaaki: A.) near neutral pH chloride waters are deeply convected meteoric waters which occupy the main upflow zones and are utilised for power production; B) CO_2-rich waters are weakly acidic and form on the cooler margins of the upflow zones (Table 1). In contrast to the chloride waters, which are well documented at Broadlands-Ohaaki and other New Zealand geothermal systems (e.g. Ellis, 1970; Mahon and Finlayson, 1972). CO_2-rich waters were recognised and sampled directly only recently (Mahon et al., 1980; Hedenquist and Stewart, 1985; Hedenquist, 1990). Their origin is attributed to condensation of steam and CO_2, separated from boiling chloride waters below, into cool, shallow and marginal ground waters as evidenced by low chloride contents and light hydrogen and oxygen isotopic compositions (Hedenquist and Stewart, 1985). Some deep CO_2-rich waters, however, have chloride concentrations close to that of the reservoir fluids (Table 1), suggesting that conductive cooling or mixing, without boiling of the gas-rich reservoir chloride water, resulted in their formation. Regardless of their origin, CO_2-rich waters tend to be weakly acidic at cooler temperatures (<200° C) due to high concentrations of H_2CO_3, making them more reactive (Giggenbach, 1984), and rich in bicarbonate (Hedenquist, 1990). Acid-sulfate waters form a third fluid type; however, their presence is restricted to a few surficial patches of steaming ground.

Alteration

Hydrothermal alteration is the product of water-rock interaction with the rank and intensity of alteration being governed by several parameters but mainly fluid composition and temperature. Two main alteration assemblages exist. The hydrothermal assemblage stable in the presence of chloride waters is quartz-albite-adularia-illite-calcite-chlorite-pyrite (Browne and Ellis, 1970), whereas montmorillonite-kaolin-calcite-siderite occur in the presence of CO_2-rich waters (Hedenquist, 1990).

Temperature measurements made in wells indicate two upflow zones exist at shallow depth (Fig. 1A).

The dominant rock types are thinly bedded water-laid tuffs, soft siltstones and sandstones deposited in a lacustrine environment; they comprise the Huka Falls Formation (Fig. 1B). Soft pumiceous Ohaaki Rhyolite occurs in two separate areas in the northwest quadrant. Two NE striking normal faults, <1.5 km long, have small vertical displacements that bound a minor graben (Grindley and Browne, 1968). These faults probably focus upflow as is indicated from the shape of the isotherms (Fig. 1A).

Hydrothermal alteration is minor and consists of locally intense silicification and adularia (Fig. 1C) midway along the more northerly fault. Disseminated pyrite also occurs in this vicinity over an area 500 x 500 m (Fig. 1D). The alteration intensity away from the zone of silicification is moderate to weak, grading into illite, and then further outwards, into montmorillonite. A zone of weak carbonate alteration overlaps the argillic alteration as defined by two lobes of calcite separated by siderite.

Most of the clay-carbonate alteration coincides with the presence of CO_2-rich waters (some clay within the Huka Falls Formation is undoubtedly detrital), and the quartz-adularia alteration formed from boiled chloride waters (Browne and Ellis, 1970).

The area of strongest silicification (i.e. Br-15) is offset slightly from the area of present boiling (Fig. 1A). Areas containing calcite are hottest being in the main upflow zones. Note that the larger area of illite occurrence (northwest quadrant) is bounded by montmorillonite, not illite/montmorillonite, corresponding to the steep thermal gradients here.

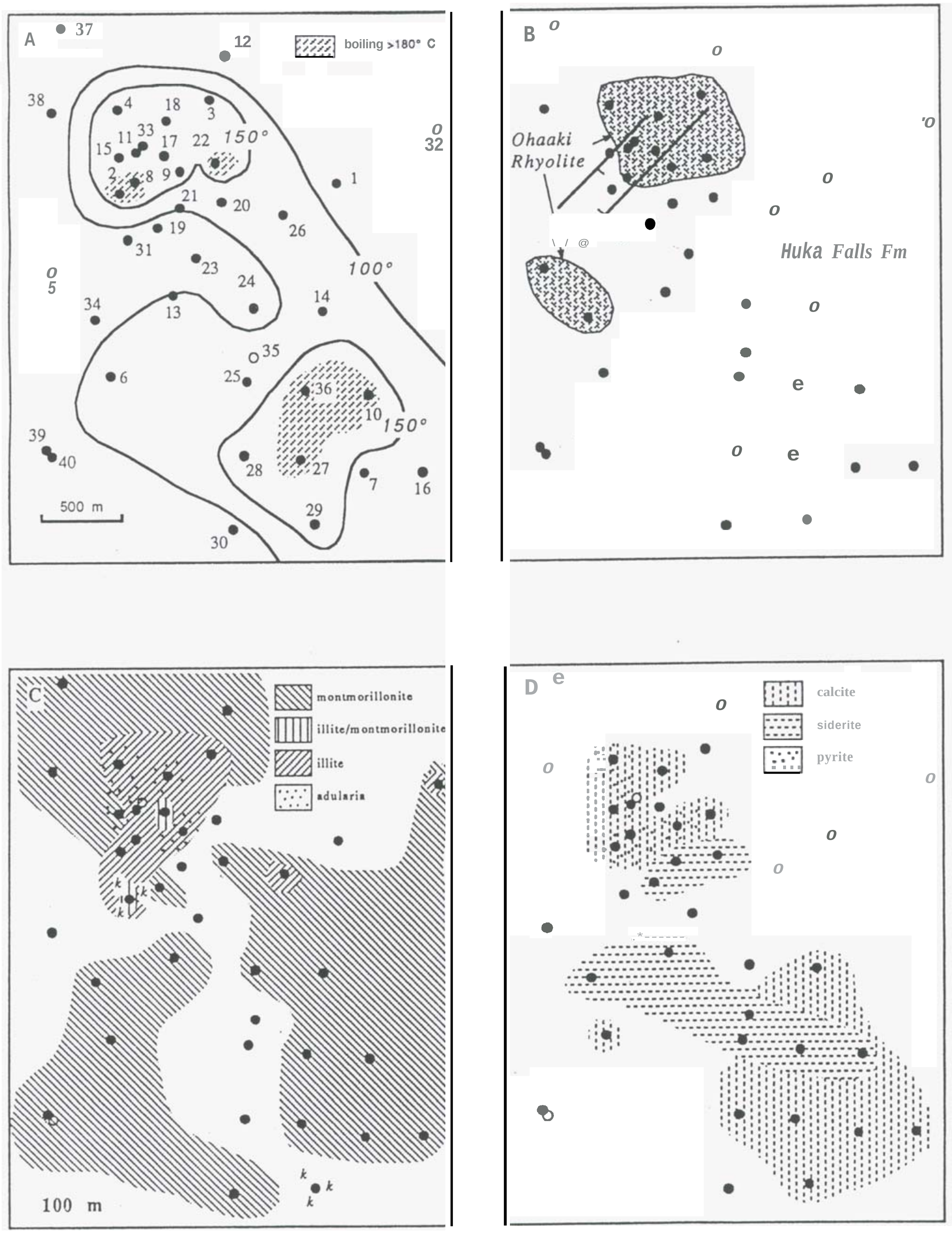

Figure 1. Maps depicting A) temperature distribution and boiling areas, B) geology, C) clay and adularia distribution and D) carbonate and pyrite distribution at 100 m below the surface (200 m asl). The data were compiled from 40 geothermal wells shown as black circles; open circles indicate geothermal wells from which no data was available, The letter k in 1C denotes the occurrence of kaolinite.

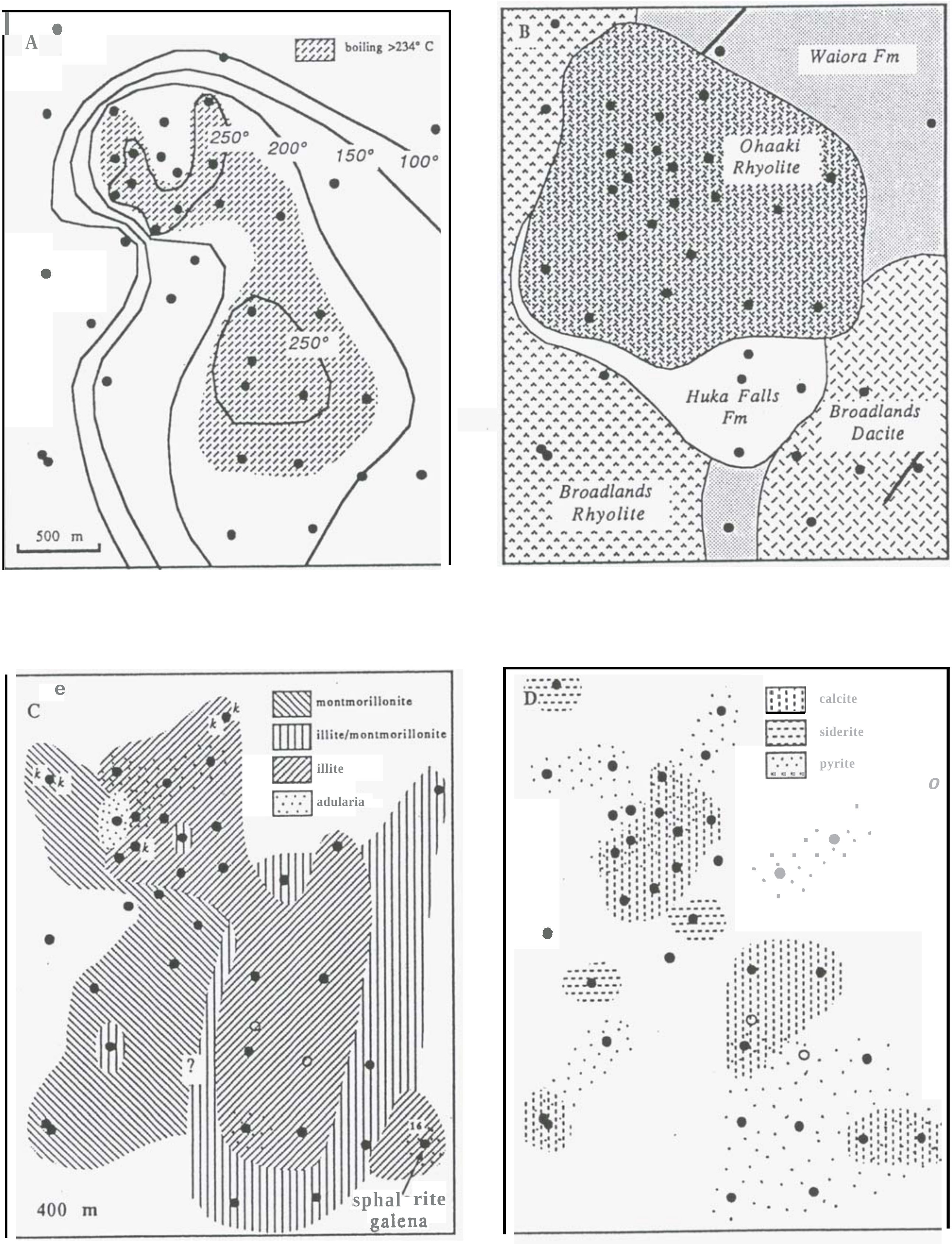

Figure 2. Maps depicting A) temperature distribution and boiling areas, B) geology, C) clay and adularia distribution and D) carbonate and pyrite distribution at 400 m below the surface (100 m bsl). The data were compiled from 40 geothermal wells shown as black circles; open circles indicate geothermal wells from which no data was available. The letter k in 2C denotes the occurrence of kaolinite.

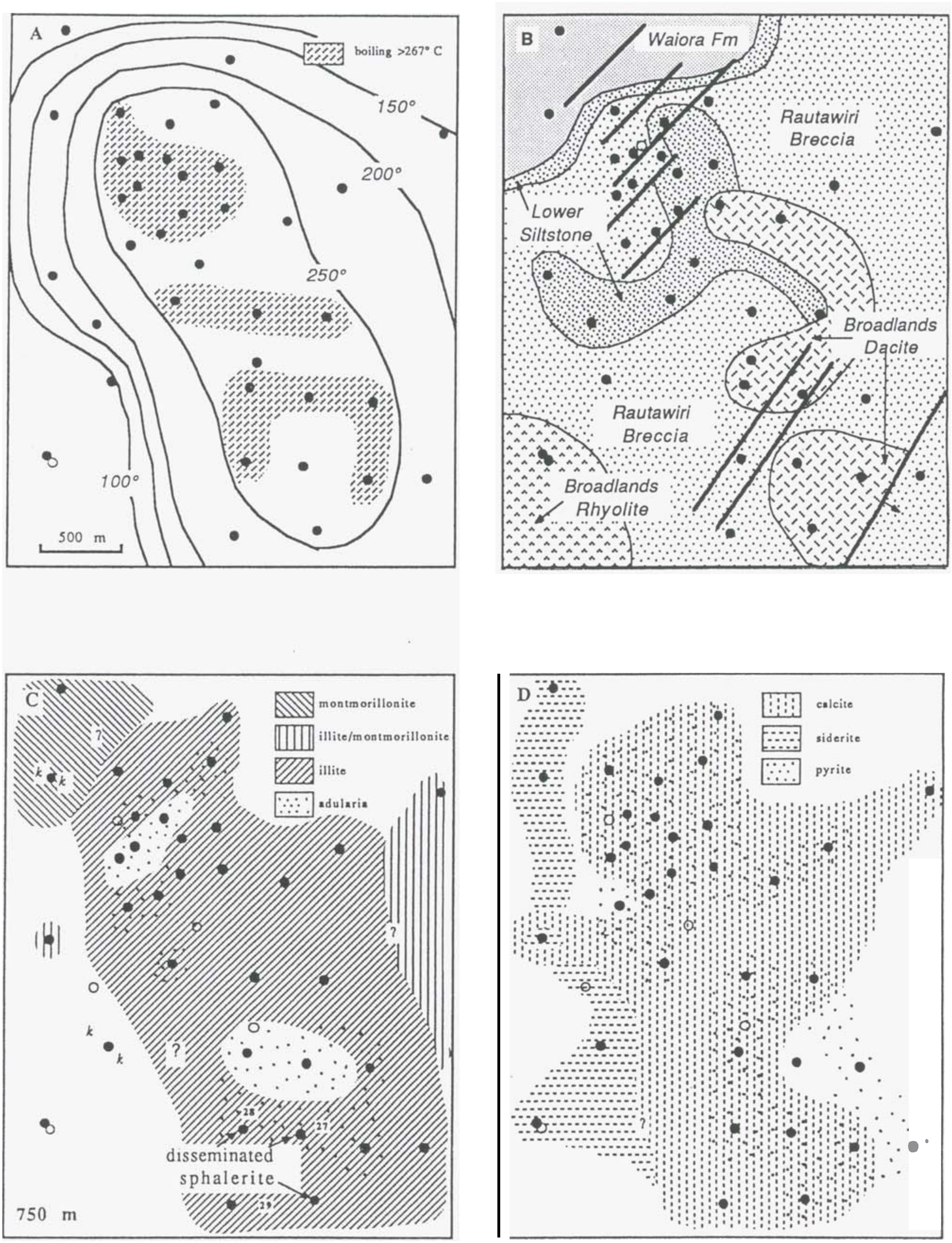

Figure 3. Maps depicting A) temperature distribution and boiling areas, B) geology, C) clay and adularia distribution and D) carbonate and pyrite distribution at 750 m below the surface (450 m bsl). The data were compiled from 40 geothermal wells shown as black circles; open circles indicate geothermal wells from which no data was available. The letter k in 3C denotes the occurrence of kaolinite.

Table 1. Characteristic water compositions at Broadlands-Ohaaki: **Br-6** CO_2-rich steam-heated water (down hole sample **24-3-86);** Br-8 chloride water (discharged sample **29-2-68);** and Br-12 CO_2-rich chloride water (down hole sample **17-8-87);.** Data (Hedenquist, **1990)** recalculated to down-hole or reservoir conditions; concentrations in mmole/kg.

well	T° C	$pH_t(pH_{neut})$	Na+	K+	Ca++	Cl-	SO_4--	HCO_3-	H_2CO_3	SiO_2
6	146	4.3(5.8)	16.4	0.8	0.1	0.5	0.1	1.3	297	2.1
8	265	6.3(5.6)	27.9	3.9	0.02	34.5	0.08	3.4	96	8.9
12	158	5.5 (5.7)	41.8	3.8	0.17	24.4	0.10	14.5	309	2.8

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The isotherms at the 400 m level (Fig. 2A) match the two upflow zones at the 100 m level (Fig. 1A) and show steep thermal gradients on the northwest margin of the field.

The stratigraphy is dominated in the centre by the Ohaaki Rhyolite. Between it and the Waiora Formation lies a sequence of mudstones, sandstones and pumiceous tuffs which are part of the lower Huka Falls Formation. The Waiora Formation is a pumice lapilli tuff interbedded with water laid tuffaceous siltstone and mudstone. In the southeast, the Broadlands Dacite underlies the Waiora Formation and where fresh is dense. In the west, the Waiora Formation is underlain by the Broadlands Rhyolite which is flow banded and contains andesine plus rare biotite. Direct evidence of faulting is confined to a few narrow zones of sheared and brecciated rock that occur in the north and the southeast comers of the area (Fig. 2B).

Intense hydrothermal alteration is centred in two areas (Fig. 2C-D). In the southeast, sphalerite and galena occur in open space filling in brecciated Broadlands Dacite in association with hydrothermal quartz, illite, adularia, calcite, chlorite and pyrite (Br-16). West of here, alteration rank decreases and the dacite is less intensely altered; hydrothermal minerals present include variable amounts of mixed layered illite/montmorillonite, chlorite and calcite with pyrite filling fractures. Alteration in the Huka Falls Formation is low to moderate in intensity with hydrothermal illite, illite/montmorillonite, chlorite, calcite and pyrite being confined to the matrix. In contrast, quartz-illite-pyrite-calcite alteration is well developed within the Ohaaki Rhyolite, increasing in intensity away from its margins.

The distribution of the clay minerals generally coincides with their estimated thermal stability range (i.e. illite > 220' C, illite/montmorillonite between 140° and 220' C, montmorillonite <140° C; Browne 1978), with the exception of illite occurring outside the 200° C isotherm in the southeast comer (compare Figs. 2A-C). The inability of clays here to reflect present condition indicates cooling since illite formed. Sharp temperature gradients in the northwest part of the field coincide with the sharp change from intensely altered to fresh rocks.

Calcite dominates the carbonate mineralogy which coincides in part with boiling. Siderite and calcite, plus montmorillonite and kaolinite on the margin reflect the presence of the CO_2-rich waters.

Quartz-illite-adularia-calcite alteration plus sphalerite-galena mineralisation in the vicinity of Br-16 indicate that temperatures and permeability here were formerly hotter. Fluid inclusion homogenisation temperatures from shallower samples of Br-16 (305 m, Th ave = 240' C) and isotopic data (Eslinger and Savin, 1973) support cooling. Despite widespread alteration and boiling, there is little other evidence for precious-metal or sulfide mineralisation at this level.

The thermal pattern at 750 m. depth shows an oval shaped 1 x 3 km area > 250° C aligned in a north northwest direction (Fig. 3A). Boiling exists within much of this area and best delineate zones of upflow. Cooler isotherms are concentric and show sharp thermal gradients along the western side of the field.

The geology plan shows minor segments of the lower parts of the Waiora Formation, the Broadlands Dacite, and the Broadlands Rhyolite (Fig. 3B). Underlying these units are the Lower Siltstone, comprised of variably bedded tuffaceous siltstones and pumiceous water-laid tuffs, and the Rautawiri Breccia, which is a coarse grained lithic lapilli tuff interbedded with water-laid tuffs. A parallel set of steeply dipping NE trending faults dominate the structural grain of this plan; most faults probably have slight vertical displacements (Henrys, 1987). The fault in the southeast comer is the upper portion of a major horst bounding structure, penetrating graywacke basement with several hundred meters of down drop to the southeast (Grindley and Browne, 1968).

Well developed quartz-illite-pyrite-calcite alteration occurs within an oval area aligned in a north northwest direction, coincident with the isotherm pattern (Fig. 3C). Disseminated sphalerite occurs in samples from Br-27, 28 and 29, and the distribution of adularia generally coincides with permeable NE trending faults and fractures. Alteration along the margin of the fields consists of isolated Occurrences of illite/montmorillonite, montmorillonite, and kaolinite, coexisting with calcite and/or siderite, matching the presence of the marginal CO_2-rich waters.

The thermal regime coincides closely with the thermal stabilities of the alteration minerals. Note that adularia occurrence coincides with boiling as does some calcite. No evidence of overprinting was recognised in samples from this level.

Relationship between hydrology and hydrothermal alteration

The relationship between hydrology and alteration mineralogy of the Broadlands-Ohaaki geothermal field was deduced and demonstrated earlier in the vertical sense (Browne and Ellis, 1970). Plan views, however, supply a 3-dimensional picture of alteration patterns, reflecting thermal, chemical and hydrologic features within the field. There are three related fluid types at Broadlands-Ohaaki each is characterised by a distinct mineral assemblage.

Chloride waters

Chloride water ascends through the field forming the principal upflow zones as indicated by the location of the hottest isotherms and boiling (Figs. 1A, 2A and 3A).

The two upflow centres coincide with the Occurrence of abundant hydrothermal quartz, calcite, adularia, albite, illite, chlorite and pyrite. Calcite (platy habit) and adularia in these zones, specifically, are key indicators of boiling as they deposit in response to gas separation (CO_2 loss) and attendant increase in pH (Browne and Ellis, 1970). The occurrence of adularia or albite as the dominant hydrothermal feldspar reflects differences in permeability, higher and lower respectively (Browne, 1970). In addition, clay abundance (not shown in plans) tends to increase significantly outward from the centres of the upflow, suggesting that chloride waters, in part, flow laterally and cool by conduction or mixing (Giggenbach, 1984).

Lateral outflow at Broadlands-Ohaaki, however, is minor (tens to hundreds of metres) compared with other geothermal systems such as Mokai (Henley, 1986), El Tatio (Hochstein and Healy, 1973) and the Valles caldera (Goff et al., 1988); these have outflows several kilometres distant from their upflow centres. Lack of lateral flow at Broadlands-Ohaaki, indicated from steep temperature gradients, is reflected by temperature sensitive clays and alteration intensity, especially in the western parts of the field.

C@-rich waters

Weakly acidic CO_2-rich waters exist on the margins of the upflow zone where fluid flow is slow or stagnant. It is possible that these waters will reside for long periods in isolated pockets (low water-rock ratios) resulting in variable alteration intensity. Their cooler temperature and weakly acidic pH is reflected by the occurrence of low temperature clays (illite/montmorillonite, montmorillonite, kaolin). Carbonate minerals reflect the high bicarbonate concentrations in the fluids. Calcite precipitation is also sensitive to heating due to its decreasing solubility with increasing temperature; iron removed from susceptible primary mafic minerals is redistributed locally to form siderite.

Acid-sulfate waters

Surficial acid-sulfate waters have not developed at Broadlands-Ohaaki except in very small isolated patches (few m^2) of steaming ground close to well Br-6 and in two areas about 100 m south of well Br-7. Their associated alteration consists of kaolinite, sulfur, residual silica and rare cinnabar; alunite is also likely present.

Implications

Hydrothermal feldspars, clays and carbonates are key minerals reflecting fluid temperture, pH and permeability (Browne and Ellis, 1970). For example, plan views of the distribution of clay minerals demonstrate the close relationship between clay type and temperature. It should be practical then to use hydrothermal mineralogy to deduce the paleohydrology of an active or extinct geothermal system (e.g. epithermal deposit), especially if used in concert with fluid inclusion and isotopic data. Interpretation may be attempted once the distribution and identity of hydrothermal minerals are known. Of course, alteration overprints are common (e.g. the southeast quadrant of Broadlands-Ohaaki-discussed above; Ohakuri-Henneberger and Browne, 1988), which is a characteristic that results from shifts in the position of upflow or decline of geothermal activity. Such overprints are useful for interpreting the evolution of geothermal system.

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