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THE GEOLOGY, MINERALOGY AND GEOTHERMOMETRY OF THE BROADLANDS GEOTHERMAL FIELD, TAUPO VOLCANIC ZONE, NEW ZEALAND

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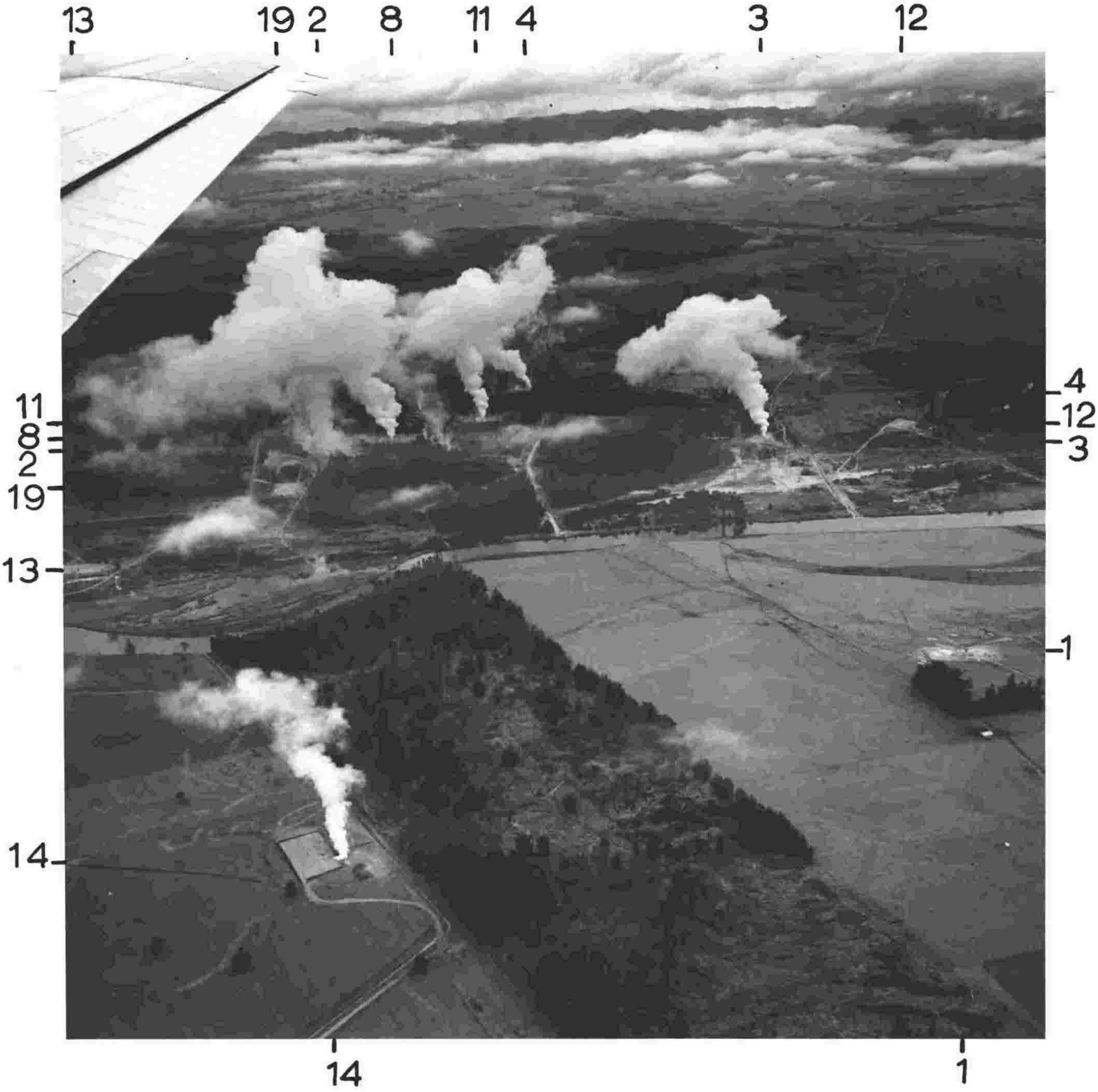

FIG. 1. View of the Ohaki area of the Broadlands geothermal field looking west-northwest across the Waikato River. Numbers locate discharging and shut bores.

Photo : February 1970 : D.L. Homer.

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SUMMARY

This thesis describes the geology and hydrothermal alteration of the Broadlands geothermal field, Taupo Volcanic Zone and attempts to assess the reliability of several suggested geothermometric methods.

Part 1 discusses the geology of Broadlands. Since 1965 the power potential of the Broadlands field has been investigated by the D.S.I.R. and by 25 drillholes (to 2421 m) drilled by Ministry of Works. Outcrops of solid rock in the vicinity of the field are few and natural surface activity is slight compared with that at Wairakei. A series of flat-lying silicic volcanic and lacustrine units overlie an irregular but generally west dipping basement surface of Mesozoic greywacke and argillite (reached between 1040 and 2284 m). Units described include Recent pumice cover, Huka Falls Formation, Ohaki Rhyolite, Upper Waiora Formation, Broadlands Dacite and Rhyolite, Rautawiri Breccia, Rangitaiki Ignimbrite, Lower Waiora Formation and both an Upper and a Lower Waikora Formation; several unnamed units are found in only one or two drillholes.

Temperatures normally increase with depth and reach a maximum of 298°*, but reversals occur in some bores where colder water circulates. Production bores are fed by a steam/ hot water mixture at about 260°, drawn mainly from the Upper Waiora and Rautawiri Breccia Formations but several zones of brecciated rock, possibly produced by faulting, are also permeable. Sub-surface waters are near neutral, dilute solutions

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* all temperatures are degrees Celsius.

having Na^+, Cl^-, HCO_3^-, K^+ and silica as major constituents; dissolved gas is mainly carbon dioxide.

Part 2 describes the hydrothermal alteration of cores and discusses the effect of temperature, permeability and fluid composition. Before alteration most rocks contained (in usual order of increasing susceptibility to alteration) quartz, plagioclase, biotite, hornblende, pyroxene, magnetite and glass. In reaction with hydrothermal fluids these may be replaced, partly or completely, by one or more of the following minerals: quartz, albite, K-feldspar(adularia), calcite, chlorite, illite, montmorillonite, kaolin, siderite, mordenite, wairakite, epidote, sphene, leucoxene, pyrite and pyrrhotite. Most of these minerals plus sphalerite, galena and chalcopyrite also form in veins and vugs where they have been deposited directly from solution. The zeolites, siderite and epidote are more sensitive to temperature than, for example, pyrite, calcite, chlorite or adularia; the type of feldspar formed is mainly a function of rock permeability. However, the high underground CO_2 activity restricts the formation of wairakite and epidote and favours calcite precipitation. Minor sphalerite, galena and chalcopyrite occur in cores and cuttings from six drillholes, and from textural evidence are in equilibrium with one another and with the dilute solutions of very low metal content discharged by the bores; this suggests that hydrothermal ore deposits may not always have been deposited from highly saline brines of high metal content. Local surface deposits related to discharge from drillholes include sinter (in places associated with metal-rich precipitates), aragonite and teschemacherite (NH_4HCO_3).

Part 3 describes several geothermometric methods applied to material from Broadlands drillholes and compares deduced deposition temperatures with those measured directly in drillholes. The method using fluid inclusion filling temperatures gave temperatures closest to those measured. However, the amount of aluminium in hydrothermal quartz could not be related to the measured temperatures. Evidence is presented to show that below 300° sphalerite compositions cannot be used to estimate temperature or pressure and that below 300° the pyrrhotite + sphalerite/pyrite + sphalerite phase boundary in the system Fe - S - Zn shifts to a field where sphalerite of low FeS content is stable.

Part 4 compares the Broadlands geothermal field with others in New Zealand and several overseas.

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INTRODUCTION

Following the commissioning of the Wairakei geothermal power station, several areas in the Rotorua-Taupo Volcanic Zone were investigated for their power-producing potential. One of these was the Broadlands district, where a resistivity survey had located a sizeable area of subsurface water. The first hole, east of the Waikato River (Fig. 2), was drilled in late 1965, but although the temperature at hole bottom is 278°*, rock permeability is low and the bore is a poor steam producer. However, further drillholes (Br 2, 3 and 4) in the Ohaki area tapped good supplies of high temperature water and prompted a full-scale scientific and exploratory drilling programme. This was completed in mid-1971 after 25 holes had been drilled and it was estimated that the field could produce about 150 megawatts of electricity.

Location

The Broadlands hydrothermal field (Figs. 1-6) is 20 km north-east of Wairakei and 3-4 km west of the Kaingaroa escarpment (Browne, 1969, Fig. 1). The field is about 3 km by 2.5 km in area; the part west of the river is called Ohaki, after Ohaki Pool, and that east of the river Broadlands. In general discussion, however, the field is commonly referred to as Ohaki-Broadlands, Broadlands-Ohaki, or simply Broadlands.

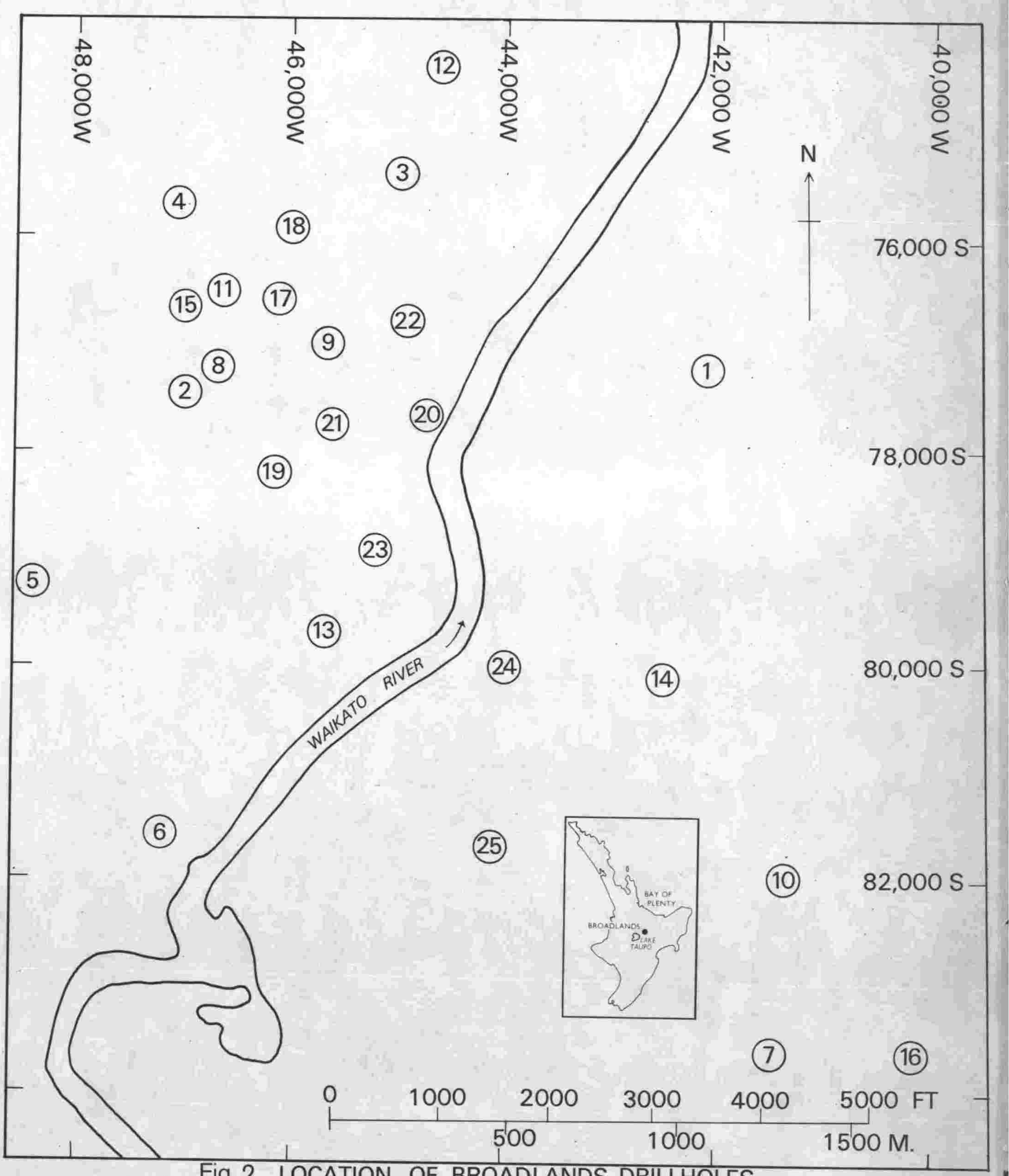

Fig. 2 LOCATION OF BROADLANDS DRILLHOLES

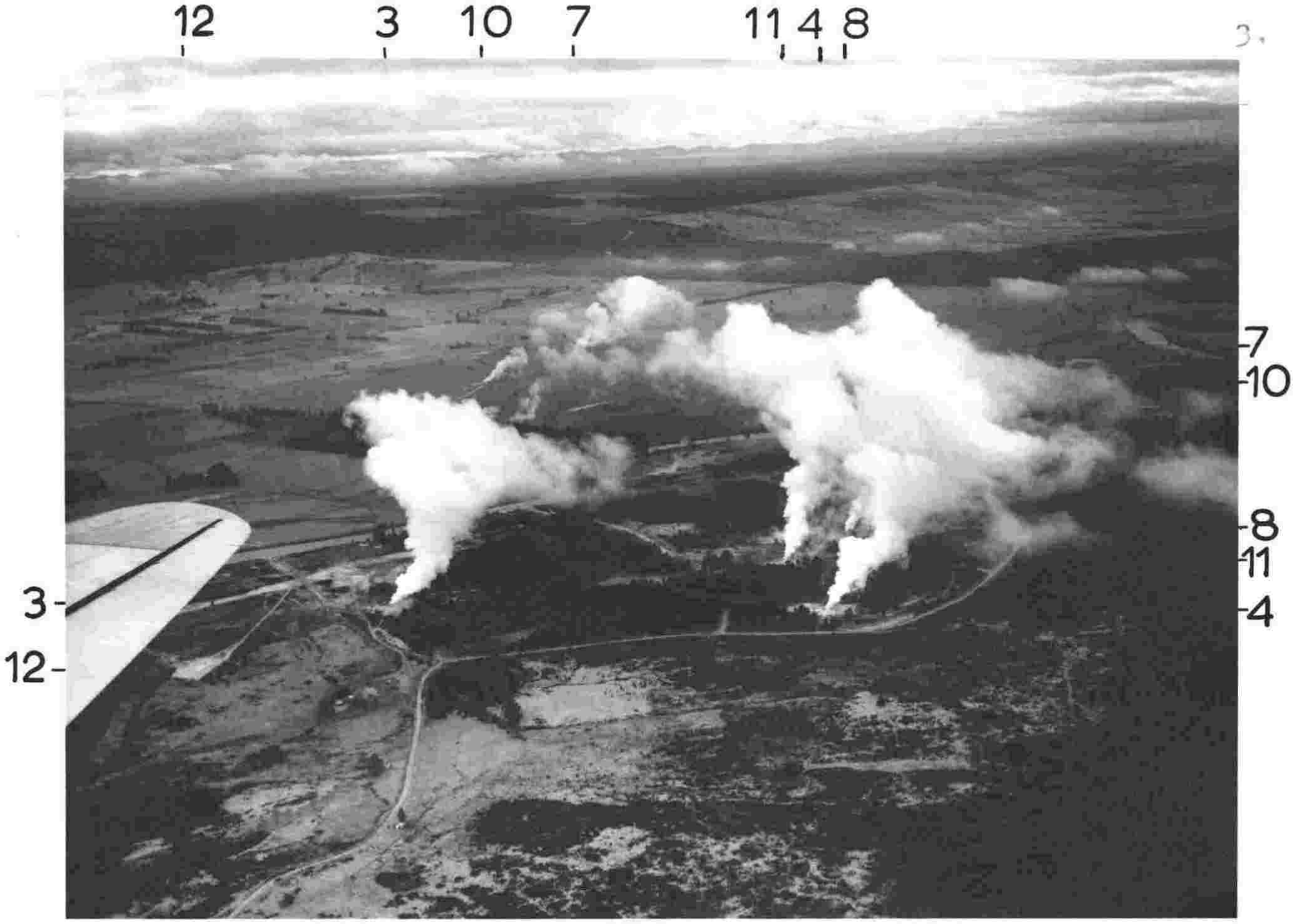

FIG. 4. View of the Ohaki area looking to the southeast across the field towards the Kaingaroa scarp (ignimbrite) and the distant Huiarua ranges (Mesozoic sediments).
Photo: February 1970; D.L. Homer.

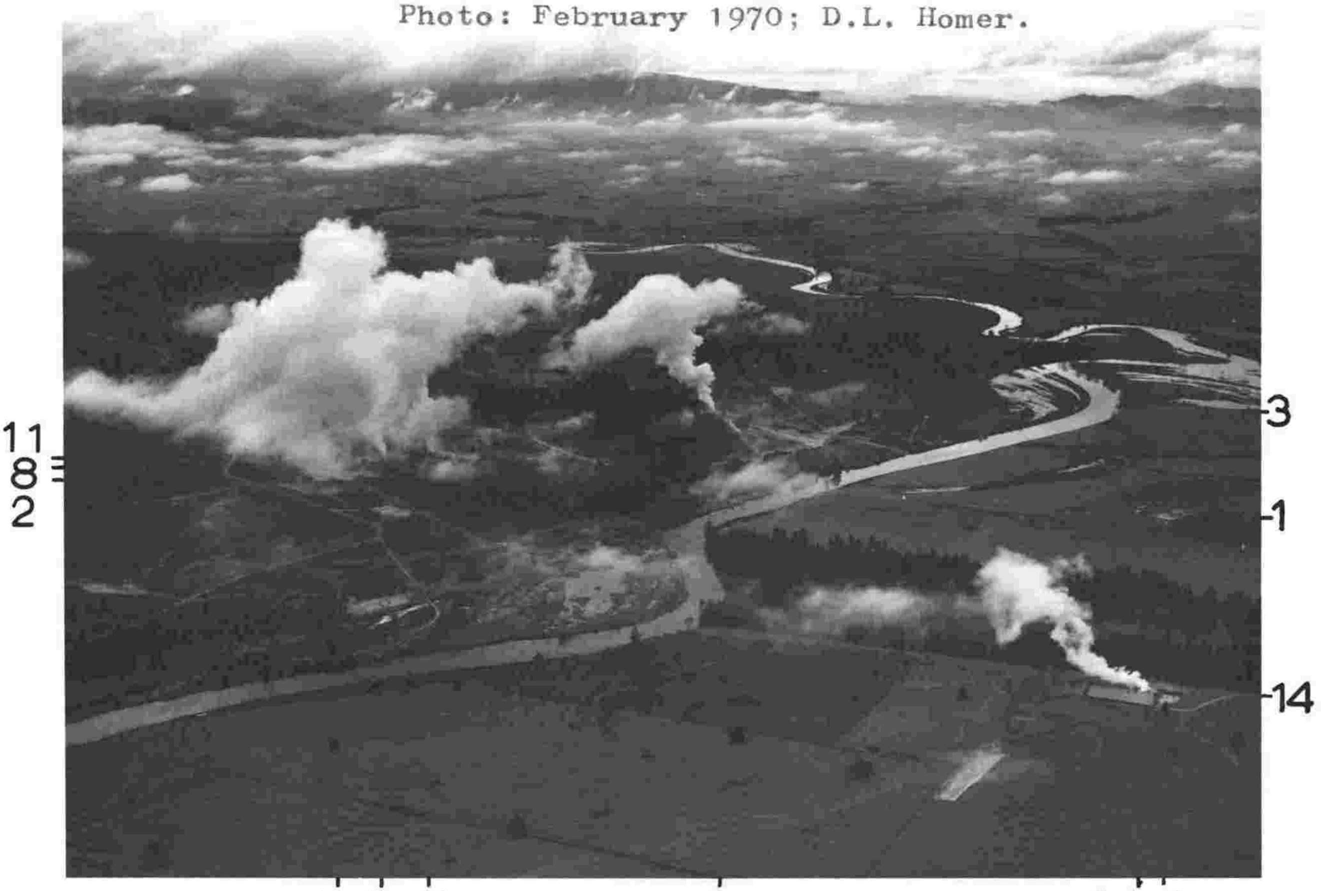

FIG. 5. View of Broadlands looking northwest across the main production area towards the Paeroa Block (mainly ignimbrites). Photo: February, 1970; D.L. Homer.

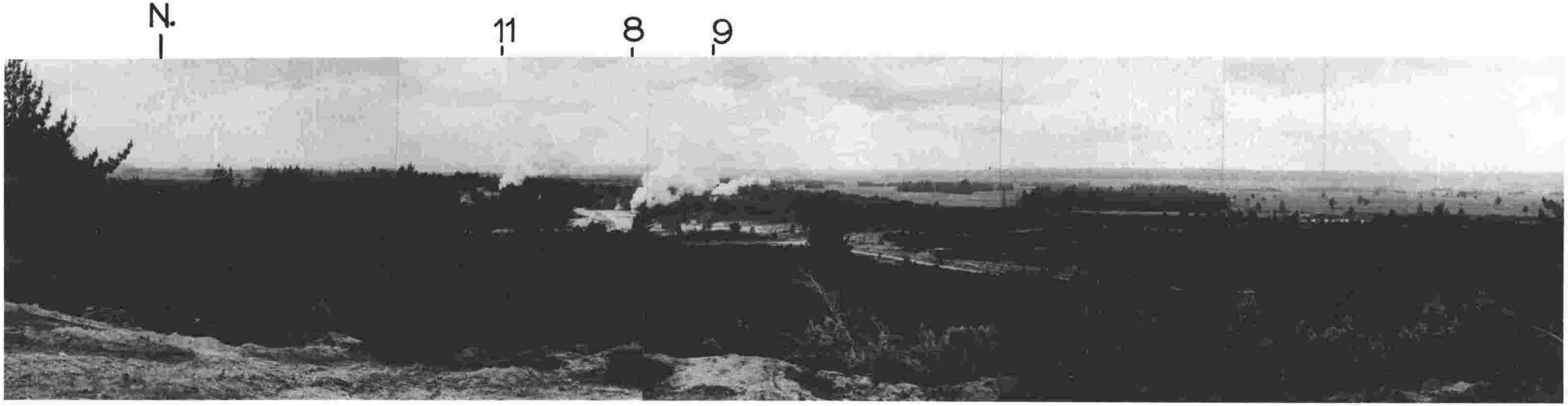

FIG. 6. Composite photograph of western (Ohaki) area of Broadlands, June, 1968. (N = north). Photo : T.R. Ulyatt.

Previous Work

The geology of sheet N94, which includes Broadlands, has been mapped at a scale of 1:63,360 by Grindley (1961) and at 1:250,000 by Grindley (1960). Work in the Broadlands area before 1965 was confined mainly to descriptions of the Ohaki Pool (Grange, 1937; L.R. Allen, unpublished account, 1948) and heat flow estimates by Grange (1955) and Gregg (1958). This has been summarised by Healy (1968a) who also described the geology of the field from drillholes Br 1-6. Grindley and Browne's (1968) report added information from drillholes Br 7-10. Healy's later report (1968b) includes results of drillholes Br 10-13.

Natural Activity

There is little surface activity at Broadlands compared with some hydrothermal areas in New Zealand and the estimated natural heat flow of 17,500 kcal/sec is much less than the 101,000 kcal/sec of Wairakei (Dawson and Dickinson, 1970; Mahon and Finlayson, 1972). The largest spring is the Ohaki Pool which covers 850 m^2 and in 1965 discharged 98° water at a rate of 10 litres/sec (Mahon and Finlayson, 1972). There are several small springs nearby and minor seepages occur along both banks of the river and in the area between Br 8 and 19, but these have a total discharge of less than 1 litre/sec. The small Broadlands thermal area itself, 3 km southeast of the Ohaki Pool and near Br 7 (Fig. 2), consists of patches of steaming ground and a few warm springs with vigorous gas discharge: water discharge from these in 1965 was only 0.3 litre/sec (Mahon and Finlayson, 1972).

Drillholes

The 25 drillholes vary in depth from 765 m (Br 11) to 2421 m (Br 15) but most are between 900 and 1400 m deep (Appendix A). Solid casing was installed to between 400 and 800 m and slotted liner below. Cores were recovered at varying intervals; in early bores the core interval was usually about 15 m but in later drillholes this was commonly extended to 70 m or more. Cutting samples were taken every 3.05 m (10 ft) except where circulation losses necessitated drilling with water. Bore outputs vary from nil to 250 metric tons/hour; most successful bores are west of the river, although Br 25 in the southeast is also a good producer. Many bores are supplied by a steam/water mixture, rather than a single phase, but their enthalpies increase after continuous discharge, suggesting that sub-surface permeability is too low for steady state production. This is because water drawdown reduces hydrostatic pressure to vapour pressure and causes boiling, higher enthalpy discharge and transfer of heat from rock to water. This contrasts with Wairakei where bores are supplied by a single (hot water) phase and sub-surface permeability is considered infinite.

FIG. 7. Bore Br 4 discharging vertically. The mass output of the bore is 51,500 kg/hour at 10 bars pressure.
Photo : T.R. Ulyatt.

FIG. 8. Bore Br 11 discharging vertically through concrete silencers. Mass output is about 250,000 kg/hour at 10 bars pressure.
Photo : T.R. Ulyatt.

PART 1 : GEOLOGY AND CHEMISTRY

PART 1 : GEOLOGY OF BROADLANDS GEOTHERMAL FIELD

Introduction

The stratigraphy is fairly well understood down to the base of the Rautawiri Breccia (approximately 900 m). Above this formations are untilted and in a regular sequence. However, below the Rangitaiki Ignimbrite, the sequence varies considerably between drillholes and this probably results from an unconformity (Fig. 3)*.

Stratigraphy

Table 1 and Fig. 3 summarise the Broadlands stratigraphy. The distribution of major formations is given in Table 2 and the more important, or better known, are described in more detail in the following pages. Brief petrographic descriptions of all cores are given in Appendix A which also includes summary drillhole logs.

Superficial Deposits

The surface layers covering the area consist of loose pumice sands and rhyolite gravels correlated with the Taupo Pumice Alluvium and the older Haparangi Rhyolite Pumice. Although usually unconsolidated, some of the sands are cemented by silica, kaolin and sulphur and at deeper levels siderite, montmorillonite and pyrite occur. Outcrops of pisolitic tuff have been correlated by Healy (1968a) with the Wairakei Breccia or Lapilli Tuff at Wairakei, but Grindley and Browne (1968) suggested an alternative correlation with the Mihi Breccia, which outcrops on the north bank of the Waikato River a few kilometers upstream.

* inside back cover

TABLE 1 : GENERALISED STRATIGRAPHIC SEQUENCE, BROADLANDS GEOTHERMAL FIELD (modified and expanded from Grindley and Browne, 1968)

Formation or Unit	Content	Thickness (m)	No. of holes
Taupo Pum. Haparangi Pum. Wairakei Brec.	Pumice alluvium and ash showers. Pumiceous sands, rhyolitic gravels and sands. Pisolitic pumice rhyolite lapilli tuff and breccia.	3 - 91	25
Huka Falls	Thick beds of lacustrine siltstone and rare sandstone, typically tuffaceous and locally diatomaceous; grit and tuff.	44 - 364	25
Ohaki Rhyolite	Biotite - hornblende - quartz - andesine rhyolite with occasional minor hypersthene and magnetite; commonly pumiceous or spherulitic; locally brecciated.	70 - 451	22
Upper Waiora	Pumice lapilli tuff with low quartz content and numerous rhyolite fragments; locally water-laid.	74 - 367	21
Broadlands Rhyolite	Dense, flow banded, plagioclase rhyolite; locally perlitic, spherulitic or glassy.	356	1
Broadlands Dacite	Dense, plagioclase dacite, andesite and dacite breccia with rare pyroxene or hornblende.	20 - 490	14
Lower siltstone or tuffaceous siltstone unit	Bedded siltstone and fine sandstone with an appreciable tuff content.	9 - 116	17

Formation or Unit	Content	Thickness (m)	No. of holes
Rautawiri Brec.	Heterogeneous; contains crystal, vitric and lithic tuff, lapilli tuff and tuff breccia. Fragments of rhyolite, pumice, tuff, siltstone and occasional greywacke present.	87 - 670	23
Ignimbrite Unit C.	Welded crystal and lithic-vitric tuff, locally lenticular. Characterized by rare, small quartz crystals.	50 - 88	2
Rhyolite A	Dense, plagioclase rhyolite with rare primary quartz crystals; locally flow banded and brecciated.	58 - 209	2
Dacite A	Plagioclase dacite with fine-grained groundmass.	12	1
Tuffaceous siltstone Unit A	Fine-grained tuffaceous siltstone with volcanic rock fragments, quartz and feldspar crystals.	68	1
Ignimbrite E	Slightly welded with low content of quartz and feldspar crystals.	69	1
Andesite C	Plagioclase andesite with crystalline groundmass.	>2	1
Rangitaiki Ignimbrite	Crystal-rich quartz-plagioclase welded vitric tuff. Characterized by large corroded quartz crystals; locally lenticular, minor volcanic fragments.	15 - 412	17

Formation or Unit	Content	Thickness (m)	No. of holes
Ignimbrite D	Welded plagioclase - vitric tuff and tuff-breccia with rare quartz, and occasional volcanic rock fragments.	> 64	1
Upper Waikora	Thin-bedded, non-volcanic sandstone, siltstone, grit; conglomerate beds with argillite, greywacke and minor pumice.	56 - 128	7
Ignimbrite A	Fine-grained crystal-vitric tuff with quartz and plagioclase crystals and fragments of siltstone, pumice and tuff.	103	1
Dacite B	Dense dacite with subparallel plagioclase phenocrysts.	79	1
Lower Waiora	Coarse crystal-vitric tuff with angular crystals of quartz and plagioclase.	49 - 265	6
Lower Waikora	Thin-bedded, non-volcanic sandstone, siltstone, grit; conglomerate beds with argillite and greywacke pebbles.	104 - 110	5
Ignimbrite B	Fine-grained, welded lithic-crystal tuff with small crystals of quartz, plagioclase and pumice and dacite fragments; locally lenticular.	>48	1
Ignimbrite F	Coarse lithic-crystal tuff, locally welded and containing abundant andesine and corroded quartz crystals, rhyolite, argillite and pumice fragments.	168	1

Formation or Unit	Content	Thickness (m)	No. of holes
Tuff Unit B	Crystal tuff with euhedral plagioclase and rare small quartz crystals and fragments of greywacke and andesite. Possible correlative of Ignimbrite Unit F.	17	1
Dacite C	Plagioclase dacite; locally brecciated	55	1
Andesite A	Pale-green, hard, andesine bearing.	25	1
Ignimbrite G	Cream-coloured, fine-grained vitric-crystal tuff, locally welded and veined. Abundant crystals of plagioclase and corroded quartz with fragments of andesite and pumice.	148	1
Greywacke Basement	Dense, indurated, massive greywacke and dense, fractured, veined argillite, poor bedding.	?	4

TABLE 2 : DISTRIBUTION OF SOME OF FORMATIONS AND UNITS IN DRILLHOLES

(Metres relative to sea level)

Hole No.	1	2	3	4	5	6	7	8	9	10	11(2)	12	13	14	15(3)	16	17	18	19(4)	20(5)	21	22(6)	23(7)	24	25(8)
Elevation	+293	+300	+299	+313	+319	+295	+308	+304	+310	+293	+313	+295	+293	+298	+310	+303	+307	+314	+296	+293	+299	+299	+293	+295	+302
Hole depth	-1105	-736	-616	-705	-960	-790	-817	-477	-1063	-998	-452	-1079	-792	-986	-2111	-1101	-777	-904	-784	-914	-824	-719	-805	-956	-956
No. formns not incl.	2	1	0	0	2	0	1	0	0	0	0	2	1	0	6	1	1	0	0	0	0	0	0	0	0
Huka Falls	+263 -18	+255 -202	+278 -210	+282 -108	+285 -180	+265 -67	+278 +166	+294 -184	+260 -194	+220 -61	+283 -205	+265 +91	+220 -240	+285 -49	+296 -207	+281 +141	+280 -153	+302 +250	+247 -228	+253 -219	+296 -210	+296 -279	+252 -225	+262 -202	+211 -167
Ohaki Rhyolite	-8 -155	+184 -163	+234 -164	+220(1) -95	+243 -149	+117 -34	N.P.	+196 -152	+240 -172	N.P.	+241 -185	+91 -103	+34 -174	-49 -138	+195 -177	N.P.	+243 -147	+250 -201	+70 -179	+83 -160	+168 -183	+209 -184	+37 -186	+54 -158	+9 -61
Upper Waiora	-155 -342	-202 -276	-210 -372	-108 -260	-180 -318	N.P.	N.P.	-184 -287	-194 -322	N.P.	-185 >-225	-103 -470	-240 -385	-138 -226	-207 >-247	N.P.	-153 -348	-201 -405	-228 -320	-219 -344	-210 -353	-279 -362	-225 -320	-202 -312	-167 -366
Broadlands Rhyolite	N.P.	N.P.	N.P.	N.P.	N.P.	-67 -423	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.
Broadlands Dacite	-342 -434	N.P.	N.P.	N.P.	N.P.	N.P.	+166 -324	N.P.	-322 -449	-61 -429	? ?	N.P.	-385 -405	-226 -479	N.P.	+141 -326	N.P.	N.P.	-320 -399	-344 -460	-353 -423	-362 -423	-320 -457	-312 -434	-366 >-461 <-518
Lower Siltstone	N.P.	-276 -350	-372 -448	-324 -382	-318 -361	-423 -439	N.P.	-287 -403	-449 -458	N.P.	? ?	-470 -497	-405 -460	-428 -452	? ?	N.P.	-348 -421	-405 -478	-399 -429	-460 -542	-423 -457	-423 -460	-457 -475	N.P.	? ?
Rautawiri Breccia	-434 -682	-350 -672	-448 >-616	-382 -693	-361 -581	-439 -762	-324 -411	-403 >-477	-458 -640	-332 -603	? >-452	-497 -1015	-460 -619	-479 -632	? ?	-326 -1054	-421 -775	-478 -816	-429 >-454 <-632	-542 -647	-457 -673	-460 >-609 <-718	-475 -661	-434 -761	? ?
Rangitaiki Ignimbrite	-682 -786	-684 >-736	N.P.	N.P.	-699 -867	-762 >-790	-620 -635	N.P.	-640 -1052	-603 -673	N.P.	N.P.	-689 >-792	-632 -747	<-771 -1003	N.P.	N.P.	>-816	<-632 >-784	-647(<-711) >-914	-673 >-824	>-609 <-718 >-719	-661 >-805	N.P.	>-461 <-518 >-702 <-762
Lower Waiora	N.P.	N.P.	N.P.	N.P.	-867 >-960	N.P.	N.P.	N.P.	-1052 <-1063	N.P.	N.P.	N.P.	N.P.	-875 -924	-1082 -1347	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	-876 -946	>-763 <-823 >-824 <-882
Upper Waikora	-786 -842	N.P.	N.P.	N.P.	N.P.	N.P.	-635 -732	N.P.	N.P.	-673 -737	N.P.	N.P.	N.P.	-747 -875	-1587 -1697	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	-761 -876	>-702 <-762 >-763 <-823
Lower Waikora	-935 -1045	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	>-924	-1722 -1826	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	-946 >-956	>-824 <-882 >-956
Basement	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	-732	N.P.	N.P.	-737	N.P.	N.P.	N.P.	N.P.	-1974	-1054	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.

(1) Middle Ohaki Rhyolite ,Br 4 from -260 to -324
Lowest " " " " " -693 to <-705

(2) No cuttings below -225.

(3) No cuttings between -247 and -771

(4) No cuttings recovered below -450
(5) " " " " -704
(8) " " " " -414

(6) No cuttings below -609
(7) " " " -722

N.P. Not present

Huka Falls Formation

This formation is named after, and correlated with, lithologically similar rocks at Wairakei (Healy, 1968a). Based on pollen spore evidence (Harris, 1965) the formation at Wairakei has a suggested age of Early Hawera to Late Castlecliffian. However, N. Briggs (pers. comm.) thinks deposition may have continued until as recently as 20,000 years B.P. (Late Hawera). Her evidence is that the overlying Wairakei Breccia is a correlative of the Oruanui Ash dated as 20,000 years B.P. and that there was no time break between deposition of the Wairakei Breccia and Huka Falls Formation (Grindley, 1965).

At Broadlands, the Huka Falls Formation is overlain by surface gravels, sands, and tuffs and the base is either the Upper Waiora Formation, Broadlands Dacite (Br 7, 10, 16) or Broadlands Rhyolite (Br 6); the Ohaki Rhyolite is interbedded in the west.

The formation was deposited in a lake or series of lakes in the Taupo-Reporoa basin which at Broadlands had a slightly irregular floor being shallowest near Br 7 and deepest near Br 13. The formation is thickest in the vicinity of Br 14 - Br 25 (Fig. 3), suggesting that subsidence may have been more rapid in this area, and thins to the west (Br 4 - 5 - 9) where deposition was apparently temporarily interrupted by extrusion of the Ohaki Rhyolite.

The sediments are of variable induration and composition and include tuffaceous sandstones, siltstones, claystones, and water-laid tuffs. Colour varies from cream to grey but deeper cores are dark brown. Typically, the rocks are moderate to poorly-sorted, contain angular crystals of quartz and plagioclase, an appreciable amount of volcanic fragments, and occasional thin diatomaceous and carbonaceous beds. The formation generally has a high porosity (20-50%) and low density (1.4 - 2.2 wet) (Grindley and Browne, 1968) with sandstone beds showing the greatest permeability. Hydrothermal minerals formed by water/rock reaction in this formation are mainly low temperature assemblages which typically include montmorillonite, calcite, siderite, pyrite and rare kaolin.

Ohaki Rhyolite

The Ohaki Rhyolite, named by Healy (1968a), has been intersected by 22 drillholes (Table 1). In most places it is interbedded with the Huka Falls Formation (Fig. 3) indicating it is of probable Castlecliffian or Haweran age.

It is composed of several flows, and one drillhole (Br 4) penetrated two petrographically similar rhyolites at deeper levels (Table 2), but feeders for these or more extensive younger flows have not been intersected. However, small, baked tuffaceous siltstone xenoliths occur in one core from Br 4 at 302 m depth and this and the brecciated rhyolite in the same drillhole may indicate that a feeder (dyke?) is nearby.

Commonly, the thin underlying Huka Falls sediments, although not baked, are sheared and brecciated, probably due to the disrupting effect of the overriding rhyolite.

The upper Ohaki Rhyolite was apparently extruded into a gentle basin possibly filled at the time by a shallow lake, although there is no evidence of subaqueous deposition other than the nature of the enclosing lacustrine beds. The rhyolite is thickest in the Ohaki area itself (Fig. 3) also suggesting that a feeder is nearby, and its upper surface approximates present ground topography; another feeder may be located near Br 5 since the rhyolite is also thick in this area.

The change in slope of the upper surface between Br 9 and Br 20 indicates that early flows were less viscous than the later ones which comprise the buried steep-sided dome. The rhyolite thins east of the Waikato River and most probably did not reach the vicinity of Br 10 and 7. Loose blocks of Ohaki Rhyolite are exposed along the scarp west of the field and were possibly ejected during an eruption. One-and-a-half kilometres north of the Ohaki area, on the west bank of the Waikato River, pumiceous, spherulitic and lithoidal Ohaki-type rhyolite crops out but its stratigraphic relation to Ohaki Rhyolite of the geothermal field is not known.

The Ohaki Rhyolite is typically soft, white or pale grey, vesicular, pumiceous above about 180 m and spherulitic below. Minerals present as phenocrysts in the unaltered rock are quartz (3-10%), plagioclase (about An_{35}, 15-20%), hornblende (0-2%), biotite (0.3-1.2%), magnetite (0.1-0.5%), hypersthene (0.0-0.3%), and cristobalite (0-11%); the last, however, may be of deuteric origin. Quartz forms slightly corroded phenocrysts up to 3 mm in diameter, and the plagioclase occurs as euhedral, strongly zoned (normal and oscillatory), twinned (albite, Carlsbad and pericline) phenocrysts up to 4 mm long. Olive-green hornblende (up to 2 mm long), in places enclosing hypersthene and brown biotite (1 mm diameter) also occurs as euhedral crystals. Both magnetite and cristobalite are present as small irregular grains. Xenoliths are rare.

Rhyolite cores from some drillholes (e.g. Br 2, 4, 8 and 11) are extensively altered, but cores from others (e.g. Br 1, 5, 6, 12, 25) have been little affected by solutions; the extent and type of alteration being dependent mainly on temperature and permeability (Browne and Ellis, 1970). Of the primary minerals, quartz always remains unaltered but the other components alter at different stages. Glass alters readily at low temperatures (Table 5) to mixtures of montmorillonite, illite, interlayered illite-montmorillonite, quartz, calcite, K-feldspar, siderite or mordenite. Magnetite and pyroxene are replaced at similar temperatures (Table 5) by pyrite, leucoxene or more rarely chlorite. Hornblende and biotite alter at progressively higher temperatures to mixtures of pyrite, leucoxene, chlorite and illite. Andesine is more stable but, depending on permeability, alters to mixtures which include illite, quartz, calcite or adularia. Densities range from 1.8 - 2.4 (wet) and porosities from 10-45%, averaging 22% (Grindley and Browne, 1968).

Upper Waiora Formation

This formation is named after lithologically similar rocks forming part of the Huka Group at Wairakei (Grindley, 1965) which has been recently reviewed by N. Briggs (pers. comm.). At Broadlands the Waiora Formation has been subdivided into Upper and Lower Formations; the former has been penetrated by 21 drillholes and the latter by 5 (Table 1).

The Upper Waiora Formation, of probable Castlecliffian age, underlies the Huka Falls Formation (the contact is sharp but apparently conformable), and overlies the Rautawiri Breccia. It varies in thickness (Fig. 3, Table 2) and was apparently deposited on a slightly irregular surface deepening northwards. Typical samples are poorly-sorted, soft, uncompacted and consist predominantly of variable-sized, subround, white and grey, pumice and pumiceous rhyolite fragments. Andesine phenocrysts occur in the unaltered rocks but quartz phenocrysts are rare. Fragments of argillite, greywacke and siltstone, up to 13 cm long are occasionally present. Bedding is vaguely visible in some cores and occasional pumice fragments have their longest axis aligned normal to the core axis. The formation appears to be mainly subaqueous and similar to Waiora Formation at Wairakei (Grindley, 1965). At Broadlands it constitutes the Upper Waiora aquifer (Grindley and Browne, 1968), which feeds bores of the Ohaki area, and is particularly susceptible to hydrothermal alteration. Quartz, adularia, calcite and illite are common hydrothermal minerals where permeability permits, but sulphides, chlorite, zeolites and albite are rare. Porosities are generally high (25-50%) and densities low (1.5 - 2.2, wet (Grindley and Browne, 1968)), as expected from the predominantly pumiceous textures.

Broadlands Rhyolite

This formation, named by Healy (1968), has been found only in drillhole Br 6 (Table 2). Initially thought

(Grindley and Browne, 1968) to be the same formation as that now called the Broadlands Dacite, geophysical evidence (Macdonald and Hatherton, 1968) and recovery of less altered cores from later drillholes, shows that the formation is distinct, although possibly of similar age to the dacite.

The Broadlands Rhyolite underlies the Upper Waiora Formation and overlies the thin Lower Siltstone Unit; it may be of Castlecliffian age. The formation is 356 m thick at Br 6, but thins abruptly north and east and is not found in drillholes Br 5, 13 or 25, all less than 1000 m away.

Typically the rhyolite is a hard, dense, black, grey or white, banded rock, with a perlitic, partly perlitic or partly spherulitic texture. The groundmass varies from glassy to devitrified and occasionally contains abundant microlites and trichites (Appendix A). Plagioclase is the most abundant primary mineral and euhedral phenocrysts up to 2.5 mm in length occur, occasionally in clusters, and in places with their longest axis approximately parallel to the flow banding. They are commonly twinned (albite, Carlsbad and rare pericline) and characteristically have strong normal and oscillatory zoning (composition range is approximately An_{46} - An_{30}). Primary quartz phenocrysts are rare, and ferromagnesian minerals are absent. Small irregular grains of magnetite and cristobalite, the latter possibly of deuteric origin, occur in shallower cores.

Broadlands Dacite

The Broadlands Dacite does not crop out but is known in cores from 14 drillholes (Table 2). It underlies the

Upper Waiora Formation and overlies the Lower Siltstone Unit; it is possibly of Castlecliffian age.

Lavas are thickest in the south-east, near Br 7-16, and thin steeply but regularly to the north-west (Fig. 3), indicating that they were erupted from vents to the south-east. Eruption was apparently not continuous since Br 1 and 10 contain respectively 125 m and 50 m of interbedded pyroclastics (Appendix A). From their textures the lavas, particularly at the edge and upper levels, were not fluid and in places moved as blocks.

Typical least altered cores are hard, dense, dark-grey to black and contain euhedral phenocrysts of zoned and twinned andesine, up to 2.5 mm long and often in clusters. Where the dacite has been brecciated, phenocrysts are broken. Some cores contain chlorite pseudomorphs after rare amphibole or pyroxene; primary quartz and xenoliths are rare. The groundmass is usually fine-grained and contains innumerable laths of plagioclase, in places aligned in subparallel manner.

Unless brecciated, the formation is impermeable and functions as a cap to the underlying Rautawiri Breccia aquifer. Where permeability and temperature are sufficient, cores have usually altered to an assemblage of quartz, illite, calcite, pyrite and chlorite. Albite and adularia are rare, but wairakite is more common than in other formations and this possibly reflects lower local CO_2 pressures resulting from the poorer permeability. Veins are more abundant than in most other formations. Densities range from 2.2 to 2.6 (wet) and porosities from 5 to 44% (Grindley and Browne, 1968).

The Tuffaceous Siltstone Unit

This varies in thickness (Table 2), being thickest in the vicinity of Br 8, with a base deepening to the east. It combines the sedimentary tuff and siltstone units described by Grindley and Browne (1968) and consists of a sequence of generally well-bedded tuffs, of varying size grade, alternating with thin beds of tuffaceous sandstone and minor siltstone. Detrital fragments present include pumice, pumiceous rhyolite and rare welded tuff, in a matrix of quartz, feldspar and hydrothermal minerals. The unit was probably deposited in a lake and was derived from older sediments and reworked pyroclastic rocks. Dips, where visible, are mostly flat but occasional cores show dips of up to 10° and probably result from either tilting or local upturning from lava intrusion (Healy, 1968a).

Porosities range from 18% - 36%, densities from 1.7 to 2.3 (wet) (Grindley and Browne, 1968), but the rocks are mainly impermeable and this is reflected in their moderate hydrothermal alteration. Illite is often abundant but hydrothermal feldspars are rare, due to the low content of primary plagioclase. In some cores, e.g. Br 12, pyrrhotite forms crystals, up to 2 mm in diameter, showing that the f_{s_2} was comparatively low (Browne and Ellis, 1970).

Rautawiri Breccia

This formation, named by Grindley and Browne (1968), crops out on the Kaingaroa escarpment, about 3 km south-east of Broadlands (N94/804528) and occurs in cores from all drillholes. It overlies the Rangitaiki Ignimbrite and underlies the Lower Siltstone Unit and Broadlands Dacite

Formation. Its age is unknown, but if the underlying Rangitaiki Ignimbrite is 0.32 million years old (B.P. Kohn, pers. comm.), then the Rautawiri Breccia must be younger.

In the Broadlands area, the formation has a very irregular base (Table 2) reaching its greatest depth near Br 16, east of the buried fault scarp (Fig. 3). The breccia is also thick in this area and north-west of Br 9.

The formation has marked variations of texture and composition, is usually poorly sorted and always contains small (less than 1.5 mm), angular, uncorroded quartz (5-15%), and larger, anhedral to subhedral, plagioclase crystals (10-30%). Rock fragments are invariably present and vary in shape (angular to round), size (0.2 mm to as much as 60 cm), abundance (2-25%) and type. Spherulitic rhyolite and pumice are the most common but other types are more abundant locally; these include argillite, greywacke, bedded sandstone and siltstone, mudstone, vitric tuff (welded and unwelded), non-spherulitic rhyolite, pumiceous rhyolite, devitrified obsidian and dacite. The groundmass, altered in many places particularly at deep levels, has a well-developed vitroclastic texture. The formation is probably predominantly of ash flow origin, since it fills buried topographic features, but airfall and water-laid beds are also present (Grindley and Browne, 1968).

The Rautawiri Breccia is an important aquifer in the geothermal system and several major bores draw from it. Consequently, it is particularly susceptible to alteration and, depending mainly on permeability, hydrothermal minerals present include albite, adularia, calcite, illite, quartz, chlorite and pyrite. Densities and porosities are affected by the amount of alteration but the former range from 2.0 - 2.4 (wet) and porosities occasionally exceed 40% (Grindley and Browne, 1968).

Rhyolite A

This formation, which occurs in drillhole Br 7 (Table 1), and possibly Br 16, underlies the Rautawiri Breccia and rests on a thin covering of Rangitaiki Ignimbrite, indicating that it may be younger than 0.32 m.y. Probably the rhyolite in Br 16 /1234-1297 m is a down-faulted correlative (Fig. 3), but this unit is known from only one core and the correlation has not been firmly established.

Typically, Rhyolite A is a hard, dense, grey-green rock with flow-banding and in places, a partly spherulitic texture. It contains small, euhedral, replaced primary plagioclase phenocrysts and smaller, rare quartz crystals; andesite xenoliths are occasionally present. Several cores are brecciated and contain veins of quartz, calcite and adularia. Most steam discharged from Br 7 comes from this formation as fault breccia zones in it evidently provide channels for geothermal fluid. Consequently cores are highly altered and characterised by abundant hydrothermal quartz; other minerals present are adularia, pyrite, pyrrhotite, base metal sulphides, calcite, well-crystallised illite (sericite) and chlorite.

Rangitaiki Ignimbrite

The Rangitaiki Ignimbrite has recently been reviewed by Briggs (pers. comm.), who considers it closely related in age to, and a possible correlative of the Whakamaru Ignimbrite which has been tentatively dated at 320,000 years (B.P. Kohn, pers. comm.). The Rangitaiki Ignimbrite forms extensive sheets along the eastern side of the Taupo-Rotorua Volcanic Zone and is thought to have had a source a few kilometres south of Mt Tauhara (Martin, 1961). An ignimbrite found in cores from Broadlands has been correlated with the Rangitaiki Ignimbrite (Grindley and Browne, 1968) because of petrographic similarities, but this is not certain and possibly the ignimbrite at Broadlands is an older flow not now exposed. Petrographically it is similar to and may be correlative with the Wairakei Ignimbrite of the Wairakei geothermal field (unpublished information). If this correlation is correct then an extensive, but discontinuous ignimbrite sheet probably underlies the area between Wairakei and Broadlands.

At Broadlands, the 17 drillholes which reach the formation show that its thickness varies considerably and the base probably marks an unconformity (Table 2, Fig. 3). It is thickest (412 m) near Br 9, but does not occur in Br 24 only 1200 m to the south-east.

The ignimbrite is composed of at least two cooling units. The upper one is characterised by abundant crystals, predominantly strongly corroded phenocrysts of quartz up to 5 mm in diameter (5-15%) and anhedral to euhedral, zoned and twinned (where fresh) andesine up to 4 mm in diameter (30-50%). Ferromagnesian mineral pseudomorphs are relatively abundant in cores from Br 5 and fragments of rhyolite, tuff, argillite and silicified pumice, are occasionally present. Cooling cracks occur locally and the rock typically has a good vitroclastic groundmass texture, although the degree of welding varies. In some samples it is extreme, and the glass shards so stretched, that their texture is little different from that of flow banded rhyolites.

Below R.L. 1280 m in Br 9, the other cooling unit is only moderately welded but exceeding rich in crystals. It is composed of plagioclase (65%) and quartz (15%) phenocrysts and occasional silicified pumice, argillite, vitric tuff, rhyolite and spherulitic rhyolite fragments.

Because of the high degree of welding, the formation is impermeable to geothermal fluids except where fractured. This is shown by the nature of the alteration of cores from Br 9; in the upper unwelded part of the flow feldspars and groundmass are highly altered, but as the degree of welding increases with depth, the extent and rank of alteration decrease so that densely welded core from 1214 m is little altered (Fig. 20). Where permeability permits, andesine alters to albite and/or adularia. Calcite, quartz, chlorite and illite are present in many places and pale green epidote forms occasional clusters and thin veins; sulphides are not usually abundant.

Densities in the upper unwelded part of the formation range between 2.0 and 2.3 (wet) and porosities vary between 10 and 32%, but in the welded zones, the density reaches 2.6 (wet) and porosity may be only 3% (Grindley and Browne, 1968). These figures are in accord with the low level of alteration.

Waikora Formation

Non-volcanic sedimentary rocks, mainly conglomerates, are found at two levels in Br 15 and with the exception of Br 16, in drillholes east of the river. Cores from both levels are lithologically similar and contrast with the tuffaceous sediments and pyroclastic rocks of the rest of the field. The rocks form a single formation but are subdivided into lower and upper units which are separated by vitric tuffs or andesite.

The sediments have been mainly derived from the basement greywacke and argillite and consist of well-bedded sandstone, siltstone, grit and conglomerate. Pebbles of argillite and greywacke in the conglomerate are usually subangular to round and were probably deposited by streams draining nearby greywacke hills; the finer-grained sediments are typical flood plain debris that would have been deposited away from major stream channels. The formation's distribution, occasional current and slump bedding dipping up to 30°, indicates a west sloping depositional surface - possibly an alluvial fan. However, the Waikora Formation is absent from Br 16 showing that it has a local distribution only, and may not extend east to the Kaingaroa scarp as originally suggested (Grindley and Browne, 1968). Both units are relatively impermeable; densities vary from 2.33 to 2.66 (wet) and porosities range from 3 to 18% (Grindley and Browne, 1968). The greywacke and argillite pebbles are little altered since their constituent minerals are in equilibrium with the underground solutions; but the fine-grained matrix may contain hydrothermal chlorite, calcite, illite, pyrite, rare wairakite, adularia and occasional base metal sulphides.

Lower Waiora Formation

This formation has an upper surface which deepens northward. Insufficient is known to determine its thickness and the attitude of the base, but data from two drillholes (Table 2) indicate that these are variable. It underlies the Rangitaiki Ignimbrite in Br 9, but elsewhere separates the upper and lower units of the Waikora Formation.

Cores (Appendix A) show it to be a heterogeneous formation consisting of pumiceous tuffs, quartz-feldspar tuffs (in places water-laid) with various types of lithic fragments; these include rhyolite, spherulitic rhyolite, pumice, andesite, basalt and greywacke. One sample (Br 24/1194 m) shows graded bedding. Little is known of the hydrological character of this formation but, except in Br 25, it does not appear to be more than moderately permeable. Hydrothermal minerals present in places, however, include quartz, illite, calcite, albite, adularia, chlorite and pyrite.

Basement

Basement greywacke and argillite have been reached by drillholes Br 7, 10, 15 and 16 (Table 2). Because the overlying rocks are sandstones, siltstones and conglomerates derived from the basement rocks, it is not possible to locate accurately the top of the basement without close coring. However, the surface has considerable relief (Fig. 3) since it is 322 m deeper under Br 16 than Br 7 only 400 m away. It deepens westward and is thought to be about 4000 m below the surface of the Wairakei geothermal field (Grindley, 1965). Several cores are fragmentary and consist of fractured and veined argillite with thin sandstone bands. Most consist of massive quartzofeldspathic sandstone with poorly defined bedding, but fractured and veined with thin quartz and calcite veins. The general mineralogy and textures are similar to the Mesozoic greywackes of the ranges south-east of the Kaingaroa Plateau (Ewart and Stipp, 1968); quartz is dominant, with less abundant sodic plagioclase, K-feldspar, secondary muscovite, chlorite, pyrite and rare epidote. This assemblage is stable under observed Broadlands hydrothermal conditions, so rocks are little changed by water/ rock reaction. However, base metal sulphides are present in greywacke and argillite cores from Br 15 and Br 16 (Appendix A).

Densities of core samples range from 2.6 to 2.7 (wet) and porosities vary from 4-8% (Grindley and Browne, 1968), but the extensive fracturing and jointing typical of the same rocks at the surface indicates they may be fairly permeable.

Structure

The Broadlands geothermal field lies in the Taupo-Reporoa basin which itself forms part of a regional graben or downwarp zone extending from Tongariro to White Island. The region is volcanically active with strong evidence for a close relationship between volcanism and tectonism. Normal faults are common. Although there is no field evidence of lateral displacement, some fractured cores from Wairakei and Broadlands have slickensides at angles which indicate that movement with a horizontal component has occurred.

The subsurface structure of Broadlands is dominated by 2 buried rhyolites and a dacite which have an important control on the hydrology of the field. Mesozoic greywacke and argillite of the Torlesse Supergroup forms a 'basement' to the field and the region; its surface deepens steeply east and west of Br 7 indicating considerable subsurface relief.

At Wairakei, geothermal fluid is carried in channels which are subsurface extensions of active faults visible at the surface (Grindley, 1965); faults are also common at the Te Kopia, Waiotapu, Kawerau and Tauhara geothermal fields. Grindley and Browne (1968) identified several recent fault traces at Broadlands from alignment of hot springs and lineations on air photographs. Most strike north-east but several strike in a more easterly direction; however, unlike Wairakei, none can be correlated directly with fracture zones in drillholes.

The vertical displacement of the faults cannot be great since the bases of shallow formations, e.g. the

Ohaki Rhyolite, are nearly level (Fig. 3). This means only a slight (vertical) movement on a fault is necessary to open channels for geothermal fluid, but to stop their filling and blocking with hydrothermal minerals, renewed movement must occur at intervals. Evidence for this is the observation that most of the world's geothermal fields are in areas of active faulting and analogy with fossil hydrothermal fields such as Tui Mine, Coromandel, where Wodzicki and Weissberg (1970) showed a close relationship between hydrothermal mineral deposition and repeated fracture movements.

Healy (1968a) has suggested that rhyolite feeder dikes and not faults are fluid channels at Broadlands, but if so, these would soon become blocked with hydrothermal minerals.

The Broadlands area is still subject to earth movements as indicated by subsidence rates calculated from C^{14} dates.

The note following has been submitted to the Director, N.Z. Geological Survey for publication in the N.Z. Jl. of Geology and Geophysics.

SUBSIDENCE RATE OF BROADLANDS FROM C^{14} DATES.

Drillhole PH 1A, a few metres west of the Waikato River in the Broadlands geothermal field (N94/37594569), penetrated woody material between a depth of 14.6 and 15.2 m. This material (sample N94/f575), consisting of a mixture of stems, twigs and splinters, has a radiocarbon age (N.Z. 1248) of 4260±60 years B.P.

The wood is interbedded with fluviatile silicic volcanic sands, ashes and grits (Appendix B) deposited by the Waikato River. Core from between 3.7 m and 4.4 m contains pumice lapilli and occasional small charcoal fragments and is correlated with the Taupo eruption of 1820±150 years B.P. (Grant-Taylor and Rafter, 1963). Banded pumice lapilli and rare plant debris from between 11.9 m and 13.1 m are similar to that associated with the Waimihia lapilli member thought to have erupted 3440±70 years B.P. (Grant-Taylor and Rafter, 1963). Magnetite grains separated from this pumice kindly analysed by Mr B.P. Kohn, have a composition very similar to magnetite from known Waimihia pumice lapilli and supports this correlation.

The 4260± year B.P. date on the wood from the drillhole represents an average accumulation rate of 3.5 ± 0.1 mm per year, and, since all core material is of fluviatile origin, this also approximates the average subsidence rate. If the correlation of the banded pumice with the Waimihia lapilli is correct, then the subsidence and accumulation rate has averaged 3.6 ± 0.2 mm per year over the last 3440 years. However, the accumulation and subsidence rate since the time of the last Taupo eruption has been only 2.2 ± 0.2 mm per year which suggests that the Broadlands area is subsiding at a declining rate.

The extent of the area affected is not known but the subsidence may be local only and a response to water drawdown and discharge from the geothermal field itself.

REFERENCE

Grant-Taylor, T.L.; T.A. Rafter, 1963: New Zealand natural radio carbon measurements 1-V. Radiocarbon 5: 118-162.

Chemistry

The chemistry of the Broadlands field has been described in a series of unpublished Chemistry Division reports; results up to and including Br 19 have been summarised by Mahon and Finlayson (1972). The relationship between fluid composition and hydrothermal alteration is described by Browne and Ellis (1970). Giggenbach (1971) determined the deuterium contents of waters discharged from Broadlands and concluded that they were probably derived from rain which fell on the Kaingaroa Plateau, east of the area.

Natural Activity

The composition of four springs is given in Table 1 of Browne and Ellis (1970). A further three are reported by Mahon and Finlayson (1972); they are of the Cl^-, HCO_3^- type and most have a near neutral pH. Mahon and Finlayson (1972) concluded that "the similar constituent ratios, such as Cl/B, Cl/F, and $Na/_{Li}$, in springs suggested a common reservoir of hot water beneath the area with varying degrees of dilution and evaporative concentration by boiling."

Drillhole Discharges

The deep waters tapped by the drillholes are essentially dilute Cl^-, HCO_3^- solutions (Table 1, Browne and Ellis, 1970) of similar composition to the spring waters. NaCl (approx. 1100 ppm), KCl (180 ppm), and silica are the major constituents in deep waters but trace metals are low. According to Mahon and Finlayson (1972) the Cl^- concentrations from the bores fall into 2 groups: (a) bores in the north-west and Br 1 with between 1150 and 1250 ppm Cl^- and (b) southeastern bores supplied by water with a Cl^- below 1100 ppm. This is also reflected in the $Cl/_B$ ratios which are highest in the north-west. They may be lower in the south-east because the basement greywackes are here closer to the surface, and these have a higher B content than the overlying volcanics. For example, greywacke and argillite in the Wellington district contain between 0.01 and 0.08% B (Reed, 1958). The Broadlands waters are saturated with SiO_2 but have low SO_4^{-2} contents due to the very low underground oxygen fugacity ($< 10^{-38.6}$ atmospheres, Browne, 1971). The deep Broadlands waters have CO_2 concentrations (0.14 molal) about 10 times those of Wairakei. The reason for the higher concentrations at Broadlands is uncertain but CO_2 may be added to the waters by reaction with the basement rocks which contain vein calcite and are closer to the surface (Fig. 3). Ammonia is also several times more abundant at Broadlands (Mahon and Finlayson, 1972) and may come from organic matter in the Huka Falls Formation sediments.

PART 2 : HYDROTHERMAL ALTERATION MINERALOGY

PART 2 : MINERALOGY OF HYDROTHERMAL ALTERATION

SURFACE DEPOSITS

Natural

An area of about 10,000 m^2 surrounding the Ohaki Pool and smaller nearby springs is covered by white, banded silicic sinter deposited from pool water overflow. A metal-rich precipitate deposited from the Ohaki Pool has been described by Weissberg (1969) and is referred to elsewhere (Browne, 1971). Traces of arsenic sulphide also occur on sinter surrounding pools near drillholes Br 7 and 16, and nearby steaming ground contains kaolinite and crystalline yellow sulphur. On the west bank, near Br 6, kaolinite and rare alunite occur in scattered superficial deposits. These minerals are stable in waters of low pH at low temperature, and probably form by steam heated groundwater reacting with surface ashes and soils.

Associated with drillholes

Silica

White silicic sinter precipitated from cooling waters of discharging bores, lines weir boxes, silencers and partly fills discharge channels. In places it has a delicate structure and fretted appearance. Five samples from Br 7 analyzed by neutron activation by G.R. Ewers, University of Melbourne (pers. comm.), contain from 68.7 to 508.6 p.p.b. gold and 1.06 to 16.05 ppm silver.

The silencers and weir boxes of several bores also

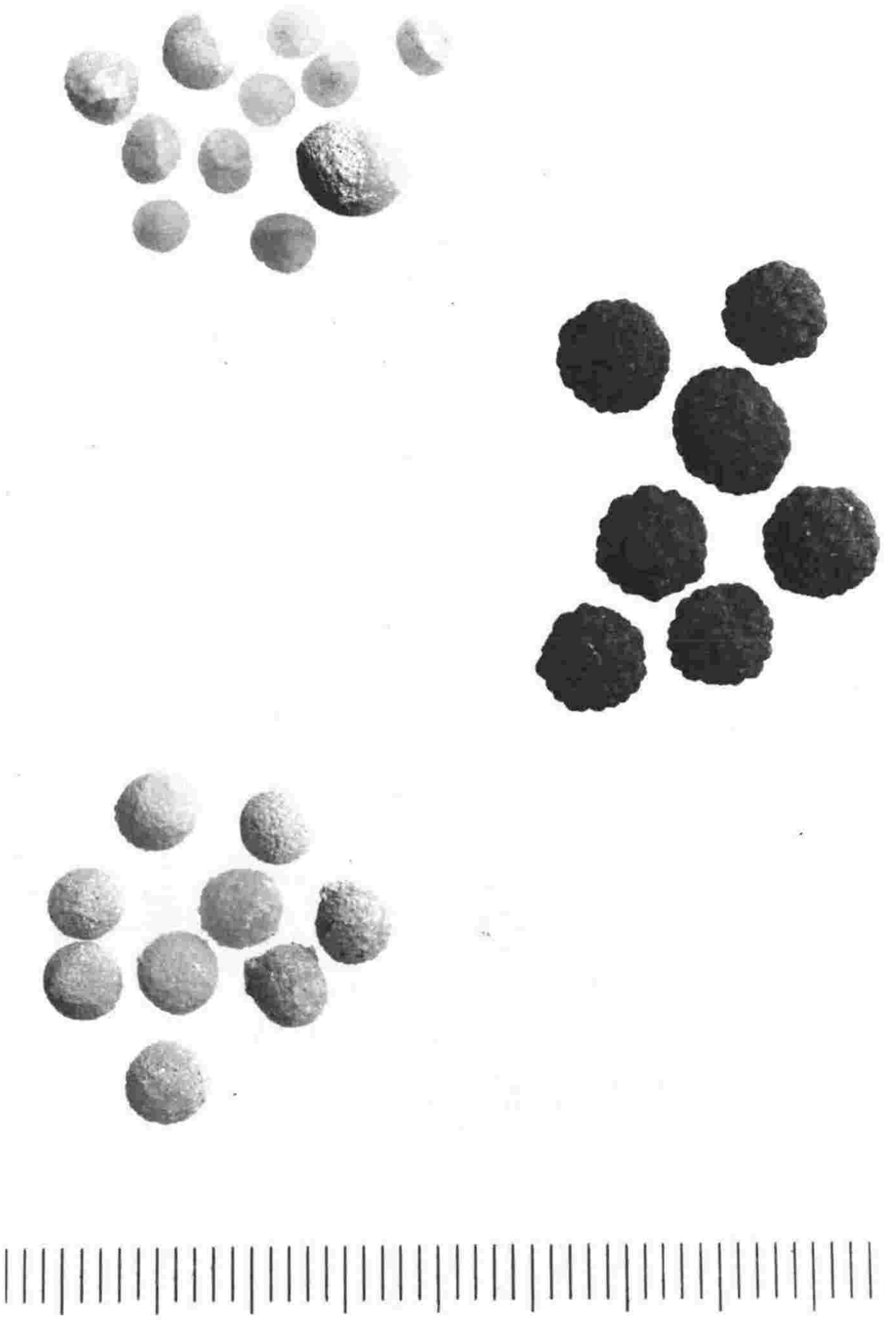

FIG. 9. Silica spherules collected from silencers and weir boxes of drillholes Br 3 (top), Ka8(middle) and Br 22: scale in millimetres.

Photo : L.R. Laronde.

contain hard, rough spherules, which are mainly composed of white to grey silica sinter (Fig. 9). These contain small quantities of mechanically admixed pyrite, clay, feldspar and calcite although none of these minerals appear to have acted as precipitation nuclei. In thin section some spherules show colour zoning interpreted as growth rings, and several contain numerous patches with abundant dendritic crystals up to 30 microns in diameter, which are visible on an electron microprobe. A few analyzed by C.P. Wood, N.Z. Geological Survey, have the approximate composition; (wt%) $SiO_2 = 77$, $Al_2O_3 = 1.7$, $Na_2O = 15$ to 20 and $K_2O = 1$ to 1.5, indicating a formula of $Na_2Si_4O_9$ - sodium tetrasilicate, which is a very siliceous form of anhydrous sodium silicate.

The spherules evidently result from silica precipitating from hot water under turbulent conditions where they are able to grow by constant rotation in a manner similar to aragonite or calcite cave pearls. The dendritic crystals may be the result of rapid crystallisation from alkalis at much the same time as the surrounding silica.

Metal precipitates

These have formed at the surface from discharge of Br 2 and 14 are referred to elsewhere (Browne, 1971).

Aragonite

Aragonite deposited from Br 6 is described in the following note submitted for publication to the N.Z. Journal of Geology and Geophysics.

ARAGONITE DEPOSITED FROM BROADLANDS GEOTHERMAL DRILLHOLE WATER.

ABSTRACT

Nearly pure aragonite has deposited from waters discharged from Broadlands geothermal drillhole, Br 6. Waters from the drillhole, in contrast with others from the geothermal field, are highly supersaturated with $CaCO_3$ and contain relatively high concentrations of Mg^{2+}, Ca^{2+}, Sr^{2+} and HCO_3^-. The formation of aragonite instead of calcite results from the rapid precipitation rate and possibly the relatively high Sr^{2+} and/or Mg^{2+} in the discharged waters.

INTRODUCTION

Waters discharged from most geothermal drillholes and hot springs at the Broadlands geothermal field deposit only silicic sinter. However, water from bore Br 6 (N94; 456197N, 376395E, Nat. Grid) at the southern part of the field, precipitated an estimated 3 tonnes of nearly pure aragonite during the 204 days the bore was open.

OCCURRENCE AND COMPOSITION

Most of the aragonite deposited is pale orange-yellow but some distance from the bore at the edge of the Waikato River, early deposited material is grey-brown. Aragonite fills the drillhole's 150-metre long discharge channel, to a maximum depth of about 0.3 m and widths varying between 0.3 m and 3 m. Typically the aragonite has a radiating fibrous form, a slightly bulbous outer surface and in places numerous 'growth' layers. Analysis of aragonite close to the bore by J. Ritchie, Chemistry Division, D.S.I.R., gave (weight %) CaO = 52.1; SrO = 0.7; BaO = 0.2; MgO = 0.2; SiO_2 = 1.2; R_2O_3 = 1.2; MnO = 0.09; CO_2 = 40.1; insolubles 0.1. This sample also contains 2.5 weight % water. The analysis shows that the aragonite is not pure but contains a small amount of silica, and possibly clay, the former presumably precipitated from the cooling water. Where the water flowed down overhanging blackberry bushes at the river bank, it has formed rods up to 0.24 m in diameter (Fig. 10). These show a sharp colour break from an inner grey-brown zone to an outer pale orange-yellow zone. Partial chemical analyses of these two zones are given in Table 3.

TABLE 3.

PARTIAL CHEMICAL ANALYSES OF INNER AND OUTER ZONES OF ARAGONITE SHOWN IN FIGURE 10.

	CO_2 (Wt%)	Organic Matter (Wt%)	Sr (ppm)	Rb (ppm)	Mn (ppm)	Zn (ppm)	Cu (ppm)	Ni (ppm)	Ba (ppm)
Inner	41.0	3.13	2025±60	<2	314±10	<3	18±3	12±3	2071±38
Outer	40.9	0.47	1940±60	<2	310±10	<3	18±3	12±3	1740±38

Trace elements determined by D. Clyma

The organic matter, mainly leaf particles, clearly causes the dark colour of the inner zone, but with the exception of barium, the other analysed constituents are little different and reflect the unchanging composition of the discharged waters (W.A.J. Mahon, pers. comm.).

DRILLHOLE DATA

Br 6, completed in September 1967, reached a depth of

FIG. 10. Aragonite deposited on blackberry stem by water discharged from Br 6. Deposition layers are visible on the cut surface.

Photo : D.L. Homer.

1085 m, penetrating lacustrine sediments, two petrographically distinct rhyolites, tuff-breccias and an ignimbrite (Grindley and Browne, 1968; Browne and Ellis, 1970). Drill cores are comparatively little altered but hydrothermal calcite, siderite, chlorite, pyrite, illite, montmorillonite, interlayered illite-montmorillonite, kaolin, mordenite, albite and quartz are irregularly distributed (Fig.19.) The drillhole temperature profile is unique in New Zealand geothermal wells and shows minima at depths of 244 m and 610 m and a maximum temperature of 160° at only 122 m depth (Browne and Ellis, 1970). The temperature reversals and the hydrothermal alteration pattern indicate that hot water is circulating laterally between the rhyolite flows. The drillhole is cased to a depth of 653 m and water feeding the drillhole seems to enter at about 671 m where there are indications of a permeable zone (Wainwright, 1970).

When first opened, the drillhole behaved as a geyser for a few hours before settling down to a steady discharge rate of 50,000 kg/hr water at 52° and 4.4 bars pressure (Dench, 1968).

FLUID COMPOSITION

Fluid discharged from Br 6 is chemically quite different from typical Broadlands drillholes (Table 4); the main differences are the enormously greater HCO_3^- and Ca^{2+} contents, the lower Na^+, K^+, Cl^- and HBO_2^-, and the near neutral pH compared with the slightly alkaline waters of other drillholes (Browne and Ellis, 1970). Because of the low temperature and absence of steam it was not possible to collect gas, but a gas detector unit

TABLE 4.

COMPOSITION OF BR 6 DRILLHOLE DISCHARGE WATER COMPARED WITH A TYPICAL DRILLHOLE AT BROADLANDS.

(in ppm)

	Br 6	Br 2
pH (20°)	7.4	8.3
Li^+	1.2	11.7
Na^+	435	1050
K^+	39	224
Ca^{2+}	160	2.2
Mg^{2+}	94	0.08
Sr^{2+}	0.42	~ 0.01
Cl^-	28	1743
I^-	0.95	0.8
$SO_4{}^{2-}$	15	8
$HBO_2{}^-$	5	196
SiO_2	180	805
$NH_3{}^-$	1.1	2.1
$HCO_3{}^-$	2284	178
$(CO_2$	137)	
Molecular ratio $Cl/_B$	~ 7	11.0
" " $Cl/_{SO_4}$	5.1	590
" " $Na/_{Li}$	110	27
" " $Na/_K$	19.0	8.0
" " $Mg/_{Ca}$	0.97	0.06

From: Mahon and Ellis (1968); Browne and Ellis (1970)
Sr by J. Ritchie, Chemistry Division, D.S.I.R.
Ca and Mg by W.A.J. Mahon, Chemistry Division.

indicated that 9% by volume of the vapour discharged was CO_2 (Mahon and Ellis, 1968).

The low Cl^- content of the Br 6 water indicates a source different from water of other Broadlands drillholes and it is most probably steam-heated ground water (Mahon and Ellis, 1968).

DISCUSSION

Precipitation of calcium carbonate in the discharge channel of Br 6 results from sudden release of pressure and loss of CO_2 as the near-neutral calcium bicarbonate water reaches the surface. This may be represented by the equation $Ca^{++} + 2HCO_3^- \longrightarrow CaCO_3\downarrow + CO_2\nearrow + H_2O$ -------(1)

A constant discharge rate of 50,000 kg/hr would have supplied 244,000 metric tonnes of water for the 204 days the bore was opened, or approximately 35.8 tonnes of Ca. Since only an estimated 3 tonnes of aragonite formed during this time this means that only about 3.5% of the discharged Ca precipitated as $CaCO_3$ before the water flowed into the Waikato River.

The numerous growth rings, cannot be due to changes of fluid composition with time as this did not fluctuate during the discharge period, nor would rain showers be heavy enough to dilute or cool the discharged waters and alter the $CaCO_3$ precipitation rate. Most probably the rings result from changes in carbonate precipitation rate caused by variations in air temperature which in turn affects the amount of CO_2 in solution and $CaCO_3$ precipitating (equation (1)). Though the temperature variations recorded in the aragonite growth rings may not be strictly diurnal, the number of rings counted in one sample, between 200 and 225, is not greatly different from the number of days (204) the bore was discharging.

Aragonite has been reported from three other active geothermal areas - Kizildere, Turkey; Cheleken, U.S.S.R. (Lebedev, 1968), and Steamboat Springs, Nevada. In the last-named, aragonite deposited in the drillpipe of the West Reno well blocked the hole in 4-5 days (White, 1968). White thought that precipitation of aragonite rather than calcite was caused by the very rapid deposition rate. Aragonite is also currently forming in caves of Moulis, Ariège, France (Pobequin, 1955) and the Luray Caverns, Virginia (Holland <u>et al</u>, 1964) where reaction kinetics are considered to be a controlling factor in its precipitation. Mackin and Coombs (1945), described cave 'pearls' from an abandoned mine in Idaho, formed by dripping water. These are composed of thin aragonite and thicker calcite layers precipitated on to a crystal nucleus and forming distinct rings. They consider that this layering results from variations in dripping rate causing changes in rate of 'pearl' rotation and carbonate growth nourishment.

Some of the factors affecting the inorganic precipitation of $CaCO_3$ include crystal impurity, pH, temperature, solubility, crystal size and the time the precipitate remains in contact with the solution (Zeller and Wray, 1956). The precipitation of aragonite from Br 6 discharge water seems to have been favoured by a very rapid deposition rate (which averaged about 15 kg/day) in contrast with calcite forming on the liner of several Broadlands drillholes which grows at a rate of only a few millimetres per year. Cloud (1962) considered the behaviour of calcium carbonate in sea water and showed that aragonite precipitates from solutions super-saturated with respect to both calcite and aragonite and that kinetic factors, such as diffusion rates, allow solutions to become supersaturated. The ionic strength of the Br 6 water is 0.045 and the calculated CO_3^{2-} molality 0.00032 m. The calculated Ca^{2+} content of water in equilibrium with calcium carbonate at 50° is $10^{-3.5}$ m compared with the measured Ca^{2+} content of $10^{-2.4}$ m, showing that Br 6 waters are highly oversaturated with calcium carbonate.

Other workers have suggested that reaction kinetics favours aragonite precipitation, including Daniels (1961), who thinks that the presence of the larger Sr^{2+} favoured the formation of aragonite which has a larger lattice unit than calcite. However, Green (1967) on the basis of thermodynamic arguments has shown that Sr is not an important factor in stabilising aragonite. Aragonite from the discharge channel of Br 6 contains appreciable Sr (Table 3) and this element is also much more concentrated in water from Br 6 than other geothermal bores (Table 4). Kinsman and Holland (1969) have shown that the fractionation coefficient of $\frac{Sr^{2+}}{Ca^{2+}}$ between co-existing aragonite and sea water is strongly dependent on rate of crystal growth as well as the composition of aragonite in contact with the solution, and temperature. However, their conclusions are based on experiments involving slow aragonite precipitation from standing sea water. These conditions do not apply to aragonite precipitation from Br 6 water and, using their graph, the calculated $\frac{Sr^{2+}}{Ca^{2+}}$ fractionation coefficient between aragonite and solution is nearly double that expected for water at 52°.

Possibly the amount of magnesium in solution affects the type of calcium carbonate that precipitates. For example, Naidenova and Kostov (1964) concluded that the deposition of either calcite or aragonite in the Iskret caves, of the western Balkans was controlled by the presence of Mg^{2+} in solution. Experiments of Lippmann (1960) showed that at 100°, aragonite precipitates from Cl^- solutions with Mg/Ca ratios greater than 0.85 but below this a mixture of calcite, vaterite and aragonite forms. The Mg/Ca molecular ratio of water discharged from Br 6 is near 1 (Table 4) compared with 0.06 for water from other Broadlands drillholes. This indicates that Mg^{2+} may in some way have affected the rate of calcium carbonate precipitation but the aragonite deposited contains only 0.2 (wt) % of MgO compared with 0.7 (wt) % of SrO.

In conclusion, the deposition of metastable aragonite from Br 6 waters results from the rapid precipitation rate and possibly the relatively high concentration of Sr^{2+} and/or Mg^{2+} in the discharging waters.

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OCCURRENCE OF TESCHEMACHERITE IN A GEOTHERMAL WELL AT BROADLANDS, NEW ZEALAND

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Abstract

Teschemacherite, NH_4HCO_3, occurs at the wellhead of a drillhole where it forms by reaction between gases separating from deep geothermal waters.

Teschemacherite, ammonium bicarbonate, was deposited inside the wellhead of the Broadlands geothermal drillhole BR 9 after the bore had been shut for several weeks.

The crystals, white and up to 4 mm long, were identified by X-ray diffraction and infra-red spectroscopy. The deposit, which filled the 198 mm diameter pipe to an estimated depth of about 0.5 m, was ejected in a block, "like a champagne cork," when the bore was opened. Gas pressure at the wellhead prior to discharge was 51.0 bars, the temperature was ambient, and the water level in the bore was about 490 m below ground surface.

The teschemacherite apparently formed from reaction between CO_2 and NH_3, which collect at the wellhead after separating from deeper waters, as represented by: $NH_3 + CO_2 + H_2O \rightleftarrows NH_4HCO_3$. The gas content of water discharged when BR 9 was opened has been calculated as 0.22 mole percent of which 93.5 mole percent was CO_2 (Browne and Ellis, 1970) and the total NH_3 content of the discharged waters was 5.5 ppm (Mahon and Finlayson, 1972).

Teschemacherite has not been reported from other geothermal fields but occurs in some guano deposits (Palache *et al.*, 1951). Cores from drillhole BR 9 were examined for the ammonium feldspar, buddingtonite (Erd *et al.*, 1964) but none was detected.

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SUBSURFACE ALTERATION

Methods

The identification of hydrothermal alteration minerals in cores is based on a combination of petrography, differential thermal analysis, quantitative infra-red spectroscopy, and semi-quantitative X-ray diffraction analyses using a technique similar to that described by Tatlock (1966) and also used by Muffler and White (1969). Clay minerals were mainly identified by X-ray diffraction of a separated clay fraction before and after treatment with ethylene glycol, and the Na_2O and K_2O concentrations in the rocks were determined by flame photometry. Tables 5 and 6 summarise the range of distribution of the common minerals in the Broadlands geothermal field, and figures 16 to 35 show the mineralogy of most holes. Brief petrographic descriptions of all cores are given in Appendix A.

Figures 16 to 35 illustrate changes in mineral abundance with depth and temperature. Not shown is the distribution of leucoxene, sphene, gypsum, and epidote which are all of limited distribution or else not present in sufficient quantity to detect by instrumental methods. The estimated lower limits of detection using X-ray diffraction and infra-red spectroscopy are (%) quartz 3; carbonates 1; feldspars 5; zeolites 5; clays 5. However, X-ray diffraction of separated clay fraction detects 0.5% clay and pyrite has about the same lower detection limit on the D.T.A.

A simplified geological column and the measured down-hole temperatures in the bore holes are also shown in figures 16 to 35. Temperatures were measured several times between drilling and initial discharge, but the readings made immediately before discharge are considered closest to the undisturbed subsurface temperature (N.D. Dench, pers. comm.). Drillholes 3, 7, 11 and 12 were discharged before sufficient time had elapsed to estimate the steady-state temperatures accurately, and may be in error by several degrees.

It may be noted from figures 16 to 35 that there is some correlation between the albite and Na_2O contents of the cores, because albite is the only hydrothermal sodium mineral, whereas potassium is present in both adularia and illite.

Stability of Primary Minerals

Before alteration most of the rocks of the Broadlands field contained quartz, andesine, and groundmass (glassy or devitrified), often with minor hornblende, biotite, hypersthene, and magnetite. Of these, only quartz is unaffected during alteration.

Volcanic glass is very susceptible to alteration and readily alters at temperatures below 80° (Tables 5 and 6) to montmorillonite, illite, and less commonly, chlorite, calcite, siderite, K-feldspar, and quartz. Magnetite (containing up to 10% Ti; B.P. Kohn, pers. comm.) is also relatively sensitive to alteration and generally alters either to pyrite or leucoxene at temperatures as low as 75°.

Hypersthene, hornblende, and biotite alter at progressively higher temperatures and are generally replaced by chlorite, illite, calcite, quartz, or pyrite. Andesine is less readily altered than biotite at Broadlands, in contrast to Wairakei (Steiner, 1968), and its stability and reaction

TABLE 5 : DEPTH (m) AND TEMPERATURE INFORMATION ON MINERALS IN CORES FROM BROADLANDS DRILLHOLES

Bore No.		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1st core		31	56	57	58	58	58	61	122	60	74	73	55	56	73	115	74	75	69	73	69	195	192	180	159	157
Depth		1398	1036	915	1018	1279	1085	1125	781	1370	1092	765	1374	1085	1284	2421	1406	1084	1218	1080	1207	1123	1018	1098	1251	1258
Biotite	G.D.	424	<120	<120	< 88	424	271	<61	<122	240	N.P.	<104	348	455	350	< 115	N.P.	302	151	440	378	435	192	437	426	363
	H.T.	170	<194	<170	<140	46	76	<60	<149	172		<112	78	164	216	< 182		177	170	150	199	257	177	152	221	258
Hornblende	G.D.	165	<120	<120	< 88	515	271	<61	<122	<103	N.P.	<104	348	< 288	73	< 115	<221	302	< 69	440	<314	195	192	<437	<305	<306
	H.T.	75	<194	<170	<140	73	76	<60	<149	<171		<112	78	<135	37	< 132	<122	164	<142	150	<187	124	177	<152	<205	<248
Pyroxene	G.D.	165	<120	<120	< 88	424	271	N.P.	<122	<103	N.P.	<104	N.P.	N.P.	<350	< 115	<221	< 75	< 69	<226	<314	<195	<192	<437	<305	<306
	H.T.	75	<194	<170	<140	46	76		<149	<171		<112			<216	< 182	<122	<142	<142	< 75	<187	<124	<177	<152	<205	<248
Magnetite	G.D.	165	<120	<120	< 88	546	709	N.P.	<122	<103	N.P.	<104	N.P.	N.P.	<350	<115	<221	< 75	< 69	<226	<314	<195	<192	<437	<305	<306
	H.T.	75	<194	<170	<140	86	73		<149	<171		<112			<216	<182	<122	<142	<142	< 75	<187	<124	<177	<152	<205	<248
Glass	G.D.	242	<120	<120	<180	546	765	433	<122	<103	74	<104	441	56	258	<115	<221	< 75	< 69	73	69	<195	<192	<437	<305	<306
	H.T.	108	<194	<170	<140	86	120	207	<144	<171	69	<112	106	51	175	<182	<122	<142	<142	42	51	<124	<177	<152	<205	<248
Andesine	G.D.	821	210	421	90	732	1085	479	<122	1210	690	<104	560	1085	1284	2238	1245	378	304	1080	1207	1123	430	1098	651	157
	H.T.	241	240	252	140	152	160	228	<149	289	245	<112	122	258	294	298	270	173	171	267	260	278	273	250	244	214
Cristobalite	S.D	205	N.P.	N.P.	N.P.	210	181	N.P.	N.P.	150	71	N.P.	101	195	N.P.	N.P.	N.P.	75	N.P.	305	69	N.P.	N.P.	437	N.P.	N.P.
	L.T.	88				46	95			176	68		50	148				142		101	51			152		
	G.D.	272				695	765			150	88		514	455				75		440	69			437		
	H.T.	119				143	120			176	76		113	164				142		150	51			152		
Siderite	S.D.	N.P.	N.P.	N.P.	N.P.	546	674	N.P.	N.P.	N.P.	71	N.P.	55	56	166	N.P.	N.P.	N.P.	N.P.	73	69	195	192	437	N.P.	157
	L.T.					86	49				68		37	37	83					42	51	124	177	152		214
	G.D.					760	800				74		607	363	166					155	69	195	142	137		157
	H.T.					162	98				69		130	130	83					59	51	124	177	152		214
Calcite	S.D.	178	56	180	88	306	90	107	640	58	88	73	472	149	73	867	74	224	69	379	159	435	192	180	159	157
	L.T.	78	120	180	140	46	98	80	265	147	76	75	108	105	37	271	76	164	142	132	117	257	177	145	147	214
	G.D.	1398	1036	915	957	1279	1085	1125	640	1370	936	765	1374	1085	1284	2238	1406	1084	1218	1080	1207	1123	1017	1098	1251	1258
	H.T.	275	285	280	270	244	160	290	265	292	258	271	274	258	294	298	275	291	290	270	269	278	276	251	287	291
Pyrite	S.D.	362	88	57	58	472	58	107	122	103	179	104	394	575	350	115	221	224	151	73	159	482	548	483	305	306
	L.T.	152	156	100	120	56	53	75	149	166	152	112	93	21	216	182	122	173	170	42	163	257	274	169	205	248
	G.D.	1216	1036	915	957	972	919	992	781	1263	936	765	1340	1085	1234	2155	1245	1084	1218	928	1004	1123	1018	1098	1075	1258
	H.T.	266	285	280	270	210	160	276	272	291	258	271	269	258	294	298	270	291	290	270	269	278	276	251	275	291
Pyrrhotite	S.D.	515	N.P.	N.P.	668	732	N.P.	844	N.P.	N.P.	N.P.	N.P.	789	489	898	2007	759	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.
	L.T.	198			260	152		272					166	183	280	295	206									
	G.D.	1273			1018	1279		844					1185	668	1186	2023	1245									
	H.T.	268			270	244		272					249	237	293	295	270									
Base metal sulphides	S.D.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	802	N.P.	N.P.	953	N.P.	N.P.	N.P.	1234	1619	280	607	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.
	L.T.							272			265				294	286	120	273								
	G.D.							955			1045				1234	2312	1386	607								
	H.T.							276			275				294	298	276	273								
Mordenite	S.D.	332	N.P.	120	N.P.	515	119	N.P.	N.P.	N.P.	N.P.	N.P.	193	288	N.P.	N.P.	N.P.	75	N.P.	226	N.P.	195	192	N.P.	N.P.	N.P.
	L.T.	141		170		73	69						59	135				142		75		124	177			
	G.D.	424		120		515	829						560					75		379		195	192			
	H.T.	170		170		73	152						122					142		132		124	177			
Wairakite	S.D.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	N.P.	619	457	N.P.	N.P.	195*	350	867	1406	607	N.P.	N.P.	533	675	668	704	1251	306
	L.T.									270	232			-	216	271	1275	273			229	266	275	215	287	248
	G.D.									711	457			668	1284	867	1406	686			664	731	730	704	1251	306
	H.T.									276	232			237	294	271	275	276			246	269	275	215	287	248
Kaolin	S.D.	N.P.	N.P.	N.P.	N.P.	515	313	N.P.	N.P.	N.P.	N.P.	N.P.	394	N.P.	N.P.	N.P.	148	N.P.	N.P.	N.P.	159	N.P.	N.P.	N.P.	N.P.	N.P.
	L.T.					73	49						93				142				117					
	G.D.					668	765						607				148				159					
	H.T.					134	120						130				142				117					
Montmorillonite (including interlayered)	S.D.	287	56	57	58	472	58	61	N.P.	56	71	69	55	56	73	N.P.	74	75	69	73	69	N.P.	N.P.	180	305	157
	L.T.	125	120	100	120	56	90	42		147	68	75	37	51	37		76	142	142	42	51			145	205	214
	G.D.	287	88	421	394	760	889	550		379	629	490	607	528	530		74	303	305	642	665			483	611	363
	H.T.	125	156	251	248	161	160	252		176	244	262	130	204	244		76	164	152	267	246			169	241	258
Illite (including interlayered)	S.D.	332	104	120	153	472	119	107	122	56	179	69	607	103	258	554	221	75	230	489	314	195	430	646	305	157
	L.T.	141	176	170	183	56	90	80	149	147	152	75	130	77	175	249	122	142	152	194	187	124	273	209	205	214
	G.D.	1398	484	822	1018	1279	1085	1125	642	1370	1092	765	1374	1085	1284	2421	1406	686	1218	1080	1207	1123	1018	1098	1251	1258
	H.T.	275	266	271	270	244	160	290	265	292	280	271	274	258	294	298	275	276	290	270	269	278	275	251	287	291
Chlorite	S.D.	638	56	302	332	515	58	208	781	56	134	436	1095	363	120	554	394	302	304	155	159	435	668	646	159	157
	L.T.	230	120	215	238	73	83	145	272	147	100	258	230	130	69	249	122	164	152	59	117	257	275	209	147	214
	G.D.	1398	1036	915	1018	1135	1085	1125	781	1370	1092	525	1374	1085	1284	2421	1406	1084	1218	1080	1207	1123	1018	1098	1251	1258
	H.T.	275	285	280	270	231	160	290	272	292	280	265	274	258	294	298	275	291	290	270	269	278	276	251	287	291
Albite	S.D.	852	333	573	485	732	856	549	781	767	629	669	789	715	851	867	1367	742	687	780	608	675	788	646	611	692
	L.T.	242	259	264	253	152	122	252	272	279	244	267	166	244	277	271	275	278	268	267	239	266	275	209	241	281
	G.D.	1398	1036	915	1018	1135	1020	1125	781	1370	1092	765	1375	1085	1284	2421	1406	1084	1218	1002	1006	1061	1018	1008	1251	1258
	H.T.	275	285	280	270	230	152	290	272	292	280	271	274	258	294	298	275	291	290	270	269	278	276	251	287	291
Adularia	S.D.	N.P.	195	240	118	N.P.	N.P.	692	243	767	279	69	1095	715	578	115	221	224	151	780	835	195	788	797	825	488
	L.T.		235	175	170			270	215	279	212	75	230	244	248	182	140	177	152	267	263	124	275	232	249	273
	G.D.		1036	915	1018			877	781	1072	1092	765	1375	1085	1234	2238	616	1084	1218	1080	1207	1123	1018	1098	1010	1258
	H.T.		285	280	263			273	272	280	280	271	274	258	294	298	160	291	290	270	266	278	276	251	269	291

Note: G.D.= Greatest depth H.T. Highest temp. N.P.= Not present
S.D.= Shallowest depth L.T. Lowest temp. * Probably detrital

TABLE 6.

SUMMARY OF DEPTH AND TEMPERATURE INFORMATION ON MINERALS IN CORES FROM DRILLHOLES.

Mineral	Bore No.	Shallowest Depth (m)	Greatest Depth(m)	Lowest Temp. (°)	Highest Temp. (°)
biotite	16	-	455	-	258
hornblende	9	-	515	-	177
pyroxene	3	-	424	-	76
magnetite	3	-	709	-	86
glass	9	-	765	-	207
andesine	23	-	2238	-	298
cristobalite	11	69	765	46	176
siderite	12	55	800	37	214
calcite	25	56	2238	37	298
pyrite	25	57	2155	42	298
pyrrhotite	9	489	2023	152	295
base metal sulphides	6	280	2312	120	298
mordenite	10	75	829	59	177
wairakite	13	306	1284	215	294
kaolin	5	148	765	49	142
montmorillonite	21	55	889	37	267
illite	25	56	2421	56	298
chlorite	25	56	2421	59	298
albite	25	333	2421	122	298
adularia	22	69	2238	75	298

products are particularly influenced by temperature, permeability, and fluid composition. Under conditions of very low permeability, andesine may persist to temperatures in excess of 298°. In the Salton Sea drillhole I.I.D. No. 1, calcic plagioclase was present in intensely altered rocks below 1524 m and above a temperature of 323°, but this was considered by Muffler and White (1969) to be due to the exceptionally high Ca content of the associated geothermal brine. At Broadlands, andesine may be replaced by one or more of the following: adularia, albite, calcite, illite, wairakite, epidote, or quartz.

Hydrothermal minerals

The composition of common minerals found at Broadlands and Wairakei is shown in fig. 11 (from Browne and Ellis, 1970). Tie lines show typical mineral associations and the average unaltered rhyolite composition is given as a solid point. Zoisite does not occur at Broadlands but epidote is a minor constituent of some cores from high temperature areas.

Comments on individual minerals follow:

Zeolites.

Both mordenite (ptilolite) and wairakite occur in cores from several drillholes, but have a limited distribution compared with Wairakei (Steiner, 1968). Heulandite occurs in only one core (Br 20, 69-70 m, T = 50°) but laumontite is absent; with increasing temperature the sequence may be summarised as (heulandite) --> mordenite --> wairakite + albite --> albite (± epidote) and represented in part by

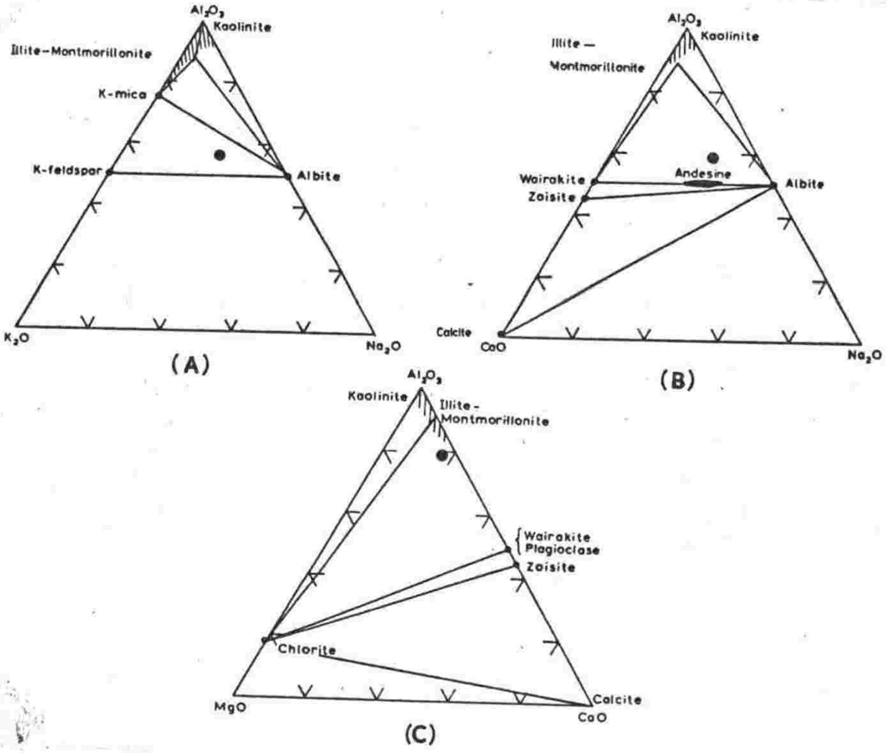

FIG. 11. Compositions of minerals occurring in the Broadlands field. Tie-lines join coexisting minerals and a solid point gives the average rhyolite composition of the region (from Browne and Ellis, 1970).

$$\underset{\text{mordenite}}{Na_2CaAl_4Si_{20}O_{48}\cdot 14H_2O} = \underset{\text{wairakite}}{CaAl_2Si_4O_{12}\cdot 2H_2O} + \underset{\text{albite}}{2NaAlSi_3O_8} + \underset{\text{quartz}}{10SiO_2} + 12H_2O$$

This compares with the typical zonation in several other geothermal fields (e.g. Wairakei) of mordenite --> laumontite + albite --> wairakite + albite --> albite.

Mordenite is present in several cores where measured temperatures are between 60° and 180° (Table 6). These temperatures are comparable with those for its occurrence at Wairakei (Steiner, 1953 and 1968) where it forms between 60° and 160°, and Iceland where it occurs at 120° (Sigvaldason, 1963), but lower than temperatures reported by Coombs and others (1959). Ellis (1960) crystallized mordenite (possibly metastably) from obsidian at 230° during exposure to natural hydrothermal solutions. In cores from Broadlands, mordenite occurs as small, fibrous crystals, which have been deposited directly from solution in pumice or rhyolite cavities, but in places it appears to also form from glass hydration or devitrification.

Wairakite occurs in cores where measured temperatures are between 215° and 294° (Table 6), which compares with temperatures from 142° to 250° at Wairakei (Steiner, 1953 and 1968; Coombs and others, 1959), and 222° to 260° in the Tauhara geothermal field. Generally the wairakite occurs as twinned, weakly birefringent, euhedral crystals up to 3 mm in diameter lining fractures, where they have been deposited from solution. It only rarely replaces plagioclase.

Optical properties of wairakite from Br 9, 625 m are: $\alpha = 1.499 \pm 0.001$, $\gamma = 1.501 \pm 0.001$, $\gamma - \alpha = 0.002$ (Na-light), 2V varying between 70 and 90°.

Both mordenite and wairakite are high-silica zeolites. Their distribution conforms with the established pattern of the more hydrated species forming at the lower temperature. At Broadlands, temperature and water composition (particularly pH, Ca contents, and silica activity) are the main factors affecting wairakite and mordenite stability, although the formation of the latter is favoured by the presence of glass in the host rock. The heulandite-mordenite relationship at Broadlands is uncertain but may be one of dehydration. However, analcite cannot be involved as a reactant phase (Seki, 1969) as this mineral is absent from Broadlands cores.

The absence of laumontite is puzzling since it is common in many geothermal fields, including Wairakei (Coombs and others, 1959), and low grade metamorphic rocks. There is no evidence that it is unstable under measured Broadlands conditions. The relationships between laumantite and wairakite, lawsonite and anorthite have recently been discussed by Liou (1970; 1971) and Thompson (1970, 1971a, 1971b) and according to Thompson (1970) the reaction laumontite ---> anorthite at low pressures proceeds via a wairakite phase. Laumontite is difficult to synthesise (Liou, 1971) because it requires perfect ordering of tetrahedral Al and Si in the framework structure, but suitable conditions should have applied in a geothermal field active for several thousand years.

Quartz

Quartz is abundant both as a primary constituent of most rocks and as product of devitrification and hydrothermal alteration. It is possible to distinguish origins only by using a microscope. Figures 16 to 35 therefore show the total quartz in the cores. In common with rocks in other New Zealand geothermal fields, primary quartz remains unaffected during contact with the silica-saturated geothermal water. Hydrothermal quartz is also widespread both as a replacement mineral and as clear, euhedral crystals up to 4 cm long lining cavities and fractures. It is particularly common as a replacement of pumice, plagioclase, and glass and forms at depths where temperatures are above about 100°, but is most abundant in zones of good steam production.

Cristobalite.

α-cristobalite (X-ray peak at 4.05 Å) is present in several holes but is most abundant in holes 5 and 6 (Figs. 13 & 14), where some cores contain up to 25 percent. It occurs as round,near isotopic spherules less than 0.1 mm in diameter, between temperatures of 46° and 176°, and to a maximum depth of 765 m. At higher temperatures it probably changes to quartz. Its origin is uncertain, but the low temperature of occurrence, its abundance, and occasional association with montmorillonite suggest that it is possibly a metastable, first alteration product of volcanic glass. However, cristobalite is commonly considered to be a high temperature devitrification product, and this is its origin in drillhole Y-1, Yellowstone National Park (Honda and Muffler, 1970). It may also have originated this way at Broadlands, but it was not reported by Ewart (1966) in surface rocks of the region.

Chlorite.

Chlorite is a common mineral in all drillholes and may constitute up to 40 percent of the rocks. It is usually formed from groundmass or pumice alteration but may be an alteration product of primary ferromagnesian minerals or occasionally plagioclase. More rarely, it is deposited directly from solution. Typically, the chlorite is green, slightly pleochroic, weakly birefringent, and of variable crystallinity. Infra-red and X-ray diffraction data show it to be an iron-rich, trioctohedral non-swelling type, similar to that commonly found at Wairakei (Steiner, 1968). The distribution of chlorite indicates that its stability is largely independent of depth, permeability, and temperature (Tables 5 & 6), and its abundance appears to be related to the initial iron content of the unaltered rocks (MgO content $\angle 3$ percent in unaltered rocks). In places however, there has also been addition of iron to the rocks to form chlorite or pyrite.

Kaolin.

Surface hydrothermal activity at Broadlands is minor compared with that at Wairakei, and supergene kaolin, opal, and alunite are rare, even in shallow cores. However, several cores from Br 5, 6, 12 and 20 contain kaolinite or halloysite which has formed as an alteration product of volcanic glass; measured temperatures here are low (Table 5).

Infra-red spectra of the core from Br 16/148-149 m shows the kaolin to be the dickite type. This is a well crystallized monoclinic polymorph known from only two other active geothermal fields, Kawerau and The Geysers, although it occurs in some hydrothermal ore deposits (Grim, 1968; Hemley et al., 1969).

The kaolin may be due to one of the following reasons:

A. It represents buried zones of superficial alteration.

B. It was formed by an inflow of oxygenated ground water, causing acid conditions by sulphide oxidation.

C. At low temperatures, kaolin is a stable phase in waters of Broadlands composition.

The third explanation is preferred because the kaolin is locally associated with small amounts of both carbonate and pyrite, implying non-acid, reducing conditions, and its comparatively broad vertical distribution in the Broadlands Rhyolite (Fig. 19) suggests that this is not fossil alteration. Extrapolated experimental data (Browne and Ellis, 1970) indicate that at a temperature of about 100° the kaolinite-mica phase boundaries for waters of Broadlands composition would be at about pH 7.

The reason for the formation of dickite instead of kaolinite in Br 16 is uncertain, but may be due to the slightly higher temperatures (142 ± 10°).

Illite, interlayered illite-montmorillonite, and montmorillonite.

These minerals are widespread and abundant at Broadlands and constitute more than half of some recovered cores. With increasing temperature and depth, there is a general sequence of montmorillonite --> interlayered illite-montmorillonite (rich in montmorillonite) --> interlayered montmorillonite - illite (rich in illite) --> illite, although local reversals are not uncommon, and in places, illite and montmorillonite may coexist, without interlayering. The amount of illite component in the interlayered illite-montmorillonite generally increases with temperature, but, unlike Wairakei (Steiner, 1968), clay mineral type appears to be unrelated to fault-fissures. Clay minerals form from the alteration of plagioclase, ferro-magnesian minerals, and particularly pumice fragments but in places, where the rocks are fractured, may also be deposited directly from solution.

Montmorillonite occurs in the calcium form, usually as minute, weakly birefringent grains with an 001 reflection about 14Å, although this decreases with increasing illite interlayering. In places, for example, Br 7 at 844 m, the illite is comparatively coarse grained, has sharp basal reflections, a high birefringence, does not have a low ✓ temperature D.T.A. endothermic peak, and may be more correctly called sericite (Taboadela and Ferrandis, 1957). In the later discussion the terms illite, sericite, and K-mica are considered synonymous. Steiner (1968) gave evidence that illite forms from silicic volcanic glass via the sequence: montmorillonite → mixed-layer illite-montmorillonite deficient in interstratified illite → mixed-layer illite-montmorillonite with dominant illite → illite. Although a similar assemblage and sequence are also found at Broadlands, the evidence would be consistent with contemporaneous formation of clays, with distribution and type dominantly a function of temperature. In some places, predominantly sedimentary rocks at depth contain illite that has not been derived from glass, and as previously mentioned illite may also be deposited directly from solution.

Montmorillonite, illite, and interlayered illite-montmorillonite distribution is similar to that at Salton Sea, where Muffler and White (1969) found montmorillonite existed at surface temperature but disappeared as a discrete phase at about 100°, and illite-montmorillonite converted to K-mica at about 210°.

Albite.

Albite is present in varying amounts in cores from all drillholes. With the exception of a small amount in Br 2 at 334 m, albite does not occur above a depth of 457 m (Table 6) - in contrast to Wairakei and Waiotapu where it forms at depths as shallow as 86 m (Steiner, 1953 and 1963) and at 61 m at Steamboat Springs drillhole GS-3 (Schoen and White, 1965).

Tables 5 and 6 show that albite may form at temperatures as low as 122° (Br 6), but in holes with geothermal gradients more typical of the area, it generally forms first between temperatures of 230° and 280°. This compares with its occurrence at temperatures of 230° to 250° at Wairakei (Coombs and others, 1959). Typically albite forms twinned, unzoned, clouded crystals, in places together with adularia, replacing, or partly replacing, primary plagioclase. Albite is seldom pure. As shown by refractive indices and infra-red spectra, it varies in composition up to about An_{15}, although most is in the range An_5 to An_{10}. The reason for the variable calcium content is not known but may be a result of incomplete reaction between water and the primary plagioclase. In later discussion the term albite refers to secondary plagioclase regardless of composition. The clouded appearance of the albite crystals contrasts with the clear, inclusion-free andesine and adularia and suggests that the inclusions formed during the alteration processes. These minute inclusions probably consist of iron oxide and indicate that iron is less soluble in sodic plagioclase than in either K-feldspar or more calcic plagioclase, a conclusion consistent with the work of Ribbe and Smith (1966). However, in rare instances, albite crystals have also grown directly from solution; for example, lapilli tuff from Br 22/917-918 m contains minor adularia and euhedral albite crystals up to 0.5 mm long lining cavities. Albite possibly forms under these conditions from slow heating of stagnant water. These crystals also contain minute inclusions giving them a dusty appearance, showing that they do not result from the different solubility of iron in albite and andesine; probably the inclusions formed at the same time as the crystals themselves.

At Broadlands, albite formation appears to be particularly affected by temperature and depth but not by permeability, since it is present in cores from all holes. Its formation also requires that plagioclase be present in the unaltered rock.

K-feldspar.

Secondary monoclinic K-feldspar (referred to as adularia) is an important hydrothermal mineral at Broadlands, because its presence and abundance are related to the measured output of individual drillholes (Browne, 1970). It has three modes of occurrence:

A. Commonly it replaces primary plagioclase in a manner similar to albite with which it may coexist in equilibrium. These crystals are clear and generally structurally complex.

B. In the groundmass of cores from several holes, particularly the upper 300 m of Br 2, 8, and 11, it occurs as minute, diamond-shaped crystals.

These must be formed by major potassium infusion, since some cores from Br 11 contain as much as 11 percent K_2O, and this cannot be accounted for by glass devitrification alone. It appears that this type of adularia may form at lower temperatures than that formed by replacement of andesine.

C. More rarely, it occurs as euhedral crystals, up to 5 mm long, lining cavities and core fractures (for example, Br 4 at 333 m, and Br 7, 844 m) where it has been deposited directly from solution in response to change of pH and loss of CO_2 during boiling. This is a rapid non-equilibrium process.

The optical characteristics of adularia from Broadlands are similar to crystals from Wairakei drillcores (Steiner, 1970). Pseudomorphs after plagioclase typically have a streaky extinction or 'tile'-like structure thought to result from minute overlapping crystals.

Adularia from Br 7, 844 m has $\overset{\alpha}{\cancel{\gamma}} = 1.518 \pm 0.001$, $\gamma = 1.524 \pm 0.001$, $\gamma - \alpha = 0.006$ and a 2V varying between about 20 and 40°.

Adularia is abundant in some cores from Br 2, 4, 7, 8, 11, 17 and 25 and is a minor constituent of several others, where it usually coexists with albite. Though in Br 11 it has formed at a depth of only 69 m, where the temperature is 75°, it commonly occurs below about 250 m and above about 220°, which compares with Wairakei where it is found below 385 m and above 230° (Steiner, 1968; Coombs and others, 1959). Adularia appears to form in places where there is good permeability, but its stability is markedly affected by changes in water composition (Browne and Ellis, 1970).

Epidote.

Epidote is an uncommon mineral at Broadlands but is abundant at Wairakei (Steiner, 1953) and the Salton Sea (Muffler and White, 1969).

At Broadlands it is present in concentrations below about 1 percent. It is most abundant in core from Br 13 at 1084 m and Br 15 at 2023 m where it occurs as euhedral, slightly pleochroic crystals in thin (1 mm wide) veins and in vugs together with calcite. In rare instances it appears that calcite has been deposited directly on epidote. An electron microprobe examination of a crystal showed it to be an iron-rich variety (approx 13 percent Fe; C.P. Wood, pers. comm. Epidote from Br 15, 2023 m is pale green, non-pleochroic, has a 2V between 70 and near 90°, and has $\alpha = 1.730 \pm 0.002$.

The formation of epidote at Broadlands is restricted because of high underground carbon dioxide activity which favours the formation of calcite (Browne and Ellis, 1970), but it does not seem to form below a temperature of about 260°. This compares with measured minimum formation temperatures of 290° at Salton Sea (Muffler and White, 1969) and about 250° at both Wairakei (Steiner, 1968) and the Tauhara field. However, this is considerably higher than Iceland where epidote occurs at about 225° at Hveragerdi and only 130° at Reykjavik (White and Sigvaldason, 1963). Muffler and White (1969) noted that at Salton Sea a decrease in calcite complemented an increase of epidote which they considered due to incorporation of Ca into epidote following the breakdown of calcite, but this does not seem to have been the case at

Broadlands.

Calcite.

This is a common and important mineral at Broadlands, present in all drillholes. It is usually most abundant below a depth of about 600 m, but it also occurs at shallower depths (Table 5) and at temperatures below 100°.

It forms as a replacement, or partial replacement, of andesine together with secondary albite, adularia, or quartz but also occurs as irregular grains in the groundmass of some rocks. Less commonly it has been deposited as scaly crystals filling or lining fractures and cavities and is occasionally ejected during initial bore discharge as white rhombohedral crystals up to 1.5 cm long. Typically it is white and nearly pure $CaCO_3$ in composition (C.P. Wood, pers. comm.).

Calcite has also been deposited on the slotted liner of several bores reducing their output; some removed from Br 11, partly analysed by X-ray fluorescence by D. Clyma, contains 44 ± 3 ppm Cu.

The formation of calcite at Broadlands is little affected by temperature, but is particularly sensitive to changes in water and gas composition, caused for example, by boiling.

Siderite.

Siderite is not a common mineral at Broadlands (Table 5) and is present in amounts up to 10 percent in cores from 12 drillholes. It occurs either as minute spherules or irregular grains up to 0.1 mm long in the groundmass of some rocks, but, unlike calcite, it does not replace plagioclase.

Siderite from Br 12 at 564 m (temp. 122°), which apparently coexists in equilibrium with calcite, was examined by electron microprobe and found to contain about 6 percent CaO and detectable MgO and MnO (C.P. Wood, pers. comm.), whereas the calcite contains less than 2 percent FeO. Siderite occurs at temperatures between 37° and up to 214° (Table 6). This compares with temperatures at the Salton Sea about 135° (Muffler and White, 1969), and drillhole 6, Wairakei, where it occurs at low temperatures and a depth of only 27 m (Steiner, 1953). It does not coexist with magnetite and seldom with pyrite, suggesting that some iron is derived from the alteration of magnetite, probably under relatively high P_{CO_2} and low P_{O_2} conditions (Garrels and Christ, 1965). Siderite does not occur with base metal sulphides, in contrast with several hydrothermal ore deposits where it is often associated with base metal sulphide veins (e.g. Shaw, 1959).

The stability relations of siderite have recently been determined between 500 and 2000 bars, by French (1971) but these pressures are too great to extrapolate data to observed geothermal conditions.

Iron Sulphides.

The iron sulphides present are pyrite and pyrrhotite. Marcasite has not been identified but occurs at Waiotapu. Pyrite in amounts up to 10 percent is the most common sulphide and is present in cores from all drillholes. In most places it forms evenly distributed, euhedral crystals up to 2 mm in diameter or small irregular grains, but it also occurs in thin veins and small vugs. Pyrite crystals from Br 4 analyzed spectrochemically by W.C. Tennant, Chemistry Division, contain up to 1000 ppm arsenic, but as local concentrations of arsenic could not be detected under the eletron microprobe (G.A. Challis, pers. comm.) it appears that this element does not form a discrete mineral. Pyrrhotite is much less abundant than pyrite, but it occurs in 9 drillholes (Table 5) below 500 m, commonly as magnetic brown-black crystals up to 4 mm in diameter, and usually in clusters. Fe-radiation X-ray diffractograms by L.A. Taylor (pers. comm.) of pyrrhotite from Br 16/787 m show a splitting of the (10.2) reflection into two peaks - the (408)-(228) and the ($\bar{4}08$)-($\bar{2}28$) reflections with $I_{\bar{4}08} > I_{408}$. This indicates that the sulphide is anomalous pyrrhotite possibly formed from the oxidation of monoclinic pyrrhotite (Taylor, 1971). Chromic acid etching of polished crystals show the pyrrhotites to be single phases and without pyrite intergrowths. The lack of reaction to etching suggests pyrrhotites are of the hexagonal type but acid etching is not considered conclusive in distinguishing hexagonal from monoclinic pyrrhotite (S.D. Scott, pers. comm.). Apparently anomalous pyrrhotite also does not react to acid etching. Pyrrhotite was also present in a scaly deposit on the slotted liners removed from Br 1 indicating low P_{H_2S}/P_{H_2} conditions.

Pyrite and pyrrhotite may form from the alteration of magnetite and ferromagnesian minerals, but the abundance of pyrite and its presence in veins and vugs suggest most must have been deposited from solution by addition of iron and sulphur. Pyrite forms readily at temperatures below 100°, but pyrrhotite is present only above 152° (Tables 5 and 6) and under the lower P_{H_2S}/P_{H_2} conditions that occur in more impermeable zones (Browne and Ellis, 1970). It may be significant that pyrrhotite is present in cores from drillholes that are all poor steam producers (Browne, 1970). The formation of pyrrhotite is also favoured by the presence of organic matter, and this seems to have been the case in some fine-grained sediments from Br 12.

Both iron sulphides coexist, apparently in equilibrium, in cores from Br 16/787 m and 988 m and 668 m in Br 13, where the measured temperatures are between 217° and 252°. Pyrite is common at Wairakei and Waiotapu (Steiner, 1953; 1963), but pyrrhotite has not been found in the latter geothermal field and is only a minor constituent at Wairakei (Steiner, pers. comm.). In the Salton Sea area, pyrite occurs in the I.I.D. No. 1 and Sportsman No. 1 drillholes below a depth of 610 m and above a temperature of 200° (Muffler and White, 1969), but pyrrhotite is a minor phase.

Base metal sulphides.

These are discussed in the two reprints following.

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Mineralisation in the Broadlands Geothermal Field, Taupo Volcanic Zone, New Zealand

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Mineralisation in the Broadlands Geothermal Field, Taupo Volcanic Zone, New Zealand

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Abstract

Small quantities of sphalerite, galena and chalcopyrite have been found in cores and cuttings from 6 drillholes in the Ohaki-Broadlands geothermal field of the Taupo Volcanic Zone, New Zealand. They occur in horizontal and near-horizontal Quaternary-Recent silicic lavas, tuffs, ignimbrites, volcanic sediments and in the underlying Mesozoic basement greywackes and argillites. The base-metal sulphides occur, and appear to be most abundant in fracture zones, at depths between 920 and 7593 ft where temperatures vary from 120° to 298°C. Associated hydrothermal minerals include quartz, K-feldspar, albite, K-mica, chlorite, calcite, pyrite, pyrrhotite and rare epidote.

Textural evidence suggests that the hydrothermal minerals in most parts of the base-metal zones are in equilibrium with one another and with the weakly saline solution of low metal content (Zn + Pb + Cu = 0.05 ppm) now being discharged from the boreholes. Sinters rich in arsenic, antimony, mercury, thallium, and gold are currently precipitating from boiling pools near the boreholes and also from steam discharged by one bore which at depth penetrates rocks with base-metal sulphides. This suggests that a crude metaliferous zoning is operating with crystallisation of Cu–Pb–Zn minerals at depth and Ag–Sb–Hg–Au material under cooler surface conditions.

* * *

Introduction

Base-metal and precious-metal sulphides have precipitated from brines discharged from wells drilled near the Salton Sea (Skinner, *et al,* 1967), base-metal sulphides and native lead from brines of wells in the Cheleken Peninsula (Lebedev, 1967, 1968) and in the Red Sea, heavy metal deposits are associated with the brines (Degens and Ross, 1969). However, except for a small quantity of galena and sphalerite in one core from Waiotapu, similar deposits had not been found in New Zealand's geothermal fields, despite extensive drilling, until December, 1967. Since this date, base-metal sulphides have been found at deep levels in 6 holes drilled at the Broadlands geothermal field. Associated in this area are hot spring deposits of Sb–Hg–As rich material. The significance of undoubted hydrothermal minerals at Broadlands lies in the probability that they formed in the immediate past under conditions similar to those now observable. Fluids discharged from Broadlands bores are, however, very dilute both in salts and minor metals compared with metal-rich, saline brines of Cheleken, Salton Sea and Red Sea. This suggests that some ore deposits may form over long periods of time from weakly saline solutions with low metal concentrations.

Geology and Fluid Movement

The Broadlands geothermal field is located along the Waikato River, 15 miles north-east of Wairakei (Fig. 1). It lies in a broad tectonic depression that is part of the active volcanic and hydrothermal zone which extends from Mt. Ruapehu to White Island in the Bay of Plenty.

Nineteen drillholes, varying in depth between 2545 ft and 7933 ft, penetrate near horizontal rhyolites, tuffs, volcanically derived sediments, pumice breccias, dacites and ignimbrites over a generally westward dipping erosion surface of Mesozoic greywacke and argillite (Grindley and Browne, 1968; Browne, 1970). The geology is summarised in Fig. 2. Hydrologically, the formations consist of a series of alternating permeable and impermeable members and, typically, the best production from drillholes is obtained from the more porous pumiceous tuff-breccia and tuffs. The denser, less porous ignimbrites, dacite, rhyolites, and fine-grained sediments generally act as cap rocks.

Cutting the hydrological system of aquifer and cap rock are several faults (not shown in Fig. 2) which, as at Wairakei (Grindley, 1965), serve as channels for the upward flow of geothermal fluid. These are apparent in the northwest (Ohaki) part of the Broadlands Field, as northeast striking fault traces along which occur an alignment of hot springs, including the Ohaki Pool. These faults govern the natural heat escape (Grindley and Browne, 1968) and where intersected by a north-west cross fault, the junctions form a locus of maximum heat flow. The aim of drilling is to intersect channels to tap steam and hot water but it is uncertain if individual faults visible at the surface are the same as those intersected at depth. However, fractured and sheared cores, often with crystal-lined cavities, have been recovered from

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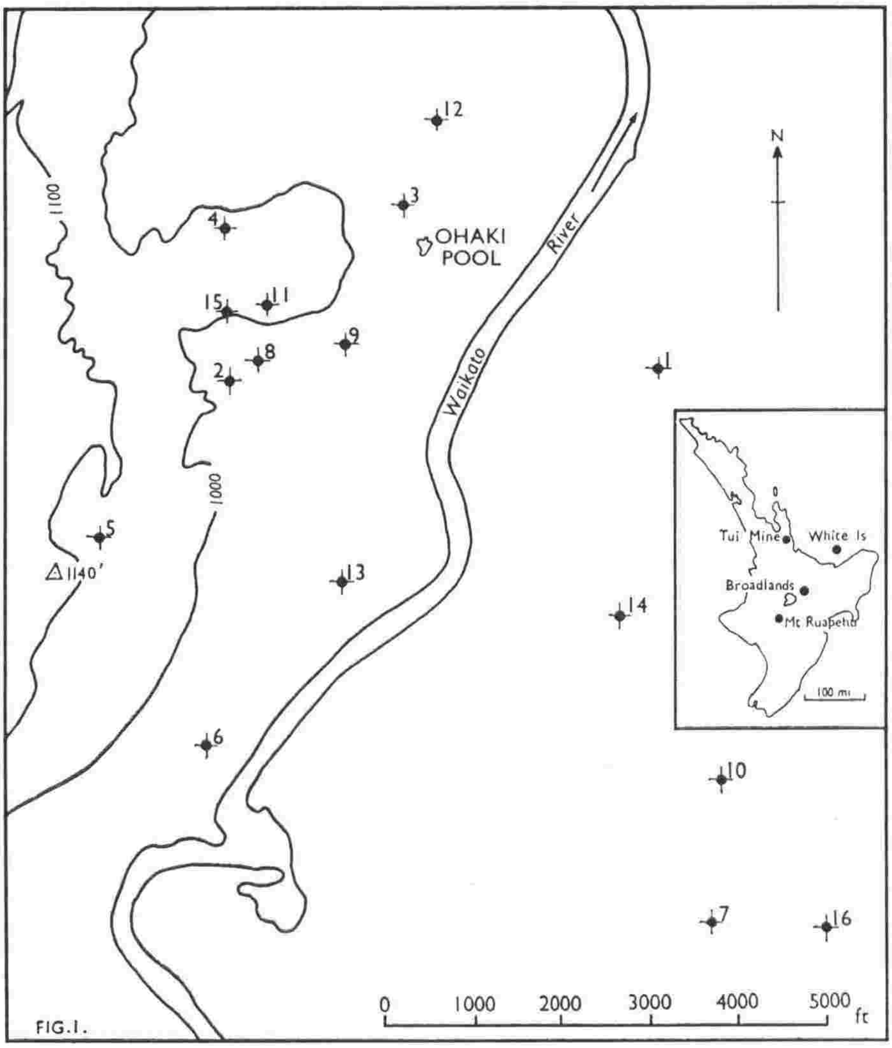

Fig. 1: Map of Broadlands geothermal field showing location of drillholes. Bore Br 17 is 900 ft east of bore Br 15.

the production zones of several bores and the fissure-fluid systems are regarded as continuous. In the Broadlands (south-east) area, a north-east alignment of hot springs probably represents an active fault trace and fractured cores were recovered from bore Br 7 at 2758 ft and Br 16 at 988 ft. Bore Br 7 discharges mainly dry steam and tests by D. K. Wainwright (Browne, 1970) show that best permeability is between 2300 and 3000 ft.

Small displacements of the base of the formations, including rhyolites, suggest that vertical movements of faults have been only of the order to tens of feet and no lateral movement has been detected. The faults are all considered, however, to be normal and consistent with the regional tensional directions. It appears that only small displacements are necessary to provide openings for the transport of geothermal fluids but it is probable that repeated fault movements are necessary to keep these open, since abundant quartz and calcite are usually deposited in permeable zones. Low natural surface activity, on the other hand, suggests that permeability at shallow levels may have been reduced by the deposition of hydrothermal minerals.

Distribution and Mineralogy of Base-Metal Sulphides

Table 1 shows the distribution of base-metal sulphides in cores and cuttings and the measured downhole temperatures from the 6 Broadlands drillholes.

The distribution of base-metal sulphides is unrelated to rock type (Table 1) but they are most abundant in the south-eastern part of the geothermal field,

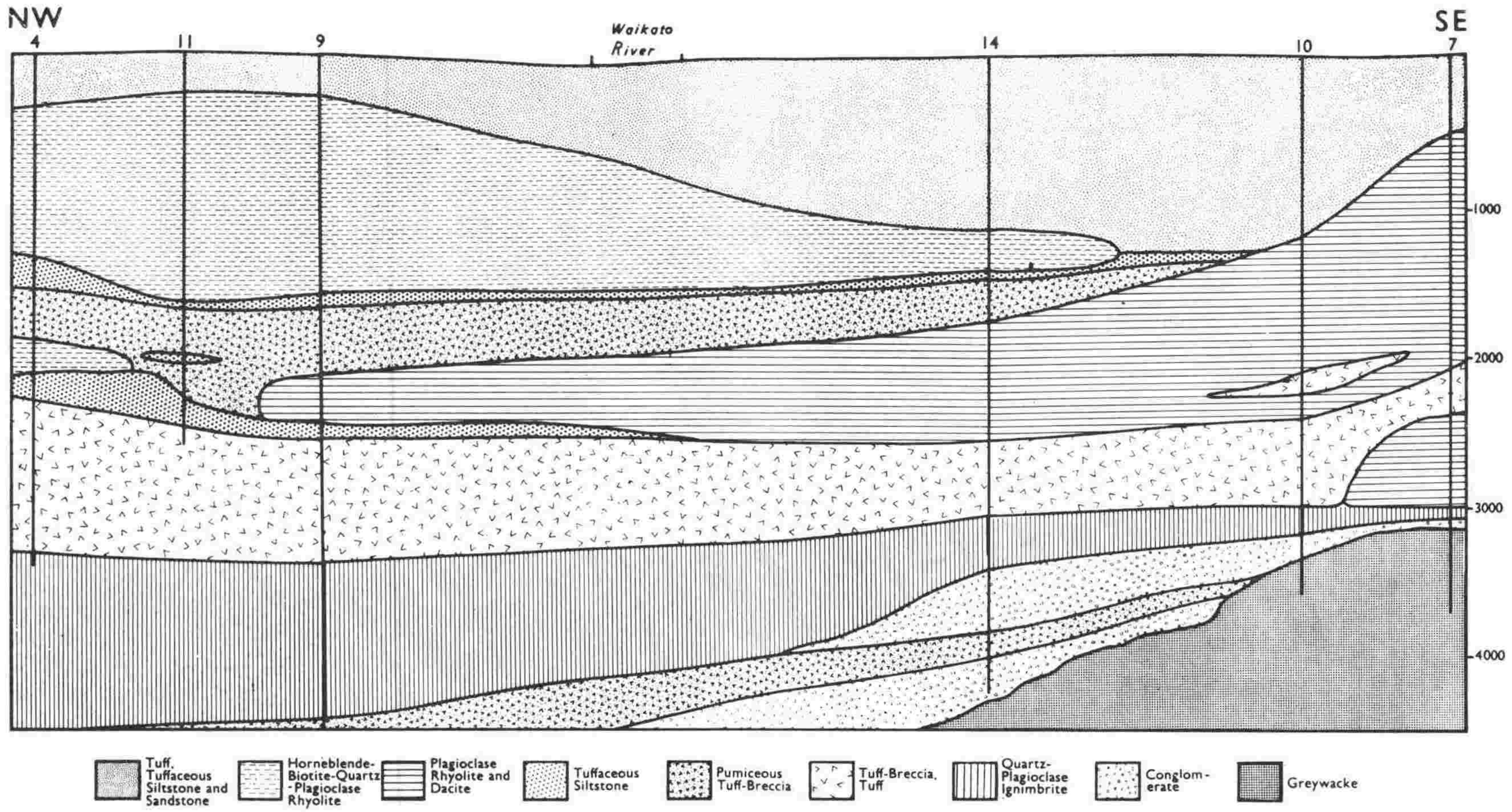

Fig. 2: Generalised diagram of subsurface geology of Broadlands geothermal field. Numbers refer to drillholes. Brown and Ellis (1970). The Ohaki-Broadlands hydrothermal area, New Zealand: Mineralogy and related geochemistry: American Journal of Science, 269, pp. 97–131.

Table 1: Distribution of Base-Metal Sulphides in Broadlands Bores and the Associated Rocks and Hydrothermal Minerals

Bore.	Depth (ft)	Shallowest depth, base-metal sulphides (ft)	Deepest base-metal sulphides found (ft)	Lowest temp. in base-metal zone °C	Highest temp. in base-metal zone °C	Rock types in base-metal zone	Associated hydrothermal minerals
7	3665	2630	3034	272	276	rhyolite, tuff greywacke	quartz, adularia, albite, calcite, pyrite, illite, chlorite
10	3566	3130	3430	265	275	conglomerate greywacke	quartz, adularia, chlorite, illite
14	4199	core only	4047	294		argillite conglomerate	quartz, adularia, chlorite, illite, pyrite
15	7933	5316	7593	286	298	ignimbrite, tuff, argillite, greywacke	calcite, quartz, chlorite, adularia, albite, pyrite
16	4602	920	4570	120	276	dacite, tuff-breccia greywacke	quartz, illite, chlorite, calcite, pyrite, pyrrhotite
17	3484	core only	1988	273		water-laid tuff	calcite, wairakite, quartz, illite, pyrite

particularly in cores from bores Br 7 and Br 16.

The base-metal sulphides have their greatest vertical distribution in Br 16 and, with the exception of Br 15, decrease in thickness towards the western and northwestern bores. They are also closest to the surface and at the lowest measured temperatures in Br 16 (Table 1) and, except for Br 17, northwest of this are first encountered at progressively deeper levels and higher temperatures.

Another observation is that the base-metal sulphides are most abundant in cores which show evidence of fracturing but some fracture zones do not have base-metal mineralisation and a direct correlation between sulphide abundance and measured permeability or bore output has not been established. In more porous, less dense and unfractured rocks such as tuffs and tuff-breccias, the sulphides typically occur as small, disseminated, euhedral crystals lining cavities. They are most abundant in a core from Br 16, at 988 ft which is fractured and consists of ground-up sulphides, in a matrix of soft clay, and a core from Br 7 at 2758 ft which is silicified, fractured and contains irregular veins of base-metal sulphide 1–22 mm wide, together with calcite and adularia crystals (Browne, 1969).

The sulphide mineralogy of cores from Broadlands is fairly simple but textures are variable. Pyrite is the most common sulphide and in places comprises up to 10% of core. It occurs over a wide range of temperatures and depths in all boreholes (Browne and Ellis, 1970). Usually it forms euhedral, disseminated crystals up to 2 mm in diameter but in less porous rocks, veins are more common and rarely it forms spheres.

Pyrrhotite is much less common and seldom constitutes more than 1% of the core. It occurs as evenly distributed plates, up to 2 mm in diameter and is commonly in the hexagonal form. In rare cases, *e.g.* Br 16, it coexists, apparently in equilibrium, with both pyrite and sphalerite.

Sphalerite is the most common base-metal sulphide although galena may predominate locally. Typically sphalerite is dark brown in colour and in thin section often shows optical zoning, a feature examined by electron microprobe. It occurs, with other sulphides and quartz, in both vugs and veinlets. Chalcopyrite is rare and is present principally as minute inclusions in sphalerite, although very occasionally it also forms small discrete crystals. Uncommon inclusions in sphalerite are arsenopyrite, and in a sample from Br 7 a silver telluride, cobaltite and nickeliferrous glaucodot (Browne, 1969).

Spectrographic analysis of galena from Br 7 by W. C. Tennant, Chemistry Division D.S.I.R. shows it contains over 100 ppm Ag. Galena usually forms small euhedral crystals but in veinlets is often intergrown with sphalerite.

In the more impermeable rocks where the sulphides usually form veins, textures vary, but it is apparent that pyrite was the first formed sulphide. Sphalerite often encloses galena but locally galena appears to be late. In the more porous rocks, where the sulphides form small disseminated euhedral crystals lining vugs, it is possible that they formed contemporaneously, but

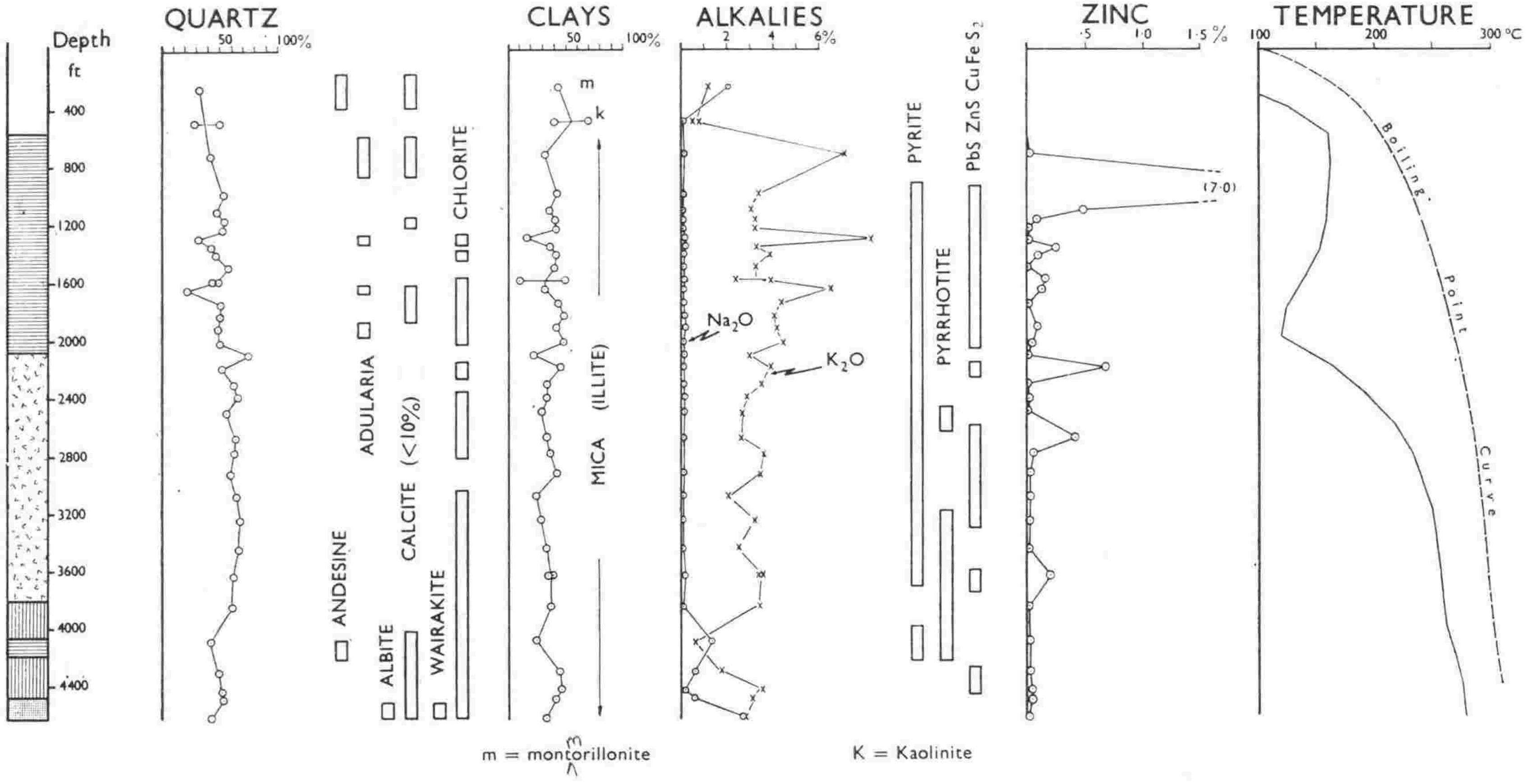

Fig. 3: Distribution of minerals in drillhole Br 16. Circles represent mineral contents of cores with straight lines arbitrarily drawn between samples. Geologic column at left has same key as Figure 2.

Table 2: Metals in Discharge Precipitates From Bores 2 and 14, the Ohaki Pool, and No. 1 Well I.I.D., Salton Sea

concentrations in ppm unless indicated as %

	Ohaki Pool[1]	Br 2[1]	Br 14[2]	No. 1 I.I.D.[3]
SiO_2	major	major	major	major
Sb	~10%	~8%	1.5%	0.66%
Tl	630	~1000	150	not found
As	400	250	150	0.13%
Ag	500	200	25	3.1%
Zn	70	200	< 5	n.f.
Au	85	55	< 5	n.f.
Hg	2000	~200 (?)	150	n.f.
Pb	25	50	< 1	700
Fe	n.d.	n.d.	n.d.	8.6%
Cu	n.d.	n.d.	200	27.5%

[1] Weissberg (1969)

[2] Spectrographic analysis by H. J. Todd and K. R. Raxworthy, Chemistry Division, D.S.I.R.

[3] Skinner *et al.* (1967); material quoted is their band No. W-768.

elsewhere no reliable sulphide paragenesis can be established.

Hydrothermal Alteration

The non-sulphide hydrothermal minerals at Broadlands and the factors influencing their formation and stability has been described by Browne and Ellis (1970). The stability of the minerals is mainly affected by temperature, fluid composition, permeability, and to a lesser extent by original rock composition and possibly total pressure. At deep levels, in the more permeable rocks, where temperatures are between 230° and 280°, the alteration mineralogy tends to an equilibrium assemblage of K-mica, albite, K-feldspar, chlorite, calcite, quartz and, less commonly, wairakite and epidote. In cooler places siderite, mordenite, cristobalite, montmorillonite and an interlayered illite-montmorillonite are stable.

Typically, the base-metal sulphides occur in rocks which also contain pyrite, secondary quartz, illite and less commonly albite, adularia, chlorite and calcite (Table 1).

The sulphides and other hydrothermal minerals present in cores from Br 7 have been described (Browne, 1969) with the aid of a semiquantitative diagram showing the downhole distribution of minerals. In a similar manner Fig. 3 shows the distribution of hydrothermal minerals in cores from Br 16. Abundances are only relative and clay values in particular may be in error by up to 10%.

Also shown in Fig. 1 are the measured downhole temperatures, a geologic column, and Na_2O, K_2O and Zn analyses. Base-metal sulphides are more abundant and widespread in Br 16 than Br 17 (Table 1) and illite is more common in the former where it usually forms small well-crystallised spheres. Secondary quartz is also common and forms euhedral crystals in vugs and veins and also replaces the groundmass and phenocrysts of the rocks. Andesine was a primary constituent of host rocks recovered from the bores but has been wholly or partly replaced by quartz, calcite, adularia, chlorite and, most commonly, illite. It is not known if adularia was at one stage more widespread and has since been replaced by illite but if this has happened, it would suggest changing conditions of temperatures and/or fluid composition with time. Textural evidence from cores in other bores such as the clear, unetched, euhedral shape of minerals in vugs shows them to be in equilibrium with one another and with the fuids discharged.

The zinc content of recovered cores is typically low (Fig. 3) and only in part of the sample from 988 ft depth reaches over 2%. Copper is consistently low in all cores and averages about 15 ppm with a maximum of 30 ppm, but lead varies considerably. In samples without visible galena, lead is often below 10 ppm but part of the sample from 988 ft contains 20% Pb (J. L. Hunt, pers. comm.). Except for one sample, therefore, none of the Cu, Pb and Zn contents are sufficiently high for the rocks to be considered ore grade. However, samples for analysis were selected to avoid veins, and the results, particularly of cores from the dacite, may be too low.

The moderate temperature inversion toward the base of the dacite indicates that at this depth there may be an inflow of colder water but the gradual temperature increase below this suggests that heating of the rocks is by conduction.

Surface Deposits in the Broadlands Area

Surface deposits related to hydrothermal activity at Broadlands include quantities of sinter, mainly in the vicinity of the Ohaki Pool, scattered pebbles of crystalline sulphur, kaolin and several tons of aragonite formed from the fluids discharged by bore Br 6 (Browne, in prep.).

Since the initial opening of Br 14, steam discharged horizontally from the well (which does not have a silencer) has deposited a red precipitate, less than a millimetre thick, on the surface of the ground. An analysis of this amorphous, antimony rich material is included in Table 2. The inside of the silencer of Br 7, which contains base-metal sulphides at depth, was examined to see if similar material had been deposited there but none was found, indicating either than Sb is not present in significant quantity in the steam discharged or that temperatures in the silencer are too high for it to form. Nevertheless, it is clear that at least one bore which has Zn–Pb–Cu sulphides at depth discharges fluids capable of depositing Sb, As and Hg.

Weissberg (1969) described recent ore-grade metaliferous precipitates associated with current hydrothermal activity in several places of the Central North Island. These include Champagne Pool, Waiotapu; Frying Pan Lake, Waimungu and the Rotokawa area. Precipitates formed at these places, all within 15 miles of Broadlands, have variable compositions but contain As (0.4–2%); Sb (400 ppm–30%); Hg (up to 170 ppm); Tl (up to 0.5%) and Pb (10–50 ppm). He has also described a red-orange flocculent precipitate (Table 2) which appeared in mid-1957, in the Ohaki Pool and became incorporated in the depositing sinter. The water level in this pool, which is at a temperature of 95°C, fluctuates with the opening and closing of the nearby bore Br 3, clearly showing that it is connected at depth with the geothermal field. The Sb-rich material, which also contains appreciable Au and some Hg, Ag, Tl and As is mainly an amorphous sulphide ("metastibnite"). Similar coloured material has also been deposited on the walls of a smaller pool a few yards south of the Ohaki Pool and on the side of the discharge channel of bore Br 2 (Table 2).

Discussion

The occurrence of hydrothermal minerals in geothermal fields allows determination of conditions under which the associated minerals may have formed. Subsequent cooling or metamorphism has not obscured, or complicated primary depositional features.

However, although study of geothermal fields provides information about mineral deposition it aids little in solving other important ore genesis problems such as the source of the metallic constituents and the form of their transport in solution.

Duration of Thermal Activity and Heat Source at Broadlands

The duration of thermal activity at Broadlands is not known but it is probably of the order of several hundred thousand years. Grindley (1965) concluded that thermal activity at nearby Wairakei has operated for 500,000 years and a comparable duration is possible for Broadlands.

The presence of very rare grains of detrital epidote and wairakite in a core of the Huka Falls Formation indicates that thermal activity was taking place somewhere at the time of its deposition. This formation has a reported age of Late Castlecliffian to earliest Hawera (Grindley, 1965)—about 500,000 years.

As pointed out by Weissberg (1969), this length of time is more than sufficient to account for the deposition of economic concentration of metals even from very dilute solutions of low metal content.

It is generally accepted that the driving force in New Zealand thermal fields is heat from a cooling magma at depth. The composition, shape, size or depth of this magma (s) is unknown but basalt was erupted in 1886, from Mt. Tarawera, about 20 miles north-east of Broadlands. Ellis (1967), pointed out that exothermic reactions involved in the alteration and devitrification of some volcanic rocks might also contribute heat to a hydrothermal system but its exact amount would be difficult to determine.

Conditions of Sulphide Deposition

It is apparent that at Broadlands the deposition of hydrothermal minerals, including base-metal sulphides, has occurred in the very recent past and may still be continuing. Textural evidence shows that the very dilute fluids of low metal content discharging from the bores are in equilibrium with minerals at depth and the fluids themselves are capable of depositing ore-grade concentrations of gold, thallium, antimony and mercury at the surface. The temperatures of base-metal sulphide deposition vary between 120° and 298° but their distribution appears to be more structurally than stratigraphically controlled, since they occur in several formations (Table 1). However, a relationship between measured permeability and sulphide deposition has not been established.

At 260° the calculated CO_2 partial pressure at Broadlands is about 12 atmospheres and at 250° the co-existence of pyrite and pyrrhotite and absence of magnetite or hematite implies that the fugacity of S and O are $10^{-13.7}$ and less than $10^{-38.6}$ atmospheres respectively (Raymahashay and Holland, 1969). Over most of the fields, however, pyrrhotite is absent and the f_S is probably slightly higher.

Source of Metals

D/H and O^{16}/O^{18} ratio (Craig, 1963) shows that most water discharged from geothermal fields is meteoric. It is considered that this water percolates downwards, is heated by a magma and returns to the surface. However, the source of dissolved constituents in the waters is not known and these may have either been contributed by the magma or leached from rock through which the fluids move (or both). The experimental work of Ellis (1966, 1968), Mahon (1967) and Ellis and Mahon, (1966) is important in this respect. It demonstrates that water can react with rocks common in the Taupo Volcanic Zone, leaching constituents (such as chloride, ammonia, fluoride and boron) which are high in natural thermal waters.

Although no data are available on the behaviour of Zn during hot water/rock reaction, Ellis (1968) found that high chloride, low sulphide solutions were effective in extracting Cu and Pb from andesite.

Changes occurring when rocks at Broadlands are hydrothermally altered are, for the most part, not isochemical, *e.g.* the alteration of andesine adds calcium to the solution and formation of adularia requires the removal of both sodium and calcium, but it seems highly probable that under some conditions trace elements are also leached.

However, the high sulphur content in rocks from thermal fields suggests that this element may have been derived directly from the magma—a conclusion supported by the isotopic work on sulphides from Wairakei (Steiner and Rafter, 1967).

Metallic constituents in ores of the Tui Mine could not have come from the wall rocks (Weissberg and Wodzicki, 1970; Cooper and Richards, 1969). White (1968) considered that some constituents in the Salton Sea geothermal system were derived by meteoric water leaching sedimentary NaCl evaporites but the isotopic composition of lead and strontium provides evidence for deriving at least part of these metals from the delta sediments (Doe *et al*, 1966). These authors consider that up to 50% of the Pb and 20% of the Sr could be magmatic.

Transportation of Metal Constituents

Once available to solution the concentration of constituents is controlled by mineral solubility or ion exchange equilibrium for the particular temperature and pressure (Ellis, 1966). However, little is known of the form of transport of metals in waters of Broadlands composition. The ratio of total sulphide to metal in the waters is many times greater than that of the Salton Sea (Table 4) and at 260° the dominant sulphur species is H_2S (Browne and Ellis, 1970) with a lesser amount of HS^-. Barnes and Czamanske (1967) showed that bisulphide complexes of Cu, Zn, Pb, Ag, Hg, Sb and As are adequately stable at reasonable pH's in solutions of high sulphur/metal ratios, and Weissberg (1969) considers that transport of As, Sb and Hg is most likely in the form of sulphide or bisulphide complexes, especially at lower, near surface temperatures. He does not, however, exclude the possibility of other mechanisms such as chloride complexes. In more recent (1970) work he has also demonstrated that Au may be transported by comparatively dilute sulphide solutions.

Both sphalerite and galena are relatively soluble in weakly acid chloride brines (Helgeson, 1964), but

Table 3: Composition of Ohaki Pool Water, Waters From Br 7 and Br 16 Drillhole Discharges (at 99°C and 1 atmosphere pressure), Ocean Water and Salton Sea Discharge

concentrations in ppm

	Br 7[1]	Br 16[2]	Ohaki Pool[3]	No. 1 I.I.D.[4]	Ocean[4]
pH	8.55		7.0	5.2	
Cl	1823	528	1,060	155,000	18,980
Na	1300	570	860	50,400	10,500
HCO_3	910		Total CO_3, HCO_3 and CO_2 490 as CO_2	> 150	140
K	234	85	82	17,500	380
Ca	n.d.	10.52	2.6(?)	28,000	400
Li	15		7.4	215	0.17
As	9		3	12	0.003
SO_4	6		100	5.4	2,650
Sb	1.5		0.3	0.4	0.0005
Fe	n.d.	n.d.	n.d.	2,290	0.01
Zn	0.015		n.d.	540	0.01
Cu	0.012		n.d.	8	0.003
Tl	0.010		0.0003	1.5	< 0.00001
Pb	0.005		n.d.	102	0.00003
Mn	n.d.	n.d.	n.d.	1,400	0.002
Ag	0.002		0.0006	1.4	0.0003
Au	0.0001 –0.001		≤ 0.00004	0.0	0.000004

[1] Browne (1969)
[2] Analysis by W.A.J. Mahon and B. Finlayson, Chem. Div. D.S.I.R.
[3] Weissberg (1969)
[4] White (1968)

the chloride content of Broadlands waters is only about 1200 ppm and the pH is not low (Browne and Ellis, 1970).

Another possibility is the transport of metals in carbonate or bicarbonate complexes. Little is known of their behaviour, but it may be significant that no base-metal mineralisation has been found at Wairakei and the underground CO_2 concentration is about 0.01 m compared with 0.15 m at Broadlands (Browne and Ellis, 1970).

Causes of Deposition

In common with most other hydrothermal ore deposits the cause(s) of base metal sulphide deposition are largely speculative and the following conclusions are necessarily tentative. A lowering of temperature and change of pressure as the ascending fluid reaches cooler ground obviously affects the stability of metal complexes. For example, Helgeson (1964) has shown that the solubility of galena and sphalerite in weakly acid chloride brines is markedly dependent on temperature, and it is apparent that Sb, Hg and As precipitate at the surface, because of a sudden decrease in temperature or loss of H_2S by boiling. Although deposition of base metal sulphides in the lower parts of Br 16 may be due solely to lowering of temperature, the sulphides are not especially abundant at about 2000 ft where there is a marked temperature inversion. This implies that another mechanism must cause deposition in shallower rocks of this bore. Boiling was considered by Browne (1969) to have resulted in the deposition of adularia and base metal sulphides in Br 7 by loss of CO_2 and H_2S with consequent change of pH. Weissberg (1969) has pointed out that boiling will also increase the activity of HS^- and S^{2-}, enhancing the solubility of any As, Sb, Hg and Au complexes but possibly causing the precipitation of Cu, Pb and Zn which form only weak HS^- complexes. However this process requires that H_2S is not boiled off. If the metals are transported as carbonate complexes then loss of CO_2 on boiling and pH change will undoubtedly affect their stability although the extent is not known. However, in Br 16, boiling temperature for a particular depth is greater than the measured downhole temperatures (Fig. 3) which means that if mineral deposition by boiling occurred, rock temperatures have since dropped several degrees. Another possibility is that intermixing of groundwater and thermal water affects the stability of the metal complexes and in the region of mixing results in the deposition of sphalerite and galena. Again, exactly how mixing would cause deposition other than by lowering temperature or dilution is not known. The present Waikato River is less than one mile from Br 16 and cores from shallower levels where base-metal sulphides occur are brecciated and fractured.

A multiple cause of metal deposition is therefore proposed—in places deposition solely by lowering the temperature and pressure of the ascending fluid; elsewhere by boiling, loss of CO_2, H_2S and concurrent change of solution pH, and in shallower levels, *e.g.* in the vicinity of Br 16, by intermixing of river and thermal waters.

Comparison of Metal Mineralisation at Broadlands and the Salton Sea Geothermal Fields

Although a relationship between thermal waters and mercury deposition has been observed in many parts of the world (White, 1967), known occurrences of base metal sulphides in active geothermal areas are few. Probably the best known of these is the Salton Sea geothermal system in the Imperial Valley, Southern California. A comparison between this field, its base-metal sulphide occurrences and those of Broadlands is summarised in Table 4.

The geological and structural settings are, in some respects, similar, but major differences are in the sulphide occurrences and the composition of the discharged fluid. At the Salton Sea, the extremely saline, metal-rich brines deposited material in surface pipes consisting predominantly of copper and silver minerals mixed with amorphous silica, but sphalerite and galena are absent although present in some recovered cores (Skinner, *et al*, 1967). By contrast, fluids discharged from Broadlands have low salinities, and metal contents (Table 3) several orders lower than those of the Salton Sea. Base-metal sulphides occur only in the subsurface rocks and there is no evidence of their having formed in discharge pipes.

One important difference in fluid composition is the high metal/sulphur ratio in the Salton Sea discharge which appears to have been of importance in determining the type of metal sulphide precipitated in the pipes. (Skinner *et al*, 1967; White, 1968). Although fluids discharged by Broadlands bores also have low sulphur contents, the approximate metal/sulphur ratio is many times lower than that of the Salton Sea.

Comparison of Broadlands and Tui Mine, Coromandel Mineralisation

The base metal sulphides and associated minerals at Broadlands are similar to many supposed hydrothermal ore bodies, such as the Tui Mine, Te Aroha, Coromandel (Table 4). Some minor differences, however, reflect changes due to the waning of thermal activity at the Tui Mine.

The geology of this deposit has recently been described by Weissberg and Wodzicki (1970) and Wodzicki and Weissberg (1970) who emphasises the importance of structural control in localising ore deposition. They explain the complex textures of the ores by periodic fault movement allowing access of separate pulses of thermal fluid.

At the Tui Mine, cinnabar is present along joint planes and was clearly deposited at a late stage when temperatures were declining. However, unlike Broadlands, there is no evidence establishing the contem-

Table 4: Comparison of the Salton Sea and Broadlands Geothermal Fields, and Their Related Sulphide Mineralisation With the Tui Mine, Coromandel

	Broadlands	Salton Sea	Tui Mine
Dominant lithology	Silicic volcanics of Pliocene and Quaternary age	deltaic sediments of Pliocene and Quaternary age	Andesite, minor dacite lava and breccia. Ignimbrite of Miocene age
Depth to 'basement'	varies between 3100 and 7600 ft	over 14,000 ft	not known; basement is folded mesozoic greywacke
Structural Setting	regional downwarp zone, normal faulting common	regional downwarp zone, normal faulting present	part of horst block; normal faulting common
Primary Mineralogy	quartz, andesine, glass and minor biotite, hornblende, magnetite and pyroxene	detrital quartz, calcite, K-feldspar plagioclase, montmorillonite, illite, dolomite and kaolinite	andesine, pyroxene, hornblende, magnetite
Measured maximum temperatures	298°C	360°C	—
Natural surface discharge	about 20 litres/sec	about ¼ litre/sec	nil
Duration of geothermal activity	uncertain, probably greater than 200,000 years, possibly about 500,000 years	unknown	unknown
Mineralogy:			
Common hydrothermal minerals	albite, K-feldspar, quartz, calcite, chlorite, illite, montmorillonite, wairakite, mordenite, epidote	ankerite, illite, chlorite, calcite, epidote, K-feldspar, hematite	four zones around ore I magnetite altered to pyrite, pyroxene partly altered to chlorite II pyroxene completely altered and andesine replaced by adularia III alteration of adularia to sericite, abundant quartz IV alteration of silicates to kaolin. Also present are: calcite, epidote, montmorillonite, albite, wairakite
Metals deposited from bore discharge	minor, some pyrrhotite in liner of Br 1, Sb rich precipitate from Br 14	major; several tons of amorphous silica with Cu(20%) and Ag(up to 6%) including digenite, bornite, chalcocite, 'dense' chalcocite, stromeyerite, arsenopyrite, tetrahedrite, chalcopyrite, pyrite and native silver. No Sb deposited	—
Metal sulphides in rocks	sphalerite, galena, chalcopyrite, pyrite and pyrrhotite	major; pyrite, minor: some sphalerite and chalcopyrite, minor galena and pyrrhotite in core from 6603–6612 ft; No. 1 River Ranch well (Skinner *et al.* (1967)): chalcopyrite occurs sporadically from 2000–5232 ft as veinlets; in I.I.D. No. 1 sphalerite as irregular masses (Muffler and White, 1969)	pyrite, sphalerite, galena, chalcopyrite, tetrahedrite and traces of cinnabar in lodes along two faults. Base metal sulphides not disseminated

Mineralogy:			
Probable temperature of most sulphide deposition	130–290°C (± 5°) in rocks	130 (± 20)°C–220°(± 30)°C in pipe scale 220° to 300°C in rocks	280°, based on S isotope fractionation between galena and sphalerite
Fluid Composition:			
Approx salinity of discharged fluids	4.3 °/oo	226 °/oo	—
Estimated underground pH	6.0 (at 260°)	4.6	—
Typical total metal content of discharged fluid	11 ppm (Cu + Pb + Zn = 0.05 ppm)	4400 ppm (Cu + Pb + Zn = 650 ppm)	—
Typical total S content of bore discharge	about 120 ppm	30 ppm	—
Total metal/sulphur in discharged fluid	approx 0.1	140	—

Salton Sea data from Skinner *et al.* (1967); White (1968); Muffler and White (1969); Helgeson (1968).
Broadlands from Browne and Ellis (1970), Grindley and Browne (1968) this report.
Tui Mine information from Weissberg and Wodzicki (1970).

poraneous deposition of volatile-metal and base-metal sulphides.

Other minerals considered to be of retrograde origin in the Tui Mine are kaolinite and montmorillonite whereas as at Broadlands these are stable in the cooler parts of the field. The alteration of adularia to sericite may also reflect declining thermal activity but the rarity of wairakite and albite compared with Broadlands is probably due to differences in fluid composition.

Acknowledgments

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Sulfide Mineralization in a Broadlands Geothermal Drill Hole, Taupo Volcanic Zone, New Zealand

P. R. L. Browne

Abstract

Base-metal sulfides have been deposited in rocks penetrated by a Broadland Geothermal drill hole. They occur in a permeable, silicified and fault-brecciated zone where the measured temperature is between 272 and 276° C. Textural evidence suggests that they are in equilibrium with the slightly saline solution of low-metal content now being discharged.

Introduction

In the course of geothermal power development based on natural high-temperature water areas in the Taupo Volcanic Zone in the North Island of New Zealand, over 150 holes have been drilled since 1950. Although the observed hydrothermal mineral assemblage is similar to that commonly associated with base-metal sulfide deposits in many parts of the world (Meyer and Hemley, 1967), only 3 drill holes in the Volcanic Zone have shown galena and sphalerite mineralization. These are at 270 m and 230° C in Hole W7, Waiotapu (A. Steiner, B. G. Weissberg, personal communication), and from Holes Br7 and Br10 recently drilled at the Broadlands Geothermal Field.

The Broadlands-Ohaki (Fig. 1) geothermal area, about 3 km in diameter, is located on both banks of the Waikato River, some 22 km, northeast of Wairakei—the site of New Zealand's first geothermal power station. To date 12 investigation holes, between 760 and 1,396 m deep, have been drilled and in Br7 and Br10 in the south-east part of the field, base-metal sulfides have been encountered. Natural surface activity in the vicinity of these drill holes is limited to a few warm springs with a total water flow of less than 2 liters/sec (Grindley and Browne, 1968).

Geology and Mineralization

The approximate downhole distribution of major primary and secondary minerals associated with the base-metal sulfides in Br7 is shown in Figure 2. This information, based on 26 core samples, was obtained by thin section examination, infra-red spectrometry, D.T.A., and a quantitative X-ray diffraction method similar to that used by Tatlock (1966). Figure 2 also shows a generalized stratigraphic column and the temperature-depth curve.

Loosely consolidated sands, tuffs, and tuffaceous sediments 142 m thick overlie rhyolite flows totalling 481 m that have been altered to varying degrees by hydrothermal solutions. The upper part of the top sheet of rhyolite has been extensively altered to quartz, clay, pyrite, and leucoxene, but the lower part is denser and relatively less permeable, clearly serving as a "cap" to high temperature water contained in the rocks beneath. Below the upper rhyolite is a pumiceous tuff 96 m thick, which probably functions as an aquifer, and a lower sheet of rhyolite 202 m thick underlain by 15 m of crystal tuff, both of which contain the bulk of the base-metal sulfides. Below 936 m, relatively unaltered graywacke and argillite sediments, although reworked in the upper few meters, probably form part of the "basement" rocks of the area.

Sphalerite occurs in all the drill cuttings, taken at approximately 3 m intervals, between 802 and 943 m, at 955 m, and also in cores from 809, 839, 880, and 925 m. Galena, although less abundant overall, accompanies sphalerite in most drill cuttings but chalcopyrite is present mainly as exsolution "blebs" in sphalerite. Some sphalerite also contains microscopic and submicroscopic inclusions (identified on an electron microprobe) of a silver telluride, cobaltite, and nickel-rich glaucodot, all apparently formed by exsolution. Pyrite is present at virtually all depths, including the base-metal zone, but co-existing pyrrhotite is rare. Measured temperatures in the mineralized zone range from 272 to 276° C. The base-metal sulfides vary from less than 0.5 to 5 percent and are apparently concentrated in small fissures marked by euhedral quartz crystals. In core samples, the sphalerite and galena form either thin, regular or irregular veins, which vary from 1–2 mm in width, or small euhedral crystals up to 1 mm in diameter lining cavities.

Hole Br10 is about 500 m north of Br7. Drill cuttings from depths of 953, 972, 1,014, 1,025, 1,027, and 1,045 m, where the temperature is between 265 and 275° C, contain galena, sphalerite and chalcopyrite.

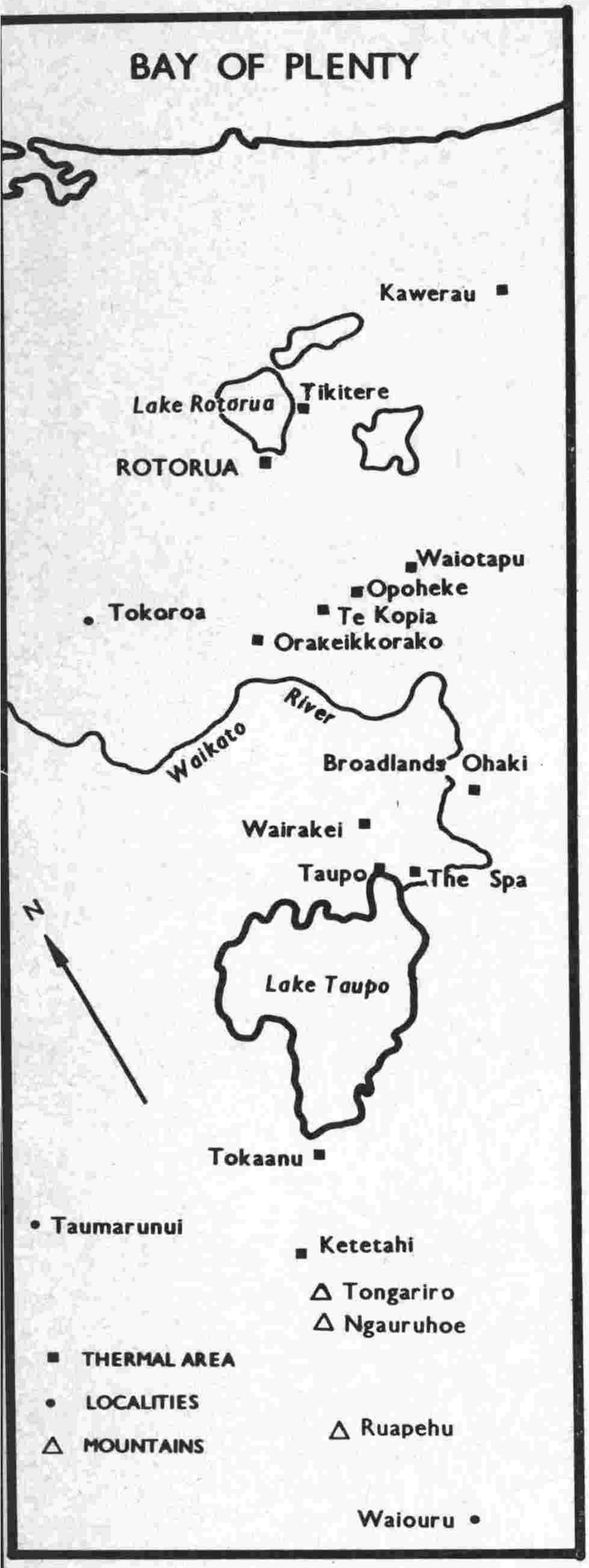

FIG. 1. Location of Hydrothermal Areas, Taupo Volcanic Zone, North Island, New Zealand (from Steiner and Rafter, 1966). Corrected spelling is Orakeikorako.

Textural relationships between the sulfides in Br7 suggest an early generation of pyrite enclosed, but not replaced, by sphalerite. Sphalerite commonly encloses galena, but the reverse is not uncommon. Although some pyrite crystals contain zones of minute black inclusions of unknown composition, suggesting minor variations in depositional conditions, the textures indicate that most of the sulfides crystallized together.

The rocks containing the base-metal sulfides have been extensively altered by hydrothermal solutions (Fig. 2). They are highly silicified, containing small, clear, euhedral quartz crystals and "globules" of well crystallized sericite lining fractures and partly filling cavities in the rhyolite. Some of these cavities have been formed by the removal of plagioclase phenocrysts. Adularia (in crystals up to 6 mm), calcite, and iron-rich chlorite (rarely as small euhedral green booklets) have also been deposited in the mineralized zone. Minor secondary amphibole (tremolite?) locally forms pseudomorphs after plagioclase or hornblende. The rhyolite and crystal tuff in the mineralized zone have been extensively fractured and fault-brecciated, forming feeding fissures for the fluids that deposited the secondary silicate and sulfide minerals. These fissures now provide the 30,000 kg/hr of steam being discharged from the drill hole.

Conditions of Deposition

The significance of the Broadlands sulfides is the probability that they formed in geologically Recent time and prior to drilling were in equilibrium with solutions very similar to that analyzed (Table 1) and at temperatures close to those measured (Fig. 2). The absence of definite replacement textures and the perfectly euhedral, uncorroded shape of the sulfide and silicate minerals where they have been growing together in cavities indicates that they are in equilibrium with one another and with water of the composition now being discharged. Mineral deposition in the fractured, near-surface, permeable rocks in Br7 is probably caused by the formation of steam, loss of CO_2, and sudden change of pH as the ascending fluid reaches its boiling pressure. An analysis of the water separated at atmospheric pressure from the mixed steam/water discharge is given in Table 1. The water is similar in composition to those from other New Zealand geothermal fields and, in particular, to the other Broadlands and Ohaki drill holes (Ellis and Mahon, 1968). Drill hole Br2, for example, which in April 1968 discharged 88,000 kg/hour of steam and 177,000 kg/hour water, produces water

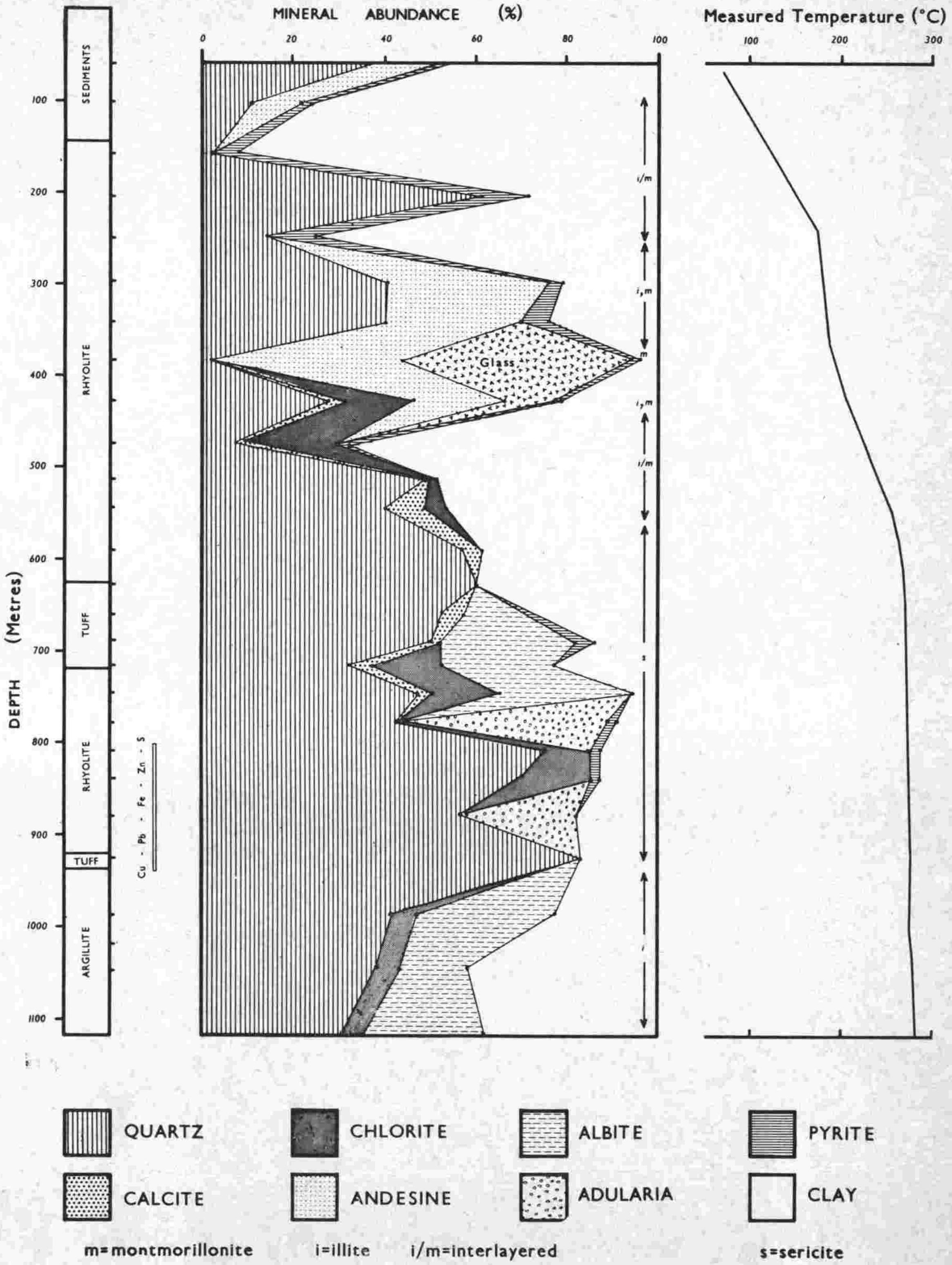

FIG. 2. Generalized geological column, graph of measured downhole temperature and approximate distribution of hydrothermal minerals associated with base-metal sulfides in drillhole, Br 7. Straight lines have been arbitrarily drawn between core samples.

TABLE 1. *Analysis of Water Separated at Atmospheric Pressure from Discharge (enthalpy = 546 gm-cal/gm) of Broadlands Drill Hole, Br 7*
May 1968

pH = 8.55 Constituent	Concentration (ppm)	Constituent	Concentration (ppm)
Cl	1,823	Cu	0.012
Na	1,300	Tl	0.010
HCO_3	910	Pb	0.005
K	234	Ge	0.004
CO_3^{--}	34	Ag	0.002
Li	15	Sn	0.0005
As	9	Au	0.0001–0.001
SO_4	6	Ni	0.0004
Sb	1.5	Bi	0.0003
W	0.03	Co	<0.0001
Zn	0.015	In	<0.00005

Analysts: A. J. Ellis, J. A. Ritchie, and W. C. Tennant, Chemistry Division, D.S.I.R.

with a similar concentration of major elements (Ellis and Mahon, 1968) to Br7 water. The former (Ellis, personal communication) is lower relative to Br7 by a factor of 2–3 for Zn, Ag, and Pb, and by a factor of about 10 for Au and Sb, but it is enriched in Cu by a factor of about 10. Both Br7 and Br2 have much lower concentrations of metallic constituents than the high-temperature Salton Sea brine (Helgeson, 1967), that produced a remarkable deposition of base-metal sulfides in drill pipes during discharge.

White (1967) suggests that base-metal sulfide deposition may, in general, be connected with Na-Ca-Cl brines, but present observations suggest that deposition can also occur, over long periods of time, from slightly saline solutions of low metal content. According to Grindley (1966), hydrothermal activity in the Wairakei area may have begun in the middle Pleistocene, and there is evidence (Grindley and Browne, 1968) to suggest that the Ohaki-Broadlands field may have been active for a comparable length of time. This would certainly be long enough to deposit the observed base-metal sulfides.

Ellis (personal communication) has shown from experimental work that the metals in the hot solutions could be leached out of rocks and that their concentration level is governed by the ~~solubility~~ salinity and consequent pH of the solutions. However, Steiner and Rafter (1966) consider, from isotopic evidence, that the sulfur originates from a magmatic source.

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Factors Influencing Hydrothermal Alteration

The formation and stability of hydrothermal minerals are influenced by: (1) temperature, (2) permeability and porosity, (3) rock type, (4) fluid composition, (5) total pressure, and (6) water flow and time for reaction. Of these, temperature, rock composition and permeability are the most important factors in a static system.

Temperature.

It is apparent from Table 5 that the temperature at which a mineral first forms varies from drillhole to drillhole because of various factors. There is, however, a temperature range for the Broadlands system outside which a mineral will not form or persist under the natural hydrothermal conditions, and Tables 5 and 6 indicate this range. For example, it is apparent that calcite and pyrite are less sensitive to temperature than are the zeolites, clays, siderite, cristobalite, and albite.

Below 1200 m depth, temperatures may reach 298°, but over most of the field, including production zones, temperatures vary between 220° and 270°. The phase diagrams (Figs. 12-15), referring to a temperature of 260°, are therefore applicable to common measured subsurface conditions. Temperatures generally increase with depth, but several inversions occur, notably in Br 6 where at 60 m the temperature is 160°, but at 670 m is only 49° (Fig. 19).

Pressure.

Over the depths drilled the moderate pressures of up to about 200 bars in excess of water vapour pressures are unlikely to have a major effect on formation of mineral assemblages. However, White and Sigvaldason (1963) suggested epidote formation may be a function of depth. Indirectly, total pressure is a very important variable as it determines the depth and temperature of boiling, a process that changes fluid composition and in turn affects mineral stabilities. Possibly the pressure changes on an ascending fluid may be sufficient to alter the stability of sulphide complexes (Barnes and Czamanske, 1967) but quantitative data on the effect of pressure in water/mineral equilibria are scarce. Ellis and McFadden (1972) reported partial molal volume data for ions important to natural hydrothermal equilibria. From this they calculated the effect of pressure on some equilibria. For example, a fluid buffered by mica-feldspar, would become slightly more acid as it ascends and this in turn would affect calcite solubility. This effect is much more important than the near zero effect of pressure on the reaction $2H^+ + CaCO_3 = Ca^{2+} + CO_{2aq} + H_2O$.

Permeability

Permeability has an important control on the formation of hydrothermal minerals, since mineralogical changes are for the most part not isochemical, and although some water is available in pore spaces, the rocks must be open for the addition and removal of constituents. It is apparent that generally the more dense, impermeable rocks, such as rhyolite and ignimbrite are little altered, even at high temperatures. For example, in some places there is incomplete alteration of andesine to calcite, clay, quartz, or albite, whereas in cores from more porous, permeable zones, reaction is complete. In some fissure zones, for example, Br 7 at 844 m and Br 2 from 506 to 634 m, where there is good permeability and a continuous flow of fluid, quartz, calcite, and adularia are abundant. These are zones of boiling, and as discussed by Browne and Ellis (1970) these minerals precipitate through the water trying to adjust its composition toward that for an equilibrium assemblage stable at the higher pH and a lower temperature. In the reprint following (Browne, 1970), the relationship between hydrothermal mineralogy and permeability has been used to identify probable production zones, estimate bore output and determine the hydrological function of subsurface formations.

Rock composition

At Broadlands the influence of rock type on hydrothermal alteration is mainly through texture and porosity variations affecting permeability. Most of the rocks, except the basement greywackes and argillites, are chemically and mineralogically similar, containing primary quartz and andesine but not K-feldspar; thus variation in original rock chemistry is not especially significant during hydrothermal alteration. However, the maximum quantity of albite which forms during alteration, is in almost all places controlled by the amount of primary plagioclase initially present in the rock.

Water composition

Browne and Ellis (1970) attempted to correlate core mineralogy with underground fluid composition by means of mineral stability diagrams.

For a silica saturated solution at 260°, they considered the following systems:- K-Ca-H, Na-Ca-H, Ca-Mg-H and Na-K-H. Although these diagrams gave no new information they were used to interpret fluid behaviour from drillhole mineralogy. The diagrams are reproduced below (Figs. 12-15) and are referred to in the discussion on alteration of cores from drillholes Br 2, 4-6, 9-15, 17-25 (p. 79-104).

The reason for the rarity of epidote and wairakite at Broadlands was explained by Browne and Ellis (1970) in terms of variations in carbon dioxide activity; high CO_2 pressures favoured the precipitation of calcite and restricted the growth of epidote and wairakite (Figs. 12-14b). This conclusion agrees with the recent experiments and thermodynamic calculations of Liou (1971) and Thompson (1971a, b).

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Hydrothermal Alteration as an Aid in Investigating Geothermal Fields

P. R. L. BROWNE *

ABSTRACT

In geothermal fields drillhole performance depends on underground temperature and permeability conditions. Hydrothermal minerals, formed by hot-fluid/rock reaction, are partly related to temperature and permeability and their identification thus aids in geothermal investigations. At Broadlands-Ohaki, some hydrothermal minerals, notably feldspars, assist in estimating the steam-producing capacity of a drillhole, in determining production depths and in defining the hydrological functions of different geological formations. Good steam-producing drillholes are characterized by cores containing adularia and occasionally abundant quartz and calcite; moderate steam producers by albite and adularia; and poor or non-producers by albite or unaltered andesine. Reasons for this observed relationship are given and it is suggested that similar, although not identical, steam-indicating minerals may be used in investigating other geothermal fields.

Introduction

Drill cores from the Broadlands geothermal field have been recovered at regular intervals and their petrography examined. Identification is important for rock drillhole correlations and, furthermore, the nature of the secondary (hydrothermal) minerals in these cores often provides information about underground temperatures and permeability. The primary minerals in rocks of the Broadlands geothermal field react with the hot geothermal fluid to form hydrothermal minerals which are preserved when cores are taken. At Broadlands the type of hydrothermal mineral which forms at a given depth depends on several factors, particularly temperature and permeability and, to a lesser extent, fluid composition. Pressure over the drilled depths is important mainly because of its effect on depth of boiling, while differences in rock chemistry are too slight to significantly affect the alteration mineral assemblages.

At Broadlands, the determination of the type of hydrothermal minerals formed in response to geothermal conditions has helped field investigations in the following ways:

1) - As an aid in determining the hydrological functions of the subsurface formations, i.e., to help distinguish permeable from impermeable units.

2) - To estimate the output of a bore before its initial discharge.

3) - To determine the location of probable or possible production zones. This includes identifying fracture zones, deciding optimum casing depth without significant loss of production and recommending places where increased steam production could be obtained by perforating the drillhole casing.

In the early bores, the relationship between permeability and hydrothermal alteration was determined by correlating observed mineralogy with the output, temperature, circulation losses during drilling and permeability. Thus, at present it is possible to determine permeability from the hydrothermal mineral assemblages observed in recovered cores.

Important assumption about use of hydrothermal alteration in geothermal investigations

In relating hydrothermal alteration to underground permeability and temperatures, it is assumed that the permeability relates to hydrothermal mineral assemblages under existing conditions. A *fossil* or cooling geothermal field, however, may be recognised by the presence of superposed retrograde mineral assemblages as, for example, in the Tui Mine, Coromandel, New Zealand, where waning of geothermal activity is suggested by the alteration of adularia to sericite and the occurrence of retrograde illite-montmorillonite and kaolin together with adularia (WEISSBERG and WODZICKI, 1970). At Broadlands, however, no definite evidence of a decline in the level of hydrothermal activity has been found except, possibly, in a few cores from shallower levels of Br 16.

Hydrothermal minerals at Broadlands

The hydrothermal minerals at Broadlands have been described briefly by GRINDLEY and BROWNE (1968), BROWNE (1969) and, more recently and in greater detail, by BROWNE and ELLIS (1970).

Many hydrothermal minerals have formed in the Broadlands geothermal field but most are of little use in estimating subsurface temperatures and permeability. Some, such as chlorite, pyrite, calcite and quartz, are common and stable over a wide temperature range, although the stability of calcite is greatly affected by un-

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derground CO_2 pressure (BROWNE and ELLIS, 1970). Other hydrothermal minerals, including mordenite, siderite and cristobalite which form at low temperature, and epidote, which forms at high temperature, are not greatly affected by permeability. Clay minerals are abundant and widespread except for kaolin which has only a limited distribution. With increasing temperature (and usually depth) there is a general sequence montmorillonite → interlayered montmorillonite → illite (rich in montmorillonite) → interlayered illite → montmorillonite (rich in illite) → illite but, although temperature sensitive, the clays are not a good guide to permeability.

The most important minerals relating to steam investigations are the feldspars, since they are sensitive to both temperature and permeability. With increasing steam production, the feldspar mineralogy changes as follows:

1) Primary andesine; 2) albite; 3) albite + adularia; 4) adularia.

Andesine is (or was) the only primary feldspar in most rocks of the field and alters at temperatures between 70 and 290 °C, depending on permeability, to one or more of the following minerals: quartz, clay, calcite,

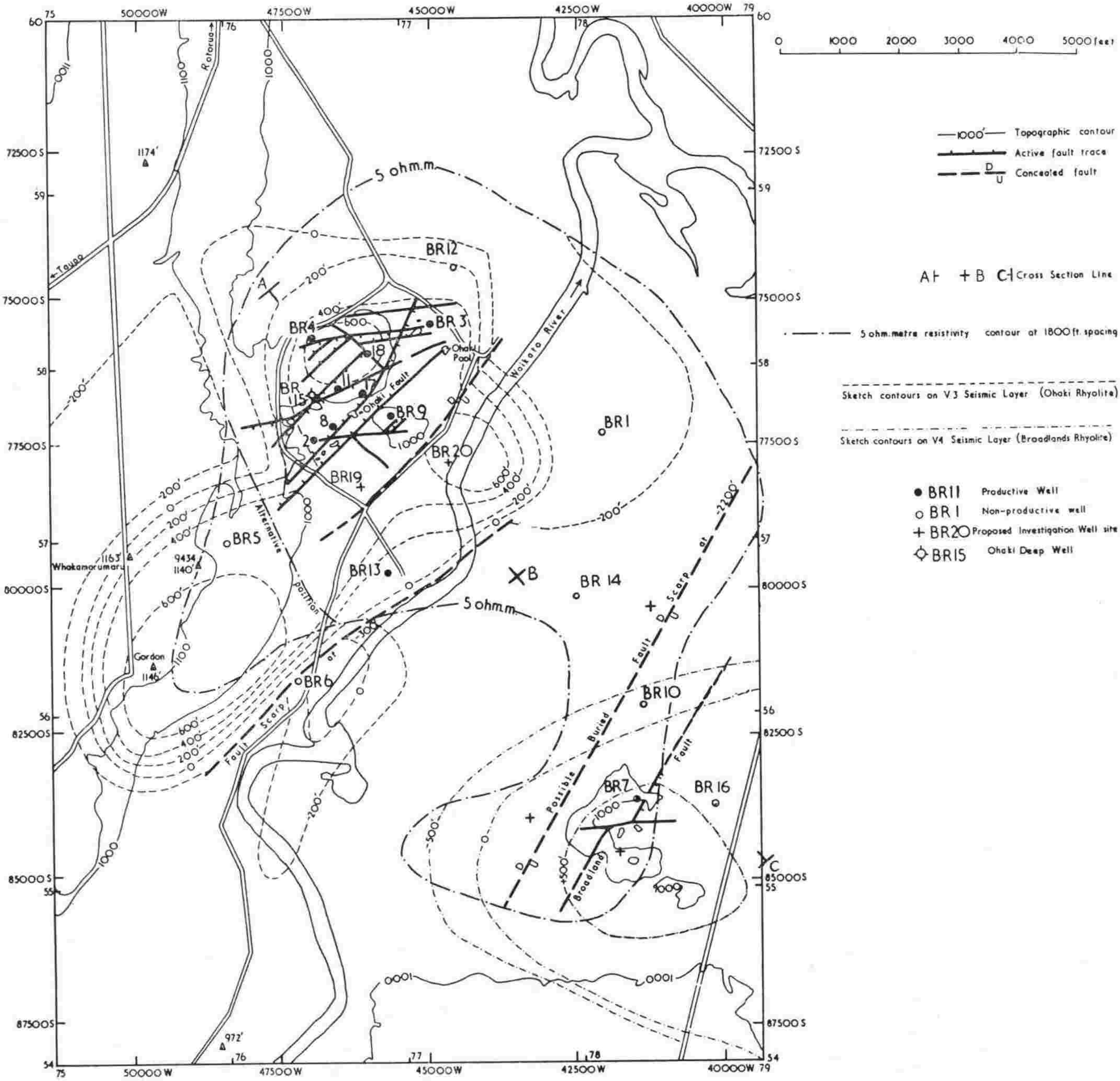

FIG. 1 — *Map of Broadlands geothermal field showing major structural features inferred from photogeology, seismic surveys and drilling.*

albite or adularia. Albite forms only as a replacement of andesine, generally above about 230°C, and does not occur in veins. Its calcium content varies and in places may reach An_{15} but its lower refractive index and clouded appearance serve to distinguish it from andesine. Adularia may also replace andesine either alone, or together, and in equilibrium, with albite. Adularia also occurs as minute crystals in the groundmass of some

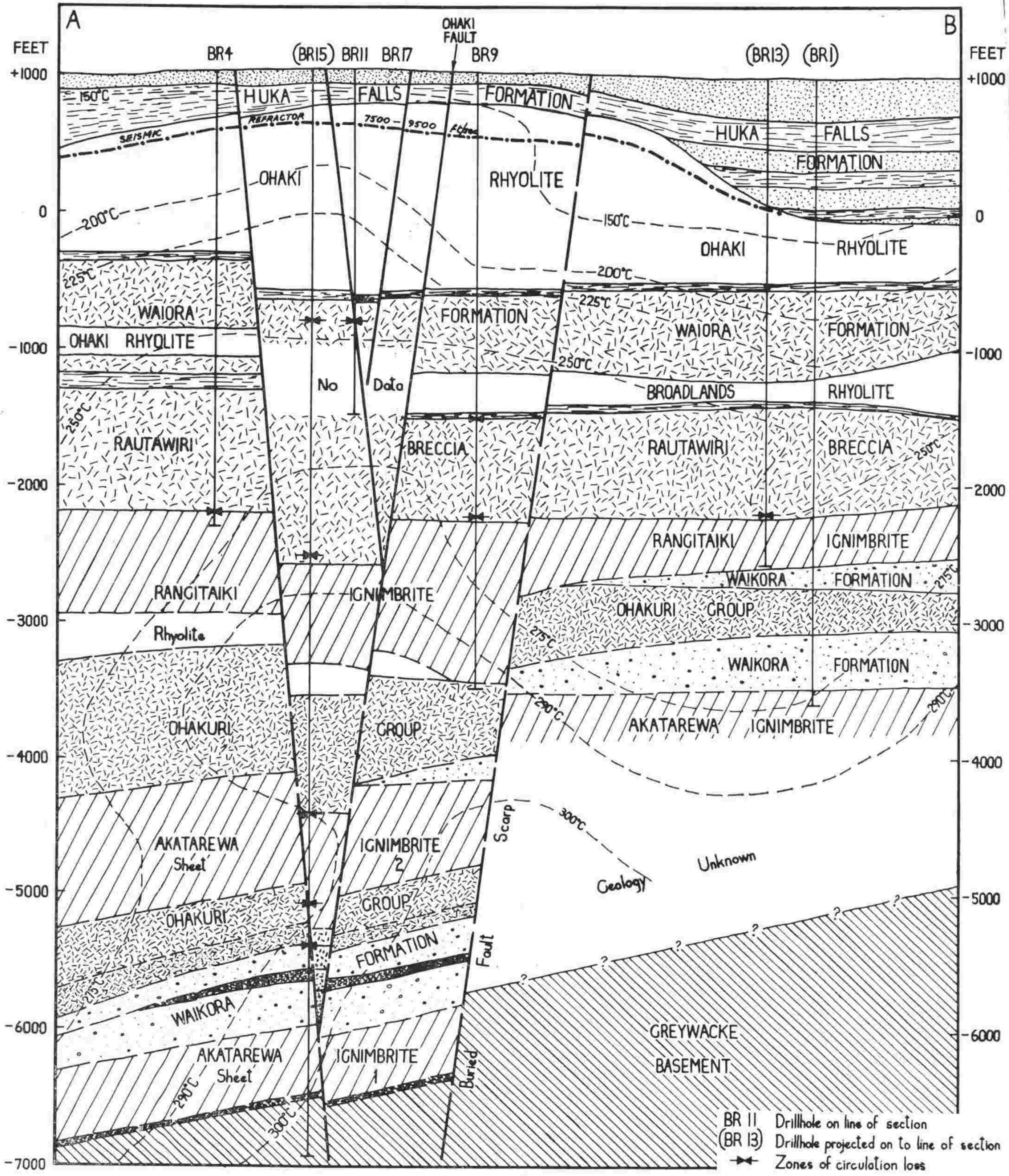

FIG. 2 — *Cross-section of Ohaki geothermal area. Broadlands geothermal field.*

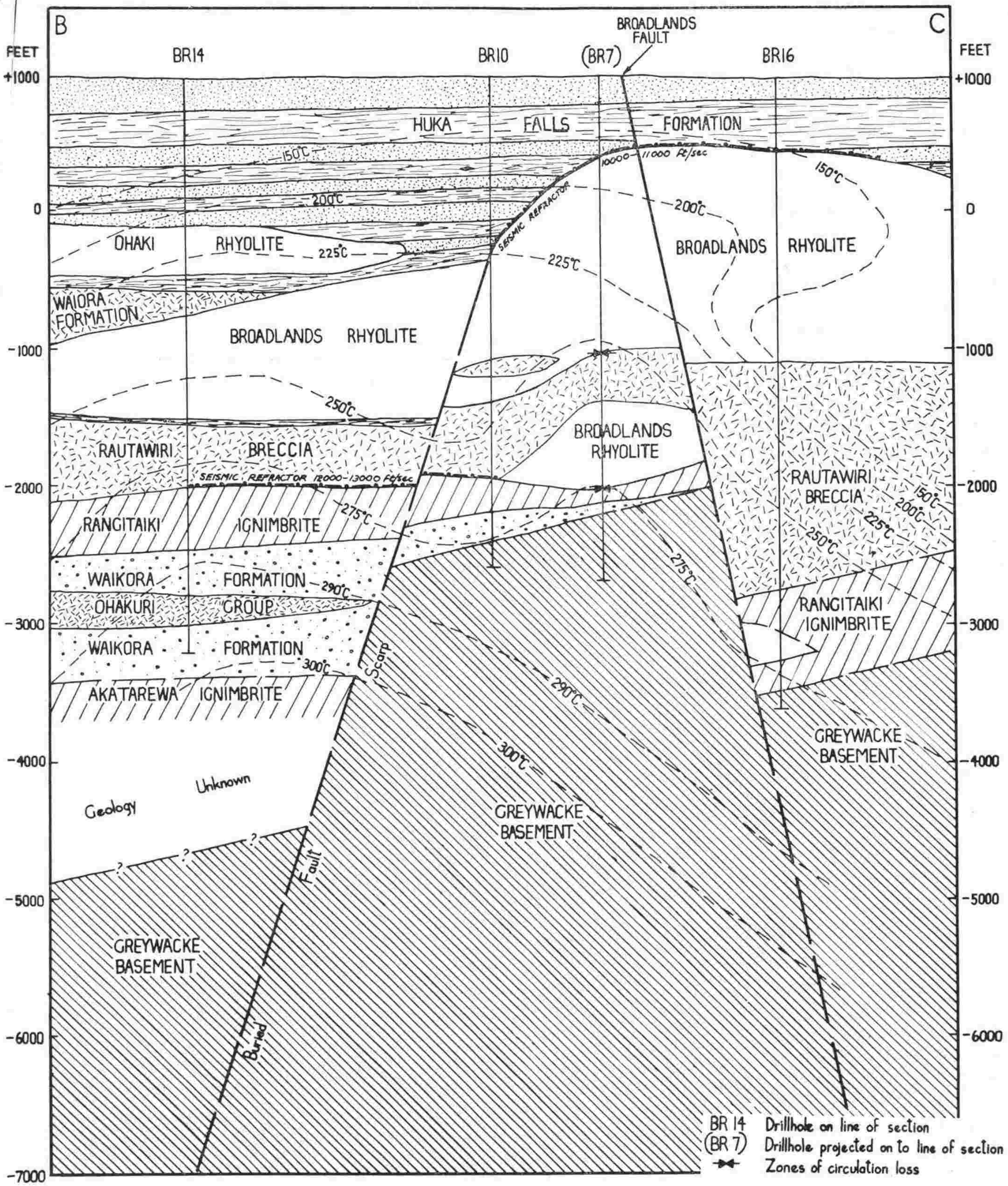

FIG. 3 — *Cross-section of Broadlands geothermal area. Broadlands geothermal field.*

shallower rocks, where there has been considerable introduction of potassium, and lining fractures where it has undoubtedly been deposited directly from solution. Cores from good production zones contain *abundant* secondary quartz, and in places calcite in addition to adularia.

Another mineral which is sensitive to both temperature and permeability is pyrrhotite which occurs above 180°C (Browne and Ellis, 1970) but its distribution is restricted to impermeable zones. It does not usually coexist with adularia, owing to the relatively high oxidation potential (Meyer and Hemley 1967).

Geology and hydrology of Broadlands geothermal field in relation to hydrothermal alteration

The subsurface geology of the Broadlands geothermal field has been described by Grindley and Browne (1968) and Healy (1968 a, 1968 b). It consists of a sequence of Quaternary, horizontal and near horizontal rhyolites, dacites, ignimbrites, tuffs and interbedded volcanic — and greywacke — derived sediments, all overlying a westward dipping basement surface cut in Mesozoic greywacke and argillite (Figures 2,3). The hydrological sequence consists of alternating permeable and impermeable formations locally disrupted by faults and possibly dikes which provide steep channels for the transport of the geothermal fluid. Porous formations such as tuffs and pumice-breccias are usually more permeable than the denser formations of ignimbrite, rhyolite and the fine-grained sediments, all of which function primarily as cap rocks. Consequently the typical hydrothermal minerals formed in the porous, permeable aquifers differ from those found in the impermeable formations.

Table 1 summarizes the content, thickness and typical alteration mineralogy of some of the formations shown diagrammatically in Figures 2 and 3, and also shows their usual hydrological functions as determined from drillhole data. It can be seen that the two main aquifers in the system are the Waiora and Rautawiri Breccia formations and these in fact provide the bulk of the steam production from the high output boreholes. Cores from both formations typically contain adularia which is absent from the interbedded impermeable formations. However, superimposed on this aquifer-cap system are several faults — the most important in the vicinity of Br's 2, 3, 8 and 11 where there appears tc be a broad fracture zone intersected by drillholes mainly between 1500 and 2000 ft. Fractured cores, probably formed by faulting were also recovered from the Ohaki rhyolite of Br 4 at a depth of 1100 ft and from the lower sheet of dense Broadlands rhyolite in Br 7 at a depth of 2758 ft. Steam is being produced from the latter but Br 4 is cased to below 1100 ft.

Few drillholes have penetrated below the Rangitaiki Ignimbrite to the Ohakuri Group, so that an assessment of the latter's potential as an aquifer is not possible at this stage. However, some cores from Br 15 contain adularia, suggesting deep production may be possible in places.

Hydrothermal alteration in relation to individual bore output

Table 2 lists measured output of individual Broadlands bores, shows the most common feldspars in cores from each hole, and the occurrence of hexagonal pyrrhotite. It can be seen that in bores which produce over 150,000 lb/h steam, the dominant feldspar is adularia with minor albite, usually in non-production zones. In the bores producing between 40,000 lb/h and 150,000 lb/h steam, albite and adularia are the common feldspars, while in poor or non-producers (< 40,000 lb/h steam), andesine and albite dominate. In some intermediate output boreholes, e. g. Br 3, secondary feldspars, although present, are not particularly abundant, and the andesine is more commonly replaced by clay and quartz. Nevertheless it is clear that identification of the type of feldspar recovered in cores from future drillholes will enable a qualitative estimate of probable output to be given before initial discharge. This information could be useful because it is usual to wait up to two months between completing a bore and the initial opening when output measurements are made. An immediate estimate of a bore's probable output can thus be used as an aid in selecting future drillhole sites.

Table 1. — *Some subsurface formations at Broadlands showing typical alteration mineralogy and usual hydrological function*

Formation	Content	Thickness (ft)	Adularia, usually present in high output bores	Function
Huka Falls	Lacustrine sediments, tuffs, grits	100-1100	No	Cap
Ohaki Rhyolite (¹)	Pumiceous and spherulitic rhyolite	0-1400	Occasional	Partial cap
Waiora	Pumiceous tuff-breccia	0-650	Yes	Aquifer
Broadlands Rhyolite (¹)	Dense, plagioclase bearing rhyolite and dacite	0-1550	No	Cap
Rautawiri Breccia	Vitric-crystal-lithic tuff and tuff-breccia	500-1500	Yes	Aquifer
Rangitaiki	Locally densely welded lithic-vitric-crystal ignimbrite	100-1200	No	Cap

(¹) includes underlying mudstone (0-200 ft thick)

TABLE 2. — *Bore outputs, production zones, dominant feldspars in bores and production zones*

Bore No.	Measured output (1) at 150 psig pressure Steam 10^3 lb/h	Water 10^3 lb/h	Hexagonal pyrrhotite present	Dominant feldspars	Principal production depths (ft) from permeability and pressure runs	Common minerals in cores from production zones
2	206	252	No	adularia, albite	1400-2400	adularia, quartz
11	199	360	No	adularia	around 1750	adularia, quartz
8	190	395	No	adularia	around 1520	adularia, quartz
3	122	386	No	albite, adularia	1572 and/or 2412	quartz, albite; illite, adularia
7	73	23	No	adularia, albite	2200-3000	adularia, quartz
13	72	222	Yes	albite, adularia	mainly at 2872	albite, adularia
4	52	59	Yes	albite, adularia	1572 and/or 2412	adularia, albite quartz, adularia;
9	47 av.	91 av.	No	albite, adularia	above and at 3371	albite, adularia
14	14	20	Yes	albite, andesine	around 2850	albite, andesine
12	negligible		Yes	andesine, albite	possible 3600	albite
1	negligible		Yes	andesine, albite	—	—
6	—	110 (2)	No	andesine	—	andesine

(1) N. D. DENCH (1968) and written comm. based on measurements by D. K. WAINWRIGHT, M.O.W., Wairakei.
(2) 52 °C; 64 psig.

Hydrothermal alteration in relation to production zones

Table 2 also shows principal production zones in 14 Broadlands bores determined from permeability tests and pressure runs conducted by M.O.W., Wairakei. As shown, cores from production zones of the three highest and fifth highest producers contain adularia and abundant secondary quartz, whereas those from production zones of the 4th, 6th, 7th highest producers contain both albite and adularia. On the other hand, cores from production zones of bores which produce less than 20,000 lb/h steam contain albite and/or andesine. As may be expected from their mineralogy it has been found that cores from good production zones have high potassium and low sodium contents and the K_2O/Na_2O ratio is high (> 4). In medium-grade production zones, where both albite and adularia are present, the K_2O/Na_2O ratio commonly varies between 0.5 and 4 but in non- and poor-production zones it is usually less than 0.5. This is clearly shown in the alteration diagrams in GRINDLEY and BROWNE (1968) and BROWNE and ELLIS (1970), where the alkali contents of the cores is shown to be related to their mineralogy and hence zones of permeability.

Hexagonal pyrrhotite has not been found in production zones of any boreholes; however, it is not always present in non-producing zones. Thus, although its presence in recovered cores implies that they are from non-producing zones, it does not follow that its absence indicates that good production can be expected.

Besides adding to the understanding of the hydrology of a geothermal field a knowledge of the location of production zones in bores can aid in determining optimum casing depths and depths at which production may be increased by perforating the casing. For example, the presence of adularia crystals in fractured cores from Br 4, 1100 ft, suggests that steam production here may be increased by perforating the liner casing.

Reasons for the observed relationship between hydrothermal alteration and permeability

Although based primarily on petrographic observations there are also good chemical reasons for expecting a relationship between alteration mineralogy, temperature, permeability and fluid composition. In a recent paper, BROWNE and ELLIS (1970) constructed mineral stability diagrams mainly based on observations at Broadlands and Wairakei and the experimental work of HEMLEY and JONES (1964). It was shown that Broadlands water at 260°C, in the presence of excess silica is in near equilibrium with albite, K-mica (illite), K-feldspar (adularia), calcite, wairakite and chlorite, and that andesine is unstable under these conditions. With steam loss through boiling in a homogenous aquifer of slowly-rising hot water, the important effects are a rise in pH, loss of CO_2 and a slight cooling. In the K_2O - Al_2O_3 - SiO_2-H_2O system, this results in the water composition moving from the K-mica to the K-feldspar stability field, according to the reaction:

$$\underset{\text{k-mica}}{KAl_2AlSi_3O_{10}(OH)_2} + 2K^+ + \underset{\text{quartz}}{6SiO_2} \rightarrow \underset{\text{adularia}}{3KAlSi_3O_8} + 2H^+$$

This results in the growth of K-feldspar (adularia) in order to remove potassium ions in excess of those for equilibrium two feldspar conditions. Boiling also results in the precipitation of calcite — a common occurrence at Broadlands because of the relatively high underground CO_2 concentrations ($M_{CO_2} = 0.15$). (BROWNE and ELLIS, 1970).

In the system Na_2O - CaO - Al_2O_3 - K_2O - SiO_2 - $MgO(FeO)$-H_2O, BROWNE and ELLIS (1970) showed that boiling, in a similar manner, will produce an equilibrium assemblage of K-feldspar, albite, chlorite and calcite. However, the rocks have a buffering action towards these changes and the amount of alteration at a particular depth depends on permeability, since this controls the volume of water passing through the rocks. In other words, the quantity of these minerals formed in a zone is related to local permeability. If, however, a flow of water, rising and boiling in a fissure is considered, the buffering effect of the rocks will be slight and adularia, calcite and quartz will be directly precipitated from solution through continuous supply of elements from the water.

The formation of pyrrhotite, instead of pyrite, is favoured by lower P_{H_2S}/P_{H_2} ratios and higher temperatures (BROWNE and ELLIS, 1970). The presence of pyrrhotite in cores may be caused by trapping of separated steam by the impermeable rocks. This steam will have a low P_{H_2S}/P_{H_2} ratio because H_2S is much more soluble in water than H_2 at 260°C and hence pyrrhotite will be the iron sulphide mineral to form. In permeable zones the steam will be able to escape and pyrrhotite will not have time to form. Pyrite, on the other hand, will precipitate from residual water, which has a high P_{H_2S}/P_{H_2} ratio, left after the steam has escaped. Therefore, although pyrrhotite forms at temperatures sufficiently high to produce steam, permeability appears to have an influence on its stability.

If this interpretation is correct, it follows that rocks under areas outlined by positive magnetic anomalies in geothermal fields may be hot but impermeable and should therefore be avoided. They should also be avoided if the positive anomaly is due to magnetite since this mineral alters at a comparatively low temperature, usually to non-magnetic pyrite.

Pyrrhotite may also form in organic-rich sediments, where the breakdown of organic material causes local low pressures, and this has probably occurred in a few places, e. g. Br 13, 1601 ft depth.

The relationships between mineralogy and permeability observed at Broadlands apply only to geothermal systems which have similar rock and fluid compositions, but it should be possible to identify similar permeability-indicating minerals in cores from early bores in other geothermal areas and use this information in later investigation and development drilling.

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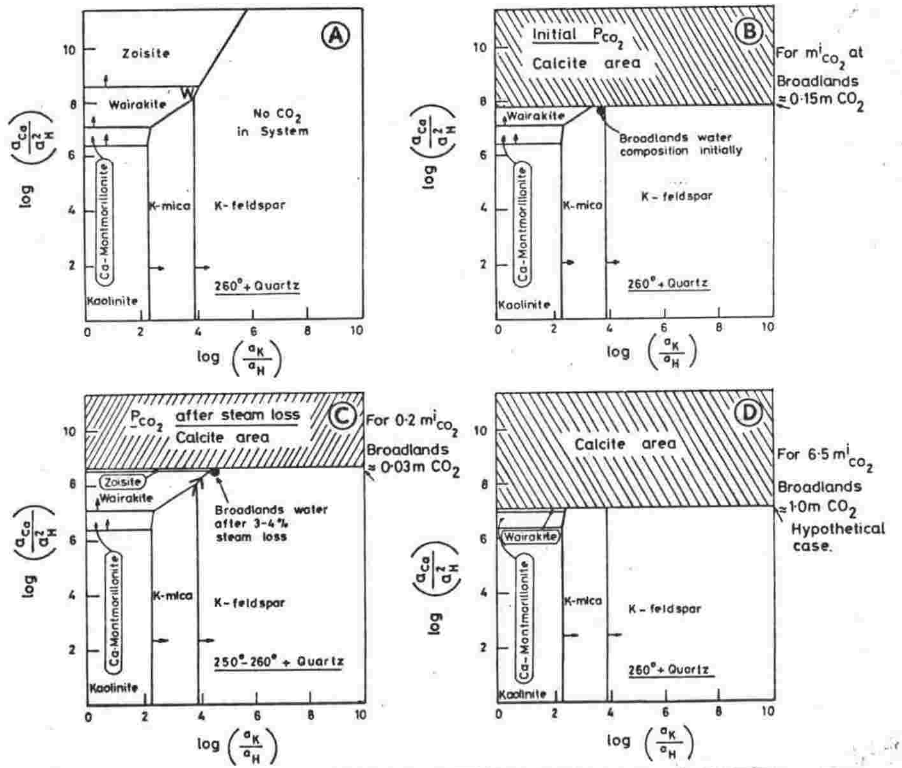

FIG 12. Mineral stability diagrams for calcium and potassium minerals at 260°, in terms of solution ion ratios and various $m^i_{CO_2}$ values (from Browne and Ellis, 1970).

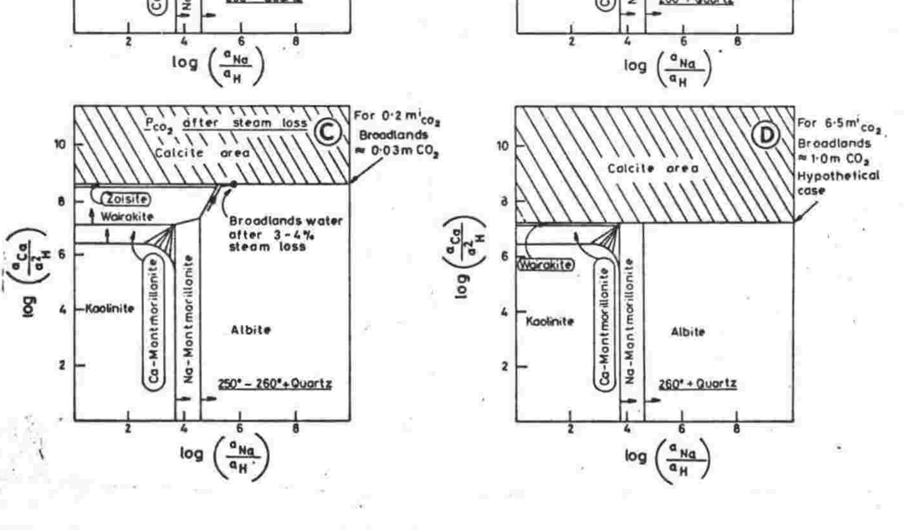

FIG. 13. Mineral stability diagrams for calcium and sodium minerals at 260°, in terms of solution ion ratios and various $m^i_{CO_2}$ values (from Browne and Ellis, 1970).

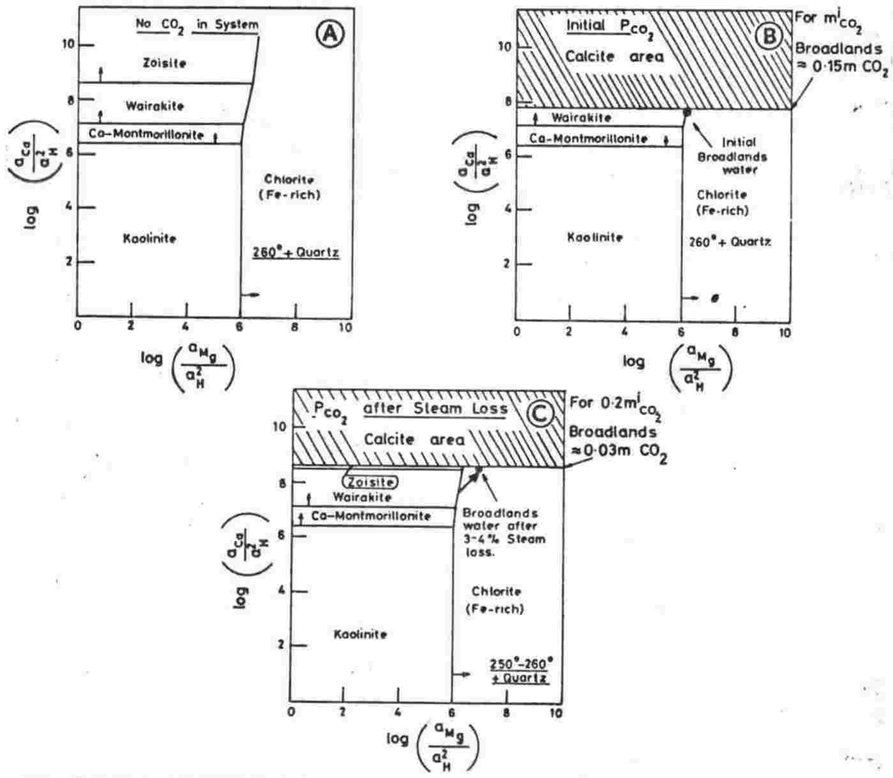

FIG. 14. Mineral stability diagrams for calcium and magnesium minerals at 260° in terms of solution in ratios and various $m^{i}_{co_2}$ values (from Browne and Ellis, 1970).

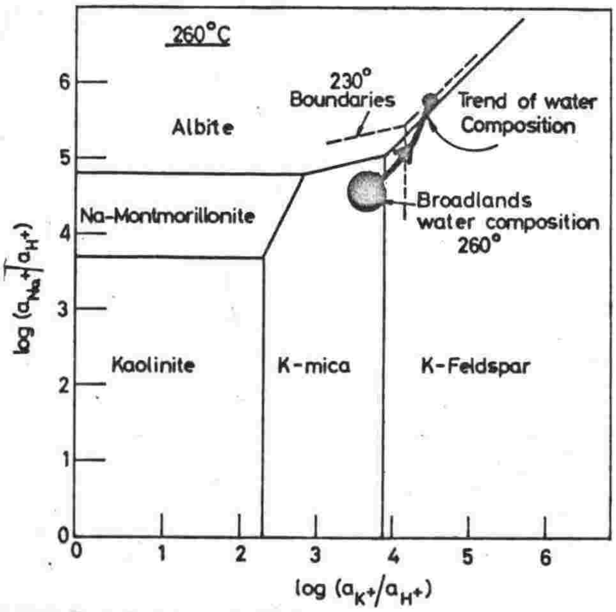

FIG. 15. Mineral stability diagram for sodium and potassium minerals at 260° in terms of solution ion concentration ratios (broken lines show 230° boundaries; from Browne and Ellis, 1970).

Alteration in individual drillholes

Further general comments follow on hydrothermal mineral assemblages at various depths in most drillholes, with reference to the stability diagrams (Figs. 12-15). These comments are intended to show how observed hydrothermal mineral assemblages in individual drillholes may be related to subsurface fluid behaviour, for although the diagrams are drawn for 260°, their general form will apply over a range of temperatures (Browne and Ellis, 1970). Interpretations of fluid behaviour in drillholes Br 1, 2, 4, 6, 7 and 9 are from Browne and Ellis (1970).

Hole Br 1.

Alteration is slight at higher levels (Appendix A) although temperatures in some places are in excess of 200°, but below about 850 m, albite and K-mica occur. This alteration corresponds to water compositions likely in impermeable rocks under static aquifer conditions, and this conclusion is supported by the fact that the hole does not produce.

Hole Br 2. (Fig. 16)

Below a depth of 700 m, albite, adularia, chlorite, calcite (random order) and very minor epidote coexist; this assemblage could be formed by water rising to these levels and boiling off a few percent steam (and CO_2) (Figs. 12-15). Between 500 m and 600 m the rocks are highly silicified and in addition to abundant hydrothermal quartz contain adularia and calcite but not albite. This suggests that this is a zone of vigorous boiling, with rapidly rising pH and cooling of the water flow (Fig. 12).

KEY TO FIGURES 16 to 35

░ Huka Falls Formation

☰ Ohaki Rhyolite

▨ Waiora Formation

▓ Lower Siltstone;
Tuffaceous Sediment Unit A

▤ Broadlands Dacite; Broadlands Rhyolite;
Dacite B, C; Andesite A

▨ Rautawiri Breccia

▥ Rangitaiki Ignimbrite;
Ignimbrite C, D, E, F, G.

○ Waikora Formation

▧ Greywacke and argillite basement

o = Core Sample

And = Andesine

Ab = Albite

Ad = Adularia

i = Illite

m = Montmorillonite

i/m = Interlayered montmorillonite-illite

m/chl = Interlayered montmorillonite-chlorite

K = Kaolin

H = Halloysite

FeS = Pyrrhotite

B. P. Curve = Boiling point
of pure water

A similar, but smaller zone of this kind also occurs between 230 m and 300 m, but the remainder of the alteration above 490 m, characterized by illite, could be attributed to the cooler conditions at higher levels, caused by considerable steam loss, and possibly also to some conduction and convection. In this situation, as the pH rise of the water is limited to the effect caused by the loss of most of the CO_2 from solution, the effect of cooling in moving the K-mica, K-feldspar boundary to higher a_{K+}/a_{H+} values could cause K-mica to become stable, overriding the opposing effect of pH-rise. Under cooler near-surface conditions, the rates of mineral growth may be more important than trends towards an equilibrium mineral assemblage (Browne and Ellis, 1970).

Hole Br 4 (Fig. 17)

At about 1000 m minor adularia occurs with illite and chlorite, indicating a cooling zone, but the absence of calcite or epidote suggests that cooling is by convection or conduction rather than by boiling.

From 700 m to 1000 m the hydrothermal minerals are dominantly albite, illite, chlorite, and calcite. This and the absence of adularia except for traces in the upper level of this section may indicate levels where water rises in temperature by conduction.

From about 460 m to 700 m there is a broad zone of albite, adularia, calcite, chlorite, and illite which suggests this is an aquifer of water containing appreciable carbon dioxide (Figs. 12 & 13). The disappearance of albite at the top of these levels may be caused by boiling, but the persistence of illite suggests that sufficient contact of

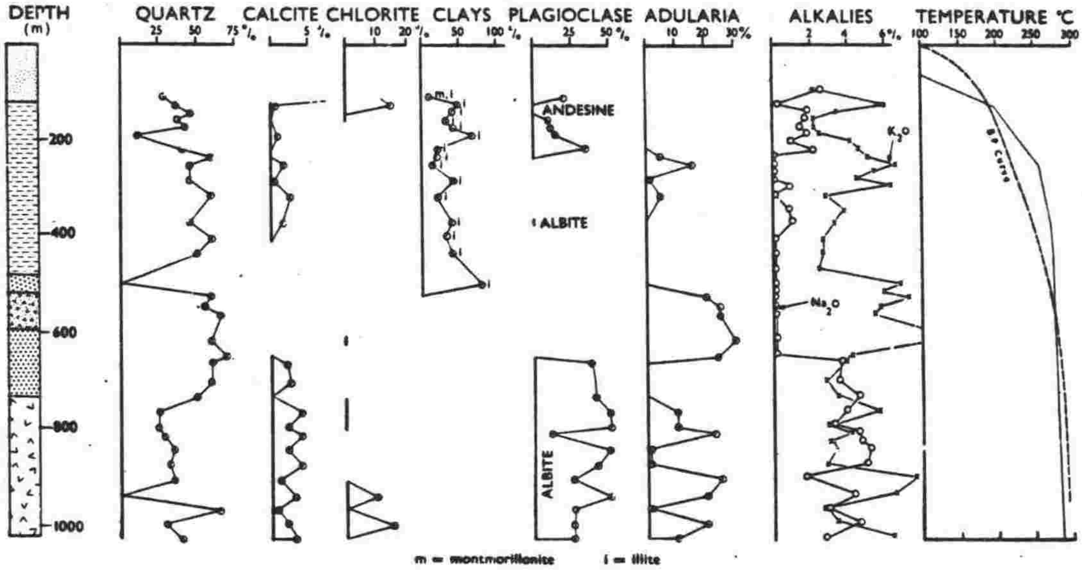

FIG. 16. Distribution of some minerals in drillhole Br 2. Cores are represented by circles and straight lines have been arbitrarily drawn between circles.

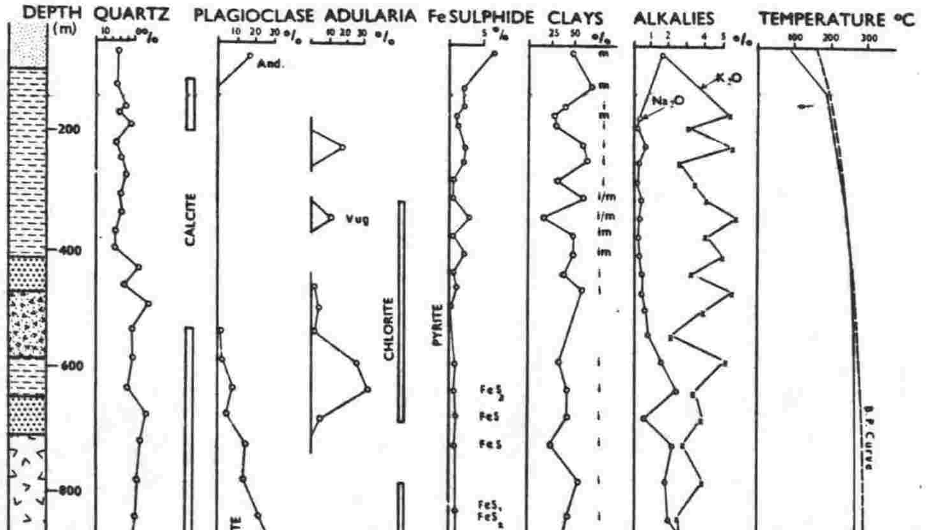

FIG. 17. Distribution of some minerals in drillhole Br 4.

water with rock surfaces was retained to hold the system on the K-mica, K-feldspar boundary line; that is, the conditions are those of a porous aquifer rather than a fissure flow. A narrow zone of adularia at a depth of about 335 m but without calcite, epidote, or albite and containing illite, suggests that this is a zone of boiling and cooling (Fig. 15), but not one of major fissure flow.

Hole Br 5 (Fig. 18)

This drillhole, a non-producer, encountered low temperatures and impermeable rocks and this is reflected in the limited alteration of the cores. The Ohaki Rhyolite is unaltered except for the introduction of cristobalite (possibly deuteric) and minor calcite at 306 m, but the underlying Huka Falls Formation contains pyrite, interlayered illite-montmorillonite, and mordenite (not shown in Fig. 18); their appearance coincides with a slight temperature increase. Several cores between 515 m and 669 m contain halloysite suggesting that rocks here have reacted with waters of lower than usual pH, but the occurrence of minor siderite from 576 to 760 m (not shown in Fig. 18) overlaps the halloysite distribution and may mean that permeability was insufficient for mineralogic equilibrium. Below 760 m, the hydrothermal minerals are calcite, illite, albite and irregularly distributed chlorite, pyrite and pyrrhotite indicating low permeability and conductive heating of country rocks which may also contain pockets of separated steam.

Hole Br 6 (Fig. 19)

The persistence of primary minerals below 730 m and absence of adularia suggest that impermeable conditions

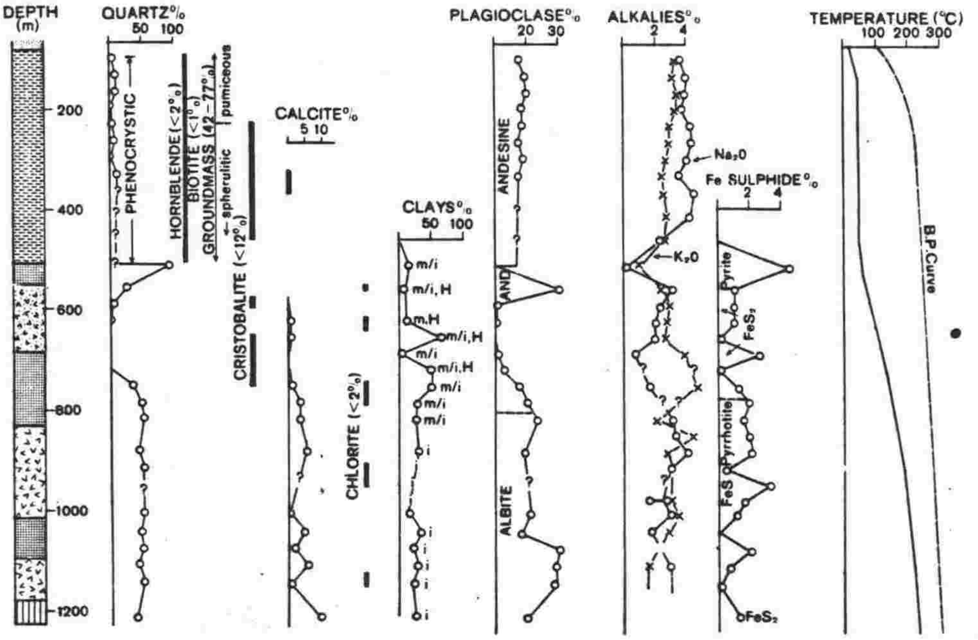

FIG. 18. Distribution of some minerals in drillhole Br 5.

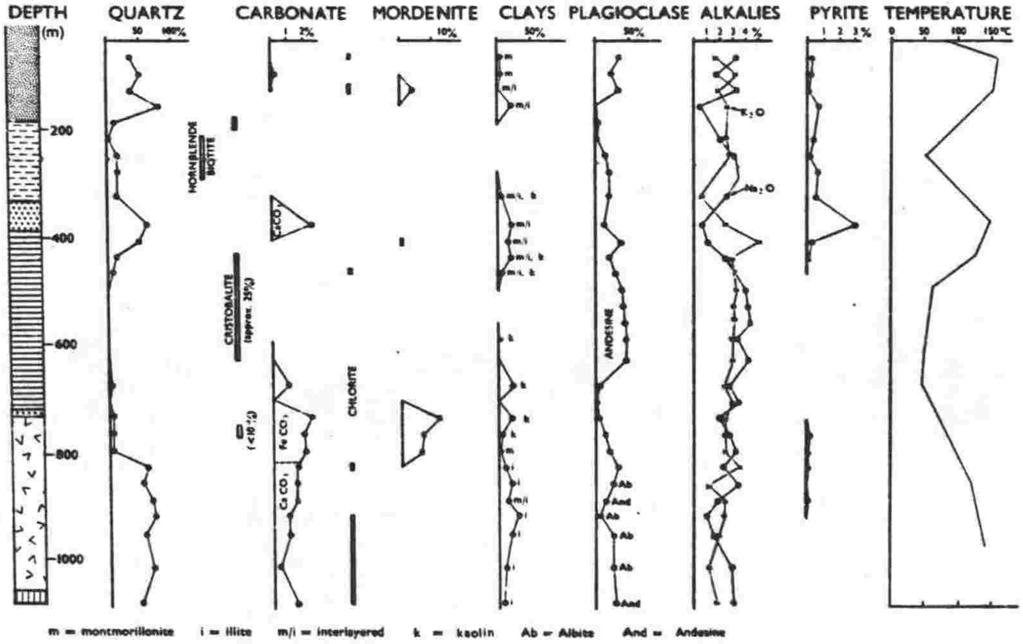

FIG. 19. Distribution of some minerals in drillhole Br 6.

occur over most of the hole, but the small amount of albite in some cores below 900 m may indicate that there is minor conductive heating. In the shallower levels of the hole, the irregular distribution of some hydrothermal minerals allied with temperature reversals implies that cooling water is circulating between rhyolite flows.

Hole Br 7.

Mesozoic greywacke and argillite basement rocks below 943 m contain albite, illite, chlorite, and calcite (Browne, 1969), but some of these minerals formed by burial metamorphism preceding geothermal activity. However, a temperature increase below 945 m points to conductive heating. From 700 to 915 m, abundant adularia, quartz, and minor calcite with little albite and illite (sericite) reveal this to be a zone with a flow of boiling water. The persistence of minor illite (sericite) suggests that the flow, however, is not sufficiently great in comparison with the surface area of exposed rock to raise the water pH above the illite-K-feldspar phase boundary (Fig. 15). Between about 275 and 520 m, unaltered plagioclase shows that there has been little access of water to allow reaction with the mainly impermeable Broadlands Dacite, but above 274 m there is abundant montmorillonite which may have formed by reaction between rocks and descending river water.

Hole Br 9 (Fig. 20)

At the deepest levels the hydrothermal minerals present in dense ignimbrite are quartz, calcite, chlorite, illite, and albite, an assemblage that suggests reaction under rather impermeable conditions of rising water temperatures.

From 780 to 980 m albite, adularia, and calcite with an absence of illite, reveal a lower aquifer in which a few percent of steam boils from water as it moves through the zone (Fig. 15).

The appearance of illite and wairakite and the disappearance of calcite and feldspars at about 640 m, just above the Broadlands Rhyolite, suggest a water of lower pH, possibly due to steam (+ CO_2) condensing into it (Fig. 12).

Hole Br 10 (Fig. 21).

The occurrence of glass, andesine and siderite to about 200 m is consistent with the low measured temperatures. However, near 300 m, in the Huka Falls Formation, the abundant adularia, coinciding with the sharp change in temperature gradient, indicates a zone cooled by convection but since calcite is absent, not boiling (Fig. 12).

Between 400 and about 750 m in the Broadlands Dacite, the persistence of andesine with illite, calcite, chlorite and occasional albite shows the generally impermeable nature of this formation in which temperatures rise by conduction. Minor wairakite and calcite at 460 m possibly result from rocks reacting with water of slightly lower pH. Adularia, illite, calcite and chlorite (no albite) between 800 and 900 m in the Rautawiri Breccia indicate cooling by steam loss through boiling (Fig. 12). Albite, K-feldspar, calcite, chlorite and illite occur in the basement greywackes, argillites and the Waikora Formation conglomerate and although stable in waters of Broadlands composition these minerals predate the onset of hydrothermal activity.

Hole Br 11 (Fig. 22).

The Ohaki Rhyolite and the underlying Upper Waiora

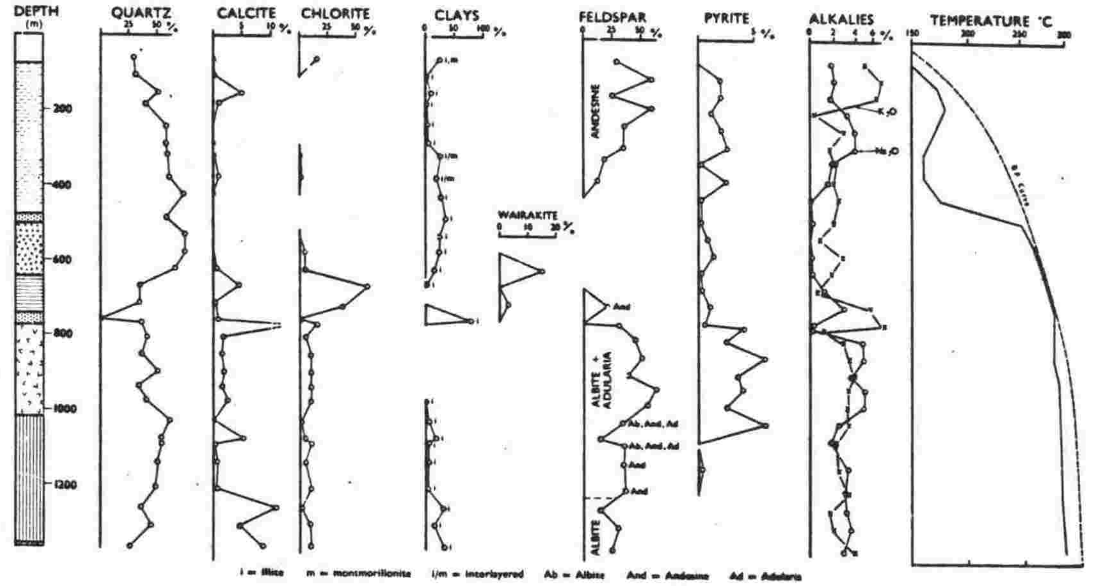

FIG. 20. Distribution of some minerals in drillhole Br 9.

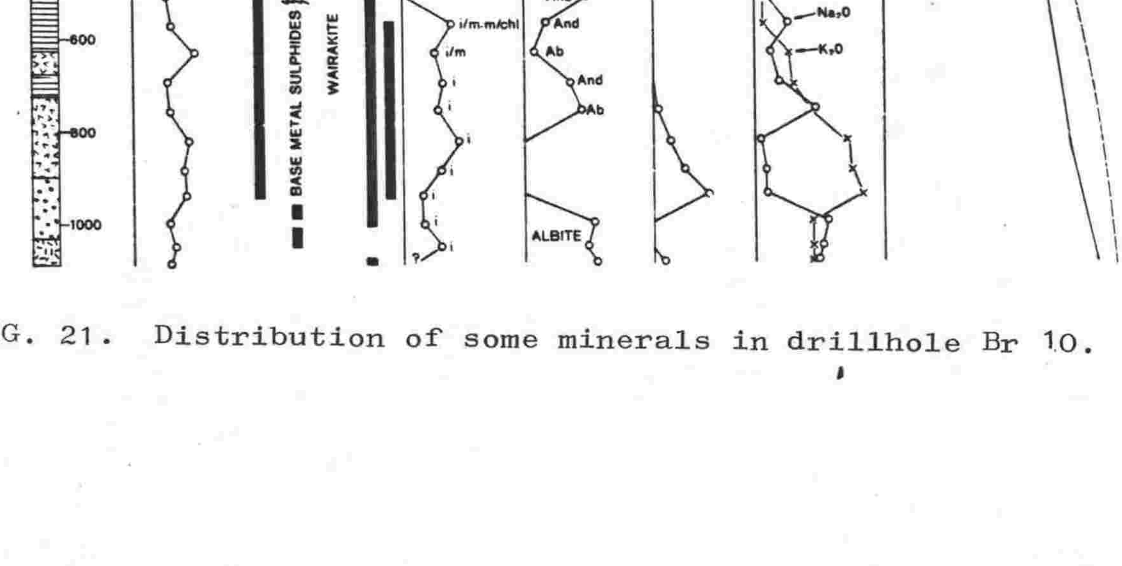

FIG. 21. Distribution of some minerals in drillhole Br 10.

Formation contain abundant quartz, adularia and a lesser amount of illite (no albite); also present are widespread pyrite, irregularly distributed calcite, minor montmorillonite and chlorite. This assemblage is consistent with subsurface boiling, and steam loss, although not sufficient flow to shift the water pH above the K-feldspar, K-mica boundary line (Fig. 15). Two cores of Rautawiri Breccia also contain albite, possibly indicating that waters here are rising and boiling off a few percent steam (and CO_2).

Hole Br 12 (Fig. 23).

Above 600 m depth, the hydrothermal alteration is typical of low temperatures and poor permeability. This is shown by the persistence of andesine, glass, biotite and hornblende (in the Ohaki Rhyolite) and occurrence of mordenite, siderite-cristobalite, kaolin and montmorillonite. In the lower part of the Upper Waiora Formation, between about 600 m and 800 m, illite is the dominant hydrothermal mineral, although calcite and pyrite also occur; this suggests static conditions with water compositions well within the stability field of K-mica although the CO_2 activity must be sufficiently high to precipitate calcite (Fig. 12). The Rautawiri Breccia is characterised by the hydrothermal assemblage albite and calcite which also indicates a static zone with dominantly conductive heating. Pyrrhotite (and pyrite) also occurs indicating low P_{H_2S}/P_{H_2} conditions and possibly that the formation is permeated with steam (Browne and Ellis, 1970). At deeper levels, the hydrothermal assemblage, illite, albite, adularia, calcite, chlorite and pyrite reveals a porous aquifer with some steam (and CO_2) loss but little through flow (Figs. 12-14).

Hole Br 13 (Fig. 24).

The persistence of biotite and andesine in the Huka

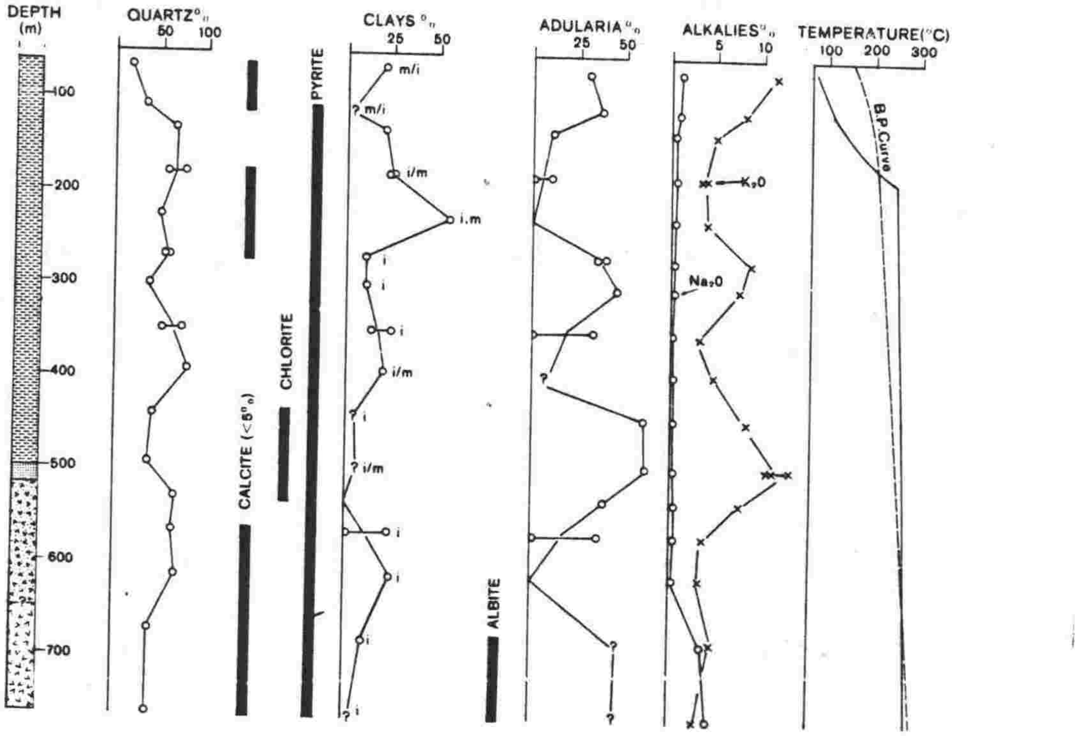

FIG. 22. Distribution of some minerals in drillhole Br 11.

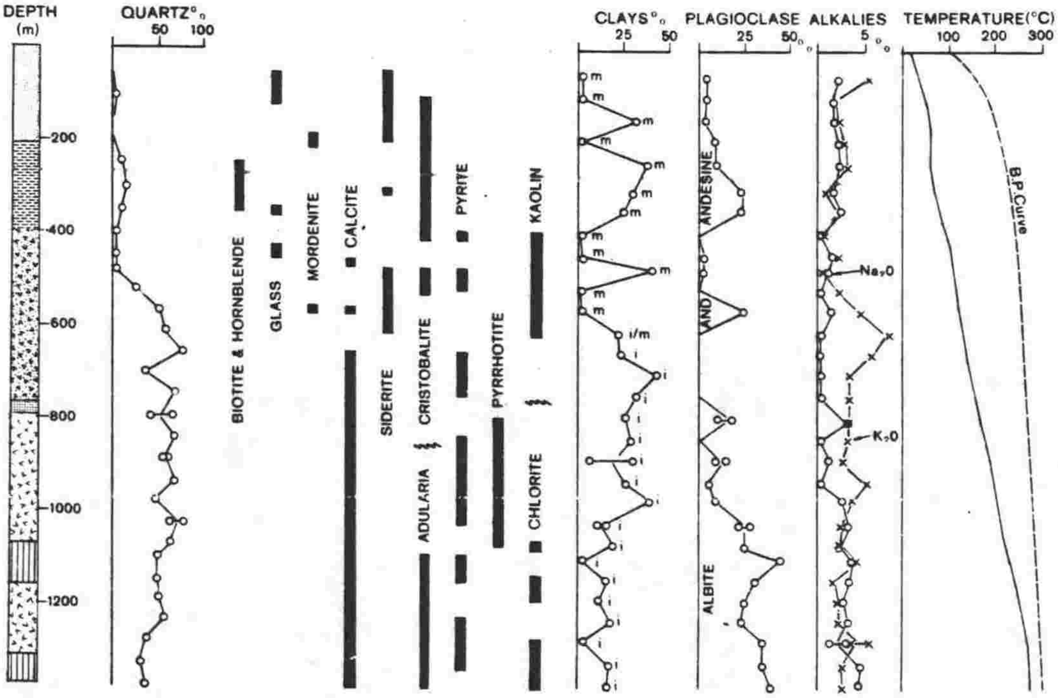

FIG. 23. Distribution of some minerals in drillhole Br 12.

Falls and Ohaki Rhyolite Formations and the occurrence of mordenite, siderite and montmorillonite, indicate that low temperatures and limited permeability occur down to about 450 m. Wairakite in siltstone from 195 m is almost certainly detrital (possibly derived from Wairakei fumarole ejecta); a minor amount was detected by infra-red spectroscopy but none was seen in thin section. Pyrrhotite irregularly distributed in sediments between 490 and 669 m may result from rock reacting with separated steam under low local P_{H_2S} conditions (relative to P_{H_2}) possibly initiated by the presence of organic matter. Between the sediments, the Waiora Formation contains pyrite, calcite, chlorite and illite indicating slightly greater permeability and a static aquifer with appreciable CO_2 (Fig. 12). The Rautawiri Breccia contains albite, adularia, chlorite, calcite, pyrite and minor illite showing that this formation is more productive. The underlying Rangitaiki Ignimbrite, however, contains the non-equilibrium feldspar assemblage, albite, adularia, and andesine illustrating the usually impermeable character of the formation.

Hole Br 14 (Fig. 25).

The Huka Falls Formation contains unaltered andesine, irregularly distributed glass and hornblende; the hydrothermal minerals chlorite, calcite, montmorillonite and, in one core, siderite. This assemblage is consistent with low temperatures and poor to moderate permeability, but illite below 258 m reflects the higher temperatures at greater depth. The Ohaki Rhyolite contains unaltered andesine, illite, calcite, pyrite and wairakite, suggesting that water at this depth may have a slightly lower pH, possibly because of steam (and CO_2) condensing into it. The Upper

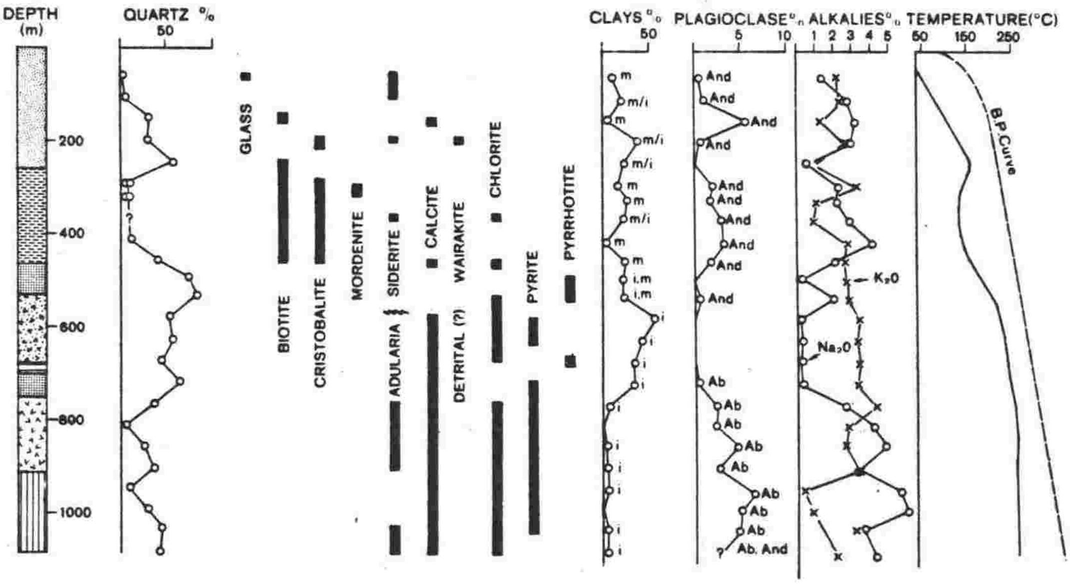

FIG. 24. Distribution of some minerals in drillhole Br 13.

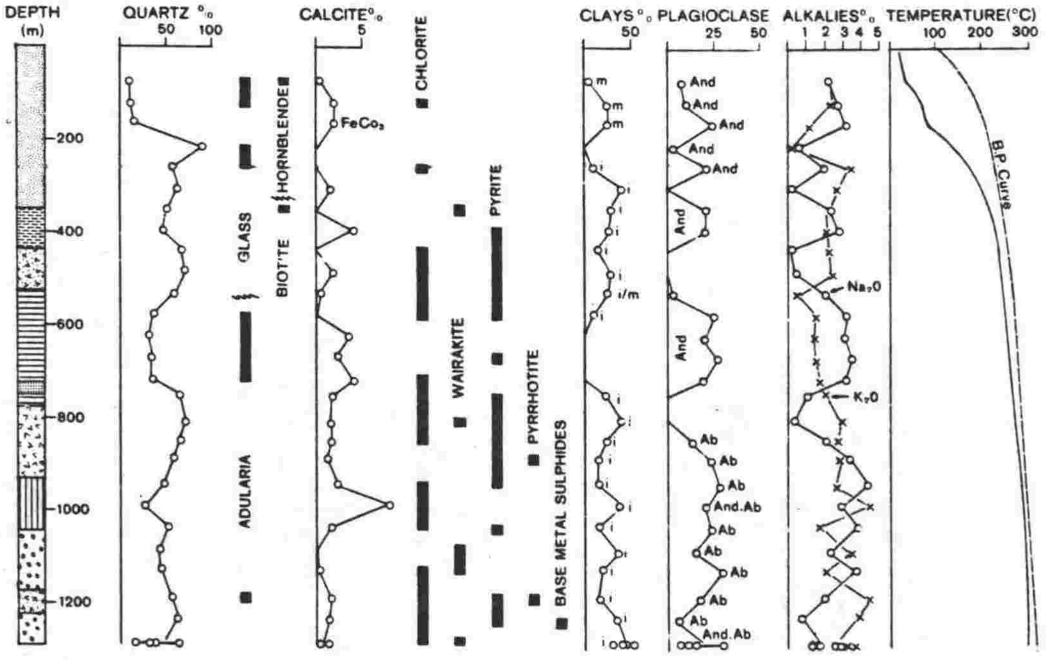

FIG. 25. Distribution of some minerals in drillhole Br 14.

Waiora Formation contains hydrothermal illite, pyrite, chlorite and calcite indicative of a static aquifer with water composition within the K-mica field (Fig. 15). The Broadlands Dacite contains a non-equilibrium assemblage which includes partly altered andesine, irregularly distributed illite, calcite, chlorite and very limited adularia; this shows that the dacite, although at temperatures between 240° and 263°, is at best only slightly permeable. The underlying Rautawiri Breccia contains calcite, pyrite, chlorite, illite and albite suggesting fairly static aquifer conditions, with slow conductive heating (Fig. 12). Wairakite in core from 806 m and in the deeper Waikora Formations may result from reaction between rock and waters of slightly lower pH. The Rangitaiki Ignimbrite contains calcite, chlorite, pyrite, albite and unaltered andesine; evidently the rocks are too impermeable for equilibrium to be attained. Before the onset of hydrothermal activity, the Waikora Formation contained albite, illite, chlorite and calcite - stable minerals in waters of Broadlands composition. The interbedded Waiora Formation, however, contains hydrothermal adularia, albite, pyrite, illite and calcite which shows the formation to be an aquifer from which some steam and CO_2 have been lost (Fig. 15); the trace amount of pyrrhotite indicates low local P_{H_2S}/P_{H_2} conditions.

Hole Br 15 (Fig. 26).

This is the deepest geothermal drillhole in New Zealand and the only one west of the Waikato River to reach basement greywackes. It encountered a zone of major fissure flow with boiling at 1620 m where recovered core, besides pyrite and base metal sulphides, contains adularia and abundant calcite and chlorite (no albite or illite).

Andesine remains unaltered in the three deep ignimbrites and Andesite Unit A despite the high measured temperatures (284-298°), showing that permeability is too low to allow access of sufficient fluid for plagioclase replacement. The lower part of the Rautawiri Breccia contains the assemblage calcite, chlorite, pyrite, albite and adularia revealing the formation to be an aquifer with some boiling and steam (and CO_2) loss (Figs. 12-15). The incoming of illite between 1224 and 1593 m, however, indicates that flow here is insufficient, compared with the surface area of available rock, to raise the water pH above the K-mica, K-feldspar boundary (Fig. 15). Below 1593 m, the irregular distribution of illite, albite, andesine, adularia, pyrrhotite and base metal sulphides reflects the fact that although permeabilities are variable no significant aquifer or fissure was encountered.

Hole Br 17 (Fig. 27).

The Ohaki Rhyolite contains unaltered andesine, hydrothermal calcite, pyrite, chlorite and at shallow levels, mordenite and cristobalite. The persistence of biotite, which coincides with a slight temperature reversal between 220 and 300 m indicates that waters are circulating within the rhyolite. Shallower levels of the Upper Waiora Formation are characterised by the hydrothermal assemblage calcite, pyrite, illite, adularia (no albite) which is con-

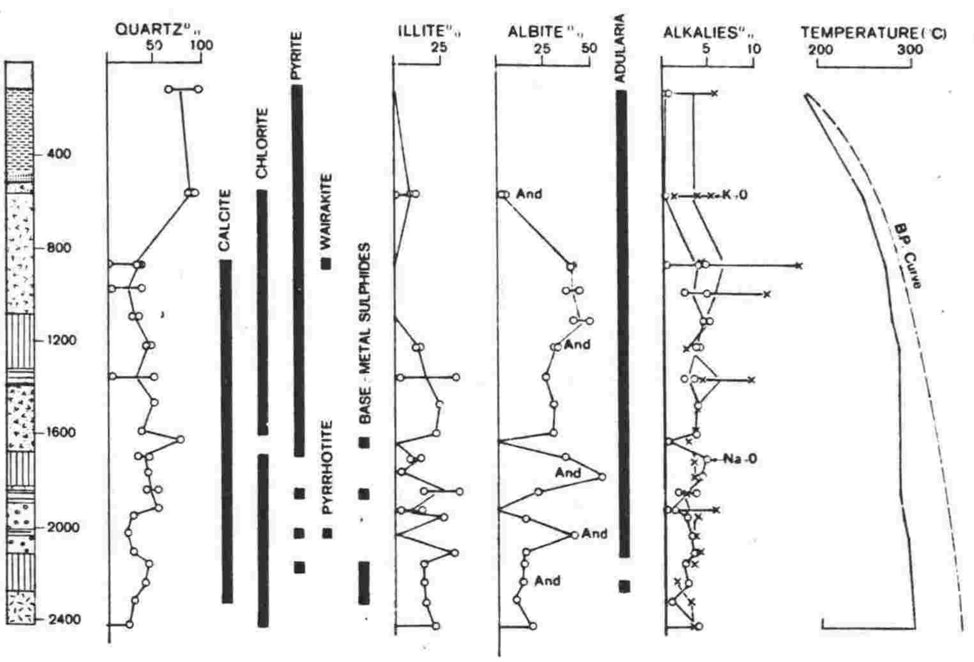

FIG. 26. Distribution of some minerals in drillhole Br 15.

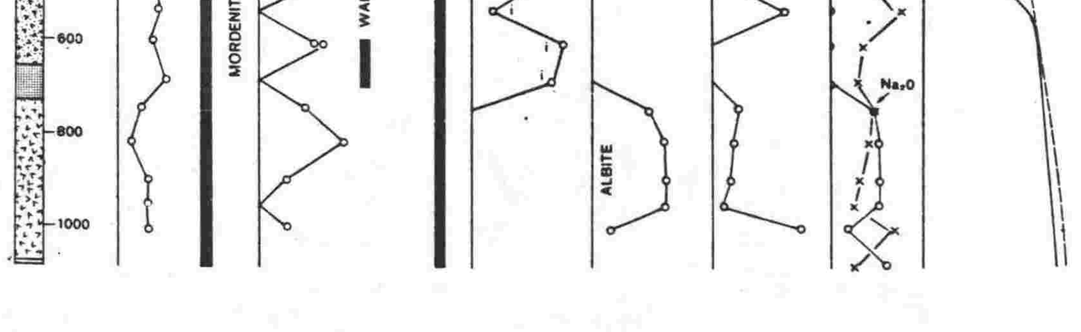

FIG. 27. Distribution of some minerals in drillhole Br 17.

sistent with boiling and steam (and CO_2) loss (Fig. 12); it is significant that at 580 m the measured temperature is very close to the boiling temperature of pure water for this depth. The occurrence of wairakite, illite, chlorite, pyrite and minor calcite (no feldspar) between 600 and 700 m suggests static conditions, and waters here may have a marginally lower pH. The Rautawiri Breccia contains chlorite, calcite, pyrite, albite and adularia (no illite) - an assemblage indicative of ascending water boiling, cooling and losing a few per cent steam and CO_2 (Figs. 12-15); apparently flow is sufficient to raise the system above the K-mica, K-feldspar boundary line (Fig. 15).

Hole Br 18 (Fig. 28).

In the Ohaki Rhyolite, andesine persists to at least 305 m but is locally part replaced by adularia, indicating that equilibrium was not attained; the other hydrothermal minerals present are calcite, illite, and montmorillonite. Convection within the rhyolite is indicated by the temperature minimum at 300-380 m which coincides with the occurrence of groundmass adularia. Below 380 m primary andesine has been replaced by illite and irregularly distributed chlorite, implying fairly stagnant conditions (Figs. 12 and 14). The underlying Upper Waiora Formation contains illite, calcite, pyrite, and, towards the base, minor albite and adularia suggesting that the formation behaves as a porous aquifer with some boiling and loss of steam and CO_2, but that there is insufficient contact between water and rock surfaces to hold all the system on the K-feldspar, K-mica boundary (Fig. 15). The Rautawiri Breccia beneath has a similar hydrothermal assemblage but contains more albite and chlorite and the adularia is distributed irregularly, showing that this formation also behaves as a porous aquifer but with no discrete fissure flow zones. The two deepest cores are of Rangitaiki Ignimbrite and contain chlorite, illite, albite, pyrite and calcite; one core (1139 m) also contains epidote and the deeper (1218 m) adularia. This indicates that waters have lost a few per cent steam and that in this drillhole the ignimbrite has greater permeability than elsewhere.

Hole Br 19 (Fig. 29).

The Huka Falls Formation contains unaltered andesine and hydrothermal siderite, pyrite, chlorite and montmorillonite resulting from low temperature alteration; this is consistent with measured temperatures of below 90°. The Ohaki Rhyolite contains mordenite, calcite, montmorillonite, minor pyrite and unaltered biotite and andesine showing that it is only moderately permeable. In the Upper Waiora Formation, measured temperatures (258°) are close to boiling but the absence of adularia or calcite and the presence of interlayered montmorillonite in the single core of this formation indicates poor permeability. The Broadlands Dacite is also relatively impermeable, as shown by the persistence of andesine to 267°, although sufficient water has reacted with the rocks to form minor calcite, chlorite, pyrite and interlayered illite-montmorillonite. The Rautawiri Breccia contains abundant adularia, albite, minor chlorite, pyrite, and very rare illite and calcite indicating boiling in a porous media with sufficient steam loss locally to raise the system slightly above the K-mica, K-feldspar boundary line (Fig. 15). As in most other drillholes, the Rangitaiki Ignimbrite is poorly permeable and this is shown by the presence of andesine in the bottom core (267°); however, there has been sufficient reaction to form some adularia, illite, calcite and chlorite.

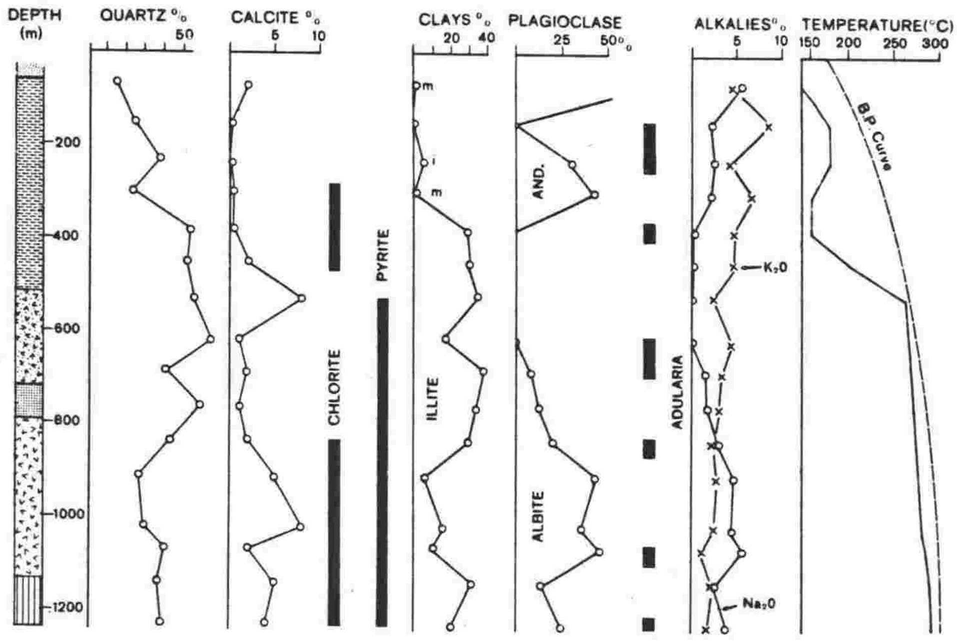

FIG. 28. Distribution of some minerals in drillhole Br 18.

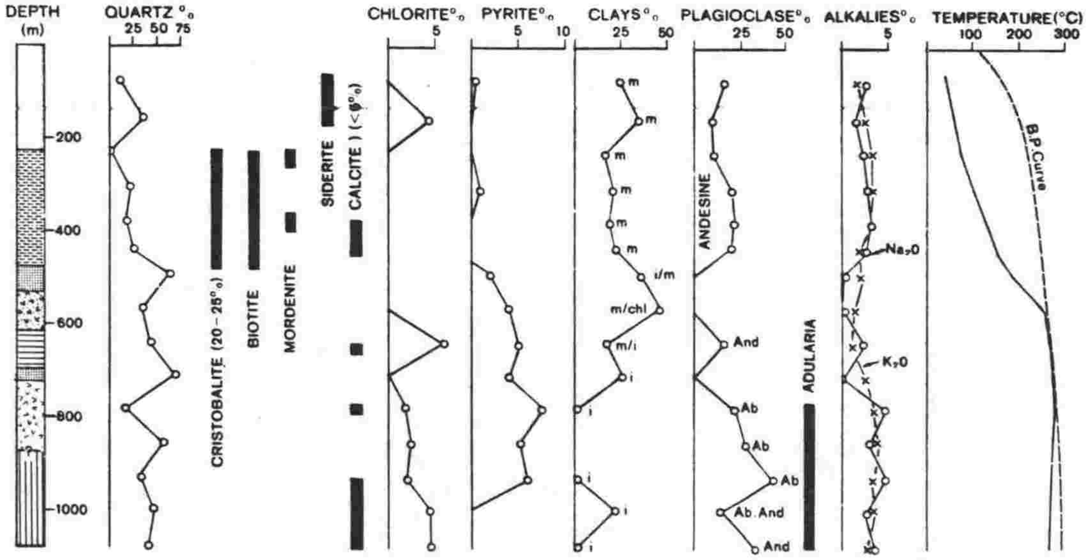

FIG. 29. Distribution of some minerals in drillhole Br 19.

This bore has a very high mass output and calcite, quartz and adularia might be expected to be more abundant; the explanation may be that the core interval of about 70-80 m was too great to locate fissure flow zones.

<u>Hole Br 20</u> (Fig. 30).

The shallower core (70 m) of the Huka Falls Formation contains some unaltered glass and the low temperature hydrothermal minerals siderite, heulandite, cristobalite and montmorillonite. The other core (160 m) contains chlorite, pyrite, calcite, very rare kaolin and (?) detrital albite. The kaolin (too little to characterise) may form from an inflow of oxygenated groundwater causing acid conditions by sulphide oxidation, but the small amount of calcite and pyrite present shows that mineralogic equilibrium was not attained; alternatively, the kaolin may also be of detrital origin. The Ohaki Rhyolite contains unaltered andesine, pyrite, chlorite, and irregularly distributed illite and montmorillonite, suggesting that the formation has low permeability. Wairakite occurs, with illite, pyrite, chlorite and rare calcite, in the Upper Waiora Formation, indicating that waters at this depth are slightly more acid, possibly because of condensing steam (and CO_2). The Broadlands Dacite is fairly impermeable and contains unaltered andesine; however, hydrothermal pyrite, calcite, chlorite, illite and montmorillonite also occur. The Rautawiri Breccia contains pyrite, chlorite, albite, calcite, and in the upper level adularia and illite - an assemblage indicative of a porous aquifer with a few per cent steam loss but sufficient contact between water and rock surfaces to hold the system on the K-mica, K-feldspar boundary (Figs. 13-15).

In common with several other drillholes, the relatively impermeable character of the Rangitaiki Ignimbrite is shown by the persistence of andesine in the two deepest cores, although the occurrence of epidote, adularia, calcite, illite and chlorite shows there has been some water/rock reaction.

Hole Br 21 (Fig. 31).

Two cores of Ohaki Rhyolite contain fresh andesine and biotite indicating limited permeability; the shallower (193 m) also contains groundmass K-feldspar and the low temperature zeolite, mordenite. The single core of the Upper Waiora Formation contains hydrothermal pyrite and illite, implying stagnant conditions although the measured temperature is close to boiling (Fig. 15). The Broadlands Dacite contains calcite, wairakite, pyrite, illite (also present in underlying siltstone), chlorite and minor albite, indicating the waters may have a slightly lower pH, possibly caused by condensation of a steam phase rich in CO_2. Calcite, chlorite, illite, albite and adularia occur in the Rautawiri Breccia revealing that the waters contain appreciable CO_2 and that the formation behaves as a porous aquifer with some steam loss. However, the core from 874 m does not contain illite and this coincides with a slight temperature reversal, suggesting the presence nearby of a fissure with sufficient flow to raise the system above the K-mica, K-feldspar boundary (Fig. 15). The hydrothermal alteration of the Rangitaiki Ignimbrite is similar to that of cores from Br 20.

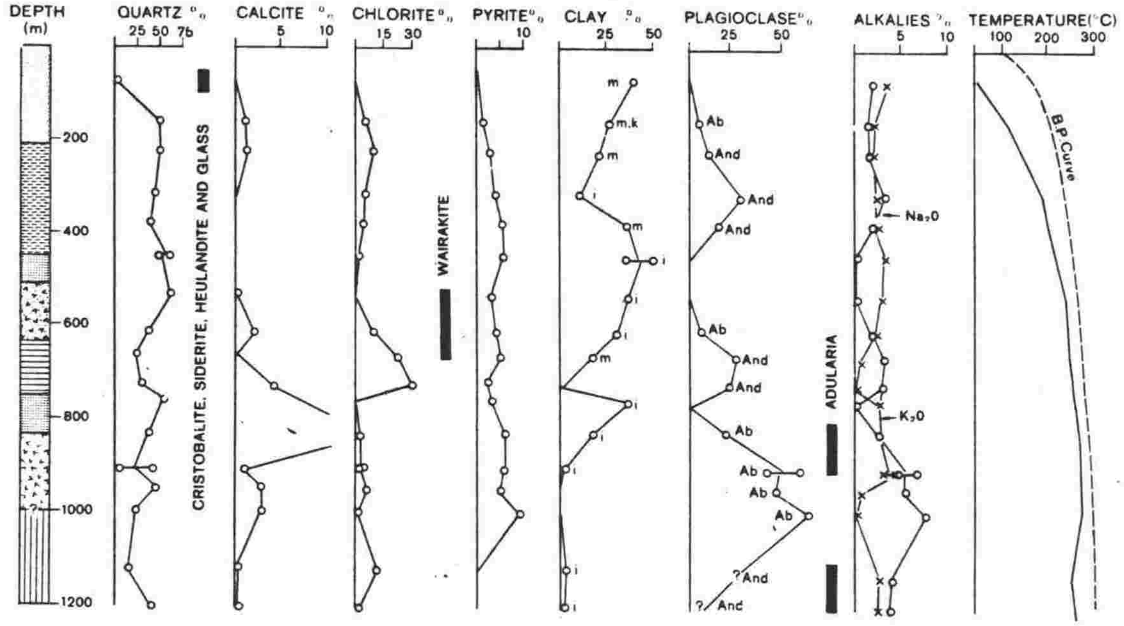

FIG. 30. Distribution of some minerals in drillhole Br 20.

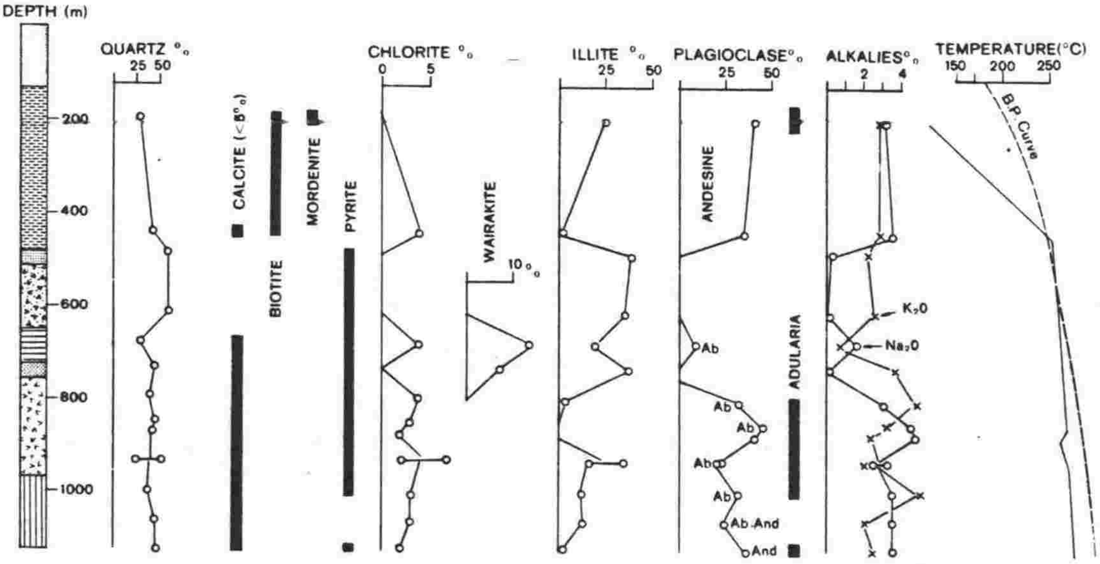

FIG. 31. Distribution of some minerals in drillhole Br 21.

Hole Br 22 (Fig. 32).

Only nine cores were recovered from this drillhole, so that subsurface fluid behaviour is difficult to interpret from the hydrothermal mineralogy. However, the low temperature minerals mordenite and siderite occur in the upper part of the Ohaki Rhyolite and andesine persists to at least 432 m, despite high temperatures, indicating fairly impermeable conditions. The Upper Waiora Formation contains pyrite, illite and calcite and consequently waters in this aquifer appear to be fairly stagnant. The single core of Broadlands Dacite with chlorite, illite, pyrite, calcite and wairakite shows water of slightly lower pH may occur here. The assemblage adularia, albite, pyrite, chlorite, calcite, and in one core, illite, occurring in the Rautawiri Breccia reveal that this formation functions as an aquifer from which several per cent steam has been lost by boiling (Figs. 12-15).

Hole Br 23 (Fig. 33).

The stratigraphic sequence and hydrothermal alteration of rocks in this drillhole are very similar to those of Br 22, so that the same remarks about fluid behaviour apply. However, measured downhole temperatures in the two drillholes contrast markedly; in Br 23 the Rautawiri Breccia is about 25^{o} cooler.

Hole Br 24 (Fig. 34).

The persistence of andesine and biotite in the Ohaki Rhyolite indicates impermeable conditions although hydrothermal calcite, chlorite and pyrite also occur. No core

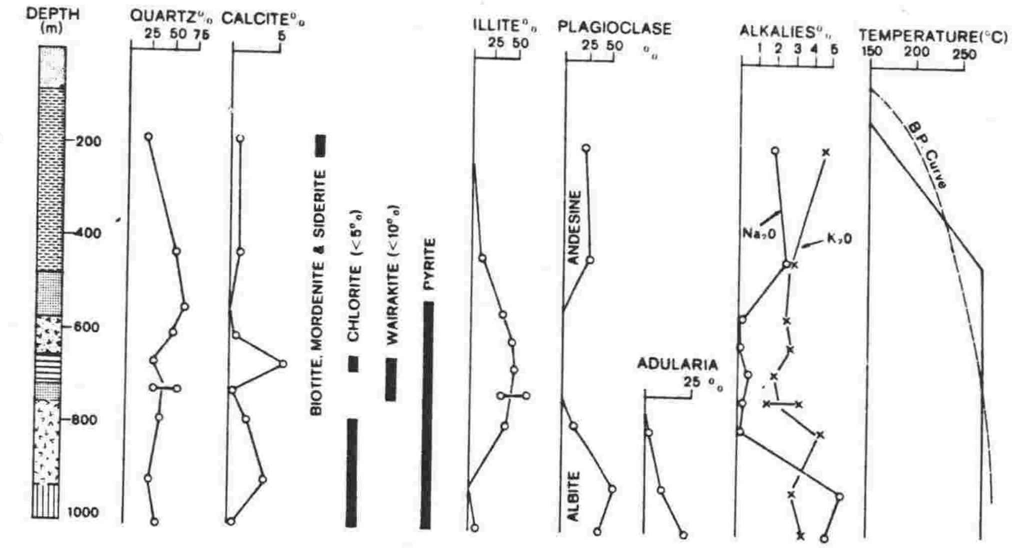

FIG. 32. Distribution of some minerals in drillhole Br 22.

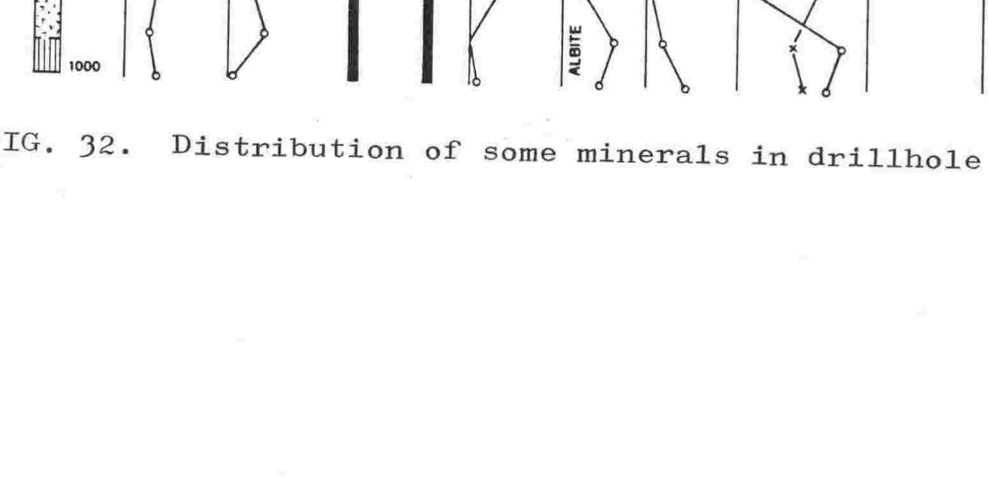

FIG. 33. Distribution of some minerals in drillhole Br 23.

of the Upper Waiora Formation was taken in this drillhole although it is recognised from cuttings. Andesine phenocrysts in the upper and lower margins of the Broadlands Dacite have been replaced entirely by mixtures of illite, quartz and calcite which suggests stagnant conditions, but slightly greater permeability than in the centre of the dacite flow where unaltered andesine persists. The Rautawiri Breccia contains the hydrothermal assemblage calcite, chlorite, pyrite, illite, albite and adularia which shows the formation to be a porous aquifer from which a few per cent steam (and CO_2) have been lost (Figs. 12-15). The occurrence of large calcite crystals and absence of illite in core from 880 m suggests that near this depth flow may be sufficient to raise the system above the K-mica, K-feldspar boundary line (Fig. 15). The Lower Waiora Formation contains illite, calcite, albite and chlorite which are hydrothermal minerals typical of static conditions. The Waikora Formations consist of argillite and greywacke conglomerate pebbles, in which calcite, chlorite, illite, quartz, K-feldspar and albite are 'primary' minerals; however, the occurrence of wairakite in the bottom core suggests waters here may be slightly more acid.

<u>Hole Br 25</u> (Fig. 35).

Hydrothermal alteration of cores from this drillhole indicates three producing horizons coinciding with the Upper Waiora, Rautawiri Breccia and Lower Waiora Formations.

The single core (307 m) of Ohaki Rhyolite contains hydrothermal illite-montmorillonite, chlorite, pyrite, calcite and wairakite which, if at equilibrium, indicate that water at this depth has a composition close to the K-mica, Ca-montmorillonite, wairakite, calcite phase boundary (Fig. 12). In the Upper Waiora Formation hydrothermal alteration is characterised by abundant adularia, chlorite, pyrite and some calcite; this demonstrates that the formation is a zone of vigorous boiling with sufficient flow to change the water pH, raising the system above the K-mica, K-feldspar boundary line (Figs. 12-15). The Broadlands Dacite is evidently less permeable since albite and illite are present, but the underlying Rautawiri Breccia and Rangitaiki Ignimbrite contain chlorite, adularia (no albite), minor illite, pyrite and irregularly distributed calcite. This suggests that this is also a zone with a flow of boiling water but, in contrast to the Upper Waiora Formation, flow is not sufficient to lift the system above the K-feldspar, K-mica boundary line (Fig. 15). Core from 1125 m, correlated with the lower Waiora Formation, contains hydrothermal chlorite, illite, pyrite and adularia revealing that this formation is also a porous aquifer from which some steam loss has occurred (Figs. 12 and 14).

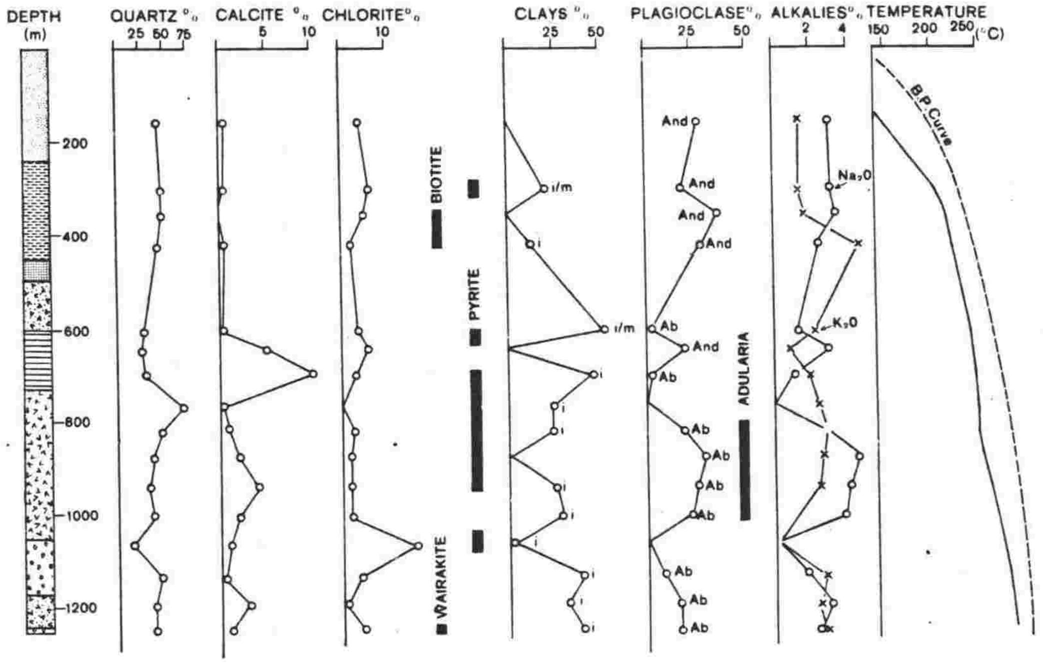

FIG. 34. Distribution of some minerals in drillhole Br 24.

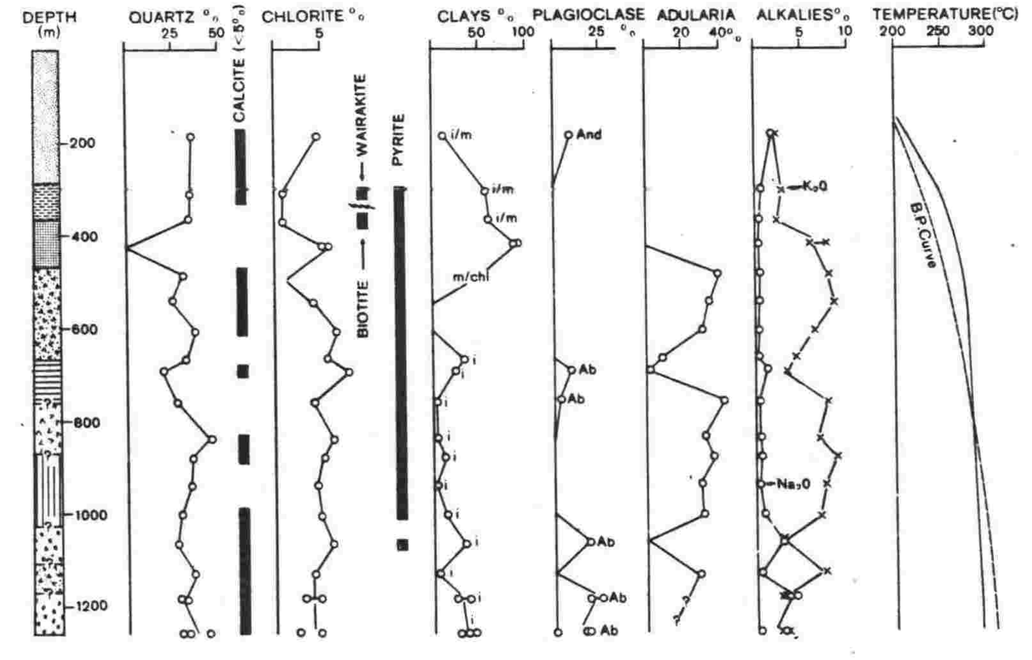

FIG. 35. Distribution of some minerals in drillhole Br 25.

PART 3 : GEOTHERMOMETRY

PART 3 : GEOTHERMOMETRY

Active geothermal fields provide an opportunity to test geothermometric methods. Five have been applied to Broadlands, and of these, fluid inclusion geothermometry gave temperatures closest to those measured.

OXYGEN ISOTOPES

Samples from Broadlands drillhole Br 16 supplied to E.V. Eslinger (Case Western Reserve University) have been reported in abstract by Eslinger and Savin (pers. comm.). They found that a plot of the δO^{18} fractionation coefficient (α) for illite and groundmass quartz coexisting in drillcore "agrees quite well" with the extrapolated laboratory calibrated plot for $\alpha_{\text{quartz-muscovite}}$. They also concluded that although quartz and illite appear to be in isotopic equilibrium at present borehole temperatures, both minerals seem to be out of equilibrium with waters discharged from the bore (Giggenbach, 1971).

SULPHUR ISOTOPES

The partitioning of sulphur isotopes between common sulphide minerals has been shown, by experiments and from thermodynamic calculations, to be temperature dependent over the range 250° to 600° (e.g. Sakai 1968; Bachinski 1969; Grootenboer and Schwartz 1969; Kajiwara and Krouse 1971).

Crystals of sphalerite, galena, pyrite and pyrrhotite were hand-picked from lightly-crushed cores and cuttings from drillholes Br 7, 15 and 16 and their S isotope compositions measured by Dr T.A. Rafter, Institute of Nuclear Sciences, D.S.I.R., New Zealand.

TABLE 7

ISOTOPIC COMPOSITION OF S IN MINERALS FROM BROADLANDS AND CALCULATED EQUILIBRATION TEMPERATURES

Drill-hole/ Depth (m)	δS^{34} w.r.t. meteorite					Temperature°	
	FeS_2	ZnS	PbS	Fe_xS_y	Zns-Pbs	Isotope*	Measured
16/302-323	4.9	4.2	3.0		1.2	543±32	160
		4.0±0.1	2.4±0.1		1.6	434±20	160
		4.3±0.1					
16/815	5.5	4.8	2.8		2.0	359±15	225
16/1053	5.1	4.3	2.6±0.1		1.7	413±20	254
16/1354		5.0	2.7		2.3	317±13	267
15/1842				3.6±0.1			
7/845	3.9	3.7	1.4	3.6	2.3	317±13	274

* Kajiwara and Krouse (1971)

Although the $\delta^{34}S$ values of these sulphides follow the established enrichment trend of pyrite > sphalerite > galena, the sulphur isotope equilibrium temperatures, using Kajiwara and Krouse's (1971) curve, differ widely from the measured temperatures. This means that either isotopic equilibrium was not reached or that the method is of doubtful value as a geothermometer. Measured and S isotope temperatures are closest at depths where permeability is best, suggesting that at shallow levels isotopic equilibrium was not attained; the sulphides in 16/302-323 also have significant in sample S isotope variation (Table 7). These sulphides, which give equilibration temperatures with the greatest difference from those measured, occur in a poorly permeable zone in which deposition was probably caused by intermixing of river and thermal waters (Browne, 1971).

Rates of S isotope fractionation between galena and pyrite and pyrite and sulphur have been considered by Salomons (1971). He was unable to achieve equilibrium for runs at 400° in 120 days and thought that isotopic inhomogeneity in pyrite crystals was the cause. He concluded that results of previous sulphur isotope fractionation studies should be regarded as doubtful. Although Salomons (1971) thought S^{34} might not reequilibrate in pyrite during periods as long as those involved in metamorphic events, the equilibration of S^{34} between galena and sphalerite appears to be more rapid, and this sulphide pair is commonly used to estimate deposition temperatures.

Assuming isotopic equilibrium between sulphur species in solution and the precipitating mineral phases, Ohmoto (1970) considered the effect of the chemistry of the hydrothermal fluids themselves, on the composition of sulphur-bearing minerals. Among other factors, the S^{34} values of sulphides are controlled by oxygen fugacity and pH, but not S fugacity. Applying this to Broadlands, it may be that at shallow depths, oxygen fugacity and pH fluctuations cause variable S^{34} precipitation values. However, it is not yet clear how these variations affect actual S isotope fractionation between coprecipitating sulphide phases.

ALUMINIUM IN QUARTZ

The use of this geothermometer was proposed by Dennen et al (1970) who postulated that quartz forming in an Al saturated environment would contain Al in solid solution in amounts varying linearly and directly with the quartz crystallisation temperature. They concluded that, assuming Al solution saturation, between 90° and 573° (the temperature of the high/low quartz transformation) the Al content of quartz increases by about 1 ppm Al for each 3.6° rise in temperature. The effect of pressure is small.

This proposal was criticised by Clocchiatti and Touray (1971) who pointed out that Al-bearing inclusions, particularly in magmatic quartz, would give incorrectly high temperatures. The same point was also made by Coveney and Kelly (1971) who specified dawsonite ($Na\ Al\ CO_3(OH)_2$) as an inclusion mineral capable of affecting the Al content of quartz. Blackburn and Dennen (1971) answered that their methods of sample preparation eliminated inclusion-bearing quartz grains.

Coveney and Kelly (1971) also recorded a marked discrepancy (for quartz from the Oriental Mine, California) between the Al (90°) and inclusion filling temperatures (201 to 233°) and concluded that a drastic revision of the Al temperature curve was required.

The Broadlands geothermal field is a good area to test the usefulness of this geothermometer as quartz is abundant and the waters are saturated with Al (about 0.34 ppm, Mahon and Finlayson, 1972). Clear, euhedral, hydrothermal quartz crystals were hand-picked from cores and cuttings from drillholes Br 19/793 m and Br 25/603 m. These were ground in a TEMA crusher and the finest fraction examined by X-ray diffraction to detect possible adherent or included clay minerals; none were detected. The Al content of the powders were determined by R.L. Gougel, Chemistry Division, DSIR, on a Parkin Elmer 303 atomic absorption unit, using a nitrous oxide-acetylene flame. Two quartz powders were also kindly analysed by W.H. Dennen, University of Kentucky. Results are given in Table 8.

TABLE 8

Al CONTENT OF QUARTZ AND COMPARISON OF Al TEMPERATURES WITH MEASURED AND THOSE OBTAINED FROM FLUID INCLUSIONS.

Drill-hole/ Depth (m)	Sample no.	Al ppm	Temperature°			Analyst
			(1)Al	Fluid(2) Inclusion	Measured	
19/793	A	45	195±6	262-266	270	Chemistry Div.
"	"	36	163±5	"	"	W.H. Dennen
"	B	50	213±7	"	"	Chemistry Div.
"	1	170	645±15	"	"	" "
"	"	150	573±14	"	"	W.H. Dennen
"	2	130	501±12	"	"	Chemistry Div.
"	3	95	375±10	"	"	" "
25/603	6	40	177±6	266-274	279	" "

(1) Dennen et al, 1970.

(2) See fluid inclusion section.

These results suggest that the amount of Al in quartz does not give a reliable estimate of crystallization temperature. Possibly samples with high Al contents contain Al-bearing inclusions such as illite or feldspar; none were seen but daughter minerals occur in fluid inclusions of other quartz crystals. Possibly the Al analyses are in error or the quartz crystals were contaminated with atmospheric dust. However, two quartz samples have Al contents which give crystallization temperatures considerably below those measured and these are more difficult to explain. Possibly some Fe^{3+} is substituting tetrahedrally in the quartz crystals (suggested by W.H. Dennen, pers. comm.) but the Fe^{3+} content of Broadlands water is so low that this is unlikely.

SPHALERITE

Introduction

The sphalerite geothermometer has been the subject of prolonged investigation and discussion since it was proposed by Kellerud in 1953. Recent literature has been summarised by Scott and Barnes (1971) who also confirmed Boorman's (1967) conclusion that sphalerite compositions could not be used to estimate temperatures between 300 and 550°. However, Scott and Barnes (1971) proposed a sphalerite geobarometer which they think can be applied to deposits between 300° and 500° in which sphalerite, pyrite and pyrrhotite crystallised together in equilibrium.

An active geothermal field, such as Broadlands, containing sphalerite and iron sulphides provides an opportunity to study phase relations below 300°. Fifty-five electron-microprobe analyses (Table 9) of sphalerites from Broadlands and Waiotapu have been made to find their chemical variation, and if possible, relate composition to measured temperatures or pressures. This was done with the co-operation of J.F. Lovering of Melbourne University; the following section is based on a joint paper submitted to 'Economic Geology'.

Analyses

Microprobe Analyses

Microprobe analyses of sphalerites from drillholes Br 7, 10, 14 and W 7 were made at the Department of Geophysics and Geochemistry, Australia National University, by J. Widdowson and N.G. Ware on an A.R.L. Electron Probe X-ray microanalyser at 20 kV with an effective specimen current of 0.05 μA. Standards used were spectrographically pure metals, troilite, and sphalerite of known composition. Four points were analysed on each grain from all except sphalerite from Br 14/1234 m, analysis 5, where 20 counts were taken by step scanning at 10 μ intervals on 3 different traverses. Williams's (1967) correction procedures were then applied. Sphalerites from drillholes Br 15 and 16 were analysed by the writer at the School of Geology, University of Melbourne, using a JEOL JXA-5A electron microprobe at 15 kV. A 400 μ^2 area of sphalerite from Br 16/1367 m was checked for homogeneity and repeatedly analysed using troilite and spectrographically pure iron, manganese and zinc standards. After applying Williams's (1967) correction procedures, this sphalerite was then used as a standard to analyse other sphalerites, some of which were also checked against pure metal standards. Table 9 also shows the accuracy of individual sphalerite analysis.

Sphalerite Compositions

In the table of results (Table 9), only sphalerites coexisting with pyrite and pyrrhotite have been corrected for the small effect of water pressure on FeS contents (Scott and Barnes, 1971) but for others, corrections are unlikely to be greater than the analytical error. Sphalerites from drillholes Br 7, 10 and 14 have also been analysed by electron microprobe for Cu, but most contain less than 1.0 weight % chalcopyrite. Sphalerite from 844 m in Br 7, spectrochemically analysed by W.C. Tennant, D.S.I.R., contains 20 ppm Ag, 7 ppm Ga, and more than 100 ppm In and Sn.

TABLE 9 : FeS and MnS content of Broadlands sphalerites with temperature and pressure data and nature of host rock and co-existing hydrothermal minerals.

Drillhole and depth (m)	Measured Temp. (°C)	Pressure Bars	Colour or anal. no.	FeS mole %	MnS mole %	Co-existing sulphides	Co-existing hydrothermal minerals	Host rock
# 16/484	140	60.3	1	13.9 ± 1.9	0.06	FeS_2, PbS	Qtz., ad., chl., illite, calc.	dacite
			2	19.6 ± 2.1	0.06			
# 16/302	160	58.6	1	22.2 ± 2.1	0.06	FeS_2, PbS $CuFeS_2$	Qtz.,illite	dacite
			2	17.4 ± 2.9	0.06			
# 16/787	219	75.5	1	7.6* ± 0.8	0.06	FeS_2, po., $CuFeS_2$	Qtz.,chl.,illite	lithic tuff
			2	7.1* ± 0.7	0.06			
			3	6.9* ± 0.6	0.06			
			4	6.7* ± 0.5	0.06			
			5	7.1 ± 0.6	0.06			
# 16/988	253	91.7	1	9.8* ± 0.9	0.06	FeS_2, po., PbS, $CuFeS_2$	Qtz., chl., illite	lapilli tuff
# 16/1353	267	119.5	1	9.9 ± 1.2	0.23 ± 0.08	PbS, $CuFeS_2$	Qtz, chl., illite, calc., ep.	lithic tuff
			2	9.7 ± 1.3	0.26 ± 0.06			
			3	7.7 ± 0.8	0.26 ± 0.06			
# 16/1367	268	121.0	1	11.4 ± 0.1	0.10 ± 0.06	PbS, $CuFeS_2$	Chl., illite, calc ep.	greywacke
10/972	268	90.1	1	16.3	0.24 ± 0.06	FeS_2, PbS	Qtz., ad., chl., illite	conglomerate
7/816	272	91.6	1	12.9	0.07 ± 0.01	FeS_2, PbS $CuFeS_2$	Qtz., ad., chl., illite	rhyolite
			2	22.9	0.09 ± 0.01			
			3	20.5	0.07 ± 0.01			
7/844	273	93.4	1	12.8	0.03	FeS_2, PbS $CuFeS_2$	Qtz., ad., chl., illite, calc.	rhyolite
			2	18.0	0.03			
			3	13.9	0.03			
			4	17.8	0.03			
			5	14.4	0.34 ± 0.03			
			6	16.0	0.15 ± 0.03			
			7	14.5	0.18 ± 0.03			
			orange	13.7	0.33 ± 0.03			
			red	16.6	0.24 ± 0.03			
			dark red	17.3	0.18 ± 0.03			
7/855	274	94.1	1	12.0	0.11 ± 0.03	FeS_2, PbS $CuFeS_2$	Qtz., ad., chl., illite	rhyolite
			2	13.4	0.07 ± 0.03			
			3	14.7	0.09 ± 0.03			
7/875	275	95.5	yellow	6.1	1.02 ± 0.03	FeS_2, PbS $CuFeS_2$	Qtz., ad., chl., illite	rhyolite
			orange	9.9	1.02 ± 0.03			
			light red	11.2	1.57 ± 0.03			
			red	12.1	0.85 ± 0.03			
			dark red	13.2	0.67 ± 0.03			
			black	10.9	1.48 ± 0.03			
10/1075	275	99.0	1	8.8	0.28 ± 0.03	FeS_2, PbS, $CuFeS_2$	Qtz., ad., chl., illite	greywacke
7/930	276	99.6	1	13.8	0.38 ± 0.03	FeS_2, PbS $CuFeS_2$	Qtz., chl., illite	tuff
			2	14.3	0.24 ± 0.03			
			3	13.8	0.29 ± 0.03			
			red	10.7	0.24 ± 0.03			
			red	14.6	0.31 ± 0.03			
7/947	276	101.1	1	14.2	0.36 ± 0.03	FeS_2, PbS, $CuFeS_2$	Qtz., ab., chl., illite, calc.	greywacke conglomerate
			2	17.4	0.28 ± 0.03			
			3	19.7	0.07 ± 0.03			
# 15/1841	289	158.8	1	12.3 ± 0.5	1.23 ± 0.03	FeS_2, PbS $CuFeS_2$	Qtz., ad., ab., chl.,,illite, ep.	dacite (?)
			2	11.3 ± 0.5	1.49 ± 0.03			
			3	10.5 ± 1.0	1.45 ± 0.03			
14/1234	294	101.1	1	13.9 ± 0.3	0.29 ± 0.03	FeS_2,$CuFeS_2$	Qtz., ad., calc., ep.	argillite conglomerate
			2	11.8 ± 0.3	0.30 ± 0.03			
			3	9.5 ± 0.3	0.22 ± 0.03			
			4	13.3 ± 0.3	0.30 ± 0.03			
			5	7.4 ± 0.3	0.21 ± 0.03			
Waiotapu W-7/271	230	26.4	white	0.4 ± 0.3	0.03	marcasite, FeS_2	Qtz.,	welded tuff
			pale yellow	1.9 ± 0.3	0.03			
			deep yellow	2.2 ± 0.3	0.03			
			bright yellow	3.5 ± 0.3	0.03			

\# P.R.L. Browne analyst
Others by J. Widdowson and N.G. Ware

* FeS content corrected by .2 mole % for pressure effect

Hydrothermal mineral abbreviations : Qtz = quartz; ad = adularia; ab = albite; chl = chlorite; calc = calcite; ep = epidote; po. = pyrrhotite

Pyrrhotite Composition

X-ray diffractograms using Fe-radiation by L.A. Taylor (pers. comm.) of pyrrhotite separated from core Br 16/787 m show a splitting of the (10.2) reflection into two peaks - the (408) - (228) and the ($\bar{4}08$) - ($\bar{2}28$) reflections - with the $I_{\bar{4}08} > I_{408}$. Taylor (1971) has shown that this pattern is characteristic of an anomalous pyrrhotite (A-po) which is usually formed by the oxidation of normal monoclinic pyrrhotite (m-po), and is particularly widespread in sulphide assemblages from relatively low-temperature environments.

Discussion

Estimate of f_{S_2}

For the few places where pyrrhotite and pyrite co-exist in equilibrium it is possible to estimate the sulphur fugacity. Extrapolating the most recent data (Scott and Barnes, 1971) below 300° and disregarding the small pressure effect, at 787 m and 988 m in Br 16, the sulphur fugacities are $10^{-13.7 \pm 0.2}$ and $10^{-12.7 \pm 0.2}$ atmospheres respectively, and at 667 m in Br 13 (237°) it is $10^{-13.0 \pm 0.2}$ atmosphere. Throughout most of the field, however, pyrite is the only iron sulphide present and the f_{S_2} may exceed 10^{-11} atmosphere.

Sphalerite Compositions

The FeS and MnS contents of the sphalerites are variable and most crystals are inhomogeneous (Table 9). Their compositions are not directly related to depth, host rock, or measured temperature and water pressure. Nor does the chemical or colour zoning, marked in some crystals (Fig. 36), appear to

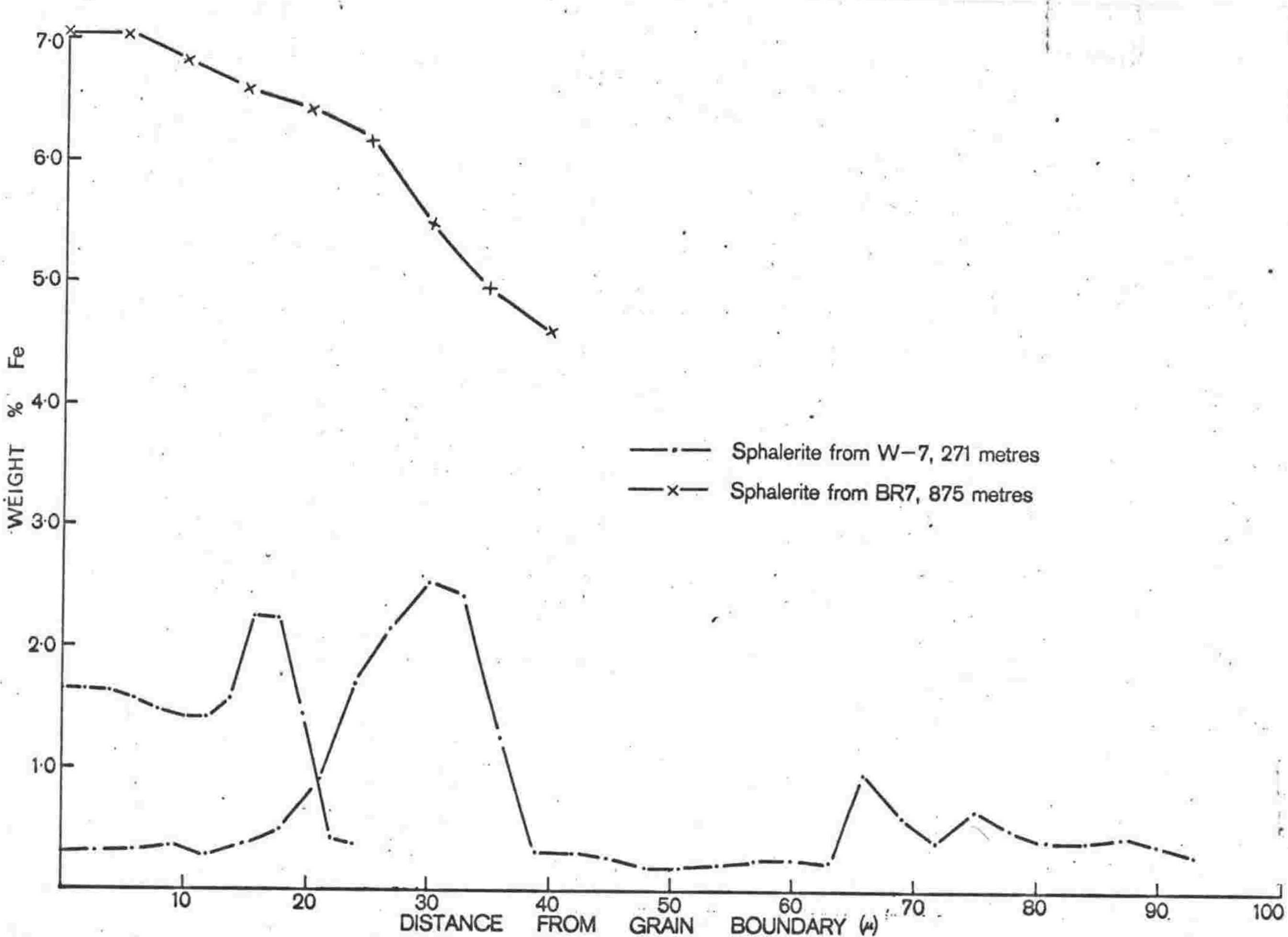

FIG. 36. Microprobe analysis scan of sphalerite crystals from Waiotapu and Broadlands. Crosses and spots represent analysis points.

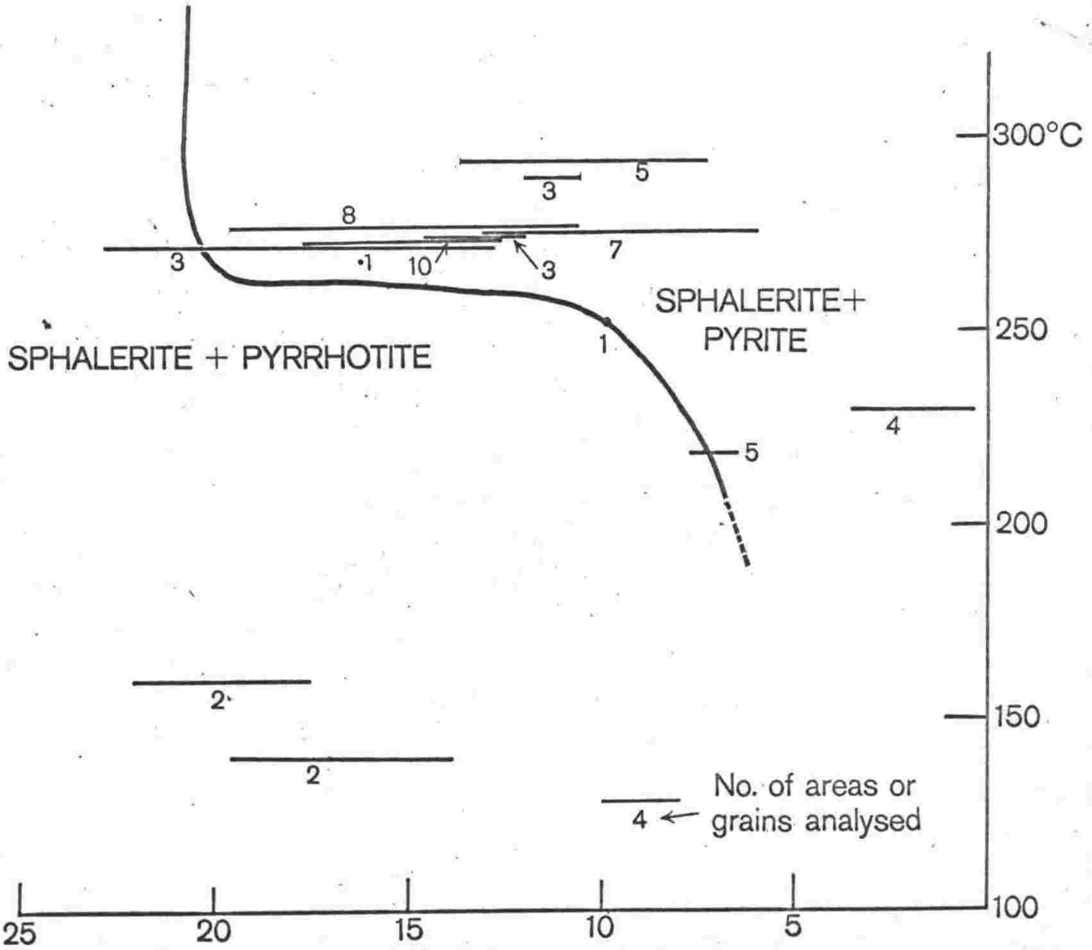

FIG. 38. Possible T-X projection of the system ZnS-FeS-S below 300°, based on composition of Broadlands sphalerites (not corrected for pressure).

result from variations in the temperature of deposition. This zoning is most probably caused by fluctuations in sulphur fugacity as pyrrhotite is absent and the minerals are therefore not buffered with respect to sulphur. Only sphalerite from 787 m, Br 16, which appears to be in equilibrium with pyrite and pyrrhotite, shows little FeS variation (Table 9), as the sulphur fugacity is buffered by the presence of both iron sulphides. The reason for sulphur fugacity fluctuations is not known but apparently these need not be great to cause marked variation in the FeS contents of sphalerite (Barton and Toulmin, 1966).

Sphalerite geothermometry and geobarometry

Boorman (1967) and Scott and Barnes (1971) showed that between 300° and 550° sphalerite in equilibrium with pyrite and hexagonal pyrrhotite has a constant composition of 20.7 ± 0.6 mole % FeS. This excludes the use of sphalerite as a geothermometer between these temperatures. In drillhole Br 16, however, pyrrhotite occurs in two cores from 787 m and 988 m with pyrite and sphalerite (Table 9), and in the former, the three sulphides co-exist in equilibrium in the same vugs (Fig. 37). The FeS contents of these sphalerites, 7.1% ± 0.6 at 219° and 9.8% ± 0.9 at 253°, are less than that determined experimentally at 300° and suggest that the pyrite + sphalerite + pyrrhotite phase boundary between 200° and 300° shifts to a region of low FeS sphalerite. Unfortunately, there are only two temperatures at which the three sulphides co-exist so the precise position of the boundary is uncertain, but the composition of sphalerite co-existing at higher temperature with pyrite alone, places a limit on its position. A possible T-X projection of the ZnS-FeS-S system below 300°

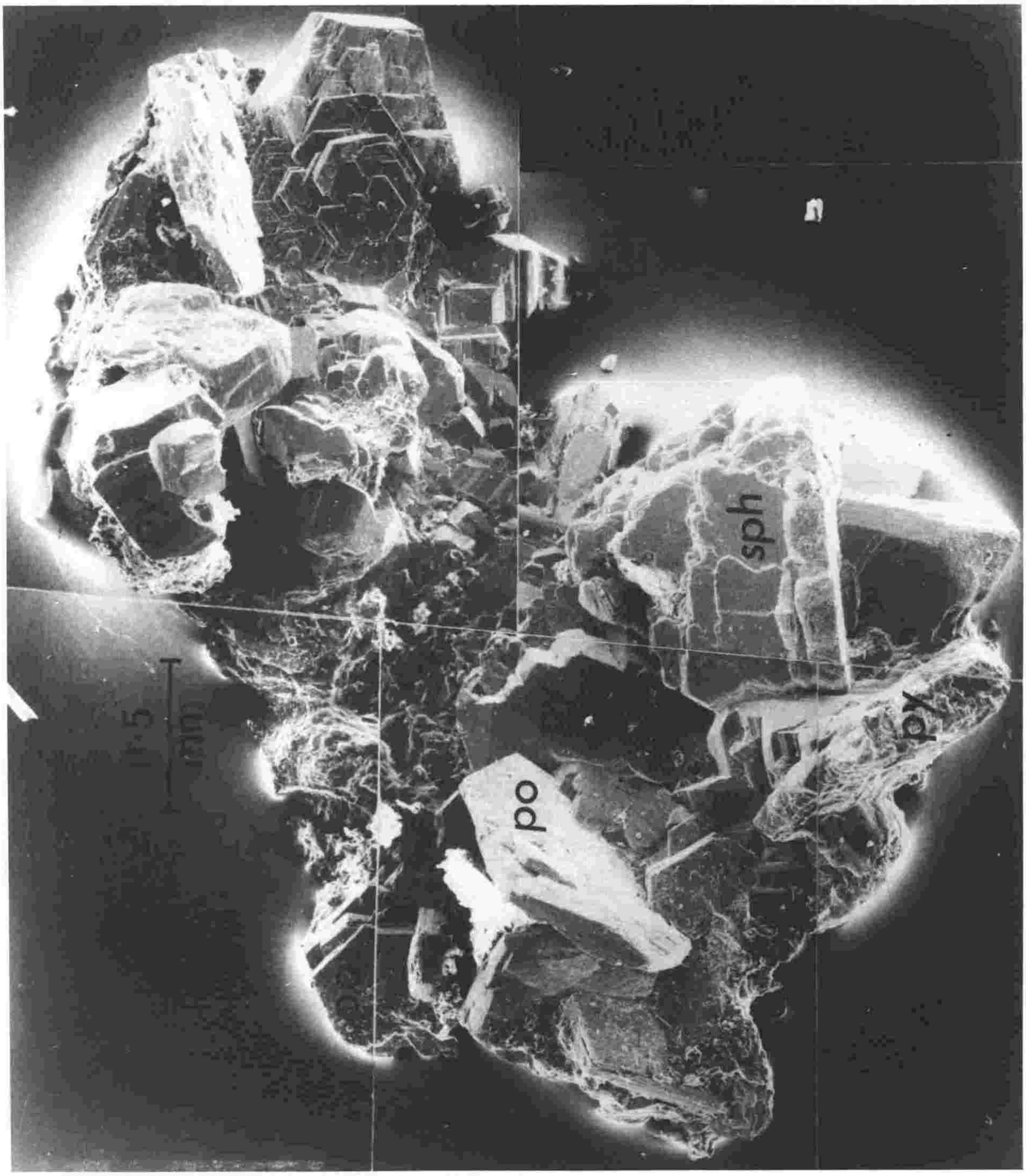

FIG. 37. Scanning electron photomicrograph of pyrite (py), pyrrhotite (po) and sphalerite (sph) from vug in core from drillhole Br 16 at 787 m depth.

Photo : J.F. Lovering.

based on the Broadlands data is shown in fig. 38. The sharp change in the FeS content of sphalerite between 240° and 280° may result from the phase change from hexagonal to monoclinic pyrrhotite. Scott and Barnes (1971) suggest that supercell transitions in hexagonal pyrrhotite may have a profound effect on the relationship between a_{FeS} and mole % FeS in sphalerite but think this might explain sphalerites with more than 20.7% FeS. However, they also point out (p. 659) that the "indications are that a_{FeS} for a monoclinic pyrrhotite + pyrite assemblage, and hence the FeS content of the coexisting sphalerite, decrease with falling temperature". The FeS content of the Broadlands sphalerites provides support for this prediction.

Hydrothermal minerals occurring with the sulphides at Broadlands (Table 9) are common in many hydrothermal deposits. Because several of these deposits contain pyrrhotite, pyrite and low FeS sphalerite apparently in equilibrium, and are thought to have formed well below 600°, Barton and Toulmin (1966) extrapolated the sphalerite + pyrrhotite + pyrite phase boundary to the low FeS field below 600°. This extrapolation was subsequently invalidated for temperatures between 300° and 550°, by the experimental work of Boorman (1967) and Scott and Barnes (1971), but the Broadlands data suggest a possible compromise.

The composition of the Broadlands sphalerites also confirms that the geobarometer proposed by Scott and Barnes (1971) cannot be extrapolated for use below 300°. Independent evidence showing that pyrite, sphalerite and hexagonal pyrrhotite crystallised in equilibrium between 300°C and 550°C, is therefore needed before the mole % FeS in sphalerite can be used to estimate crystallisation pressure of hydrothermal deposits.

Sphalerite in other geothermal fields.

Sphalerite occurs in one core from the Waiotapu geothermal field, 20 km north of Broadlands, but has a low and variable FeS content (Table 9). It coexists with pyrite and marcasite but not pyrrhotite. Iron-rich sphalerite (up to 27% wt Fe) occurs as irregular and subhedral particles together with marcasite, but not pyrite or pyrrhotite, in Red Sea mud samples (Stephens and Wittkopp, 1969) and sphalerite has been deposited in storage tank wells at the Cheleken iodine-bromine plant (Lebedev, 1968). The temperature in one well is 66°, but pyrrhotite does not appear to be present and the sphalerite composition is not reported. Sphalerite, with FeS contents varying from 3.0 to 16.6 mole % occurs in the reservoir rocks of the Salton Sea geothermal field where the measured temperature is 325° and at 2015 m in River Ranch No. 1 well, co-exists with 'presumably' hexagonal pyrrhotite and scarce pyrite (Skinner et al., 1967). This indicates an a_{S_2} of $10^{-10.2 \pm 1.0}$ atmosphere, on the most recent estimate (Scott and Barnes, 1971) which is comparable with conditions at Broadlands, but the FeS content of the sphalerite is not in agreement with that predicted from Boorman (1967) and Scott and Barnes (1971).

Conclusions

The variable compositions of the Broadlands sphalerites support the conclusion that sphalerite cannot be used to determine deposition temperatures; FeS variations are thought to mainly result from S fugacity fluctuations. However, the occurrence of pyrite and pyrrhotite in equilibrium with each other and with sphalerite fixes the S fugacity and restricts the FeS content of the sphalerite. Despite this, sphalerites cannot be used to estimate deposition temperatures below 300° since the sphalerite + pyrite + pyrrhotite phase boundary shifts too sharply to the low FeS field (Fig. 38).

The structural relations of pyrrhotite below 300° are apparently complex and require further study.

FLUID INCLUSIONS

Introduction

Two-phase H_2O inclusions occur in quartz crystals from altered drill cores and cuttings and provide an opportunity to compare inclusion filling temperatures with measured temperatures. Older quartz crystals may also record previous field conditions, as at the Salton Sea geothermal field, where Roedder (p. 325 in Skinner et al., 1967) found that sphalerite filling temperatures were below measured drillhole temperatures.

Method

Heating measurements were made by the writer and A. Wodzicki, N.Z. Geological Survey, on polished quartz crystals from drillholes Br 7, 8, 19, 23, 24 and 25, using a Leitz heating stage and a Pt-Pt.Rh thermocouple. The apparatus was calibrated in the range 208-400° against a laboratory substandard Chromel-Alumel thermocouple by Mr A.J. Glover (Physics & Engineering Laboratory, D.S.I.R.) and gave an accuracy of $\pm$ 1°. There was, however, a temperature gradient of -9° between the thermocouple and the centre of the heating stage where the sample was positioned, and all results have been adjusted accordingly.

Replicate measurements for all inclusions agree within $\pm$ 5°. A sample from Br 19/790 m was kindly examined by Dr E. Roedder, United States Geological Survey, who measured primary inclusion filling temperatures between 262° and 266°; in close agreement with results shown in figs. 39 and 40. Both primary and secondary inclusions occur in the quartz crystals, the latter being far more abundant. Primary inclusions are usually found in clear tips of crystals while vast numbers of tiny secondary inclusions commonly occur near the base giving it a milky appearance, although the distinction between the two is not always obvious. In the sample from Br/893 m, however, large inclusions are spatially related to crystal growth zones and are almost certainly of primary origin. In other samples inclusions are considered primary if they are larger than 0.1 mm, isolated, and not arranged along planes that might be healed fractures. Typical examples of primary inclusions are shown in fig. 41a-e. Secondary inclusions are generally much smaller than 0.1 mm and often occur in planes which are probably healed fracture surfaces (Fig. 41f).

Results

The results (Fig. 40) compare filling with measured drill-hole temperatures. Pressure corrections were not applied, since under Broadlands conditions, they would be at most 2-4° (Roedder, 1967; Ohmoto and Rye, 1970) and less than the observational error. Consequently, the filling temperatures of primary inclusions, initially containing only one phase, are considered close to the actual trapping temperatures.

Filling temperatures of secondary inclusions are generally lower and have a wider spread than primary inclusions (Fig. 40). However, filling temperatures of both types overlap in some samples, and a few inclusions shown as secondary (Fig. 40) may in fact be pseudo-secondary.

The samples can be divided into two groups:

Group one comprises samples from Br 7/893 m, Br 8/552 m, Br 19/790 m, Br 23/631 m and Br 25/600 and 713 m. The filling temperatures of primary inclusions in each of these samples have a narrow spread ($<16°$) and all average within 18° of measured downhole temperatures (Fig. 40). This shows that quartz inclusion geothermometry gives a good estimate of deposition temperatures.

Group two comprises samples from Br 24/579, 758, 811, 823 and 841 m in which primary inclusion filling temperatures are 16-60° higher than measured temperatures. Primary inclusions from 579 m and 823 m are vapour-rich; those from 758 m are liquid-rich; and inclusions from 811 m and 841 m are of both types.

The presence of both vapour-rich (Fig. 41e) and liquid-rich inclusions in Br 24 suggests that during deposition the hydrothermal fluid was boiling. However, the boiling point of pure water at these depths is about 295° - some 40° above the measured temperature. Three possible models (or their combination) can be used to explain this difference:

1) If the temperature and fluid composition are assumed to have remained constant, then the fluid pressure, at the time of quartz deposition must have been approximately 30 bars lower (Fig. 39). Conceivably, this may mean that the water table was lower, there was less overburden, or that the area near Br 24 was vapour dominated.

2) Assuming that temperature and pressure have remained constant, then changes in fluid composition must have lowered the vapour pressure curve some 40°. The effect of NaCl, at Broadlands concentrations, is minimal and would in fact raise the boiling point slightly (Sourirajan and Kennedy, 1962; Haas, 1971). However, liquid with 1 mole % CO_2 (compared with present-day 0.20-0.25) would boil close to the present-day measured temperatures (Takenouchi and Kennedy, 1964). The presence of up to 10% calcite and the absence of wairakite and epidote in cores between 500 m and 900 m indeed indicate that at the time of mineral deposition the CO_2 concentration

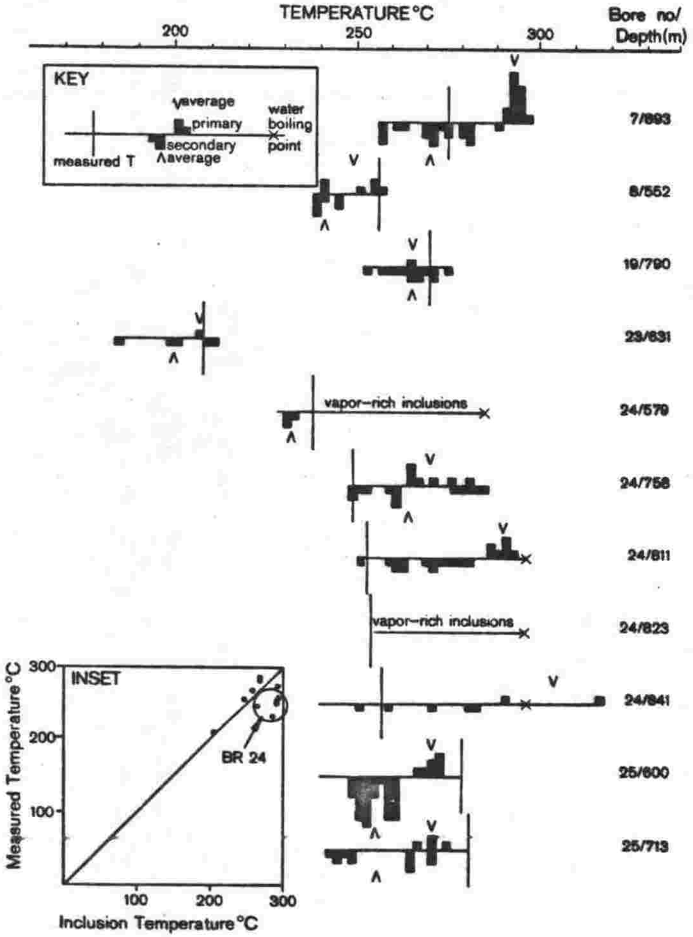

FIG. 40. Filling temperatures of fluid inclusions. Each square represents one measurement.
Inset compares measured drillhole with inclusion filling temperatures.

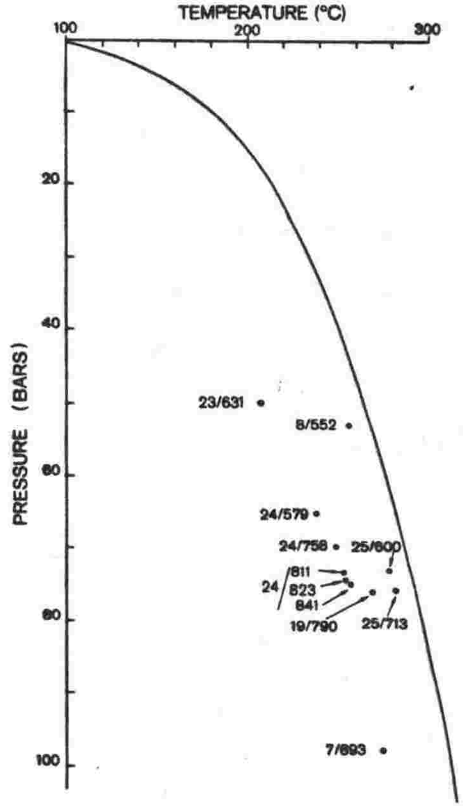

FIG. 39. Boiling point curve for water and the measured temperature and pressure at depths where samples were collected.
Sample numbers give drill-hole number and depth.

may have been of this order (Browne and Ellis, 1970).

3) Assuming that pressure and fluid composition have remained unchanged, the temperature at time of quartz deposition at 579, 811, 823 and 841 m was about 40° higher. It is not possible to determine the filling temperatures of the vapour-rich inclusions because the phase change is difficult to observe; however, data on the filling temperatures of liquid-rich primary inclusions are shown in fig. 40. As noted by Roedder (1967), the temperature of a liquid-gas system should approximate the lowest filling temperature of primary inclusions. In samples from 811 and 841 m the lowest temperatures are 286° and 290° respectively; in reasonable agreement with estimates from the boiling point curve (Fig. 39).

Unfortunately, there are no definite criteria to choose between these models, but because there is some mineralogical evidence for model 2, and some fluid inclusion evidence for model 3, a combination of both is probable.

Conclusions

Primary inclusion filling temperatures give an accurate measure of quartz deposition temperatures (Fig. 40, inset). In five drillholes these are within 18° of the measured drillhole temperatures. In the sixth, Br 24, evidence of boiling indicates that physical and/or chemical conditions have changed since quartz deposition; and bore output is low, possibly because mineral deposition has blocked feed fractures. The temperature difference is not great and may be partly due to discharge and drawdown from earlier drillholes. It is therefore concluded that fluid inclusion geothermometry can give a close measure of hydrothermal deposition temperatures.

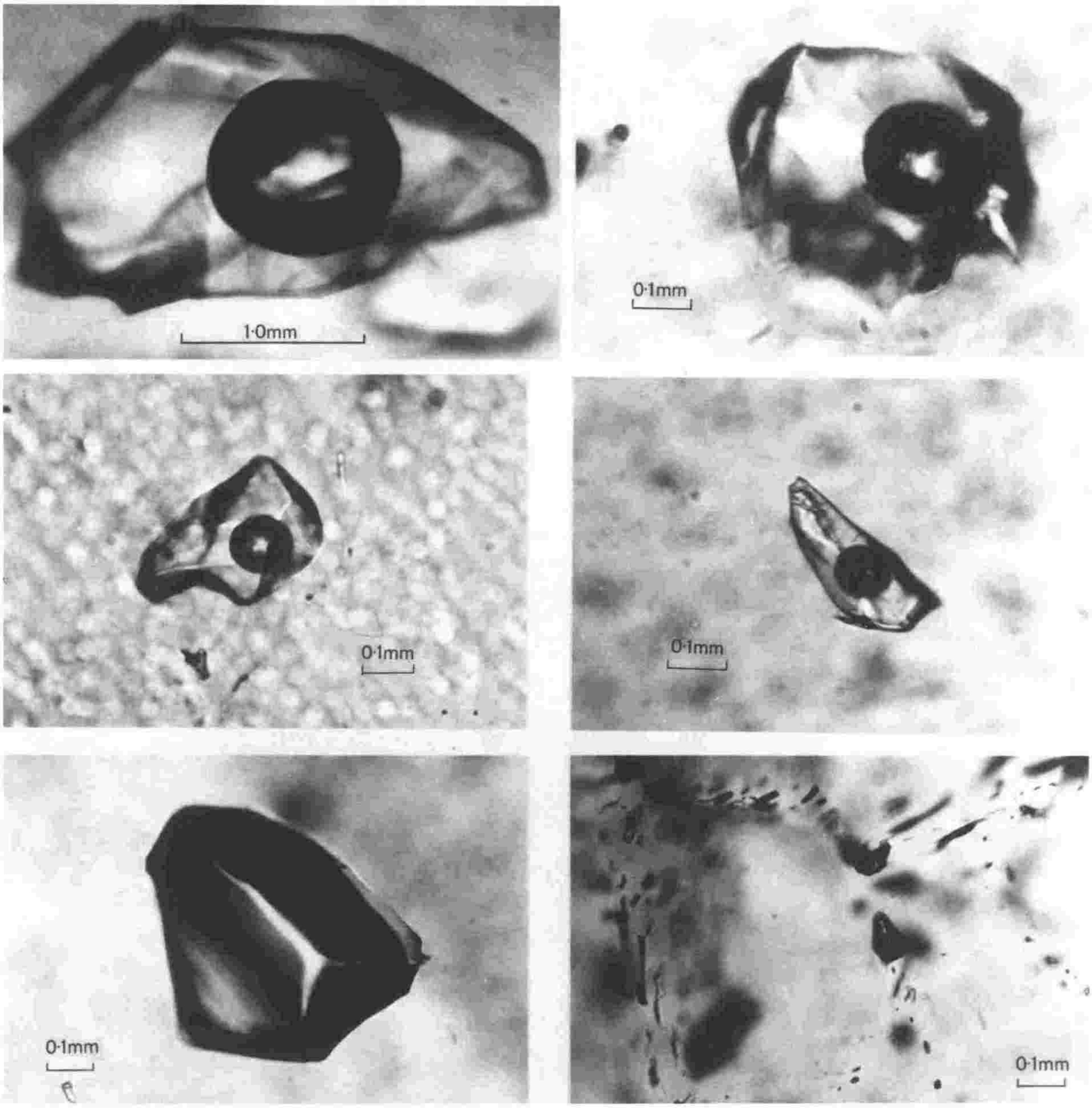

FIG. 41. Examples of inclusions -

top left : primary liquid-rich inclusion from Br 24/811 m.
top right : primary liquid-rich inclusion from Br 24/758 m.
middle left : primary liquid-rich inclusion from Br 8/552 m.
middle right : primary liquid-rich inclusion from Br 7/893 m.
bottom left : primary vapour-rich inclusion from Br 24/841 m.
bottom right : secondary inclusions from Br 24/841 m.

Photos : D.L. Homer.

PART 4 : HYDROTHERMAL ALTERATION IN OTHER GEOTHERMAL FIELDS.

PART 4 : HYDROTHERMAL ALTERATION IN OTHER GEOTHERMAL FIELDS.

INTRODUCTION

Progress made within the last decade in the study of hydrothermal alteration has been in four different ways:

1) The experimental work of, for example, Hemley and his co-workers (e.g. Hemley et al., 1969; Hemley, 1959; Hemley and Jones, 1964) which has helped determine the stability fields of the more common hydrothermal minerals. Isotopic and sulphide mineral equilibrium studies have also contributed to the understanding of hydrothermal systems although the latter usually involve higher temperatures than those found in explored geothermal fields.

2) The thermodynamic calculations of Helgeson and his associates, on mineral equilibrium in fluid systems (e.g. Helgeson, 1964, 1968, 1969, 1970 a.b.; Helgeson et al., 1970) and on reaction kinetics of alteration (Helgeson, 1970c).

3) Study of hydrothermal alteration associated with ore bodies - particularly porphyry copper deposits where good 3-dimensional sampling is possible (e.g. Creasey, 1966; Lowell and Guilbert, 1970; Rose, 1970). This includes fluid inclusion studies (e.g. Roedder, 1972).

4) Investigation of hydrothermal alteration in active geothermal systems where it is possible to measure directly temperatures and depths where minerals occur and to analyse the fluids discharged from drillholes (e.g. Steiner, 1953, 1968, 1970).

GENERAL FEATURES

Turner (1970) pointed out the unique nature of many geological events and the difficulty of compartmentalizing geologic phenomena. This is also true of geothermal systems, for although the principles of fluid/rock reaction are universal, every geothermal system studied has some unique characteristic. However, this uniqueness is in one way an advantage since it makes possible a wider study of the factors controlling hydrothermal alteration.

Unfortunately the hydrothermal alteration assemblages of several explored geothermal systems have not been examined, despite such alteration commonly being useful in understanding subsurface hydrology.

The locations of high temperature hydrothermal fields are shown in fig. 42 and table 10 includes a summary account of the geology of fifteen of them. Table 11 lists the hydrothermal minerals found in these fields, and table 12 shows the composition of the associated thermal waters. This information indicates that many geothermal fields have common features and most differences between their hydrothermal mineral assemblages can be explained in terms of differences in fluid composition, temperature, and to some extent permeability. All the 'wet' systems, except Ngawha, contain rocks of either late Tertiary or Quaternary age and typically volcanics either predominate or are possibly related to the thermal activity. It may be significant that the two 'dry' systems and Ngawha occur in 'chaos breccia' formations and the host rocks are older than those of the 'wet' systems.

FIG. 42. Location of some well-known geothermal fields.

FIG. 42. Location of some well-known geothermal fields.

TABLE 10 : CHARACTERISTICS OF SOME GEOTHERMAL FIELDS

FIELD	No. of deep drill-holes	Deepest drill-hole	Type of System	Max. Temp.	Max. Output (MW)	Water composition (Table 12)	Summary Geology	Structure	Surface Activity	Main difference in alteration from Broadlands	References
BROADLANDS	25	2421	Wet	298	possibly 150	dil.Na^+, Cl^-	Flat-lying Quaternary rhyolites, sediments, ignimbrites, tuffs overlying Mesozoic greywacke	Regional graben, faults common	Springs discharge 20 litre/sec. Sinters contain Hg-Sb-Au-Tl precipitates	-	Browne & Ellis, 1970; Grindley & Browne, 1968; Weissberg, 1968.
WAIRAKEI	117	2196	Wet	265	192	dil.Na^+, Cl^-	Lacustrine sediments of Pleistocene age; aquifer of pumice breccia /tuff; impermeable ignimbrite	Regional graben, block faulting	Extensive fumaroles and hot springs with acid altered ground	Less calcite; more wairakite and epidote	Coombs et al., 1959; Grindley, 1965; Steiner, 1953, 1968.
WAIOTAPU	7	1115	Wet	295	-	dil.Na^+, Cl^-	Tilted, Pleistocene ignimbrites with minor interbedded breccias and sediments	Regional graben	Numerous hot springs; surface deposits of sinter with precipitates of Hg-Sb-As-Tl.	No chlorite or montmorillonite reported	Grindley, 1963, 1966; Steiner, 1963; Wilson, 1963,
NGAWHA	1	585	Wet	236	-	dil.Na^+,SO_4^{2-}, Cl^-	Chaotic sequence of Cretaceous-Eocene sediments	Complex; faulting common	Hot springs with surface cinnabar, marcasite, stibnite and Hg.	No secondary feldspars; dolomite present	Banwell, 1965; Fleming, 1945; Skinner, 1966; Steiner, 1966,
MATSUKAWA, JAPAN	Approx. 50	?600	Wet then Dry	230	20	Acid condensate	Miocene, Pliocene and Quat. andesites and ignimbrites overlying Miocene sediments	Gentle folding; fluid movement related to fractures	Previously more active. A few hot springs and extensive sinter.	Attributed to fluid composition. Abundant kaolin and alunite.	Sumi, 1968a and b.
PAUZHETSK, KAMCHATKA	15	800	Wet	195	5	Dilute Na^+, Ca^{2+}, Cl^-, SO_4^{2-}	Quaternary flat-lying andesites and ignimbrites overlying Tertiary sediments	Numerous faults controlling fluid circulation	Area of active volcanism with numerous hot springs	Wider variety of hydrothermal minerals; most non-equilibrium assemblages	Naboko, 1966a and b, 1970a and b; Piip et al., 1963.
TAHUANGTSUI, TAIWAN	29	155	Wet	175	-	Acid SO_4^{2-}	Locally folded andesitic volcanics overlying Tertiary sediments	2 thrust faults may control fluid circulation	Large number of fumaroles	Reflects low pH, abundant kaolinite and alunite	Chen, 1966, 1967.
THE GEYSERS, CALIFORNIA	23	1535	Dry	246	51	-	Folded Mesozoic sediments, basalts and serpentinites; chaotic sequence.	Complex; faulting common, dominantly transcurrent.	Hot springs and geysers common nearby. Quaternary rhyolites.	Little information; calcite common.	McNitt, 1963a and b; Steiner, 1958; White, & McNitt, 1966.
SALTON SEA, CALIFORNIA	12	2469	Wet	360	-	Highly saline Na^+, Ca^{2+}, K^+, Cl^- metal rich	Near flat upper Tertiary shales overlying reservoir of a non-marine arkosic sand.	Structural depression possibly related to San Andreas fault system.	Numerous cool mudpots and a few CO_2 hot springs nearby. Spectacular thermal activity last century.	Ag-Cu minerals in pipes; similar silicate assemblage to Broadlands.	Helgeson, 1968; Skinner et al., 1967; Muffler and White, 1968, 1969; White, 1968.
STEAMBOAT SPRINGS, NEVADA	8	203	Wet	173	-	Dilute Na^+, Cl^- HCO_3^-	Tertiary and Quaternary volcanics overlying Mesozoic granodiorite	Local faulting	Abundant sinter, Hg-Sb minerals near surface	No zeolites; Possibly 2 periods of alteration	Schoen and White, 1965 1968; Sigvaldason and White, 1961, 1962; White, 1967, 1968.
REYKJAVIK, ICELAND	?	2200	Wet	146	-	Dil.Na^+, Cl^- HCO_3^-	Pleistocene dolerite over Tertiary basalt	Inactive faulting	None	Low temperature assemblage	Sigvaldason, 1963.
HENGILL, ICELAND	8	1200	Wet	260	-	Dil.Na^+, Cl^-	Quaternary basalt and rhyolite overlying Tertiary basalt	Active faulting	Numerous fumaroles and hot springs; acid leaching at surface	Differences reflect rock composition.	Arnason et al., 1969; Sigvaldason.
LARDERELLO, ITALY	>240	1660	Dry	240	350	-	Permian metamorphics overlain by more permeable Mesozoic evaporites and limestones; Tertiary mudstone cap.	Complex; block faulting common	Minor, a few fumaroles	Little information except that assemblages are similar.	Cataldi et al., 1968(?); Marinelli, 1969.
ET TATIO, CHILE	6	737	Wet	255	-	Na^+ Cl^-	Flat-lying Quaternary silicic tuffs and ignimbrites, interbedded with minor dacite and rhyolite over Tertiary sediments	Possibly graben; faulting	Hot springs; surface sinter and kaolinite	Similar, except iron oxides present and iron sulphides rare.	Browne (unpublished information); Healy (pers. comm.).
PATHÉ, MEXICO	20	772	Wet	150	3.5	Na^+, Cl^-, SO_4^{2-}	Pliocene to Recent tuffs, rhyolites, basalts and lacustrine beds over Cretaceous(?) sediments	High angle cross faults in a major east-west fault zone	Hot springs, with mineable kaolin at surface	Quartz, montmorillonite, pyrite, gypsum and zeolites common	de Anda et al., 1963; Nichols, 1968, 1970.

TABLE II

Common hydrothermal minerals reported from selected geothermal fields.

	Broadlands (1)	Wairakei (2) (3)	Waiotapu (4)	Ngawha (5)	Matsukawa (6)	Pauzhestk (7) (8)	Tahuangtsui (9)	The Geysers (10)	Steamboat Springs (11-16)	Salton Sea (17)	Yellowstone (18) (19)	Hveragerdi (20)	Reykjavik (20)	Larderello (21)	El Tatio (22)	Pathé (23)
Cristobalite	+	+	+	+	+	+	+	+	+	+	+				+	+
Quartz	+	+	+	+	+	+	+	+	+	+	+		+	+	+	+
Allophane						+										
Alunite		+	+		+	+	+	+	+							
Gypsum	+				+	+				d						+
Anhydrite					+	+				d				+	+	
Sulphur	+	+	+	+	+	+	+	+								+
Kaolin group	+	+	+	+	+	+	+	+	+	d	+				+	+
Montmorillonite group	+	+		?+	+	+			+	d	+	+	+		+	+
Interlayered illite-montmorillonite	+	+			+				+	+						+
Illite (incl. sericite)	+	+	+		+	+		+	+	+	+				+	+
Biotite	+					+										
Chlorite	+	+			+	+			+	+	+	+	+	+	+	+
Celadonite						+			+		+				+	
Corrensite	+								+							
Pyrophyllite					+									+		
Calcite	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Aragonite	+								+							
Siderite	+	+				+		+							+	
Ankerite						+				+						
Dolomite				+						d						
Mordenite	+	+				+					+		+		+	+
Analcite		+				+		+			+					+
Erionite											+					
Laumontite		+		+		+						+	+		+	+
Phillipsite						+										
Scolecite						+										
Chabazite						+										
Thomsonite				+		+										
Clinoptilolite											+					+
Heulandite	+	+				+					+					+
Wairakite	+	+	+					+						+		
Stilbite																+
Prehnite		+				+										

TABLE II

(continued)

	Broadlands (1)	Wairakei (2) (3)	Waiotapu (4)	Ngawha (5)	Matsukawa (6)	Pauzhestk (7) (8)	Tahuangtsui (9)	The Geysers (10)	Steamboat Springs (11-16)	Salton Sea (17)	Yellowstone (18) (19)	Hveragerdi (20)	Reykjavik (20)	Larderello (21)	El Tatio (22)	Pathé (23)
Pumpellyite												+	+			
Tremolite										+						
Aegirine											+					
Epidote	+	+				+				+		+	+	+		
Clinozoisite												+	+			
Adularia	+	+	+			+		+	+	+	+			+	+	
Albite	+	+	+			+		+	+	+	+		+			
Brookite						+										
Rutile					+	+										
Leucoxene	+	+			+	+										
Sphene	+	+				+										
Zunyite					+											
Andalusite					+											
Diaspore					+											
Hematite						+				+	+				+	
Pyrite	+	+	+	+	+	+	+	+	+	+	+	+			+	+
Pyrrhotite	+	+	+	+						+						
Marcasite			+	+					+							
Base metal sulphides	+		+							+						
Cinnabar	+		+	+				+	+							
Sb minerals	+		+	+					+							

MAIN REFERENCES: (1) Browne and Ellis, 1970; (2) Steiner, 1953; (3) Steiner, 1968; (4) Steiner, 1963; (5) Steiner, 1966; (6) Sumi, 1968; (7) Naboko, 1966a; (8) Naboko, 1970a; (9) Chen, 1967; (10) McNitt, 1963; (11)-(16) Sigvaldason and White, 1961, 1962; Schoen and White, 1965, 1968; (17) Muffler and White, 1969; (18) Fenner, 1936; (19) Honda and Muffler, 1970; (20) Sigvaldason, 1963; (21) Marinelli, 1969; (22) Browne (unpublished information); (23) Nichols, 1970.

Also used - Browne, 1969; Ellis, 1967, 1969; Grindley, 1965; Weissberg, 1969; White, 1967.

d = possibly detrital

TABLE 12 : MAJOR CONSTITUENTS IN WATERS FROM SOME DRILLED HYDROTHERMAL AREAS

Field	Depth (m)	Source Temp. °	pH (20°)	Li	Na	K	Rb	Cs	Mg	Ca	F	Cl	Br	I	SO_4	SiO_2	HBO_2	NH_3	CO_2	H_2S	Reference
Broadlands drillhole, Br 13	1085	260	8.6	12.6	980	200	2.2	1.3	0.02	2.4	4.5	1668	-	-	7	750	195	1.9	118	1	(1)
Wairakei drillhole, 44	695	260	8.4	14.2	1320	225	2.8	2.5	0.03	17	8.3	2260	6.0	0.3	36	690	117	0.15	19	1.0	(2)
Waiotapu drillhole, 6	915	275	8-9	6.6	860	155	2.4	0.8	0.06	10	7.5	1450	4.7	0.2	52	470	56	0.9	65	2.0	(2)
Ngawha drillhole, 1	585	230	7.4	12.2	950	80	0.8	0.4	Ca+Mg 28		0.8	1625	-	-	17	460	4849	46	62	1	(3)
Matsukawa Hot water from well T.1	162	100	2.8	-	-	-	-	-	2.1	12.0	-	4.1	-	-	176	30	-	1.9	-	45.4	(4)
Paúzhetsk drillholes	300-400	190	8.9	-	Na+K 940				7	119	0.7	1470	2.80	0.0	164	170	127	0.7	61	-	(2)
Tahuangtsui Hot water from drill-hole 18	154.9	175	1.5	-	239	30.6	-	-	30.1	52.2	-	805	-	-	2108	214	25	-	0	-	(5)
Steamboat Springs, drillhole G.S.-2	175*	160	8.8	5.7	655	73	1.2	1.9	Nil	4.4	1.0	871	1.5	0.7	132	-	146	0.0	125	1.1	(2)
Salton Sea drillhole I.I.D. No.1	1600	340	5.5	320	54,000	23,800	100	20	100	40,000	-	184,000	700	-	10	-	2100	500	-	-	(2)
Yellowstone spouter geyser near drill-hole Y-1	-	92	8.8	3.3	425	20	-	-	1	1	35	312	-	-	18	313	14.6	-	383	-	(6)
Reykjavik drillhole	600	100	8.6	0.1	95	1.5	0.02	0.02	-	0.5	-	31	-	-	16	155	0.1	0.1	58	-	(2)
Hveragerdi drillhole G-3	650	216	9.6	0.3	212	27	0.04	0.02	0.0	1.5	1.9	197	0.45	0.0	61	480	2.5	0.1	55	7.3	(2)

References: (1) Browne and Ellis, 1970; (2) Ellis. 1967; (3) Ellis, 1969; (4) Sumi, 1968; (5) Chen, 1967; (6) Honda and Muffler, 1970.

* Sigvaldason and White (1961) show depth as 122 m.

Most geothermal fields occur in areas of complex structure and are associated with recent faulting. In many places it is likely that faults provide channels for fluids and control the location of surface activity. However, in some places it is also possible that some of the fluid supply channels are breccia zones caused by the intrusion of lava feeder dykes.

All known geothermal fields have some surface manifestations varying from a few springs to extensive areas of vigorous activity; however, it may be possible to have a geothermal system which has no surface activity.

The composition of fluids discharged from geothermal fields also varies considerably and this accounts for some differences in hydrothermal alteration patterns. For example, the low pH of waters at Tahuangtsui and Matsukawa result in alunite and kaolin being stable phases, and this is consistent with the experimentally determined stability fields of these minerals (Hemley, et. al., 1969). The metalliferous, highly-saline brines of the Salton Sea, which deposited Cu and Ag minerals in their discharge pipes (Skinner et al., 1967) are apparently in equilibrium with a similar suite of hydrothermal minerals to those at Broadlands (Muffler and White, 1969), indicating that constituent ratios and not concentrations are important in controlling mineral stability.

In many places, equilibrium between water and rock has not been attained. For example, at Broadlands, some deep cores contain andesine, and at drillhole Y-1, Yellowstone National Park, equilibrium between metastable glass and fluid has not been reached (Honda and Muffler, 1970). At Pauzhetsk and the geothermal fields of the Kuril Islands, the large number of hydrothermal minerals present indicates non-equilibrium. Naboko (1970a) has measured composition differences between trapped pore fluid of impermeable formations, and the fluids discharged by the bores. This contrasts with cores from depths where circulation is unrestricted, equilibrium is attained and the hydrothermal assemblages have a simpler mineralogy

NEW ZEALAND GEOTHERMAL FIELDS

In New Zealand, several geothermal areas in the Central Volcanic Region and one in Northland have been drilled for geothermal steam but published information on their hydrothermal alteration is available for only Wairakei, Broadlands, Waiotapu and Ngawha.

Wairakei

An account of the geology and exploitation of this important geothermal field has been given by Grindley (1965) and some aspects of the hydrothermal alteration have been discussed by Steiner (1953, 1955, 1968, 1970). The main difference between the alteration of rocks at Wairakei and Broadlands is the greater abundance of epidote and wairakite at the former and of calcite at the latter. An explanation of these differences has been given elsewhere by Browne and Ellis (1970) who considered that the higher underground CO_2 content of the Broadlands solutions restricts the formation of the silicate phases in favour of calcite (Figs. 12-15). The importance of the higher underground CO_2 content at Broadlands is further emphasised by the deposition of calcite on slotted liners removed from Br 8 and 11. In contrast, calcite deposition has not occurred in drillpipes at Wairakei.

A 2300 m drillhole at Wairakei did not record temperatures above 265° whereas at Broadlands temperatures increase steadily to reach 298° at 2400 m in Br 15 (Fig. 26).

Waiotapu

Waiotapu, 13 km north of Broadlands and also in the Taupo-Rotorua depression, was investigated in the mid 1950's; seven drillholes, the deepest to 1115 m, were completed before drilling was abandoned. The geology, structure, geological history and hydrothermal alteration of the field have been described by Grindley (1963, 1966) and Steiner (1963). The thermal area, which covers about 18 sq. km, is characterised by numerous hot springs, mud pools and fumaroles. As revealed by drilling, the subsurface rocks consist of east-tilted Plio-Pleistocene ignimbrite sheets with minor dacite, andesite and rhyolite and some interbedded sediments (Table 10). The ignimbrite are poorly permeable and vertical flow is confined to closely spaced, north-east striking fissures. This contrast with both Broadlands and Wairakei where the porous Rautawiri Breccia and Waiora Formations serve as hot water aquifers.

Steiner (1963) recorded that the primary minerals, in decreasing order of susceptibility to alteration, are as follows: magnetite, pyroxene and hornblende, biotite, andesine and quartz (always unaffected). Surface patches of supergene acid alteration, at most 30 m thick, occur locally and are considered to have formed by lateral penetration of acid waters from nearby springs, resulting in the formation of alunite, opal and kaolin. Weissberg (1969) described a metal-rich sinter composed of mainly amorphous opaline silica formed at the rim of the largest hot pool (75°). This contains 2% As, 2% Sb, 320 ppm Tl, 175 ppm Ag, 170 ppm Hg and 80 ppm Au; minerals present are disseminated pyrite, possibly stibnite, realgar, cinnabar and yellow spherules of either orpiment or sulphur.

Steiner (1963) recognised two types of feldspar alteration - potassium silicate and albitisation, the latter occasionally also associated with calcite and wairakite. The hydrothermal minerals are irregularly distributed and, as at Broadlands, this partly reflects poor permeability. Albite is common and forms at shallower depths than at Broadlands; in bore 3 it is present in core from a depth of only 85 m. Wairakite is not an abundant mineral but calcite is more common than at Wairakei, especially in the albite zone, because of higher underground CO_2 activities. Steiner (1963), does not mention the presence of mordenite, siderite, cristobalite, chlorite or montmorillonite but all are known at Broadlands and Wairakei. Weissberg (1969) reports pyrrhotite and he and Browne (1969) noted the presence of small quantities of sphalerite, galena and marcasite in core from bore 7/274 m.

Veins are more common in cores from Waiotapu than either Broadlands or Wairakei and are commonly filled with pyrite, calcite and/or quartz. The maximum measured temperature at Waiotapu is 295° and temperatures over most of the field are higher than at the same depth in Broadlands; this may explain the absence of mordenite, siderite and montmorillonite which are stable at lower temperatures (Table 5).

Waters separated from the bore discharges (Wilson, 1963) are generally lower in major constituents than those of Broadlands or Wairakei (Table 12) but the underground pH cannot be calculated (Ellis, 1967) as the discharge waters have already lost steam to the country rocks. They are close to saturation with respect to calcite and silica and the underground gas content is five times that of Wairakei and similar to Broadlands. Steiner (1963) considered albite at Waiotapu formed by steam containing mainly CO_2 and H_2S separating from hot water at depth, ascending and redissolving in pore water at shallow levels. The resulting acid solution then attacking the country rocks converting andesine and oligoclase to albite. However, Hemley and Jones (1964) showed that, at constant temperature and pressure, albite is stable in waters with a high $\frac{Na^+}{H^+}$ ratio (Figs. 13 and 15) and at Broadlands albite forms by reaction of andesine with unseparated subsurface water. As at Broadlands, some adularia has formed by boiling and loss of CO_2, resulting in the $\frac{K^+}{H^+}$ ratio of the remaining waters shifting to the K-feldspar stability field (Fig. 15).

Ngawha, Northland.

Ngawha, a thermal area characterised by a few hot springs, is located 5 km south-east of Kaikohe. The geology of the area has been described by Skinner (1966), the geological history by Fleming (1945) and the surface cinnabar deposits by Brothers (1965).

A 585 m deep drillhole penetrated a chaotic sequence of mainly impermeable shales, sandstones and argillites in which temperatures gradually increase to 236° at 548 m (Banwell, 1965). Core recovered from between 29 and 215 m contains small amounts of thomsonite, (?) kaolinite and calcite and from 238 to 518 m, calcite, pyrite, pyrrhotite and bentonite [?montmorillonite]. Below 533 m cores contain dolomite, pyrrhotite, pyrite and secondary quartz which possibly formed during regional metamorphism (Steiner, 1966).

Dolomite has not been found at either Broadlands or Wairakei although it is stable in sediments of the Salton Sea (Muffler and White, 1969), and its occurrence reflects the high CO_2 pressure as the Ca/Mg ratio decreases at high CO_2 pressures until it reaches that for dolomite formation in equilibrium with calcite. Total sulphide, expressed as H_2S, is also much greater at Ngawha than at Broadlands (Table 12), and pyrrhotite may have formed in preference to pyrite because of organic matter providing low P_{H_2S}/P_{H_2} conditions locally. Thomsonite, a Ca, Na zeolite, has not been found at Broadlands, Wairakei or Waiotapu, but is uncommon in silicic rocks.

The Ngawha district is well-known for its cinnabar deposits from which 20 tons of mercury were recovered between 1928 and 1934 (Brothers, 1965) and a further quantity during the war years (Williams, 1965). The cinnabar is sparsely distributed in slightly silicified deposits within 3 m of the surface, and co-exists with sinter, sulphur, marcasite, rare stibnite, realgar and native mercury. Fleming (1945) thought it unlikely that cinnabar was then being deposited and Henderson (as quoted by Brothers (1965)) considered past deposition was due to factors including decrease of pressure, lowering of temperature, mixing of thermal solutions and swamp water and reaction between thermal solutions and carbonaceous material.

OVERSEAS GEOTHERMAL FIELDS

At Matsukawa, Japan, Pauzhetsk, Kamchatka, the Kuril Islands, and Tahuangtsui, Taiwan, andesites predominate, and fluid composition, particularly pH, has had a dominating effect on the nature of the hydrothermal minerals developed. Both at Tahuangtsui and Matsukawa, sub-surface fluids have a low pH, and kaolin and alunite are stable but secondary feldspars are absent. Sumi (1968b) described the zoning of hydrothermal minerals at Matsukawa and considered it due to increasing pH away from well-defined fluid channels. This has resulted in mineral zones characterised, from the channel outwards, by alunite, kaolinite, montmorillonite and saponite. Calcite has been identified at both fields but its relationship to the other minerals is not clear. An interesting feature is that Chen (1967) considered the porosity of some rocks has increased by alteration of feldspar to clay, followed by its removal by solutions.

The large number of hydrothermal minerals in the Pauzhetsk geothermal fields includes all those at Broadlands except pyrrhotite, base metal sulphides and possibly interlayered illite-montmorillonite. Wairakite, epidote and albite occur at lower measured temperatures than at Broadlands, and at Paratunka in the Kuril Islands, albite and epidote occur in zones where temperatures are as low as 100° (Naboko, 1970a and b). Naboko (1966a and b) notes that in these fields albite forms below the zone of CO_2 loss where solutions are alkali-rich, whereas adularia forms at the level of CO_2 loss /?boiling/, where fluids change their pH. Browne and Ellis (1970) also consider that these conditions result in the deposition of vein adularia (and calcite) at Broadlands but both also form more slowly by the replacement of primary plagioclase phenocrysts.

Little detailed information is available on hydrothermal alteration at The Geysers but near the surface, opal, dickite and twelve sulphate minerals occur in a zone of acid leaching. At depth, calcite, siderite, analcite and sericite occur (McNitt, 1963a and b; White and McNitt, 1966) and wairakite has been ejected from drillholes (Steiner, 1958). However, it is not certain if these minerals result from water/rock or steam/rock reactions.

A comparison between hydrothermal alteration at Broadlands and the Salton Sea has been presented elsewhere (Browne, 1971, p.73).

Hydrothermal alteration at Steamboat Springs has been described in some detail by Sigvaldason and White (1961, 1962) and Schoen and White (1965, 1968). The area is well-known for widespread sinter and near surface Hg, Sb, Au and Ag deposits, and, except for zeolites and epidote, most hydrothermal minerals here also occur at Broadlands. Schoen and White (1965, 1968) considered that the observed mineral assemblages are in equilibrium with waters of Steamboat Springs composition, a possible exception being well G.S.6 where there is evidence for two distinct periods of alteration. The first resulted in widespread K metasomatism at depth, and the latter in clay formation. White (1967) considered that some form of thermal activity has been in progress at Steamboat Springs for at least one million years and that the present active area is much smaller than that of the past. As mentioned elsewhere (Browne,

1971) the duration of thermal activity at Broadlands is possibly of the order of 500,000 years.

Three types of hydrothermal systems have been recognised at Yellowstone National Park (L.J.P. Muffler, pers. comm.) -

1) Hot water systems which deposit sinter;
2) Warm water systems which deposit surface travertine; and
3) 'Dry steam' systems.

Although drillholes are relatively shallow, it is probable that study of hydrothermal alteration here will be an important contribution to the understanding of low temperature thermal systems. Alteration associated with steam systems is characterised by illite clay, but zeolites are absent (White et al., 1971). This contrasts with alteration in cores from drillhole Y-1 (Honda and Muffler, 1970) where zeolites are abundant, in both cavities and as alteration products of obsidian. Honda and Muffler (1970) considered temperature was the main control of zoning of hydrothermal minerals in this drillhole, and that the composition of the interstitial altering fluid causes the sharp boundary between clinoptilolite and analcite; kinetic factors may also be important. Cores from Y-1 also contain aegirine, the first reported occurrence of this mineral in geothermal fields.

Unfortunately little information is available about hydrothermal alteration at Larderello except for a brief account by Marinelli (1969), who considered that deep alteration, similar to that at Broadlands and Wairakei, results from water/

rock reaction. He thought that below the drilled depth, steam separates from hot water and that the only alteration due to the steam phase itself is the formation of borate sublimates at the surface.

At El Tatio, Northern Chile, hydrothermal alteration of cores is similar to that at Broadlands. However, underground permeability is considerably poorer and consequently, alteration less widespread. Another difference between alteration at the two fields is that hematite is stable at El Tatio and sulphide is very rare, suggesting that either the f_{O_2} is greater, or the f_{S_2} (or both) are less than that at Broadlands. This field also has exceptionally low measured hydrogen sulphide pressures (A.J. Ellis, pers. comm.).

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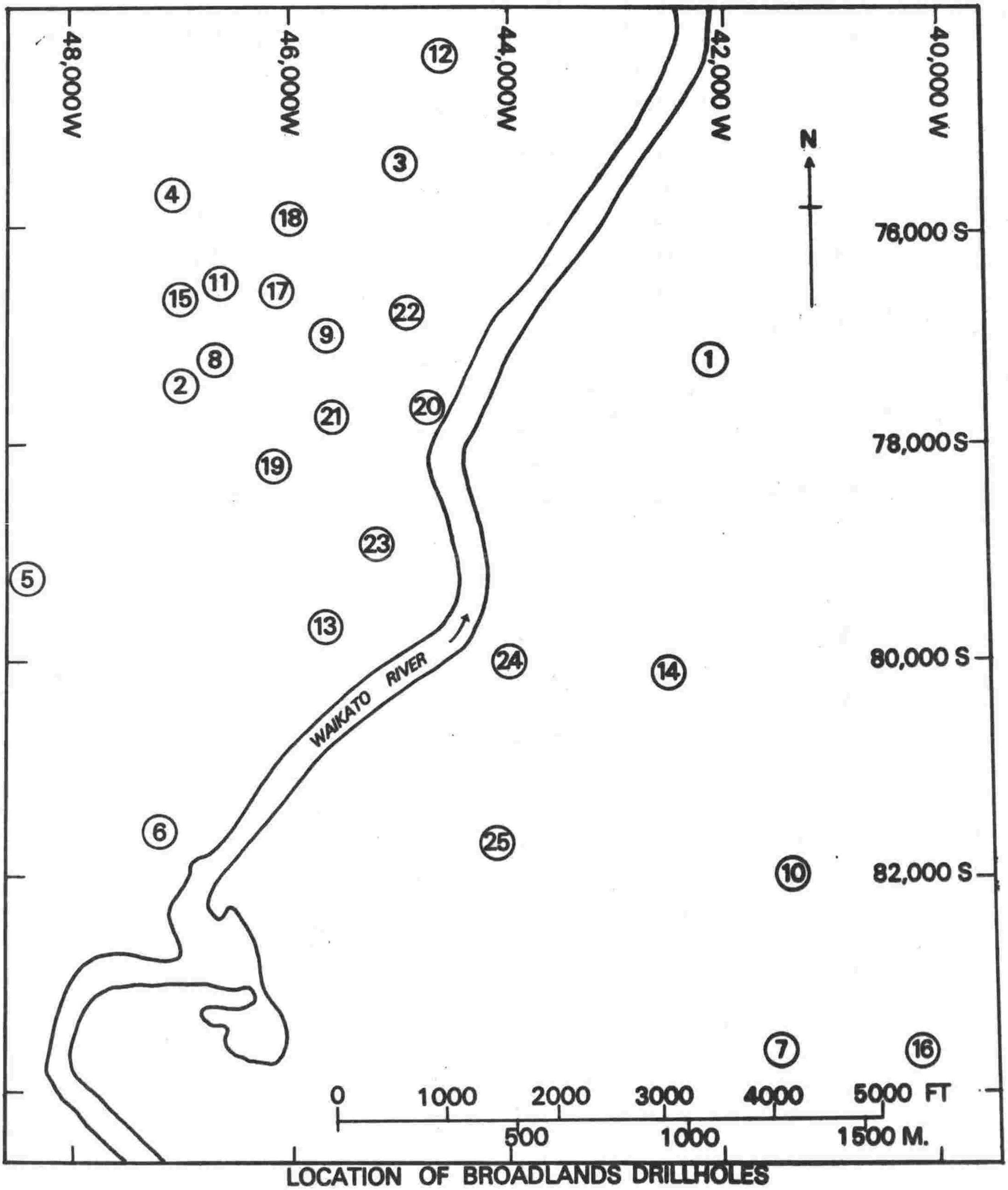
P. NOS. FOR BROADLANDS DRILLHOLE CORES

(Portion of cores from the Broadlands geothermal field are stored in the petrology museum, New Zealand Geological Survey, Lower Hutt. These have the following catalogue (P) numbers).

Drillhole number		
1	34859	34902
2	34275	34317
3	35041	35069
4	36735	36770
5	36772	36804
6	36805	36832
7	37185	37210
8	37211	37217
9	37218	37247
10	37248	37268
11	37496	37514
12	37787	37811
13	37519	37542
14	37937	37963
15	38552	38574
16	38575	38610
17	38611	38625
18	38866	38881
19	38882	38896
20	38897	38912
21	38913	38925
22	38926	38936
23	38937	38947
24	38948	38963
25	39367	39384

APPENDIX A

CONTENTS



LOCATION OF BROADLANDS DRILLHOLES

PETROLOGICAL LOGS OF DRILLHOLES - BROADLANDS GEOTHERMAL FIELD

Petrographic descriptions of cores given in this report are based primarily on hand specimen and thin section examination. Mineral identifications have been checked by X-ray diffraction and infra-red analyses.

Nomenclature

Rock types are named solely on their texture and (often deduced) primary mineralogy. Field criteria could not be used in naming because of the scarcity of good outcrops. Nor is chemical classification possible because of the pronounced chemical changes which take place during hydrothermal alteration.

LAVAS

(a) Rhyolite. A flow rock containing abundant primary or groundmass quartz.

(b) Dacite. A flow rock without quartz phenocrysts but initially with a quartzose rather than feldspathic groundmass.

(c) Andesite. A flow rock without quartz phenocrysts but with a groundmass consisting predominantly of plagioclase.

PYROCLASTICS

(a) Tuff-breccia. Indurated volcanic material containing rock fragments most of which are greater than 32 mm in diameter.

(b) Lapilli tuff. Indurated volcanic material containing rock fragments mostly between 4 and 32 mm in diameter.

(c) Coarse tuff. Indurated volcanic material containing crystals and rock fragments mainly between 1 and 4 mm in diameter.

The following qualifying prefixes are used where appropriate -

(a) Lithic - containing an appreciable quantity of rock fragments, except that where these are predominantly pumice the prefix pumiceous is used instead.

(b) Crystal - containing an appreciable crystal content.

(c) Vitric - containing an appreciable quantity of glass shards.

For some rocks a double or triple prefix is used, in which case the most abundandant component is given closest to the rock type. For example, a lithic-crystal tuff is an indurated ash containing abundant rock fragments and crystals with the latter predominanting.

SEDIMENTS

(a) Water-laid Tuff. These are defined as ash deposited directly into water with a minimum of sorting and crystal rounding.

(b) Tuffaceous Sediments. These contain material with a moderate amount of rounding and sorting. There are degrees of gradation from a to b.

Naming of other sediments follows Pettijohn (1957).

In these descriptions no attempt has been made to distinguish between ash-flow and air-fall pyroclastic rocks although in the summary logs the word 'ignimbrite' is used. For this purpose it is defined as a welded-tuff or a tuff genetically associated with and petrographically similar to a welded tuff.

Drillhole Logs

Grid references are in terms of the Broadlands Grid.

Core depths are given in metres below groundsurface but for easier reference to stored cores, are also expressed in feet below Kelly Drive.

Reference Sources

BR 1 and BR 2: Core descriptions from Healy (1968a) checked and, where necessary, modified. Formation boundaries from Healy (1968a) and Grindley and Browne (1968).

BR 3: Core descriptions checked with unpublished work by W.A. Watters and formation boundaries from Healy (1968a) and Grindley and Browne (1968).

BR 4-BR 25: Petrographic descriptions are based on unpublished petrographic work by Browne. Formation boundaries for Br 4 to Br 7 from Grindley and Browne (1968); Br 7 to 10 from Rishworth (1968); Br 11 to 13 from Healy (1968b); remainder on observations by Browne.

DRILLHOLE BR 1

Grid Ref.42,098 W;77,272 S.   R.L. 292.91 M

Metres Gd*	Feet KD**	
31-32	(112-115)	Siltstone pebbles
79-80	(170-173)	Diatomaceous siltstone and pumiceous tuff
58-60	(200-206)	Diatomaceous, tuffaceous siltstone
73-75	(250-256)	Fine diatomaceous and tuffaceous sandstone
94-97	(320-327)	Diatomaceous siltstone
104-106	(350-355)	Diatomaceous siltstone
119-121	(400-405)	Diatomaceous siltstone
134-136	(450-455)	Diatomaceous siltstone
165-166	(550-555)	Pumiceous tuff containing fresh quartz, andesine, hornblende, hypersthene and magnetite
178-179	(593-595)	Pumiceous tuff similar to 165-166 m but containing a trace of calcite
205-207	(683-688)	White, tuffaceous siltstone containing cristobalite
242-244	(804-809)	Unaltered diatomaceous-vitric tuff
270-272	(896-901)	Pumiceous tuff with a trace of calcite
287-289	(953-960)	Fine pumiceous tuff containing unaltered quartz and andesine with some secondary calcite and montmorillonite. Minor flecks of organic matter are also present
302-305	(1000-1005)	White siltstone
318-320	(1053-1058)	Pumiceous rhyolite. A light grey, brecciated and partly silicified rock containing fresh quartz,andesine and biotite but also abundant hydrothermal calcite

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* Gd = Core depth below ground surface

** KD = Core depth below Kelly drive

Metres Gd*	Feet KD**	
332-334	(1099-1104)	Pumiceous rhyolite. White coloured with similar mineralogy to core from 318-320 m. Hydrothermal illite, mordenite and calcite present.
360-362	(1191-1196)	Spherulitic rhyolite. Containing quartz, andesine, biotite and secondary pyrite. Abundant hydrothermal quartz and minor calcite present.
393-395	(1300-1305)	Rhyolite. Brecciated, with partly altered biotite and secondary pyrite present. Andesine replaced by illite and quartz.
424-426	(1400-1405)	Rhyolite. Perlitic, but with a similar mineralogy to core from 393-395 m. Contains devitrified glass and minor mordenite.
455-457	(1502-1507)	Pumice tuff. A well-compacted rock containing unaltered andesine and quartz and minor hydrothermal pyrite and calcite.
483-485	(1593-1598)	Water-laid coarse pumice tuff. Contains fragments of spherulitic rhyolite, crystals of andesine and quartz and hydrothermal illite, calcite and pyrite.
515-517	(1700-1705)	Pumice lapilli tuff. This rock contains unaltered quartz and andesine but also traces of hydrothermal calcite, pyrite and pyrrhotite.
547-549	(1806-1811)	Coarse pumice tuff. Contains abundant quartz, minor andesine and hydrothermal pyrite and illite.
575-578	(1898-1903)	Pumiceous tuff. Similar to the core from 547-549 m.
607-608	(2000-2005)	Pumice lapilli tuff. Similar mineralogy to core from 547-549 m but also containing a trace of calcite.
638-639	(2104-2105)	Dacite breccia. A hard, pale grey and green coloured rock containing partly altered plagioclase and hydrothermal illite, calcite, quartz, chlorite and leucoxene.

Metres Gd*	Feet KD**	
667-669	(2198-2203)	Dacite breccia. A dense, hard, green coloured rock containing euhedral crystals of unaltered plagioclase and hydrothermal chlorite, quartz, pyrite, leucoxene and calcite.
698-700	(2300-2305)	Dacite breccia. Similar to core from 667-669 m, but also containing some secondary illite
730-732	(2406-2411)	Pumice lapilli tuff overlying siltstone. A veined and pyritised rock containing hydrothermal quartz, abundant calcite, and illite.
759-761	(2500-2506)	Breccia. A light grey coloured rock containing quartz, andesine and minor hydrothermal calcite, pyrite, leucoxene and illite.
787-788	(2591-2596)	Coarse lithic-vitric tuff. Similar alteration to core from 759-761 m.
820-821	(2700-2705)	Coarse crystal-vitric tuff. A light-grey rock containing quartz, andesine, and hydrothermal calcite and illite.
852-854	(2805-2810)	Dacite breccia. Contains hydrothermal albite, calcite quartz, illite, chlorite and leucoxene.
880-882	(2897-2902)	Pumice tuff. A dark-grey rock with partly altered andesine. Hydrothermal minerals present are albite, calcite, illite, pyrite, quartz and chlorite.
908-910	(2988-2993)	Vitric tuff. A pale grey-coloured rock composed of quartz, calcite, albite, and illite.
942-945	(3100-3105)	Fine vitric tuff. A pale-coloured rock containing small angular quartz crystals and a few volcanic rock fragments. Hydrothermal minerals present are illite, pyrite, albite and calcite.
972-973	(3199-3204)	Pumice lapilli tuff. A poorly-sorted rock containing fragments of silicified pumice, and rare argillite, with angular crystals of quartz and altered plagioclase. Hydrothermal minerals present are albite, illite, calcite, and pyrrhotite.

Metres Gd*	Feet KD**	
1000-1002	(3291-3296)	Welded vitric-crystal tuff. Lenticular ignimbrite containing corroded crystals of quartz and anhedral feldspar. Hydrothermal minerals present are calcite, albite and illite.
1017-1019	(3348-3353)	Welded vitric-crystal tuff. Similar to core from 1000-1002 m.
1033-1035	(3400-3403)	Welded vitric-crystal tuff. Lenticular ignimbrite containing chlorite lenticules. Hydrothermal albite, quartz and calcite are also present.
1058	(3482-3483)	Welded vitric-crystal tuff. Similar to core from 1033-1035m. except chlorite lenticules are absent.
1092-1094	(3594-3599)	Bedded, dark-grey tuffaceous siltstone and sandstone with rounded greywacke and argillite grains. Contains hydrothermal illite, albite, and calcite.
1125-1127	(3700-3705)	Crystal vitric tuff. A fine grained rock containing crystals of quartz and plagioclase together with fragments of siltstone, flattened pumice and tuff. Hydrothermal minerals present are albite, illite, calcite and chlorite.
1156-1158	(3804-3809)	Crystal-vitric tuff. Similar to core from 1125-1127 m.
1183-1185	(3892-3897)	Crystal-vitric tuff. Similar to core from 1125-1127 m.
1216-1218	(4000-4005)	Crystal-vitric tuff. Similar to core from 1125-1127 m.
1248-1250	(4103-4108)	Argillite and greywacke conglomerate. Contains hydrothermal quartz, calcite, albite and illite.
1276-1278	(4197-4202)	Stratified tuffaceous sandstone. A fine-grained, poorly-sorted rock with abundant grains of argillite and greywacke. Contains hydrothermal quartz, albite and illite.
1306-1308	(4291-4296)	Subangular fragments of greywacke and argillite.

Metres Gd*	Feet KD**	
1341-1343	(4410-4415)	Argillite and greywacke conglomerate with hydrothermal quartz, albite, calcite, and chlorite.
1360-1362	(4473-4478)	Lithic-crystal tuff. A fine-grained rock composed of rounded quartz crystals, variable sized feldspar crystals and fragments of flattened pumice and dacite. Hydrothermal minerals present are calcite, albite, illite and chlorite.
1397-1398	(4592-4597)	Crystal tuff. Composed of crystals of quartz, feldspar and a few fragments of flattened pumice. Hydrothermal albite, chlorite, illite and calcite are present.

SUMMARY LOG

Metres	
30 -311	Huka Falls Formation
311-448	Ohaki Rhyolite
448-635	Upper Waiora Formation
635-727	Broadlands Dacite
727-852	Rautawiri Breccia
852-880	Lower Broadlands Dacite
880-975	Rautawiri breccia
975-1079	Rangitaiki-type Ignimbrite
1079-1125	Upper Waikora Formation
1125-1228	Ignimbrite Unit A
1228-13[illegible]	Lower Waikora Formation
13[illegible]-1398	Ignimbrite Unit B

DRILLHOLE BR 2.

Grid Ref.46,943 W; 77,472 S.   R.L. 300.39 m.

Metres Gd*	Feet KD**	
56-58	(195-200)	Pale cream-coloured, fine grained calcareous tuff, containing hydrothermal quartz, andesine and abundant calcite.
88-90	(300-305)	Water-laid tuff. Poorly sorted, composed of angular quartz and andesine crystals together with fragments of rhyolite, pumice and tuff. Hydrothermal minerals present are montmorillonite, pyrite, and a trace of calcite.
104-106	(350-355)	Interbedded mudstone, siltstone and tuff. Composed of quartz, andesine and a trace of calcite.
120-123	(402-408)	Rhyolite. A white, veined partly pumiceous rock containing larger phenocrysts of corroded quartz. Plagioclase is pseudomorphed by quartz and illite and hornblende by pyrite and quartz. Other hydrothermal minerals present are calcite in veins and traces of anhydrite.
134-136	(450-455)	Rhyolitic breccia. A mottled white coloured rock in which andesine has been replaced by albite and adularia. Hydrothermal quartz, calcite and pyrite are also present.
148-150	(495-500)	Rhyolite. A white coloured rock in which andesine is mainly fresh. The groundmass contains hydrothermal illite, calcite, pyrite and quartz.
194-196	(546-551)	Rhyolite. Similar to core from 148-150 m depth but with a coarser grained groundmass and less andesine. Abundant groundmass illite.
180-182	(600-605)	Rhyolite. Andesine fresh but groundmass and ferromagnesian minerals have altered. Hydrothermal minerals present are illite, calcite, quartz, pyrite and leucoxene.

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* Gd = Core depth below ground surface
** KD = Core depth below Kelly drive

Metres Gd*	Feet KD**	
195-197	(650-655)	Rhyolite. A pale grey-coloured rock in which ferromagnesian minerals and the pumiceous groundmass have been replaced by illite and quartz. Andesine phenocrysts have altered to illite, quartz and a trace of adularia and small amounts of pyrite and calcite are also present.
210-212	(700-705)	Rhyolite. Hard and dense, with a partly spherulitic groundmass Ferromagnesian minerals have been replaced by illite, quartz and leucoxene but andesine has only part altered to illite. Abundant hydrothermal groundmass quartz, minor calcite and pyrite are also present.
226-228	(750-755)	Rhyolite. A hard, silicified rock in which the ferromagnesian minerals, andesine and the groundmass have been replaced by hydrothermal quartz and minor illite. Some calcite is also present.
241-243	(800-805)	Rhyolite. Hard and slightly brecciated. Similar alteration mineralogy to core from 226-228 m, except illite is the main plagioclase replacing mineral and traces of adularia and pyrite are also present.
257-259	(854-859)	Rhyolite. Similar alteration to core from 241-243 m depth.
271-273	(900-905)	Rhyolite. Ferromagnesian minerals have been replaced by illite and quartz but andesine phenocrysts have been replaced either by illite or adularia plus minor illite. Other hydrothermal minerals present are calcite, quartz and pyrite.
287-289	(950-955)	Rhyolite. A partly spherulitic rock in which andesine has been replaced by adularia and calcite. Also present are hydrothermal quartz, illite and pyrite.
306-308	(1014-1017)	Brecciated rhyolite. Loosely cemented fragments of rhyolite in which andesine phenocrysts have been completely replaced by illite.

Metres Gd*	Feet KD**	
333-335	(1102-1108)	Rhyolite. Pale grey-coloured rhyolite with ferromagnesian minerals replaced by illite and quartz and andesine by calcite, albite, quartz and illite. Minor pyrite is also present.
359-361	(1189-1194)	Rhyolite. Andesine and ferromagnesian minerals have been replaced by illite and minor quartz. Groundmass quartz, calcite and traces of veinlet pyrite are also present.
393-395	(1300-1305)	Rhyolite. Similar to core from a depth of 359-361 m.
427-430	(1400-1411)	Rhyolite. Similar to rhyolite from 393-395 m depth.
456-458	(1505-1510)	Rhyolite. Andesine, ferromagnesian minerals and the groundmass have been replaced by illite, and quartz. Minor pyrite present.
484-486	(1598-1603)	Sheared, irregularly interbedded grey-brown mudstone and white pumice lapilli tuff, mainly composed of quartz, illite and minor pyrite.
501-503	(1655-1660)	(a) Sheared breccia similar to core from 484-486 m. (b) Pumice lapilli tuff. A hard, silicified rock containing numerous poorly-sorted fragments of pumice and rarer rhyolite, mudstone and tuff in a groundmass with a vitroclastic texture. Abundant hydrothermal quartz and less adularia and calcite.
509-511	(1681-1686)	Brecciated and silicified tuff. Composed of cemented angular fragments of poorly-sorted tuff. The tuff itself consists of quartz, and feldspar grains and silicified fragments of tuff, pumice and rhyolite. Adularia, quartz, calcite and pyrite are the hydrothermal minerals present.
530-532	(1748-1752)	Pumice lapilli tuff. A hard silicified slightly brecciated rock containing variable sized pumice, rhyolite and tuff fragments together with a few crystals of primary quartz and altered feldspar. The hydrothermal minerals present are quartz, adularia and pyrite.

Metres Gd*	Feet KD**	
447-449	(1805-1810)	Pumice lapilli tuff. A hard, highly silicified rock containing variable sized pumice and rhyolite fragments. Abundant hydrothermal quartz, less adularia, calcite and pyrite are also present.
574-575	(1892-1894)	Brecciated pumice tuff. Hard, silicified and containing abundant vein quartz. Adularia and pyrite are also present.
600	(1977-1979)	Water-laid tuff. A pale grey, fine-grained rock composed of small fragments of altered pumice and poorly sorted, angular crystals of quartz and feldspar. Quartz, adularia, pyrite and a trace of calcite are the hydrothermal minerals present.
628-630	(2071-2076)	Tuffaceous siltstone. Thinly bedded, fine-grained and containing abundant primary and hydrothermal quartz. Adularia and pyrite are also present.
647-649	(2133-2138)	Tuffaceous siltstone. A hard well-sorted, fine-grained rock composed of quartz, albite and minor calcite and pyrite.
683-685	(2250-2255)	Pumice lapilli tuff. Contains variable sized fragments of altered pumice. Hydrothermal minerals present are fine-grained albite, adularia, pyrite and abundant quartz.
713-715	(2350-2355)	Tuff. A white-coloured, fine-grained rock containing small subangular fragments of pumice and rhyolite and subangular crystals of quartz and altered feldspar. Hydrothermal minerals present are quartz, adularia, albite and pyrite.
745-747	(2455-2460)	Coarse lithic-crystal tuff. A white, friable rock containing numerous variable sized quartz and feldspar crystals and sub-rounded fragments of silicified pumice, rhyolite and spherulitic rhyolite. Hydrothermal minerals present are adularia, quartz, albite, calcite, pyrite and chlorite.

Metres Gd*	Feet KD**	
775-777	(2552-2557)	Lithic-crystal lapilli tuff. Contains large lapilli of welded tuff and smaller grains of rhyolite, spherulitic rhyolite and vitric tuff. Numerous quartz and altered feldspar crystals are present and the hydrothermal minerals are quartz, albite, adularia, calcite, chlorite and pyrite.
790-792	(2602-2607)	Coarse lithic tuff. A pale grey, poorly sorted rock containing abundant fragments of silicified pumice, rhyolite, vitric tuff and welded vitric tuff. Also present are crystals of primary quartz and feldspar and the hydrothermal minerals quartz, adularia, albite, calcite, chlorite and pyrite.
805-807	(2650-2655)	Coarse lithic-crystal tuff. Contains fragments of silicified pumice, spherulitic rhyolite, rhyolite, vitric tuff and poorly sorted crystals of quartz and feldspar. Hydrothermal albite, adularia, quartz, calcite, chlorite and pyrite are present.
820-822	(2700-2705)	Vitric tuff. A pale grey rock with a good vitroclastic texture. Fragments of silicified pumice, rhyolite, vitric tuff and small crystals of quartz and feldspar are present and the hydrothermal minerals are quartz, adularia, albite, calcite and pyrite.
849-851	(2794-2799)	Lithic-crystal tuff. Contains abundant subhedral and anhedral crystals of quartz and plagioclase and variable sized fragments of spherulitic rhyolite, silicified pumice, rhyolite, vitric tuff and welded vitric tuff. Hydrothermal minerals present are quartz, albite, adularia, calcite, and pyrite.
881-883	(2899-2905)	Coarse lithic-crystal tuff. Similar to core from 849-851 m.
914-916	(3010-3015)	Welded vitric-crystal tuff. A hard silicified rock containing numerous euhedral feldspar phenocrysts (but not quartz) and occasional fragments of argillite and tuff. Hydrothermal minerals present are albite, adularia, quartz, chlorite, calcite and pyrite.

Metres Gd*	Feet KD**	
942-944	(3100-3105)	Crystal tuff. Hard, contains angular crystals of quartz and feldspar and fragments of spherulitic rhyolite and rhyolite. Hydrothermal minerals present are quartz, albite, calcite, pyrite, chlorite and a trace of adularia.
972-973	(3200-3204)	Dacite. A pale green coloured rock consisting of euhedral crystals of altered feldspar in a fine-grained groundmass. Albite, calcite,quartz, illite, adularia, chlorite, epidote and pyrite are the hydrothermal minerals present.
1003-1005	(3300-3305)	Crystal-lithic lapilli tuff. A white, poorly sorted rock contain large corroded quartz phenocrysts and subhedral feldspar. Variable-sized fragments of rhyolite and spherulitic rhyolite are also present and the hydrothermal minerals are albite, adularia, calcite, pyrite and chlorite.
1035-1036	(3404-3409)	Lithic lapilli tuff. A hard,poorly sorted rock composed of variable sized fragments of greywacke, spherulitic rhyolite and rhyolite with numerous crystals of subhedral plagioclase and larger grains of quartz. Hydrothermal minerals present are quartz, adularia, albite, calcite and pyrite.

SUMMARY LOG

Metres	
45-116	Huka Falls Formation
116-463	Ohaki Rhyolite
463-502	Huka Falls Formation
502-576	Upper Waiora Formation
576-650	Lower Siltstone
650-972	Rautawiri Breccia
972-984	Dacite Unit A
984-1036	Rangitaiki-type Ignimbrite

DRILLHOLE BR 3.

Grid Ref. 44,962 W; R.L. 298.80 m.
75,410 S.

Metres Gd*	Feet KD**	
61-62	(200-205)	Fine siltstone. A pale cream-coloured, thinly bedded rock containing abundant montmorillonite and minor pyrite.
88-90	(300-305)	Rhyolite. Contains euhedral andesine and corroded quartz phenocrysts. The rock has a microcrystalline, partly spherulitic groundmass in which some hydrothermal montmorillonite is present. Biotite and hornblende have been replaced by illite and an opaque mineral.
120-122	(402-407)	Rhyolite. Partly pumiceous, partly glassy rhyolite containing unaltered andesine and quartz phenocrysts. Ferromagnesian minerals have been partly replaced by illite and opaques and the groundmass contains abundant mordenite.
152-154	(510-515)	Rhyolite. White, friable rhyolite containing hydrothermal illite.
180-181	(600-605)	Rhyolite. Spherulitic groundmass. Ferromagnesian minerals have been replaced by illite and andesine has partly altered. The groundmass also contains illite, secondary quartz and minor calcite.
212-214	(704-709)	Rhyolite. Andesine, ferromagnesian minerals and the groundmass have been replaced by calcite, illite, quartz and rare pyrite.
240-242	(798-803)	Rhyolite. Andesine phenocrysts have been replaced by illite and rare adularia; ferromagnesian minerals by illite and quartz. The devitrified groundmass contains abundant hydrothermal quartz and minor pyrite.
271-273	(900-907)	Rhyolite. Soft, white and slightly brecciated. Andesine mainly fresh although locally altered to calcite and illite. Ferromagnesian minerals and the groundmass have been replaced, the former completely, by quartz and a trace of montmorillonite.

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* Gd = Core depth below ground surface
** KD = Core depth below Kelly drive

Metres Gd*	Feet KD**	
302-304	(1000-1005)	Rhyolite. Contains large phenocrysts of corroded quartz and unaltered andesine. Ferromagnesian minerals have been replaced by illite.
330-331	(1092-1097)	Pumiceous rhyolite. Contains hydrothermal illite and calcite.
360-362	(1192-1197)	Rhyolite. Ferromagnesian minerals have been replaced by illite and quartz, andesine partly by adularia and calcite and the groundmass partly by illite, quartz and traces of pyrite.
393-395	(1300-1305)	Rhyolite. Ferromagnesian minerals have completely altered to illite and quartz and andesine phenocrysts to illite and minor adularia. Quartz, illite and pyrite are present in the groundmass.
421-423	(1393-1400)	Rhyolite. A white-coloured rock with a partly spherulitic groundmass. Andesine phenocrysts are generally fresh although slightly brecciated and have rarely part altered to calcite,but ferromagnesian minerals have been replaced by illite and quartz. Hydrothermal quartz and traces of pyrrhotite are present in the groundmass.
452-454	(1493-1497)	Rhyolite. Feldspars and ferromagnesian minerals have been replaced by illite and the groundmass also contains hydrothermal quartz, illite and a trace of pyrite.
482-484	(1590-1597)	Siltstone. Thinly bedded, well-sorted,silicified siltstone containing hydrothermal quartz and illite.
512-514	(1691-1696)	Coarse pumice tuff. A pale grey-coloured rock containing variable sized pumice, and minor rhyolite fragments together with a few angular quartz crystals. Hydrothermal minerals present are quartz, illite, calcite and pyrite.
543-544	(1790-1795)	Coarse pumice tuff. Same as core from 512-514 m but with a trace of adularia present.
573-575	(1890-1896)	Pumice lapilli tuff. Similar to, but coarser grained than, core from 512-514 m. Also present are a few argillite, greywacke and tuff fragments and hydrothermal illite, albite, quartz, calcite and pyrite.

Metres Gd*	Feet KD**	
605-607	(1995-2000)	Pumice lapilli tuff. Same as core from 573-575 m.
636-638	(2097-2102)	Coarse pumice tuff. Similar to, but finer grained than core from 573-575 m.
669-671	(2204-2209)	Pumice lapilli tuff. Pale grey-coloured, containing variable sized pumice lapilli and a few crystals of quartz and altered feldspar. Hydrothermal minerals present are calcite, albite, quartz, illite and pyrite.
697-699	(2296-2302)	Irregularly interbedded brown tuffaceous siltstone and coarse water-laid tuff. The latter contains altered pumice fragments and crystals of quartz and altered feldspar. Hydrothermal minerals present are albite, illite, calcite, pyrite and quartz.
728-729	(2397-2403)	Tuffaceous sandstone and siltstone. A cream-coloured, stratified, poorly sorted rock containing angular crystals of quartz and feldspar and occasional pumice and fine siltstone fragments. Quartz, albite, adularia, calcite, illite and pyrite are the hydrothermal minerals present.
759-761	(2499-2509)	Coarse pumice tuff. Contains variable sized pumice and rarer tuff fragments together with occasional angular crystals of quartz and altered feldspar. Hydrothermal minerals present are quartz, calcite, illite, albite, adularia and pyrite.
787-789	(2591-2597)	Coarse lithic tuff. A pale grey coloured, poorly sorted rock containing a few angular quartz crystals and fragments of silicified pumice and rhyolite. Quartz, calcite, illite, pyrite and a trace of albite are the hydrothermal minerals present.
819-822	(2698-2708)	a) Tuff. Poorly-sorted, contains sub-rounded fragments of welded vitric tuff, silicified pumice, rhyolite and spherulitic rhyolite. Also present are small quartz and euhedral and subhedral feldspar crystals. Hydrothermal minerals present are albite, calcite, quartz, pyrite, adularia and illite. b) Tuffaceous siltstone. Composed of quartz, abundant illite and minor pyrite.

Metres Gd*	Feet KD**	
850-853	(2800-2810)	Coarse lithic tuff. A poorly sorted rock, containing fragments of altered pumice and, more rarely, welded vitric tuff and spherulitic rhyolite. Phenocrysts of quartz and altered feldspar are also present and the hydrothermal minerals are quartz, calcite, albite, adularia, chlorite and pyrite.
884-885	(2910-2915)	Coarse lithic tuff. Similar to core from 850-853 m.
911-915	(3000-3010)	Coarse crystal-lithic tuff. Contains numerous subhedral crystals of feldspar and less abundant subrounded quartz. Variable sized fragments of silicified pumice, tuff and spherulitic rhyolite are also present as are the hydrothermal minerals, quartz, albite, adularia, calcite, chlorite and pyrite.

SUMMARY LOG

Metres	
21-75	Huka Falls Formation
75-463	Ohaki Rhyolite
463-509	Huka Falls Formation
509-671	Upper Waiora Formation
671-747	Lower Siltstone
747-915	Rautawiri Breccia

DRILLHOLE BR 4.

Grid Ref. 47,025 W R.L. 313.45 m
75,675 S

Metres Gd*	Feet KD**	
58-59	(200-205)	Fine tuffaceous sandstone. Mainly composed of volcanic debris and angular crystals of quartz and andesine. Pyrite and abundant montmorillonite are also present.
88-90	(300-305)	Rhyolite. This rock contains large phenocrysts of corroded quartz and fractured andesine in a devitrified groundmass. Biotite has altered to illite clay and leucoxene but the rock also contains abundant pyrite and montmorillonite. Adularia partly replaces andesine and also occurs in the groundmass. Part of the core is cut by thin (<1.0 mm wide) veinlets of quartz and calcite.
118-119	(396-401)	Rhyolite. Andesine phenocrysts have been replaced by illite, quartz and a trace of adularia. Pyrite present.
153-155	(512-517)	Rhyolitic breccia. A silicified rock containing crystals of broken quartz and altered feldspar. Andesine has completely altered to illite and quartz and biotite to leucoxene, illite and quartz. Quartz and calcite occur in small cavities and leucoxene and pyrite are also present.
165-167	(551-557)	Rhyolite. Andesine has altered to illite, biotite to leucoxene and illite and the groundmass contains secondary quartz, adularia and pyrite.
183-184	(610-617)	Rhyolite. Similar to core from 165-167 m except adularia is absent and there is less quartz and leucoxene.
213-215	(710-715)	Rhyolite. Contains hydrothermal adularia, quartz, illite, leucoxene and pyrite.
241-243	(800-806)	Rhyolite. Similar to core from 213-215 m. but adularia is absent.
271-273	(900-905)	Rhyolite breccia. Loosely cemented fragments of rhyolite in which andesine ferromagnesian minerals and the groundmass have been altered to illite, montmorillonite and quartz.
302-304	(1002-1007)	Rhyolite breccia. A white-coloured pumiceous rock containing a few fragments of tuffaceous sediment. Alteration is the same as in core from 271-273 m.

Metres Gd*	Feet KD**	
332-335	(1100-1110)	Rhyolite. Hydrothermal minerals present are pyrite, chlorite leucoxene, illite, quartz and adularia.
363-365	(1200-1206)	Rhyolite. Andesine has been replaced by illite, ferromagnesian minerals by illite and luecoxene.
394-395	(1302-1307)	Rhyolite. A slightly brecciated rock with a pumiceous groundmass composed of quartz and illite. Other hydrothermal minerals present are leucoxene, adularia, a trace of sphene and pyrite. Andesine completely replaced by illite.
424-426	(1600-1605)	Pumice tuff. A poorly sorted, partly silicified rock, composed of pumice and rhyolite fragments and a few angular quartz crystals. The hydrothermal minerals present are adularia, sphene and illite.
454-456	(1500-1505)	Coarse pumice tuff. Composed of angular, pumice and occasional argillite fragments and a few small quartz crystals. The rock also contains illite, pyrite, sphene and a trace of adularia.
485-486	(1600-1605)	Pumice lapilli tuff. Similar to the core from 454-456 m. Calcite,illite, pyrite, and a trace of albite are the hydrothermal minerals present.
527-529	(1740-1745)	a) Coarse pumice tuff. The rock is poorly sorted and composed of pumice rhyolite and greywacke fragments and a few quartz crystals. Hydrothermal minerals present are albite, illite, and a trace of adularia. b) Siltstone. A fairly well-sorted rock with chlorite, leucoxene, epidote, calcite present.
577-578	(1902-1907)	Rhyolite. A hard silicified rock containing phenocrysts of quartz. Biotite has been replaced by illite and andesine by albite and adularia.
621-622	(2050-2055)	Rhyolite. A partly silicified rock containing phenocrysts of quartz and albite, the latter partly replaced by calcite and rare illite. Primary mafic minerals have been replaced by leucoxene and illite and the rock also contains minor adularia and interlayered illite-montmorillonite.

Metres Gd*	**Feet KD****	
668-669	(2200-2203)	Coarse pumiceous sandstone. A stratified rock, mainly composed of silicified and slightly brecciated pumice fragments. Hydrothermal minerals present include pyrrhotite, calcite, illite and traces of adularia and albite.
714-715	(2353-2357)	Water-laid tuff. A poorly consolidated rock containing pumice, spherulitic rhyolite, occasional welded tuff fragments and quartz and feldspar crystals. Hydrothermal minerals present are albite, quartz, calcite, leucoxene, pyrite and illite.
774-776	(2550-2555)	Water-laid tuff. Similar in composition and alteration to core from 714-715 m except that it is more consolidated and contains occasional well-rounded dacite fragments, chlorite and pyrrhotite.
835-837	(2750-2755)	Lithic-crystal tuff. Composed of pieces of pumice, spherulitic rhyolite, rare vitric tuff and dacite and crystals of albite and minor quartz. Calcite, pyrite, chlorite and illite are also present.
896-898	(2950-2955)	Crystal tuff. The rock consists of feldspar and a few quartz crystals with minor silicified pumice and rhyolite fragments. Secondary minerals present are albite, illite, pyrrhotite, chlorite and abundant calcite.
956-957	(3145-3150)	Lithic-crystal tuff. This rock is composed of fragments of pumice, spherulitic rhyolite, vitric tuff and argillite, with crystals of albite and quartz. Hydrothermal minerals in this core are albite, calcite, quartz, pyrrhotite, illite and chlorite.
1010-1011	(3323-3328)	Rhyolite. A hard, pale grey rock containing phenocrysts of quartz and altered feldspar in a crystalline, silicified groundmass. Plagioclase has altered to illite, albite and rare adularia,and biotite to illite plus quartz. Hydrothermal quartz and pyrrhotite are also present.

SUMMARY LOG

Metres	
31-93	Huka Falls Formation
93-408	Ohaki Rhyolite
408-421	Huka Falls Formation
421-573	Upper Waiora Formation
573-637	Ohaki Rhyolite (middle)
637-695	Lower Siltstone
695-1006	Rautawiri Breccia
1006-1018	Ohaki Rhyolite (lowest)

DRILLHOLE BR 5

Grid Ref. 48,434 W
79,206 S

R.L. 318.76 m

Metres Gd*	Feet KD**	
58-59	(199-204)	Water-laid pumice-crystal tuff. A loosely compacted rock, composed of angular crystals of quartz, andesine and rare biotite, together with fragments of glass, pumice, perlitic and spherulitic rhyolite. Minute grains of iron oxide are disseminated throughout most of the rock.
86-88	(293-298)	Pumiceous rhyolite. This rock has a glassy, pumiceous groundmass containing phenocrysts of corroded quartz, normal and oscillatory zoned andesine (some with small glass inclusions), and brown biotite.
123-125	(411-416)	Pumiceous rhyolite. Similar rock to core from 86-88 m, but has a higher crystal content, and also contains green hornblende and a trace of hypersthene.
151-153	(506-511)	Pumiceous rhyolite. A slightly brecciated rock which contains phenocrysts of quartz, andesine, biotite and hornblende in a glassy pumiceous groundmass.
177-179	(591 - 596)	Pumiceous rhyolite. Same as core from 151-153 m but occasional biotite and hornblende crystals are partly bleached.
210-212	(700-705)	Spherulitic rhyolite. A pumiceous vesicular rhyolite with a spherulitic, partly devitrified groundmass disseminated throughout by minute crystals of iron oxide. Phenocrysts of quartz, andesine, biotite and hornblende are present and also minor magnetite and hypersthene. Abundant small crystals of cristobalite occur in the groundmass.
240-242	(798-803)	Spherulitic rhyolite. Same as the core from 210-212 m.
271-273	(900-905)	Rhyolite. A denser rock than core from 240-242 m, and with a devitrified, partly spherulitic groundmass containing minute crystals of iron oxide. Minerals present are quartz, andesine, hornblende, biotite, magnetite and cristobalite. The rock is slightly brecciated.

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* Gd = Core depth below ground surface
** KD = Core depth below Kelly drive

Metres Gd*	Feet KD**	
306-307	(1014-1019)	Rhyolite. Similar in texture and mineralogy to core from 271-273 m except calcite is present in the groundmass.
333-335	(1103-1108)	Rhyolite. Similar to core from 306-307 m but with a trace of pyroxene present.
380-381	(1256-1261)	Rhyolite. Unaltered. The groundmass is devitrified, and partly spherulitic.
424-425	(1400-1405)	Rhyolite. Same as core from 380-381 m.
472-473	(1557-1562)	Breccia. This rock is composed of large (some 50 mm) fragments of irregularly interbedded dark brown mudstone and pale grey pumiceous tuff. The mudstone is generally well-sorted, but contains occasional angular fragments of an even darker mudstone. Two hydrothermal minerals present are interlayered illite-montmorillonite and a few small crystals of pyrite.
515-517	(1700-1705)	Tuffaceous sandstone. A pale grey rock composed of fragments of pumice (some up to lapilli size), angular pieces of mudstone, devitrified rhyolite (spherulitic and non-spherulitic), crystals of quartz, andesine, magnetite and a small amount of green hornblende. Hydrothermal minerals present are interlayered illite-montmorillonite, leucoxene, halloysite and abundant mordenite.
446-447	(1800-1805)	Pumice lapilli tuff. A poorly sorted rock, mainly composed of large (up to 20 mm), subrounded pumice and pumiceous rhyolite fragments with varying degrees of vesiculation. Also present, but in a lesser amount, are other rhyolite fragments, both glassy, and slightly devitrified. These are occasionally banded and may contain abundant minute crystallites. A few grains of greywacke and a pyroxene-bearing volcanic rock, probably andesite, also occur, and the primary minerals present are andesine, quartz, cristobalite and magnetite. A small amount of siderite is the only hydrothermal mineral in the sample.

Metres Gd*	Feet KD**	
576-578	(1900-1905)	Pumice lapilli tuff. Similar to core from 446-447 m, except sorting is slightly better and fragments are smaller. In addition, a few fragments of andesite and spherulitic rhyolite are present and the rock also contains siderite.
607-608	(2000-2005)	Pumice lapilli tuff. A similar rock to core from 446-447 m, but with a few rounded vitric tuff fragments and a greater proportion of greywacke. A small amount of calcite is also present.
639-640	(2106-2109)	A stratified rock consisting of (a) fine tuffaceous siltstone and (b) water-laid tuff. The latter is similar to core from 607-608 and has a fine-grained pumiceous matrix containing greywacke, pumice and rhyolite fragments and crystals of quartz and andesine. Small amounts of siderite, cristobalite and a zeolite, probably heulandite, are the hydrothermal minerals present.
668-669	(2201-2206)	Tuffaceous Siltstone. A pale grey, well-sorted rock containing angular crystals of quartz, andesine, a few small grains of magnetite, and a few fragments of pumice, spherulitic rhyolite and glass. Hydrothermal minerals present include a small amount of cristobalite, a trace of siderite, and illite, montmorillonite and halloysite.
695-696	(2289-2294)	Interbedded tuffaceous sandstone and siltstone. A thinly bedded (< 3 mm), well-sorted rock, mainly composed of quartz and andesine. Hydrothermal minerals present are siderite, illite-montmorillonite and a trace of pyrite.
732-734	(2412-2417)	Coarse water-laid pumice tuff. This rock has a fine-grained quartz matrix, but about 30% of it consists of rounded, partly silicified pumice fragments of differing sizes (up to 7 mm long). Hydrothermal minerals present are calcite, illite, leucoxene, quartz, illite-montmorillonite, pyrrhotite, siderite and a trace of albite.

Metres Gd*	Feet KD**	
759-760	(2499-2504)	Fine tuffaceous sandstone. A well-sorted rock mainly composed of quartz and silicified pumice. Hydrothermal minerals are calcite, siderite, quartz, numerous small crystals of disseminated pyrrhotite and illite-montmorillonite.
789-791	(2600-2605)	Lithic lapilli tuff. A poorly sorted rock, composed of quartz crystals and subrounded fragments of silicified pumice, mudstone, greywacke, silicified rhyolite, spherulitic rhyolite and vitric tuff. Hydrothermal minerals present are calcite, albite, pyrrhotite, leucoxene, illite and chlorite.
820-821	(2700-2705)	Water-laid coarse tuff. This rock contains numerous angular quartz crystals and subrounded fragments of mudstone, silicified pumice, devitrified rhyolite and spherulitic rhyolite. There are a few clusters (about 2 mm in diameter) of intergrown calcite, secondary quartz and pyrrhotite, and the other hydrothermal minerals are illite and albite.
850-852	(2800-2805)	Lithic lapilli tuff. Fragments of silicified pumice, devitrified rhyolite, spherulitic rhyolite and mudstone in a quartz-rich tuffaceous matrix. Calcite and lesser amounts of pyrrhotite, quartz, illite, chlorite, albite and leucoxene are the hydrothermal minerals present.
881-882	(2900-2905)	Lithic lapilli tuff. This rock contains abundant angular quartz crystals and fragments of vitric tuff, devitrified rhyolite, silicified pumice, spherulitic rhyolite and mudstone. The hydrothermal minerals present are calcite, albite, chlorite, illite, pyrrhotite and quartz.
909-911	(2993-2998)	Welded vitric tuff. Composed of quartz, crystals and fragments of rhyolite and abundant flattened silicified pumice. Albite, calcite, illite, leucoxene, quartz and pyrite are the hydrothermal minerals present.

Metres Gd*	Feet KD**	
936-937	(3080-3083)	This sample contains two different rock types - (a) Fine silstone. This silicified rock is mainly composed of poorly sorted, sub-angular quartz crystals. (b) Lenticular welded vitric tuff. Also silicified, it contains numerous euheudral plagioclase and a few quartz phenocrysts, together with sub-rounded fragments of spherulitic rhyolite, tuff and lenticules of silicified pumice. Hydrothermal minerals present are albite, calcite, leucoxene, illite, chlorite, pyrite and pyrrhotite.
971-972	(3195-3200)	Brecciated tuffaceous silstone. This rock has a fine-grained quartz matrix which contains a few pumice, spherulitic rhyolite and andesite fragments and crystals of quartz and albite, the latter now partly altered to a calcite. Other hydrothermal minerals present are leucoxene, illite and pyrite.
1000-1002	(3292-3297)	Coarse water-laid tuff. This rock consists of angular quartz and feldspar crystals and sub-rounded fragments of silicified pumice and spherulitic rhyolite. Hydrothermal minerals present are calcite, albite, illite and pyrrhotite.
1033-1035	(3400-3405)	Lithic-crystal tuff. The sample contains abundant large corroded quartz and subhedral plagioclase crystals and a few fragments of spherulitic rhyolite, vitric tuff and mudstone. The hydrothermal minerals present are albite, calcite, leucoxene, pyrrhotite and illite.
1067-1068	(3510-3514)	Crystal tuff. Similar to core from 1033-1035 m.
1133-1135	(3727-3732)	Welded vitric-crystal tuff. A crystal-rich rock, containing large phenocrysts of corroded quartz and smaller, more abundant crystals of albite in a vitroclastic matrix. Other hydrothermal minerals present are pyrrhotite, illite, chlorite and calcite, the last in veinlets up to 5 mm wide.

Metres Gd*	Feet KD**	
1277-1279	(4200-4205)	Tuff. A white, fractured rock with a fine-grained quartz and illite matrix containing altered pumice and rare rounded rhyolite fragments. The hydrothermal minerals present are calcite, mainly as phenocrysts, illite and pyrrhotite.

SUMMARY LOG

Metres	
34-76	Huka Falls Formation
76-468	Ohaki Rhyolite
468-499	Huka Falls Formation
499-637	Upper Waiora Formation
637-780	Lower Siltstone
780-900	Rautawiri Breccia
900-950	Ignimbrite Unit C
950-1018	Tuffaceous Sediment Unit A
1018-1186	Rangitaiki-type Ignimbrite
1186-1279	Lower Waiora Formation

DRILLHOLE BR 6

Grid Ref. 47,219 W R.L. 295.03 m
81,598 S

Metres Gd*	FEET KD**	
58-59	(200-205)	Pumice tuff. A poorly-sorted, loosely compacted tuff composed of abundant pumice fragments (some containing plagioclase phenocrysts), angular crystals of quartz and fresh plagioclase, and a few fragments of devitrifield rhyolite. Montmorillonite is present.
90-93	(304-312)	Siltstone. This rock has a fine-grained, mainly quartz matrix and contain~~ed~~s a few larger fragments of mudstone and silicified rhyolite. Crystals of unaltered plagioclase and quartz are also present.
119-121	(400-405)	Coarse tuffaceous sandstone. A loosely compacted, poorly-sorted rock, mainly composed of angular crystals of quartz and andesine, but also containing a few subrounded fragments of andesite and devitrified rhyolite. Hydrothermal minerals present are calcite, montmorillonite, chlorite, leucoxene and mordenite.
151-152	(504-508)	Brecciated siltstone. This rock is composed of angular fragments (up to 30 mm long) of pale grey, fine-grained, well-sorted siltstone.
181-183	(605-611)	Brecciated pumiceous rhyolite. Phenocrysts of quartz, andesine and partly altered ferromagnesian minerals occur in a soft pumiceous groundmass. Minor magnetite and cristobalite are present and the hydrothermal minerals are leucoxene, montmorillonite-illite and a small amount of a fibrous zeolite.
212-214	(707-715)	Pumiceous rhyolite. A light, very vesicular rhyolite containing phenocrysts of quartz, andesine, hornblende, biotite and minor magnetite set in a partly devitrified, pumiceous matrix. The rock is not hydrothermally altered.
241-242	(800-805)	Rhyolitic debris. Soft, pumiceous rhyolite debris containing crystals of shattered andesine and quartz, biotite, hornblende and minor magnetite. No hydrothermal alteration.
271-273	(900-903)	Rhyolitic debris. Similar to core from 241-242 m, but even more friable. Unaltered.

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* Gd = Core depth below ground surface
** KD = Core depth below Kelly drive

Metres Gd*	Feet KD**	
313-315	(1047-1055)	Pumiceous rhyolitic tuff. This soft rock contains broken phenocrysts of quartz and andesine. The pumiceous matrix has partly devitrified and is an orange-brown colour due to the presence of iron. Small amount of hydrothermal illite-montmorillonite and halloysite present.
369-370	(1220-1225)	Brecciated rhyolite. Sub-angular glassy rhyolite fragments occur in a soft, fine-grained siltstone matrix mainly composed of quartz and andesine. A small amount of leucoxene, chlorite illite-montmorillonite and calcite are present.
401-404	(1325-1334)	Banded rhyolite. A devitrified rhyolite with rare phenocrysts of replaced plagioclase. The rock is composed of numerous spherulites (containing abundant minute iron oxide grains) and lenses of small interlocking secondary quartz crystals. Two hydrothermal minerals present are pyrite and illite-montmorillonite.
431-433	(1425-1431)	Banded rhyolite. Similar to core from 401-404 m.
462-463	(1525-1530)	Banded rhyolite. Phenocrysts of andesine occur in a dark groundmass composed of occasional laths of andesine, much disseminated iron oxide and abundant small granules of cristobalite. Some pyrite and illite-montmorillonite present.
492-494	(1625-1630)	Banded rhyolite. Similar to core from 462-463 m except that the groundmass contains more andesine, and the cristobalite granules are fewer in number but larger in size.
523-525	(1726-1731)	Banded rhyolite. Similar to 462-463 m core, but slightly vesicular and not hydrothermally altered. Also contains a few small quartz phenocrysts.
553-555	(1825-1830)	Banded rhyolite. Same as core from 523-525 m depth.
584-585	(1925-1930)	Banded rhyolite. This rock, with a partly devitrified, cristobalite-bearing groundmass, contains zoned phenocrysts of andesine and numerous minute crystallites. Unaltered.
622-623	(2050-2055)	Banded rhyolite. Same as core from 584-585 m depth.

Metres Gd*	Feet KD**	
674-675	(2215-2222)	Brecciated rhyolite. A friable rock composed of glassy, perlitic, crystallite-rich, rhyolite fragments and angular crystals of andesine and quartz. Some hydrothermal kaolinite and siderite present.
708-709	(2315-2318)	Perlitic rhyolite. A hard, black, glassy rock containing a few phenocrysts of andesine and magnetite. The perlitic, occasionally banded, groundmass contains innumerable microlites and trichites. Not hydrothermally altered.
733-735	(2415-2220)	Water-laid fine vitric tuff. A thinly-bedded, well-sorted rock composed of glass shards, pumice, and rare spherulitic rhyolite fragments; angular crystals of quartz and andesine. Some siderite, mordenite and kaolinite are present.
764-765	(2515-2520)	Crystal-vitric tuff. This rock is composed of crystals of andesine, corroded quartz, and also contains vitric tuff, pumice and spherulitic rhyolite fragments and occasional chalazoidites. Siderite, mordenite, kaolin are the hydrothermal minerals present.
797-800	(2625-2634)	Lithic lapilli tuff. This rock contains angular fragments of pumice, vitric tuff, spherulitic rhyolite, pumiceous rhyolite; crystals of andesine, and minor quartz; the hydrothermal minerals mordenite, siderite, calcite, montmorillonite and a trace of pyrite.
826-829	(2720-2725)	Lithic tuff-breccia. Consists of variable-sized fragments of pumice, rhyolite, perlitic rhyolite, tuff and altered glass. Angular crystals of quartz and andesine are also present and the hydrothermal minerals are mordenite, calcite, illite, pyrite and chlorite.
856-858	(2820-2825)	Coarse pumice-vitric tuff. Angular pumice fragments and a few quartz crystals in a groundmass with good vitroclastic texture. Some calcite, illite and albite present.
889-891	(2926-2933)	Crystal-vitric tuff. Similar to core from 856-858 m, but with fewer pumice fragments and containing crystals of andesine and quartz. Some calcite, illite and pyrite are present.

Metres Gd*	Feet KD**	
918-919	(3021-3026)	Water-laid vitric tuff. A fine-grained, well-sorted rock, containing quartz and feldspar crystals and a few pumice fragments. Hydrothermal minerals present are calcite, albite, illite, chlorite and pyrite.
954-956	(3140-3147)	(a) Tuff-breccia. White pebbles and boulders of vitric tuff, containing phenocrysts of either quartz and plagioclase, or only plagioclase, in irregular contact with pale brown lithic-crystal tuff. The latter contains abundant, but unevenly distributed, angular crystals of quartz and albite, and rare oxidised biotite. The lithic fragments present include spherulitic rhyolite, devitrified obsidian and pumice and the hydrothermal minerals present are albite, calcite, illite and chlorite. (b) Water-laid tuff. A hard rock, composed of crystals of albite and pumice fragments in a fine-grained devitrified quartz, calcite matrix.
1018-1020	(3350-3355)	Tuff-breccia similar to core from 954-956 m (a).
1084-1085	(3566-3568)	Welded vitric-crystal tuff. A crystal-rich rock containing large phenocrysts of corroded quartz, and smaller more abundant crystals of andesine, in a leucoxene-bearing, partly silicified, matrix. Some calcite, illite, and chlorite are present.

SUMMARY LOG

Metres	
30-178	Huka Falls Formation
178-329	Ohaki Rhyolite
329-362	Huka Falls Formation
362-718	Broadlands Rhyolite
718-734	Lower Siltstone
734-1067	Rautawiri Breccia
1067-1085	Rangitaiki-type Ignimbrite

DRILLHOLE BR 7

Grid Ref. 41,474 W
83,688 S
R.L. 307.6 m

Metres Gd*	Feet KD**	
63-65	(208-213)	Water-laid tuff. A soft rock composed of crystals of quartz, andesine and rare oxidised biotite and hornblende. There are also a few pumice fragments and some montmorillonite present.
107-110	(350-362)	Interlayered soft, grey tuffaceous sandstone and cream-coloured siltstone. Abundant illite-montmorillonite and minor calcite present.
162-164	(533-538)	Brecciated dacite. Contains primary plagioclase phenocrysts now completely replaced by clay minerals. Hydrothermal minerals present are illite-montmorillonite, pyrite and abundant calcite.
208-211	(683-693)	Dacite. This contains fewer phenocrysts than the core from 162-164 m and is cut by thin quartz veins. Chlorite, illite-montmorillonite and abundant pyrite are present.
254-255	(834-836)	Dacite breccia. A poorly sorted rock composed of large, subangular, feldspar-rich rhyolite fragments in a fine-grained matrix of similar composition. Also present are chlorite, illite-montmorillonite and pyrite.
301-303	(988-993)	Brecciated dacite. A dark-grey rock containing abundant phenocrysts of andesine (some now partly altered to illite-montmorillonite) in a fine-grained groundmass. Some chlorite and leucoxene present and there is abundant pyrite.
347-348	(1138-1141)	Dacite. Similar to core from 301-303 m.
387-388	(1270-1274)	Dacite. A hard, dark rock with similar mineralogy to the core from 301-303 m, except more leucoxene, some calcite and a few quartz veinlets are also present.
433-435	(1421-1426)	Dacite. Plagioclase is not greatly altered but does contain a small amount of interlayered illite-montmorillonite. The groundmass contains opaques, dark calcite in irregular-shaped patches, green chlorite and pyrite.

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*Gd = Core depth below ground surface
**KD = Core depth below Kelly drive

Metres Gd*	Feet KD**	
479-481	(1572-1577)	Dacite. Andesite crystals have been partly replaced either by a dark opaque mineral or by a mixture of calcite, interlayered illite-montmorillonite and leucoxene . The groundmass is partly replaced by leucoxene, quartz and chlorite.
517-519	(1697-1702)	Dacite. Plagioclase has completely altered to calcite and illite-montmorillonite and the groundmass to quartz, leucoxene, calcite, chlorite and pyrite.
549-550	(1800-1805)	Dacite. A grey-coloured rock, with all primary plagioclase now replaced by illite-montmorillonite and calcite. The core is cut by numerous veinlets of pyrite and calcite and the groundmass contains chlorite, leucoxene, and a trace of albite.
594-595	(1950-1953)	Dacite. Similar to core from 544-550 m but darker, containing more leucoxene, and with secondary quartz 'envelopes' around the replaced phenocrysts. Also present are illite and abundant pyrite.
634-635	(2079-2084)	Coarse tuff. A vesicular rock with a silicified groundmass containing quartz crystals and silicified pumice fragments. The vesicles, now lined with many small euhedral quartz crystals, appear to have formed from the leaching out of original feldspar phenocrysts (probably after first being replaced by calcite). The primary quartz phenocrysts have overgrowths of secondary quartz and the other hydrothermal minerals present are calcite, illite, and a small amount of pyrite.
664-666	(2179-284)	Crystal-lithic lapilli tuff. A poorly sorted rock composed of quartz and feldspar phenocrysts and silicified fragments of pumice and rhyolite. The hydrothermal minerals present are calcite, albite, illite, pyrite, leucoxene and quartz.
692-694	(2271-2276)	Coarse crystal-vitric tuff. A white poorly-sorted rock containing feldspar and rarer quartz phenocrysts plus fragments of silicified pumice, rhyolite, The hydrothermal minerals present are quartz, albite, adularia, calcite, illite and pyrite.

Metres Gd*	Feet KD**	
720-721	(2361-2366)	Rhyolite. This hard, grey-green rock contains phenocrysts of altered plagioclase and rare quartz. Calcite, leucoxene, illite, pyrite, quartz and a trace of albite are the hydrothermal minerals present.
750-752	(2461-2466)	Rhyolite. Similar to core from from 720-721 m, but containing a few xenoliths of andesite. There are also a few thin pyrite and calcite veins and other hydrothermal present are albite, quartz, chlorite, illite, and a trace of adularia.
784-785	(2572-2577)	Brecciated rhyolite. Angular, broken pieces of white, partly spherulitic, rhyolite containing a few altered feldspar phenocrysts and with cavities lined with quartz, calcite and pyrite. Adularia and chlorite are also present.
814-816	(2672-2676)	Rhyolite. A broken, veined and silicified rock with the primary feldspar replaced by quartz. Thin veins present contain euhedral quartz, pyrite, sphalerite, and minor galena. Some hydrothermal illite, chlorite and adularia are also present.
844-846	(2770-2775)	Brecciated rhyolite. A hard, very silicified rhyolite but with little primary quartz. Feldspar has been replaced by quartz and illite and there is also abundant chlorite. Some pieces of core are lined with quartz and adularia crystals, the latter up to 6 mm long. Sulphides present are pyrite, sphalerite, galena, pyrrhotite and chalcopyrite.
875-877	(2872-2877)	Rhyolite. Hydrothermal minerals present are quartz, illite, chlorite, pyrite, sphalerite, galena and adularia.
930-931	(3050-3053)	Crystal tuff. A hard, green silicified rock with vague, slightly welded vitroclastic texture, containing crystals of corroded primary quartz and feldspar now replaced by secondary quartz. Also present are rare fragments of pumice and rhyolite. Hydrothermal minerals present are quartz, chlorite, illite, pyrite, sphalerite and galena.

Metres Gd*	Feet KD**	
992-993	(3255-3257)	Greywacke breccia. Angular pieces of hard well-sorted greywacke consisting mainly of angular and sub-angular quartz crystals, and rare albite. There are several calcite veinlets present and the other secondary minerals are illite, pyrite and chlorite.
1054-1055	(3457-3462)	Argillite. A fine-grained well-sorted rock mainly composed of angular quartz grains. The secondary minerals present are pyrite, illite, calcite and a small amount of quartz. Calcite and quartz usually occur in thin veinlets.
1123-1125	(3688-3690)	Argillite. Same as core from 1054-1055 m.

SUMMARY LOG

Metres	
30-142	Huka Falls Formation
142-632	Broadlands Dacite
632-719	Rautawiri Breccia
719-928	Rhyolite Unit A
928-943	Rangitaiki-type Ignimbrite
943-c 1040	Waikora Formation
c 1040-1125	Argillite and greywacke "basement"

DRILLHOLE BR 8

Grid Ref. 46,666 W
77,216 S
R.L. 303.6 m

122-123	(400-405)	Rhyolite. A soft, altered rock with 'relict' pumiceous texture. Phenocrysts of corroded quartz are present but biotite and hornblende have altered to iron oxide and illite and andesine has been completely replaced by illite. Also present are leucoxene and many small disseminated pyrite grains.
153-154	(501-506)	Rhyolite. Similar to core from 122-123 m but slightly brecciated.

Metres Gd*	Feet KD**	
243-244	(797-802)	Rhyolite. A slightly brecciated rock containing phenocrysts of quartz and ferromagnesian minerals replaced by illite. The pumiceous groundmass is partly silicified and contains adularia.
463	(1520-1523)	Brecciated mudstone. Soft, well-sorted, sheared and broken.
552	(1810-1812)	Pumice lapilli tuff. A hard, very silicified rock mainly composed of pumice lapilli, but also with a few rhyolite fragments and primary quartz phenocrysts. The hydrothermal minerals present are pyrite, illite, adularia and quartz.
640-642	(2101-2106)	Brecciated siltstone. Well-sorted, broken siltstone cut by numerous calcite veins. Illite and leucoxene are also present.
779-781	(2557-2562)	Crystal-lithic lapilli tuff. A soft rock containing fragments of silicified pumice, welded vitric tuff and smaller fragments of spherulitic rhyolite and devitrified obsidian. Phenocrysts of quartz and feldspar are present and the hydrothermal minerals are albite, adularia, quartz, chlorite, and pyrite.

SUMMARY LOG

Metres	
10-108	Huka Falls Formation
108-456	Ohaki Rhyolite
456-488	Huka Falls Formation
488-591	Upper Waiora Formation
591-707	Lower Siltstone
707-781	Rautawiri Breccia

DRILLHOLE 9

Grid Ref. 45,661 W; R.L. 309.7 m
76,982 S

Metres Gd*	Feet KD**	
60-62	(197-202)	Siltstone. Soft, pale grey, well-sorted rock, mainly composed of quartz and andesine but calcite, illite and montmorillonite are also present.
106-108	(349-354)	Pumiceous rhyolite. This rock is composed of phenocrysts of quartz, andesine, oxidixed hornblende and biotite in a devitrified, pumiceous matrix. The hydrothermal minerals present are illite, pyrite, and traces of K-feldspar, chlorite and calcite.
154-155	(505-510)	Pumiceous rhyolite. A soft phenocryst rich rock containing calcite, quartz, feldspar, pyrite and illite.
197-198	(645-650)	Spherulitic rhyolite. Phenocrysts of quartz, feldspar, and part oxidised biotite occur in a devitrified, partly spherulitic groundmass. Vesicles are lined with small euhedral quartz and calcite crystals and minor adularia is present.
243-245	(798-803)	Spherulitic rhyolite. Similar to core from 197-198 m.
290-291	(950-955)	Spherulitic rhyolite. Similar to core from 197-198 m but biotite and hornblende have been replaced by secondary quartz and an opaque mineral. A fractured piece of the core is lined with quartz and calcite crystals.
327-328	(1072-1077)	Rhyolite. The slightly spherulitic, devitrified groundmass of this rock contains quartz and andesine phenocrysts, but most of the latter have been replaced, partly or completely, by illite montmorillonite and quartz. Illite and leucoxene have replaced the hornblende and biotite, and minor calcite and chlorite are present.
382-389	(1254-1259)	Rhyolite. Similar to core from 327-328 m, but the groundmass is non-spherulitic; pyrite is present and andesine phenocrysts are more extensively altered.
427-428	(1400-1405)	Rhyolite. Andesine has been completely replaced by illite and quartz and illite also occurs in the groundmass. Abundant but unevenly distributed pyrite present.

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* Gd = Core depth below ground surface
** KD = Core depth below Kelly drive

Metres Gd*	Feet KD**	
488-489	(1600-1605)	Two rock types; (a) Soft, well-sorted brown-grey mudstone; (b) Water-laid lapilli tuff. Rounded fragments of pumice, rhyolite, tuff, and crystals of completely altered feldspar and rare quartz occur in an altered pumiceous matrix. The hydrothermal minerals present are leucoxene, pyrite and abundant illite.
533-535	(1750-1755)	Water-laid coarse tuff. A rock with a fine-grained matrix containing crystals of quartz, altered feldspar and fragments of vitric tuff, rhyolite and altered pumice. Abundant illite and minor pyrite present.
576-578	(1891-1896)	Lithic lapilli tuff. A white, poorly-sorted rock, composed of fragments of altered pumice, dacite, tuff, and pieces of greywacke up to 4 cms long. Also present are crystals of quartz, altered feldspar and hydrothermal minerals; illite, pyrite and chlorite.
623-625	(2044-2049)	Pumice lapilli tuff. Composed mainly of flattened pumice lapilli and crystals of altered feldspar and rare quartz. Pyrite, illite, wairakite, calcite, leucoxene, and chlorite are the hydrothermal minerals present. Possibly water-laid.
669-671	(2195-2200)	Dacite breccia. This rock consists of poorly-sorted, sub-angular fragments of andesine dacite, cemented by fine-grained secondary quartz. Chlorite, pyrite, and a trace of calcite are also present.
714-716	(2344-2349)	Dacite. A slightly brecciated rock which is veined and contains mainly fresh andesine but in some cases the more calcic cores of the phenocrysts have been replaced by secondary quartz.
761-763	(2497-2502)	Claystone. A soft, fine-grained, bedded rock containing abundant illite, minor apatite and a few large pyrite crystals.
771-772	(2528-2533)	Coarse crystal-pumice tuff. This rock contains poorly-sorted, sub-angular to rounded fragments of silicified pumice, argillite, spherulitic rhyolite and vitric tuff. Phenocrysts of quartz and feldspar are present and the hydrothermal minerals include albite, quartz, calcite, illite, chlorite, adularia and pyrite.

Metres Gd*	Feet KD**	
807-809	(2648-2653)	Crystal vitric tuff. A white, generally well-sorted rock, but with occasional larger lithic fragments up to lapilli size. Crystals of quartz and feldspar and fragments of silicified pumice, rhyolite and argillite are present as are the hydrothermal minerals, adularia, calcite, albite, pyrite, illite and quartz.
853-855	(2800-2805)	Lithic-crystal lapilli tuff. A poorly sorted rock containing lapilli of silicified pumice and smaller fragments of vitric tuff and spherulitic rhyolite in a vitroclastic groundmass. Quartz, adularia albite,calcite, pyrite and chlorite are the hydrothermal minerals present.
897-899	(2943-2948)	Lithic-vitric-crystal tuff. Similar to core from 853-855 m.
937-938	(3074-3079)	Crystal-vitric lapilli tuff. Phenocrysts of albite and adularia occur in a silicified groundmass with good vitroclastic texture. There are also rare large fragments (up to 3 cm) of another tuff present and the hydrothermal minerals are calcite, quartz, pyrite, chlorite and epidote.
983-985	(3226-3231)	Lithic-vitric-crystal lapilli tuff. This rock contains crystals of quartz and feldspar; fragments of welded tuff and silicified pumice; the hydrothermal minerals, calcite, quartz, albite, adularia, chlorite, pyrite and a trace of illite.
1029-1030	(3375-3378)	Welded crystal-vitric tuff. A hard, dense, rock containing abundant feldspar and rounded quartz. There are also a few fragments of rhyolite, tuff, argillite and flattened pumice present and the hydrothermal minerals are adularia, albite, illite, chlorite, quartz, calcite and pyrite.
1076-1077	(3530-3535)	Welded crystal-vitric tuff similar to core from 1029-1030 m, but with fewer lithic fragments (mainly tuff) and more feldspar. However, there is less adularia than in core from 1029-1030 m.
1092-1093	(3582-3585)	Welded crystal-vitric tuff. Similar to core from 1076-1077 m but some unaltered plagioclase present.

Metres Gd*	Feet KD**	
1146-1147	(3761-3764)	Welded crystal-vitric tuff. A hard dense rock containing some calcite, illite leucoxene and chlorite. Andesine is mainly unaltered.
1214	(3982-3983)	Welded crystal-vitric tuff. Unaltered andesine and hydrothermal chlorite, illite, calcite and epidote are present.
1267-1269	(4157-4162)	Welded crystal tuff. A slightly welded rock containing abundant quartz and feldspar crystals and fragments of silicified pumice, argillite, vitric tuff, rhyolite and spherulitic rhyolite. Not greatly altered, but contains illite, calcite, albite, pyrite and epidote.
1310-1312	(4300-4305)	Welded crystal tuff. Similar to core from 1267-1269 m, but containing more crystals and fewer rock fragments. Abundant albite, some chlorite, calcite, illite and epidote present.
1372-1373	(4500-4505)	Water-laid lapilli tuff. This is a poorly-sorted rock with graded-bedding and mainly consists of quartz and large fragments of tuff and rhyolite. Calcite, illite, albite, chlorite and epidote are the hydrothermal minerals present.

SUMMARY LOG

Metres	
50-70	Huka Falls Formation
70-482	Ohaki Rhyolite
482-506	Huka Falls Formation
506-632	Upper Waiora Formation
632-759	Broadlands Dacite
759-768	Lower Siltstone
768-950	Rautawiri Breccia
950-1362	Rangitaiki-type Ignimbrite
1362-1373	Lower Waiora Formation

DRILLHOLE BR 10

Grid Ref. 41,360 W; R.L. 292.62 m
82,010 S

Metres Gd*	Feet KD**	
74-76	(244-249)	Water-laid tuff. A pale-grey, bedded rock mainly composed of angular quartz and andesine crystals and abundant glass. Some montmorillonite, siderite and cristobalite are also present.
77-79	(254-259)	Water-laid tuff. Similar to core from 74-76 m.
91-93	(300-305)	Mudstone. A pale-grey, fine-grained, bedded, well-sorted rock composed of quartz, andesine, montmorillonite, cristobalite and calcite.
137-139	(450-455)	Lithic-vitric-crystal tuff. A fine-grained, poorly-sorted rock containing crystals of quartz and andesine and fragments of pumice. Some chlorite and montmorillonite are also present.
183-184	(600-605)	Fine sandstone. Mainly composed of quartz, and unaltered plagioclase but also present are a few large fragments of rhyolite and pockets of coarse water-laid tuff. The latter consist of angular crystals of quartz and andesine and rare fragments of pumice, and spherulitic rhyolite. Pyrite, chlorite and andesite are also present. Bedding dips at about 10°.
237-239	(778-783)	Brecciated brown mudstone composed of quartz, interlayered illite-montmorillonite, chlorite and pyrite.
283-285	(928-933)	Vitric tuff. A hard, bedded rock which is extensively silicified and also contains pyrite, leucoxene and adularia.
343-344	(1125-1130)	Pale-grey mudstone containing a few streaks of carbonaceous material. Illite, pyrite and chlorite are the hydrothermal minerals present.
404-405	(1325-1330)	Dacite. A soft, friable, extensively altered rock which has all primary plagioclase completely replaced by quartz. Pyrite and illite-montmorillonite are also present.
461-462	(1512-1517)	Dacite. A grey-coloured, veined, rock containing hydrothermal illite-montmorillonite, chlorite, pyrite, quartz, calcite and untwinned wairakite.

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* Gd = Core depth below ground surface

** KD = Core depth below Kelly drive

Metres Gd*	Feet KD**	
507-508	(1665-1668)	Dacite. A hard, dark grey-coloured rock containing andesine phenocrysts slightly altered to calcite. Pyrite and chlorite are also present.
572-573	(1875-1880)	Dacite. A soft, medium-grey coloured rock in which the feldspar phenocrysts have been almost completely replaced by calcite. Also present are hydrothermal quartz, pyrite, chlorite and illite-montmorillonite.
632-634	(2075-2080)	Crystal-lithic lapilli tuff. Poorly sorted tuff composed of quartz and altered feldspar crystals and abundant subrounded lithic fragments up to 2 cm long. These include bedded siltstone, vitric tuff, silicified pumice and rare devitrified obsidian. The hydrothermal minerals present are quartz, pyrite, illite-montmorillonite, albite chlorite and calcite.
693-695	(2275-2280)	Brecciated dacite. Andesine phenocrysts have been almost entirely replaced by calcite, illite and quartz. Pyrite, chlorite and leucoxene are also present and there are numerous veinlets of quartz and calcite.
754-756	(2485-2490)	Crystal-vitric tuff. This rock contains euhedral feldspar and rare primary quartz crystals. Also present are fragments of silicified pumice, spherulitic rhyolite, dacite and the hydrothermal minerals, quartz, albite, adularia, illite and pyrite.
822-823	(2696-2701)	Crystal-vitric tuff. Quartz and feldspar crystals, together with tuff and silicified pumice fragments occur in a groundmass of good vitroclastic texture. The hydrothermal minerals present are adularia, quartz, illite, calcite and pyrite.
887-889	(2910-2916)	Coarse lithic-crystal tuff. This rock consists of angular quartz and abundant feldspar crystals; fragments of silicified pumice, vitric tuff and argillite (up to lapilli size); hydrothermal minerals are quartz, adularia, calcite, illite, pyrite and chlorite.
940-941	(3083-3088)	Welded vitric tuff. A silicified rock with a slightly welded vitroclastic texture. It contains only a few crystals of altered plagioclase and strongly corroded quartz, although some primary feldspar has apparently been dissolved and not replaced. Hydrothermal minerals present are quartz, adularia, pyrite, illite, calcite and chlorite.

Metres Gd*	Feet KD**	
1002	(3286-3289)	Greywacke. A poorly-sorted rock composed of angular quartz, albite and microcline grains and a few rock fragments. Illite and chlorite are also present.
1052	(3450-3453)	Greywacke. Similar to core from 1002 m, but finer grained and fractured.
1091-1092	(3586-3583)	Greywacke. Brecciated, and containing secondary quartz and illite veins.

SUMMARY LOG

Metres	
73-354	Huka Falls Formation
354-625	Broadlands Dacite
625-675	Rautawiri Breccia
675-722	Broadlands Dacite
722-896	Rautawiri Breccia
896-966	Ran~~t~~gitaiki-type Ignimbrite
966-1030	Waikora Formation
1030-1091	Greywacke 'basement'

DRILLHOLE BR 11

Grid Ref. 46,591 W; R.L. 313.19 m
76,505 S

73-74	(240-242)	Brecciated mudstone. A pale grey-brown, well-sorted rock composed of quartz, adularia, calcite and illite-montmorillonite.
108	(353-355)	Spherulitic rhyolite. A hard, silicified rock containing phenocrysts of quartz, feldspar and relict ferromagnesian minerals. Primary feldspar has been replaced by adularia, illite and quartz and the other hydrothermal minerals present are calcite and pyrite.
132-133	(433-438)	Rhyolite. A soft, brecciated rock in which all the feldspar phenocrysts have altered to clay. Illite-montmorillonite, pyrite, adularia and quartz are the hydrothermal minerals present.

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*Gd = Core depth below ground surface
**KD = Core depth below Kelly drive

Metres Gd*	Feet KD**	
179-180	(587-592)	(a) Rhyolite. Similar to core from 132-133 m. Hydrothermal minerals present are quartz, illite, pyrite, calcite and adularia. (b) Rhyolite. A brecciated rock containing quartz, relict feldspar, hornblende and biotite and angular xenoliths of baked mudstone. The hydrothermal minerals present are illite, pyrite, quartz and a small amount of adularia.
225-227	(739-744)	Rhyolite. Brecciated and generally soft and friable but hard, silicified and pyritized in places; minor calcite and illite present.
266-268	(874-878)	Rhyolite. Andesine has altered to illite; hornblende and biotite to illite and quartz. Pyrite and calcite are also present.
300-301	(984-989)	Rhyolite. Dense, hard, very silicified rhyolite in which andesine and ferromagnesians have completely altered to illite and quartz. Abundant quartz and minor pyrite and calcite are present in the groundmass.
347-348	(1137-1142)	Rhyolite. Andesine phenocrysts have altered to fine-grained illite and ferromagnesian minerals to well-crystallised illite. A trace of adularia and minor pyrite are present.
392-393	(1287-1291)	Rhyolite. Similar to core from 347-348 m but the groundmass contains abundant hydrothermal quartz.
439-440	(1441-1443)	Rhyolite. A hard, silicified rock in which andesine phenocrysts have altered to adularia and minor illite, and ferromagnesian minerals to illite and quartz. Chlorite and pyrite are also present.
493-494	(1617-1620)	Rhyolite. A hard, dense, silicified rock in which andesine has altered to quartz, adularia, and illite. Pyrite, chlorite and some montmorillonite are also present.
528-530	(1733-1738)	Coarse pumice tuff. Contains abundant hydrothermal quartz, adularia and minor leucoxene and pyrite.
?543	(?1790)	Pumice lapilli tuff. Mainly consists of sub-rounded fragments of silicified pumice, pumiceous rhyolite and minor argillite, dacite and vitric tuff. Hydrothermal minerals present are abundant secondary quartz and adularia and a small amount of pyrite.

Metres Gd*	Feet KD**	
565-567	(1853-1859)	Water-laid tuff. A pale-grey rock containing irregular shaped pumice fragments, minor argillite and rare quartz grains. Hydrothermal minerals present are illite, quartz, leucoxene, minor adularia and pyrite.
611-613	(2006-2011)	Water-laid pumice tuff. Poorly-sorted, containing pumice fragments and a few quartz grains, but not feldspar. Illite-montmorillonite, pyrite and calcite are the hydrothermal minerals present.
671-672	(2200-2204)	Coarse lithic-crystal tuff. A poorly sorted rock consisting of fragments of silicified pumice, spherulitic rhyolite , devitrified obsidian and quartz and feldspar crystals. Hydrothermal minerals present are albite, quartz, illite, minor pyrite and adularia.
764-765	(2506-2511)	Crystal-lithic lapilli tuff. A poorly sorted rock containing fragments of pumice, rhyolite, dacite, vitric tuff, spherulitic rhyolite and quartz and feldspar crystals. Hydrothermal minerals present are albite, calcite, adularia, illite and pyrite.

SUMMARY LOG

Metres	
30-72	Huka Falls Formation
72-498	Ohaki Rhyolite
498-518	Huka Falls Formation
518-below 538	Upper Waiora Formation
c670-765	Rautawiri Breccia

(no cuttings recovered from below 538 m)

DRILLHOLE BR 12

Grid Ref. 74,408 S;
44,579 W
R.L. 295.26 m

Metres Gd*	Feet KD**	
58-60	(192-197)	Vitric tuff. A soft, grey, poorly consolidated tuff containing a small amount of siderite and monrmorillonite.
104-106	(342-347)	Water-laid vitric tuff. A thinly bedded, pale grey rock which contains a few small angular quartz crystals and minor andesine, glass, cristobalite and hydrothermal montmorillonite and siltstone.
152-154	(500-505)	Fine tuffaceous mudstone. Pale brown, well-sorted mudstone containing irregular flecks of organic material, siderite, montmorillonite and cristobalite.
197-199	(645-649)	Water-laid vitric tuff. A pale-grey rock composed of abundant glass shards, small angular quartz and andesine crystals and an occasional rock fragment. Minor siderite, mordenite, cristobalite are present.
243-245	(797-802)	Rhyolite. Contains phenocrysts of unaltered biotite, hornblende and andesine in a pumiceous groundmass. Cristobalite and illite-montmorillonite are also present.
305-307	(1000-1006)	Rhyolite. Soft, friable slightly brecciated rhyolite which contains unaltered biotite and andesine. Montmorillonite, siderite and cristobalite are present in the groundmass.
352-354	(1155-1160)	Rhyolite. A pumiceous rock containing unaltered glass, hornblende, biotite and andesine. Some cristobalite and montmorillonite are present in the groundmass.
398-400	(1306-1311)	Brecciated pumice tuff. A sheared rock mainly composed of fragments of poorly sorted pumice, pumiceous rhyolite and mudstone. A few angular crystals of quartz are also present but feldspar is absent. Other minerals present are pyrite, illite and kaolin.

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*Gd = Core depth below ground surface
**KD = Core depth below Kelly drive

Metres Gd*	Feet KD**	
444-446	(1458-1463)	(a) Water-laid diatomaceous pumice tuff. A grey, fine-grained well-sorted tuff, containing abundant pumice and some glass and glassy rhyolite fragments. Diatoms and sponge spicules are also present, and kaolin occurs in the groundmass. (b) Water-laid tuff. A grey, friable poorly-sorted tuff containing pumice, perlitic rhyolite, spherulitic rhyolite, diatoms, sponge spicules, quartz and andesine.
475-477	(1560-1565)	Water-laid pumice lapilli tuff. A very poorly-sorted, crudely bedded rock, mainly composed of pumice lapilli but with minor rhyolite (including spherulitic), devitrified obsidian and lithic tuff fragments. Minerals present are quartz, andesine, calcite, pyrite, montmorillonite and cristobalite.
518-519	(1699-1704)	Water-laid pumice lapilli tuff. A poorly-sorted rock composed predominantly of pumice fragments with varying degrees of vesiculation and lesser amounts of mudstone, argillite, rhyolite, and devitrified obsidian. A small amount of quartz is present, but andesine has been replaced by kaolin. Other hydrothermal minerals present are montmorillonite, pyrite, siderite and cristobalite.
564-565	(1850-1855)	Crystal-lithic tuff. This rock contains angular crystals of andesine and rarer quartz and also fragments of pumice, greywacke, rhyolite and dacite. The hydrothermal minerals present are mordenite, calcite, siderite, kaolin and montmorillonite.
610-612	(2002-2007)	Pumice lapilli tuff. Composed of irregularly-shaped, poorly-sorted pumice lapilli and rare argillite fragments. The rock has a low crystal content and contains illite, kaolin, calcite and a trace of siderite.
657-658	(2155-2160)	Pumice lapilli tuff. Similar to core from 610-612 m with hydrothermal illite, calcite and pyrite present.
700-702	(2298-2303)	Pumice lapilli tuff. This rock is mainly composed of irregularly shaped pumice lapilli, but also contains a few rounded mudstone fragments. Minor quartz and feldspar crystals are present and the hydrothermal minerals are illite, pyrite and calcite.

Metres Gd*	Feet KD**	
747-748	(2450-2455)	Pumice lapilli tuff. Similar to but finer-grained than core from 700-702 m.
793-795	(2602-2607)	Water-laid coarse pumice tuff. A pale brown rock containing pumice fragments, and a few quartz and altered feldspar crystals. Hydrothermal minerals present are calcite, illite, pyrrhotite, ~~siderite~~ and a trace of albite.
839-840	(2752-2757)	Water-laid pumice lapilli tuff. A pale grey rock mainly composed of pumice lapilli (occasionally silicified) but also with minor mudstone and rhyolite fragments and rare quartz and altered feldspar crystals. Illite, calcite, pyrite and pyrrhotite are the hydrothermal minerals present.
885-886	(2903-2907)	Pumice lapilli tuff. A poorly-sorted rock containing pumice lapilli, fragments of devitrified obsidian, rhyolite and tuff and also crystals of quartz and altered feldspar. Hydrothermal minerals present are calcite, albite, illite, epidote, pyrite and pyrrhotite.
931-932	(3054-3059)	Coarse pumice tuff. Contains angular crystals of altered feldspar and fragments of pumice and rhyolite. Quartz, calcite, illite, pyrite, pyrrhotite and albite are the hydrothermal minerals present.
976-977	(3202-3207)	Lithic-crystal lapilli tuff. This rock contains crystals of abundant quartz and feldspar, pumice lapilli and fragments of greywacke, lithic tuff and rhyolite. Albite, calcite, illite, pyrite and pyrrhotite are also present.
1023-1025	(3357-3362)	(a) Coarse crystal-vitric tuff. Composed of euhedral phenocrysts of altered feldspar and rare quartz, a vitroclastic groundmass, and the hydrothermal minerals illite, albite, pyrite, pyrrhotite, calcite and quartz. (b) Lithic-crystal lapilli tuff. Fragments of rhyolite, vitric tuff and crystal tuff occur together with crystals of euhedral plagioclase and angular quartz. The rock contains the hydrothermal minerals, albite, quartz, illite, calcite and pyrrhotite.

Metres Gd*	Feet KD**	
1069-1071	(3508-3513)	(a) Lithic-vitric tuff. Contains angular fragments of tuff, ~~chlorite~~ rhyolite and devitrified obsidian, sometimes up to 1.5 cm long, and crystals of feldspar and minor quartz. Hydrothermal minerals present are albite, illite, calcite and pyrrhotite. (b) Crystal tuff. Plagioclase-bearing, welded, dense rock cut by secondary quartz veins and also containing albite, illite, calcite and pyrite.
1098-1100	(3603-3608)	Welded crystal tuff. Contains euhedral plagioclase phenocrysts, rare primary quartz and a few rounded fragments of dacite and other volcanic material. Calcite, chlorite, illite, quartz, albite, adularia and pyrite are the hydrothermal minerals present.
1143-1144	(3749-3754)	Welded lithic-vitric tuff. A pale-grey rock with a good vitroclastic texture; it contains phenocrysts of plagioclase and rarer small corroded quartz crystals. Lithic fragments present are rhyolite and tuff, and the rock also contains albite, calcite, illite, adularia, chlorite and pyrite.
1188-1190	(3899-3904)	Coarse lithic tuff. Composed of flattened pumice lapilli, fragments of rhyolite, spherulitic rhyolite and calcite and crystals of feldspar and uncorroded quartz. Albite, calcite, chlorite, illite and a trace of adularia are also present.
1232-1233	(4051-4056)	Lithic-vitric tuff. A poorly-sorted rock containing fragments of pumice, rhyolite, spherulitic rhyolite, tuff and dacite, with crystals of quartz and feldspar. Hydrothermal minerals present are calcite, albite, illite, chlorite, pyrite and a trace of adularia.
1275-1276	(4182-4187)	Lithic lapilli tuff. Composed of subangular and subrounded fragments of pumice, argillite, rhyolite, welded vitric tuff and dacite; crystals of quartz and feldspar. The rock is brecciated in places and contains veins of quartz and adularia. Also present are albite, chlorite, calcite and illite.

Metres Gd*	Feet KD**	
1327-1329	(4354-4357)	Tuff-breccia. Composed of large angular blocks of plagioclase bearing welded tuff. Quartz is not a primary constituent but occurs as a hydrothermal mineral together with chlorite, illite, albite, and adularia.
1373-1374	(4504-4509)	Welded crystal-vitric tuff. A hard, white rock containing small crystals of plagioclase, rare quartz and an occasional volcanic rock fragment. Calcite, quartz, albite, adularia and illite are the hydrothermal minerals present.

SUMMARY LOG

Metres	
30-204	Huka Falls Formation
204-398	Ohaki Rhyolite
398-765	Upper Waiora Formation
765-792	Lower Siltstone
792-1070	Rautawiri Breccia
1070-1158	Ignimbrite Unit C
1158-1310	Rautawiri Breccia
1310-1374	Ignimbrite Unit D

DRILLHOLE BR 13

Grid Ref. 79,705 S
45,686 W
R.L. 293.39 m

Metres Gd*	Feet KD**	
56-59	(194-199)	Pumiceous siltstone. Contains quartz, andesine, glass shards, siderite and montmorillonite.
103-105	(345-350)	Fine vitric tuff. Composed of quartz, andesine, siderite and montmorillonite.
149-151	(497-503)	Pale grey, well-sorted mudstone irregularly interbedded with poorly-sorted coarse arkosic sandstone. The latter contains angular crystals of quartz, biotite, abundant andesine and minor rounded fragments of andesite. Montmorillonite and calcite are also present.
195-196	(645-650)	Pale cream-coloured siltstone, containing quartz, siderite, montmorillonite, cristobalite and ~~heulandite(?)~~ Wairakite
242	(800-802)	Pale-grey, thinly bedded mudstone, composed of quartz and illite-montmorillonite.
288-290	(953-958)	Pumiceous rhyolite. This rock contains phenocrysts of quartz, andesine, fresh biotite and relict hornblende. The hydrothermal minerals present in the groundmass are montmorillonite and mordenite.
321	(1060-1061)	Brecciated, pumiceous rhyolite. Andesine and biotite unaltered but montmorillonite and cristobalite are present in the groundmass.
363-365	(1198-1203)	Rhyolite. A crystal-rich, part pumiceous, part perlitic rock containing phenocrysts of quartz, biotite and partly altered andesine. Cristobalite, siderite, montmorillonite and chlorite are the hydrothermal minerals present.
410-411	(1351-1356)	Spherulitic rhyolite. Contains fresh biotite, completely altered hornblende and andesine showing incipient clay alteration. Cristobalite and montmorillonite are also present.
455-457	(1503-1508)	Rhyolite. Andesine phenocrysts have altered to montmorillonite. Calcite, cristobalite and chlorite are also present.

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*Gd = Core depth below ground surface

**KD = Core depth below Kelly drive

Metres Gd*	Feet KD**	
489-490	(1613-1618)	Mudstone. A brown, well-sorted, thinly, though irregularly, bedded rock which contains clusters of hexagonal pyrrhotite and minor illite.
529-530	(1744-1749)	Siltstone. Cream-coloured, well-sorted siltstone with thin beds dipping at approximately 10°. Illite-montmorillonite, andesine, chlorite and pyrrhotite are present.
575-576	(1896-1901)	Water-laid pumice lapilli tuff. A poorly-sorted rock which contains altered pumice lapilli up to 2 cm long and rare quartz crystals and argillite fragments. The hydrothermal minerals present are chlorite, illite, calcite, leucoxene quartz and pyrite.
622-623	(2049-2054)	Water-laid pumice lapilli tuff. Similar to core from 575-576 m.
668-669	(2201-2206)	Coarse lithic sandstone. This rock is mainly composed of angular, volcanically derived material and rare quartz crystals. The hydrothermal minerals present are well-crystallised illite, pyrite, pyrrhotite, wairakite, sphene, chlorite and calcite.
715-716	(2354-2359)	Brecciated siltstone. A soft, cream-coloured rock composed of poorly-sorted siltstone and occasional volcanic fragments. Illite, calcite, albite, adularia and pyrite are also present.
761-762	(2506-2511)	Crystal tuff. This rock contains angular crystals of quartz and altered feldspar, fragments of spherulitic rhyolite, argillite, welded tuff, silicified pumice; the hydrothermal minerals quartz, albite, adularia, calcite, illite, and pyrite.
807-808	(2657-2662)	Crystal-vitric-lithic lapilli tuff. The lithic fragments present in this rock include welded tuff, silicified pumice and devitrified obsidian. Also present are the hydrothermal minerals albite, calcite, pyrite, quartz, illite, chlorite and a trace of adularia.

Metres Gd*	Feet KD**	
852-854	(2796-2801)	Crystal-lithic tuff. A soft, friable rock containing fragments of silicified pumice, spherulitic rhyolite, vitric tuff and crystals of quartz and feldspar. The hydrothermal minerals present are quartz, albite, adularia, calcite, pyrite and chlorite.
899-900	(2948-2953)	Pumice-crystal-vitric lapilli tuff. Similar composition to core from 852-854 m. Quartz, albite, illite, chlorite, calcite, pyrite and a trace of adularia are the hydrothermal minerals present.
945-946	(3100-3105)	A slightly welded rock which contains a few quartz and feldspar crystals and occasional silicified pumice lapilli. The hydrothermal minerals present are quartz, albite, pyrite, chlorite, calcite and illite.
992-993	(3253-3258)	Welded crystal tuff. Contains abundant quartz and feldspar crystals but also a few fragments of vitric tuff, pumice and spherulitic rhyolite; albite, adularia, chlorite, calcite, pyrite and illite are the hydrothermal minerals present.
1038-1039	(3404-3410)	Welded vitric-crystal tuff. A crystal-rich rock with a pronounced welded vitroclastic groundmass. Also present are fragments of rhyolite, spherulitic rhyolite, and andesite and the hydrothermal minerals albite, illite, chlorite, calcite and pyrite.
1084-1085	(3557-3561)	Welded crystal tuff. A dense, welded rock containing the hydrothermal minerals albite, illite, calcite, chlorite, epidote, pyrite and a trace of adularia.

SUMMARY LOG

Metres	
73-259	Huka Falls Formation
259-467	Ohaki Rhyolite
467-533	Huka Falls Formation
533-678	Upper Waiora Formation
678-698	Broadlands Dacite
698-753	Lower Siltstone
753-912	Rautawiri Breccia
912-981	Ignimbrite Unit E
981-1085	Rangitaiki type Ignimbrite

DRILLHOLE 14

Grid Ref. 80,092 S R.L. 298.48
42,500 W

Metres Gd*	Feet KD**	
73-74	(250-253)	Diatomaceous, water-laid tuff. A soft brown-grey, fine-grained rock containing small angular crystals of andesine, quartz and rare hornblende. Also present are occasional glass shards and abundant diatoms (identified as melosira) and a trace of calcite.
120-122	(405-410)	Tuffaceous sandstone. Cream-coloured, poorly-sorted sandstone consisting of crystals of angular quartz and plagioclase in a groundmass of glass shards, quartz, rare diatoms, calcite and montmorillonite.
166-168	(556-561)	Rhyolite tuff. Composed of subangular crystals of andesine and quartz; fragments of pumice, pumiceous rhyolite and the hydrothermal minerals siderite, calcite and montmorillonite.
213-214	(708-713)	Fine siltstone. Pale brown, soft, well-sorted siltstone containing quartz and specks of iron oxide and organic material. Unaltered.
258-259	(856-861)	Tuffaceous sandstone. This rock contains angular crystals of quartz and andesine and a few volcanic fragments including silicified pumice. Some illite and a trace of calcite and chlorite is present in the groundmass.
304-305	(1007-1012)	Water-laid tuff. A white, well-sorted rock, composed of angular quartz crystals and some volcanic rock fragments. Illite, calcite and hydrothermal quartz are present.
350-351	(1158-1163)	Rhyolite. Unaltered andesine is present but biotite has been partly replaced by secondary mica. Illite, pyrite, wairakite and quartz are the hydrothermal minerals present.
396-397	(1308-1311)	Rhyolite. Andesine is unaltered but the part-spherulitic groundmass contains quartz and well-crystallised secondary illite. Some calcite is present.
436-437	(1440-1445)	Water-laid lithic lapilli tuff interbedded with fine tuffaceous siltstone. The former is a pale brown, poorly-sorted rock containing subangular fragments of siltstone, argillite, vitric tuff, crystal tuff, flattened pumice and minor angular quartz crystals. Quartz, chlorite and pyrite are the hydrothermal minerals present.

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*Gd = Core depth below ground surface.
**KD = Core depth below Kelly drive

Metres Gd*	Feet KD**	
486-488	(1605-1610)	Water-laid lithic lapilli tuff. A silicified, very poorly-sorted rock composed of subrounded fragments of argillite, greywacke, rhyolite and pumice. Feldspar has been replaced by illite and the other hydrothermal minerals present are calcite, chlorite, pyrite and abundant quartz.
530-532	(1750-1755)	Dacite breccia. Coarse, angular fragments of altered rock are cemented by fine-grained quartz, pyrite and leucoxene. Andesine has been almost entirely replaced by illite and calcite and chlorite and montmorillonite are also present.
578-579	(1905-1910)	Dacite. Less extensively altered than core from 530-532 m, but it contains hydrothermal calcite, illite, quartz, pyrite and chlorite.
623-624	(2053-2057)	Dacite. Andesine is generally fresh but hydrothermal illite, pyrite, leucoxene, calcite,quartz and chlorite are present in small amounts.
669-671	(2206-2210)	Dacite. Similar to core from 623-624 m.
715-716	(2356-2359)	Dacite. Contains hydrothermal calcite and chlorite.
752-753	(2476-2480)	(a) Dacite. Andesine has completely altered to illite and calcite. Hydrothermal quartz, chlorite and pyrite are also present. (b) Lithic tuff. Contains angular quartz crystals and fragments of silicified pumice, spherulitic rhyolite, mudstone and tuff. The hydrothermal minerals present are illite, chlorite, calcite, pyrite and leucoxene.
806-808	(2655-2660)	Lithic lapilli tuff. Composed of poorly-sorted fragments of pumice, vitric tuff and rhyolite, together with a few angular quartz crystals. Calcite, chlorite, illite, quartz, pyrite and wairakite are the hydrothermal minerals present.
851-853	(2803-2808)	Coarse lithic tuff. A white poorly-sorted rock mainly composed of pumice fragments but also containing rare rhyolite and argillite fragments and a few angular quartz crystals. Illite, calcite, chlorite, pyrite, quartz and albite are the hydrothermal minerals present.

Metres Gd*	Feet KD**	
897-899	(2954-2959)	Welded vitric-lithic-crystal lapilli tuff. Consists of crystals of plagioclase and quartz and fragments of pumice, vitric tuff, and rare spherulitic rhyolite. Andesine has been replaced by albite and also present are pyrite, calcite, quartz and illite.
943-945	(3104-3109)	Welded vitric tuff. Slightly welded, containing large rock fragments and the hydrothermal minerals albite, calcite, illite, quartz, chlorite, pyrite and a trace of adularia.
989-990	(3253-3257)	Welded tuff. Contains fewer rock fragments and is more densely welded than core from 943-945 m. Some fresh andesine is present, together with hydrothermal calcite, illite, quartz, albite and chlorite.
1035-1036	(3404-3409)	Welded tuff. Consists of fragments of greywacke, vitric tuff, lenticules of pumice up to lapilli size, and crystals of quartz and feldspar. Albite, calcite, illite, epidote, chlorite, quartz and pyrite are the hydrothermal minerals present.
1081-1082	(3555-3560)	(a) Mudstone. Grey-brown, moderately-sorted, indurated mudstone containing angular quartz crystals, rock fragments and fine-grained illite. Small-scale slump folding visible. Chlorite and albite are also present. (b) Argillite conglomerate. Rounded and subrounded pebbles of argillite and greywacke cemented by veins of quartz and minor wairakite.
1125-1127	(3702-3707)	Argillite and greywacke conglomerate. A poorly-sorted rock, composed of rounded argillite and greywacke pebbles in a matrix containing calcite, wairakite, chlorite and minor epidote. Illite is present but may not be of hydrothermal origin.
1186-1187	(3900-3903)	Crystal-vitric tuff. A hard, white rock containing phenocrysts of euhedral feldspar and rarer angular quartz. The quartzose groundmass has a relict vitroclastic texture and also contains angular fragments of spherulitic rhyolite, pumice, andesite and weakly metamorphosed greywacke. The hydrothermal minerals present are illite, calcite, pyrite, chlorite, adularia, epidote and albite.

Metres Gd*	Feet KD**	
1234-1235	(4059-4062)	Argillite conglomerate. A poorly-sorted rock composed of subrounded to subangular argillite and greywacke fragments. The secondary minerals present, all in small amounts, are quartz, calcite, epidote, K-feldspar, pyrite, sphalerite and chalcopyrite.
1282-1284	(4217-4222)	(i) Argillite and greywacke conglomerate, Poorly-sorted, subangular to subrounded argillite and greywacke pebbles in a matrix of chlorite, quartz, wairakite, calcite and epidote. (ii) Water-laid crystal tuff. A pale grey, poorly-sorted rock containing abundant subhedral plagioclase and rarer angular quartz crystals. A few rock fragments are present and the matrix contains abundant well-crystallised secondary mica and some chlorite. Some plagioclase has been partly replaced by wairakite. (iii) Coarse tuffaceous sandstone. A dark grey, poorly-sorted rock composed of crystals of altered euhedral plagioclase and rare angular quartz. Angular fragments of argillite and andesite are present and the hydrothermal minerals are wairakite, illite, chlorite, calcite, quartz and epidote.

SUMMARY LOG

Metres	
13-347	Huka Falls Formation
347-436	Ohaki Rhyolite
436-524	Upper Waiora Formation
524-726	Broadlands Dacite
726-750	Lower Siltstone
750-777	Broadlands Dacite
777-930	Rautawiri Breccia
930-1045	Rangitaiki-type Ignimbrite
1045-1173	Upper Waikora Formation
1173-1222	Lower Waiora Formation
1222-1289	Lower Waikora Formation

DRILLHOLE 15

Grid Ref. 76,664 S R.L. 309.98
46,995 W

Metres Gd*	Feet KD**	
115	(390)	The material recovered from the stabiliser while opening the hole at 115 m consists predominantly of rhyolite. This is hard, extensively silicified, and contains abundant adularia in the groundmass.
554-555	(1833-1888)	(rock samples recovered from junk basket). Coarse lithic tuff. A poorly-sorted, very silicified rock containing subangular to subrounded fragments of argillite, greywacke, silicified pumice, andesite, vitric tuff and a very few small angular quartz crystals. Abundant hydrothermal adularia and quartz crystals present, together with pyrite and illite.
867-869	(2860-2868)	(a) Coarse lithic-crystal tuff. Crystal-rich, poorly-sorted rock, containing abundant angular quartz and euhedral plagioclase crystals. Rock fragments present include andesite, silicified pumice and rare spherulitic rhyolite. Hydrothermal minerals are albite, adularia, quartz, calcite, pyrite and a trace of wairakite. (b) Fine tuffaceous siltstone. Grey, soft, well-sorted siltstone containing adularia and illite.
970-972	(3199-3207)	Lithic-vitric tuff-breccia. White, poorly-sorted and containing angular fragments of welded vitric tuff and rarer siltstone. Hydrothermal minerals present are quartz, albite, adularia, pyrite, calcite and chlorite.
1101-1102	(3625-3629)	Lapilli tuff. A white poorly-sorted rock containing subhedral and euhedral plagioclase crystals and a few small quartz grains. Subangular fragments of silicified pumice, vitric tuff and andesite are also present and the hydrothermal minerals are albite, calcite, quartz, pyrite, and, in the groundmass, adularia. The rock has a lightly welded vitroclastic texture.
1224-1225	(4017-4020)	Welded vitric-crystal tuff. A hard, dense rock with a high content of corroded quartz and euhedral plagioclase crystals. A few volcanic rock fragments are also present. Some andesine remains unaltered, but the rock also contains adularia, calcite, illite, chlorite, epidote and pyrite.

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*Gd = Core depth below ground surface
**KD = Core depth below Kelly drive

Metres Gd**	Feet KD**	
1355-1356	(4462-4465)	Dacite. A pale grey rock containing sub-parallel euhedral phenocrysts of plagioclase. The hydrothermal minerals present are albite, calcite, pyrite, illite, quartz, and chlorite.
1462-1463	(4813-4816)	Lithic-vitric tuff. A pale grey rock composed of pumice and rhyolite fragments, crystals of euhedral plagioclase and small angular quartz. Albite, calcite, adularia, pyrite, chlorite, illite and quartz are the hydrothermal minerals present.
1591-1593	(5237-5244)	Tuff. Contains poorly-sorted angular fragments of quartzose tuff rhyolite, together with phenocrysts of altered plagioclase. The hydrothermal minerals are calcite, quartz, albite, minor adularia, pyrite, chlorite and illite.
1619-1621	(5328-5333)	Breccia. A few angular crystals of quartz and feldspar and some volcanic fragments disseminated in a matrix of calcite. Other hydrothermal minerals present are quartz, adularia, pyrite and sphalerite.
1693-1695	(5571-5576)	Coarse lithic-crystal tuff. Pieces of pale grey to green rock containing abundant crystals of plagioclase and corroded quartz, but also a few poorly-sorted fragments of rhyolite, spherulitic rhyolite, pumice and argillite. Albite, adularia, pyrite, calcite, illite, quartz and chlorite are the hydrothermal minerals present.
1767-1769	(5815-5820)	Welded crystal-vitric tuff. A hard, dense rock containing subangular fragments of rhyolite, spherulitic rhyolite and argillite. Corroded quartz and partly-altered andesine phenocrysts are abundant and the rock has a good vitroclastic texture. Hydrothermal minerals present are chlorite, calcite, illite, epidote and minor adularia.
1841-1843	(6057-6062)	(a) Crystal tuff. Contains crystals of euhedral plagioclase, rare small, angular quartz and fragments of greywacke and andesite. Albite, calcite, illite and quartz are the hydrothermal minerals present. (b) Brecciated plagioclase-bearing rock, probably dacite, with a chlorite matrix which also contains albite, adularia, quartz, chlorite, epidote, sphene, illite, pyrite, chalcopyrite, galena and sphalerite.

Metres Gd*	Feet KD**	
1915-1918	(6300-6310)	(a) Tuffaceous sandstone. A pale grey to green, poorly-sorted rock containing fragments of pumice and rhyolite and angular crystals of quartz and feldspar. Hydrothermal minerals present are chlorite, adularia, illite, quartz and calcite. (b) Pumice tuff. A pale-green coloured, hard rock composed of variable-sized pumice fragments and a few crystals of primary quartz. Hydrothermal minerals present are quartz, calcite and abundant chlorite.
1952-1955	(6421-6429)	Conglomerate. A poorly-sorted rock containing rounded to sub-angular pebbles of quartzose argillite and occasional greywacke. Secondary minerals present in the matrix are chlorite, quartz, calcite, adularia and epidote.
1973	(6490)	Cuttings. Andesite
1998	(6570)	Cuttings. Argillite fragments, presumably from conglomerate similar to those at 2105-2106 m. and 1952-1955 m.
2007-2022	(6600-6650)	Cuttings. Andesite. Pale-green, hard andesite containing phenocrysts of andesine. Hydrothermal minerals present are chlorite, illite, sphene, pyrite, pyrrhotite, epidote and a small amount of adularia.
2023-2024	(6652-6655)	Similar to cuttings from 2007-2022 m. Hydrothermal minerals present are epidote, calcite, sphene, chlorite, pyrite, minor quartz, adularia and pyrrhotite.
2105-2106	(6922-6927)	Argillite and greywacke pebble conglomerate. Contains rounded to sub-rounded, poorly-sorted granules and pebbles of greywacke and argillite. Some hydrothermal quartz, epidote and chlorite also present.
2155-2156	(7086-7090)	Crystal-vitric tuff. A cream-coloured, fine-grained rock with some irregular vertical green chloritic bands 1½ cm wide. It contains andesite and rhyolite fragments and small corroded quartz and euhedral plagioclase crystals. The hydrothermal minerals present are albite, adularia, quartz, chlorite, calcite, sphene, pyrite, sphalerite and galena.

Metres Gd*	Feet KD**	
2238-2239	(7358-7363)	Welded vitric-crystal tuff. Crystal-rich, hard, white rock containing small fragments of andesite, flattened pumice and rhyolite and crystals of corroded quartz and plagioclase. Most plagioclase is unaltered but a small amount of adularia is present and the other hydrothermal minerals are chlorite, calcite, illite, sphene, sphalerite, galena and chalcopyrite.
2312-2313	(7602-7605)	Argillite and greywacke. Dark-grey, hard argillite and greywacke containing hydrothermal sphalerite, galena and chalcopyrite.
2420-2421	(7955-7960)	Greywacke. Little altered except for the presence of some hydrothermal chlorite and illite.

SUMMARY LOG

Metres	
14-115	Huka Falls Formation
115-487	Ohaki Rhyolite
487-517	Huka Falls Formation
517-557	Upper Waiora Formation
557-1081	No cuttings but the 867-869 and 970-972 cores are correlated with the Rautawiri Breccia
c1081-1313	Rangitaiki-type Ignimbrite
1313-1392	Dacite Unit B
1392-1657	Lower Waiora Formation
1657-1825	Ignimbrite Unit F
1825-1842	Tuff~~s~~ Unit A
1842-1897	Dacite Unit C
1897-2007	Upper Waikora Formation
2007-2032	Andesite Unit A
2032-2136	Lower Waikora Formation
2136-2284	Ignimbrite Unit G
2284-2421	Greywacke and argillite "basement"

DRILLHOLE BR 16

Grid Ref. 83,687 S R.L. 304.80
40,174 W

Metres Gd*	Feet KD**	
74-77	(252-263)	Tuffaceous siltstone. A pale brown and grey, fine-grained siltstone contain a few large, angular quartz and andesine crystals. Some calcite and montmorillonite are present.
148-149	(495-500)	Tuffaceous sandstone. Pale grey and white, bedded, but poorly-sorted sandstone and sedimentary breccia. Minor organic material is present and the breccia contains abundant dickite.
221-223	(735-740)	Dacite. Hard and extensively altered. Plagioclase, ferromagnesian minerals and the groundmass have been replaced by illite, abundant pyrite, leucoxene and a trace of adularia. Quartz and calcite form thin veins.
302-303	(1000-1005)	(a) Dark grey, veined extensively altered rhyolite containing hydrothermal quartz, illite, leucoxene and abundant pyrite. (b) Fault 'pug'. A dense dark grey section of core containing fragments of dacite, galena, sphalerite, pyrite and minor chalcopyrite.
340-341	(1124-1130)	Dacite. Brecciated and veined with feldspars, ferromagnesian minerals and groundmass completely replaced by quartz, illite, leucoxene and pyrite. Sphalerite and galena are also present.
358-360	(1186-1192)	Dacite. Brecciated and veined and containing the following hydrothermal minerals: quartz, calcite, illite, pyrite, sphalerite, galena, leucoxene and apatite.
376-377	(1242-1248)	Dacite. Similar to core from 358-360 m.
394-395	(1301-1306)	Dacite. Similar to core from 358-360 m but contains a small amount of chlorite and adularia.
412-413	(1361-1366)	Dacite. Brecciated and silicified. With hydrothermal quartz, illite, pyrite, sphalerite, galena and chlorite.
430-432	(1420-1426)	Dacite. Alteration similar to core from 412-413 m.
457-459	(1510-1515)	Dacite. Grey, extensively silicified dacite containing hydrothermal quartz, illite, pyrite, sphalerite and galena.

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* Gd = Core depth below ground surface
** KD = Core depth below Kelly drive

Metres Gd*	Feet KD**	
484-486	(1599-1604)	Dacite. Contains quartz, illite, pyrite, chlorite, leucoxene and traces of calcite, adularia, sphalerite and galena.
504-505	(1662-1667)	Dacite. Similar to core from 484-486 m.
530-532	(1750-1755)	Dacite. Brecciated and veined with a similar alteration assemblage to core from 484-486 m.
558-560	(1841-1847)	Dacite. Similar to core from 530-532 m.
585-586	(1930-1933)	Dacite. Silicified and brecciated and containing illite, calcite, chlorite, quartz, pyrite, sphalerite and galena.
613-616	(2022-2030)	Dacite. Similar to core from 585-586 m.
643-647	(2119-2133)	Tuff-breccia. A very poorly-sorted rock containing angular to subrounded fragments, up to 8 cm long, of bedded siltstone, greywacke and argillite. Hydrothermal minerals present are illite, quartz and minor pyrite.
671-674	(2210-2220)	Water-laid lapilli tuff. A poorly-sorted rock containing subrounded fragments of mudstone, rhyolite and flattened pumice with some rounded primary quartz crystals. The hydrothermal minerals present are quartz, illite, pyrite, sphalerite and chlorite.
703-705	(2316-2324)	Lithic lapilli tuff. Poorly-sorted with subangular to subrounded fragments of mudstone, argillite, greywacke, rhyolite and abundant pumice. Primary and secondary quartz crystals are present and the other hydrothermal minerals ane illite and pyrite.
732-733	(2411-2416)	Lithic lapilli tuff. Similar to, but finer grained, than core from 702-705 m. Contains fragments of argillite, silicified pumice; crystals of primary quartz; and the hydrothermal minerals quartz, illite, chlorite, pyrite and a trace of calcite.
759-761	(2500-2506)	Coarse lithic tuff. A poorly-sorted rock containing subangular fragments of argillite, greywacke, mudstone, pumice and crystals of quartz and replaced plagioclase. Hydrothermal minerals present are quartz, chlorite, illite, pyrite and hexagonal pyrrhotite.

Metres Gd*	Feet KD**	
787-789	(2591-2597)	Coarse lithic tuff. Also poorly-sorted, but is finer grained than core from 759-761 m. It contains fragments of argillite and pumice and angular crystals of quartz but the plagioclase crystals have been dissolved and the resulting cavities partly filled with quartz. Illite, chlorite, pyrite, pyrrhotite and sphalerite are also present.
814-817	(2682-2690)	Coarse lithic tuff. Contains crystals of quartz, replaced plagioclase and fragments of argillite, pumice and pumiceous rhyolite. Hydrothermal minerals present are illite, quartz, pyrite, galena, sphalerite and chlorite.
845-847	(2783-2790)	Coarse lithic-vitric tuff. Similar to the core from 814-817 m.
892-893	(2935-2941)	Lithic tuff. Fragments of pumice, rhyolite and tuff occur together with crystals of quartz and replaced feldspar. Illite, quartz, pyrite, and a trace of sphalerite are the hydrothermal minerals present.
941-944	(3096-3107)	Coarse lithic tuff. A poorly-sorted rock, containing fragments of andesite, pumice and rhyolite, together with the hydrothermal minerals, quartz, illite, well-crystallised chlorite, pyrite and chalcopyrite.
988-990	(3251-3257)	Lithic lapilli tuff. Also poorly-sorted with fragments of pumice, argillite, rhyolite and crystals of quartz and replaced plagioclase present. The hydrothermal minerals are quartz, illite, chlorite, sphalerite, pyrite, pyrrhotite and galena.
1052-1054	(3462-3467)	Lithic lapilli tuff. A pale-green, poorly-sorted rock containing fragments of rhyolite, argillite and altered pumice. Plagioclase crystals have been replaced by quartz and other hydrothermal minerals present are illite, chlorite, pyrite and pyrrhotite.
1108-1110	(3646-3651)	Lithic lapilli tuff. Fragments of greywacke, argillite, tuff and silicified pumice occur with a few quartz and replaced plagioclase crystals. Illite, pyrite, quartz, chlorite, sphalerite and pyrrhotite are the hydrothermal minerals present.

Metres Gd*	Feet KD**	
1170-1172	(3850-3855)	Coarse vitric-lithic tuff. A pale-grey, poorly-sorted rock containing fragments of pumice, argillite, vitric tuff and a few crystals of corroded quartz and replaced feldspar. Hydrothermal minerals present are illite, quartz, chlorite and pyrrhotite.
1245-1247	(4096-4101)	Rhyolite. Dark-green, hard, plagioclase bearing rhyolite with minor primary quartz. Some fresh andesite but also present are illite, quartz, epidote (?), calcite, pyrite and pyrrhotite.
1309-1311	(4306-4311)	Coarse lithic tuff. Crystals of corroded quartz and replaced feldspar are present together with fragments of vitric tuff and rhyolite. Illite, quartz, chlorite, calcite, epidote, sphalerite and galena are the hydrothermal minerals present.
1353-1355	(4450-4454)	Lithic tuff. A pale green rock containing crystals of quartz and replaced feldspar; greywacke, rhyolite and other volcanic rock fragments; the hydrothermal minerals calcite, epidote, illite, quartz, chlorite, sphalerite and galena.
1367-1368	(4494-4499)	Greywacke. This core contains hydrothermal calcite, illite, epidote, chlorite, sphalerite, chalcopyrite and galena.
1405-1406	(4620-4624)	Greywacke. Wairakite, calcite, quartz, chlorite and illite are the hydrothermal minerals present.

SUMMARY LOG

Metres	
24-164	Huka Falls Formation
164-631	Broadlands Dacite
631-1234	Rautawiri Breccia
1234-1292	Rhyolite Unit ~~B~~ A
1292-1359	Rautawiri Breccia
1359-1406	Greywacke and argillite 'basement'

DRILLHOLE BR 17

Grid Ref. 76,594 S R.L. 307.05
46,099 W

Metres Gd*	Feet KD**	
75-76	(255-260)	Pumiceous rhyolite. Contains unaltered andesine and biotite phenocrysts with minor amphibole and magnetite. The groundmass contains abundant cristobalite, mordenite and a trace of illite-montmorillonite.
150-152	(503-508)	Rhyolite. Ferromagnesian minerals have been replaced by well-crystallised illite and andesine by finer-grained illite.
224-225	(744-749)	Rhyolite. A partly spherulitic rock in which biotite phenocrysts have been partly replaced by well-crystallised mica but andesine is mainly fresh. Traces of adularia present and there is also minor calcite and pyrite.
302-303	(1000-1005)	Rhyolite. Hornblende and biotite crystals have been partly replaced by illite-montmorillonite, but andesine is fresh. Traces of calcite and chlorite present.
378-380	(1250-1255)	Rhyolite. A slightly brecciated rock in which the ferromagnesian minerals have been replaced by illite and the fractured andesine crystals are partly enclosed by calcite. Pyrite present.
451-453	(1490-1495)	Rhyolite. Plagioclase, ferromagnesian minerals and some of the groundmass have been replaced by illite. Other hydrothermal minerals present are quartz, calcite, chlorite and pyrite.
534-537	(1762-1772)	Pumice lapilli tuff. Possibly water-laid. This rock contains fragments of altered pumice, and rarer greywacke, argillite, spherulitic rhyolite and dacite. Occasional quartz crystals are present and all andesine has been replaced by adularia and minor illite. The groundmass contains hydrothermal adularia, illite, calcite and pyrite.
607-609	(2000-2008)	(1) Fine-grained, well-sorted siltstone composed of quartz and illite, with minor pyrite, calcite, wairakite and chlorite

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* Gd = Core depth below ground surface

**KD = Core depth below Kelly drive

Metres Gd*	Feet KD**	
607-609	(2000-2008)	(2) Water-laid pumice lapilli tuff. Contains flattened pumice lapilli, a few siltstone fragments, and crystals of quartz. Hydrothermal minerals present are quartz, illite, chlorite, wairakite, sphalerite, galena and pyrite.
686-687	(2260-2265)	Interbedded tuffaceous siltstone and water-laid tuff. Both are poorly-sorted rocks; the latter contains a few small angular quartz crystals, fragments of pumice, siltstone and tuff. Quartz, calcite, illite, wairakite and pyrite are the hydrothermal minerals present.
742-744	(2445-2450)	Crystal-lithic lapilli tuff. A soft, white and pale-grey, poorly-sorted rock containing crystals of quartz and feldspar and fragments of spherulitic rhyolite, rhyolite, mudstone and tuff. Hydrothermal minerals present are calcite, adularia, albite, pyrite, and quartz.
818-819	(2692-2697)	Coarse crystal tuff. A poorly-sorted rock with rare quartz and abundant feldspar crystals. Also present are a few fragments of spherulitic rhyolite, andesite, mudstone and silicified pumice. Adularia, albite, chlorite, calcite and pyrite are the hydrothermal minerals present.
900-902	(2964-2969)	Lithic-crystal tuff. White, poorly-sorted rock containing abundant feldspar and rare quartz crystals. Rock fragments present include vitric tuff, tuff, pumice and rhyolite. Adularia, albite, quartz, calcite, chlorite and pyrite are the hydrothermal minerals present.
955	(3144-3146)	Lithic-crystal tuff. A poorly-sorted rock containing crystals of quartz and more abundant plagioclase. Fragments of pumice, andesite, part-spherulitic rhyolite and vitric tuff are also present. Adularia, quartz, albite, pyrite and calcite are the hydrothermal minerals present.

Metres Gd*	Feet KD**	
1005-1006	(3306-3310)	Lithic crystal lapilli tuff. A poorly-sorted rock containing subangular to subrounded fragments of spherulitic rhyolite, tuff, dacite, water-laid tuff and silicified pumice, together with abundant angular quartz and feldspar crystals. Hydrothermal minerals present include calcite, adularia, albite, quartz, pyrite and chlorite.
1083-1084	(3562-3567)	Andesite. Contains euhedral phenocrysts of altered plagioclase in matrix of small feldspar crystals. Hydrothermal minerals present are chlorite, albite, pyrite, calcite, sphene and minor adularia.

SUMMARY LOG

Metres	
27-64	Huka Falls Formation
64-454	Ohaki Rhyolite
454-460	Huka Falls Formation
460-655	Upper Waiora Formation
655-728	Lower Siltstone
728-1082	Rautawiri Breccia
1082-1084	Andesite Unit C

DRILLHOLE BR 18

Grid Ref. 75,908 S R.L. 313.64
45,994 W

Metres Gd*	Feet KD**	
69-71	(238-244)	Rhyolite breccia. A dark-grey friable rock composed of loosely cemented rhyolite fragments. Contains unaltered andesine and biotite but calcite and montmorillonite are present in the groundmass.
151-153	(506-511)	Rhyolite. Grey, hard, rhyolite with a microspherulitic groundmass. Biotite has been partly replaced by calcite, and/or pyrite and the euhedral plagioclase phenocrysts by adularia and traces of calcite. However, some fresh plagioclase remains. A small amount of secondary quartz is also present.
230-231	(764-769)	Rhyolite. A white-coloured rock in which plagioclase is mainly unaltered, but the ferromagnesian minerals have been replaced by well-crystallised illite. Some calcite is also present.
304-305	(1007-1012)	Rhyolite. Some andesine phenocrysts have been partly replaced by montmorillonite and minor calcite and all the ferromagnesian minerals by illite and calcite.
378-380	(1250-1255)	Rhyolite. Both ferromagnesian minerals and the feldspar crystals have been completely replaced by illite. The microcrystalline groundmass also contains calcite and adularia.
452-454	(1493-1499)	Rhyolite. Plagioclase has altered to illite, quartz, leucoxene and calcite, and the ferromagnesian minerals to illite, quartz and chlorite.
533-536	(1760-1768)	Pumice lapilli tuff. Contains fragments of pumice, rarer rhyolite and argillite. Also present are a few angular quartz crystals but the feldspars have been replaced by calcite. Illite and pyrite present.
614-616	(2023-2031)	Pumice lapilli tuff. A poorly-sorted rock containing pumice lapilli and a few fragments of vitric tuff. Some quartz present with minor groundmass and phenocryst adularia. Other hydrothermal minerals are illite, pyrite and calcite.
687-689	(2264-2270)	Pumice lapilli tuff. A poorly-sorted rock containing angular pumice lapilli, a few angular quartz and altered feldspar crystals and the hydrothermal minerals illite, calcite, albite, minor adularia, pyrite, leucoxene and sphene.

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*Gd = Core depth below ground surface

**KD = Core depth below Kelly drive

Metres Gd*	Feet KD**	
761-763	(2505-2513)	Siltstone. A well-sorted, soft, white, siltstone containing calcite, albite, quartz, illite and pyrite.
835-837	(2749-2754)	Vitric-lithic tuff. Contains fragments of silicified pumice, tuff and siltstone. The hydrothermal minerals present are albite, adularia, calcite, pyrite, quartz, illite and chlorite.
912-914	(3002-3007)	Crystal-lithic tuff. A pale-green, poorly-sorted rock composed of fragments of spherulitic rhyolite, tuff, vitric tuff; small crystals of corroded quartz and altered feldspar; the hydrothermal minerals albite, calcite, leucoxene, pyrite, illite, sphene, chlorite and minor adularia.
1021-1023	(3360-3365)	Lithic-crystal tuff. Contains fragments of spherulitic rhyolite, silicified pumice, dacite, and some quartz crystals. Hydrothermal minerals present are albite, calcite, illite, chlorite, sphene, quartz, pyrite and minor adularia.
1065-1067	(3505-3510)	Lithic tuff. A coarse, poorly-sorted rock containing fragments of silicified pumice, rhyolite, and rarer andesite. Large crystals of quartz and smaller ones of feldspar are also present. Hydrothermal minerals are quartz, calcite, pyrite, chlorite, sphene, illite, adularia and albite.
1139-1141	(3748-3753)	Welded vitric-crystal tuff. Contains large corroded phenocrysts of quartz and smaller more numerous ones of altered plagioclase. Also present are a few round volcanic rock fragments - mainly rhyolite. Hydrothermal minerals present are calcite, chlorite, illite, albite, epidote and trace of pyrite.
1216-1218	(4000-4005)	Welded vitric-crystal tuff. Contains large corroded quartz crystals and altered feldspar. The groundmass is partly spherulitic. Calcite, illite, albite and adularia are the hydrothermal minerals present.

SUMMARY LOG

Metres	
12-64	Huka Falls Formation
64-515	Ohaki Rhyolite
515-719	Waiora Formation
719-792	Lower Siltstone
792-1130	Rautawiri Breccia
1130-1218	Rangitaiki-type Ignimbrite

DRILLHOLE BR 19

Grid. Ref. 78,225 S R.L. 295.96
46,154 W

Metres Gd*	Feet KD**	
73-75	(250-255)	Tuffaceous sandstone. A pale-brown, poorly indurated, vaguely bedded rock containing crystals of detrital quartz, andesine, and grains of glass and pumice. Some siderite and montmorillonite present.
155-158	(520-529)	Siltstone. A soft, brown, well-sorted siltstone containing quartz, andesine, montmorillonite, siderite, and traces of chlorite and illite.
226-227	(750-755)	Rhyolite. White, with fresh andesine, corroded quartz and biotite. The groundmass is partly pumiceous and shows flow banding. Cristobalite, montmorillonite and mordenite are the hydrothermal minerals present.
305-307	(1011-1016)	Rhyolite. Slightly brecciated with crystals of unaltered quartz, plagioclase and biotite. Groundmass is pumiceous and contains cristobalite and montmorillonite.
379-380	(1252-1257)	Rhyolite. Also slightly brecciated, with crystals of unaltered andesine and biotite, but hornblende has altered to montmorillonite. The hydrothermal minerals present are calcite, mordenite, cristobalite and montmorillonite.
440-441	(1455-1458)	Rhyolite. Plagioclase is fresh, biotite slightly altered, and hornblende is mostly altered to montmorillonite. The perlitic groundmass contains calcite, cristobalite, quartz and montmorillonite.
489-491	(1614-1620)	Siltstone. Brown-grey coloured, bedded siltstone containing quartz, illite, and irregularly shaped organic material.
562-563	(1854-1856)	Water-laid pumiceous tuff. Contains fragments and lapilli of pumice and rarer rhyolite, tuff and sandstone. Primary quartz is present and the hydrothermal minerals are illite, pyrite and leucoxene.
641-642	(2112-2116)	Dacite. A hard, pale green-grey, veined rock containing phenocrysts of partly-altered plagioclase. Hydrothermal minerals present are chlorite, calcite, illite, pyrite, quartz and sphene.
707-708	(2329-2334)	Siltstone. Pale grey and cream-coloured, thinly bedded, well-sorted siltstone composed of quartz and illite.

Metres Gd*	Feet KD**	
780-782	(2570-2575)	Coarse lithic-crystal lapilli tuff. Contains lapilli of andesite, pumice, rhyolite and spherulitic rhyolite with some crystals of quartz and feldspar. Albite, adularia, pyrite, calcite, chlorite and quartz are the hydrothermal minerals present.
854-856	(2812-2817)	Coarse lithic-crystal tuff. This rock contains fragments of pumice, rhyolite and spherulitic rhyolite, and crystals of quartz and feldspar. Adularia, albite, chlorite, pyrite and quartz are the hydrothermal minerals present.
928-929	(3054-3059)	Welded vitric lithic-crystal tuff. Contains large (up to 4 mm in diameter) corroded quartz, and altered plagioclase crystals. Rock fragments present include devitrified obsidian, silicified rhyolite, flattened pumice, andesite and argillite. The hydrothermal minerals are calcite, quartz, epidote, chlorite, adularia, pyrite, illite and albite.
1002-1003	(3296-3301)	Welded crystal tuff. Contains fewer rock fragments than core from 928-929 m. Hydrothermal minerals present are albite, illite, calcite, chlorite and adularia. Some unaltered andesine remains.
1079-1080	(3550-3554)	Welded vitric-crystal tuff. Andesine is mostly fresh but in places has partly altered to illite. Also present are chlorite, calcite, quartz, epidote and traces of adularia.

SUMMARY LOG

Metres	
49-226	Huka Falls Formation
226-475	Ohaki Rhyolite
475-524	Huka Falls Formation
524-616	Waiora Formation
616-695	Broadlands Dacite
695-725	Lower Siltstone
725-750	Rautawiri Breccia

No cuttings were recovered below 750 m but cores between 780 and 856 m are correlated with the Rautawiri Breccia and those between 928 and 1080 with the Rangitaiki type Ignimbrite.

DRILLHOLE BR 20

Grid Ref. 77,671 S   R.L. 293.37
44,715 W

Metres Gd*	Feet KD**	
69-70	(236-241)	Water-laid tuff. A pale, cream-grey well-sorted, vaguely bedded rock containing glass shards and small angular quartz and feldspar crystals. Secondary minerals present are cristobalite, heulandite and traces of siderite and montmorillonite.
159-160	(530-535)	Siltstone. A pale brown, well-sorted, slightly brecciated rock containing quartz, montmorillonite and minor organic material. Some kaolin and calcite are also present.
314-317	(1040-1050)	Rhyolite. A soft, unconsolidated rock containing phenocrysts of andesine and quartz. Biotite has been replaced by illite and chlorite.
378-379	(1249-1254)	Pumiceous rhyolite. Quartz and andesine are fresh but biotite has been partly replaced by illite and the groundmass by montmorillonite.
451-455	(1491-1501)	(a) Rhyolite breccia. Biotite and feldspar have altered to illite and quartz and the latter mineral is also present in the groundmass. (b) Brecciated and sheared mudstone. Brown, well-sorted mudstone composed of quartz and illite.
533-535	(1760-1765)	Water-laid pumice lapilli tuff. A poorly-sorted, white rock containing pumice lapilli, rare quartz phenocrysts, and occasional lithic fragments. Hydrothermal minerals present are illite, calcite, quartz, pyrite and wairakite.
608-610	(2006-2012)	Pumice lapilli tuff. Mainly composed of pumice lapilli but with some quartz and feldspar crystals. Occasional fragments of spherulitic rhyolite and greywacke are also present and the hydrothermal minerals are illite, quartz, pyrite, calcite, albite, chlorite and wairakite.
664-665	(2187-2192)	Dacite. A hard, dense, pale-green rock containing andesine phenocrysts which have partly altered to illite. Some greywacke xenoliths are present and the veins contain pyrite, wairakite, calcite, chlorite, quartz and an unusual clay minerals - possibly interlayered chlorite-montmorillonite.
722-723	(2377-2382)	Dacite. Pale green, hard and with fresh plagioclase. The pyroxenes have altered to chlorite and the groundmass contains chlorite, ~~montmorillonite~~, calcite and sphene.

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*Gd = Core depth below ground surface

**KD = Core depth below Kelly drive

Metres Gd*	Feet KD**	
761-763	(2507-2514)	Tuffaceous siltstone. A cream-coloured, poorly-sorted, fine-grained rock containing illite, calcite, quartz and pyrite.
835-836	(2748-2754)	Lithic lapilli tuff. White to pale-green in colour, this poorly-sorted rock contains fragments of silicified pumice and tuff. Andesine has altered to adularia and minor albite and calcite, illite, chlorite and pyrite are also present.
910-911	(2994-3000)	Pumice-crystal lapilli tuff. A soft, poorly-sorted rock containing silicified pumice lapilli and crystals of altered feldspar. Hydrothermal minerals present are adularia, albite, chlorite, pyrite, calcite and quartz.
947-949	(3117-3122)	Lithic tuff. Cream-coloured tuff with a low quartz and feldspar content. Fragments of greywacke and silicified pumice are also present. The hydrothermal minerals are quartz, albite, chlorite, pyrite and calcite.
1004-1006	(3305-3312)	Crystal tuff. A hard, dense rock containing abundant feldspar and large corroded quartz crystals. Hydrothermal minerals are calcite, pyrite, chlorite, albite and a trace of illite.
1127-1128	(3707-3710)	Welded crystal tuff. A hard, dense rock with a good vitroclastic texture and high crystal content. Andesine is mainly fresh but some adularia is also present. Other hydrothermal minerals are epidote, chlorite, calcite and a trace of illite.
1206-1207	(3968-3971)	Welded crystal tuff. A hard, dense crystal-rich rock with phenocrysts of corroded quartz and plagioclase. Some andesine has been partly replaced by adularia and minor calcite, illite, chlorite and epidote are also present.

SUMMARY LOG

Metres	
40-210	Huka Falls Formation
210-453	Ohaki Rhyolite
453-512	Huka Falls Formation
512-637	Waiora Formation
637-753	Broadlands Dacite
753-835	Lower Siltstone
835-997	Rautawiri Breccia

No cuttings recovered below 997 m but the cores between 1004 and 1207 m are correlated with the Rangitaiki-type Ignimbrite.

DRILLHOLE BR 21

Grid Ref. 77,763 S R.L. 299.01
45,606 W

Metres Gd*	Feet KD**	
195-196	(648-653)	Rhyolite. White, crystal-rich rhyolite containing phenocrysts of andesine and corroded quartz in a pumiceous groundmass. Biotite is mainly fresh; but hornblende has partly altered. The groundmass contains hydrothermal illite, mordenite, siderite, quartz and secondary K-feldspar.
435-437	(1437-1442)	Rhyolite. Plagioclase mainly fresh, but in places has partly altered to illite; biotite has partly altered to illite plus calcite and hornblende has been replaced by chlorite. The groundmass contains secondary quartz.
482-483	(1590-1594)	Siltstone. A pale brown-grey, fine-grained, brecciated rock composed of quartz, illite and a trace of pyrite.
611-613	(2015-2020)	Water-laid pumice lapilli tuff. A soft, white, poorly-sorted rock composed of altered pumice lapilli and occasional fragments of rhyolite, argillite and vitric tuff. Also present are illite, quartz, and pyrite.
675-676	(2224-2229)	Dacite breccia. A pale green-grey rock containing phenocrysts of partly-altered plagioclase in a microcrystalline groundmass. Veinlets of secondary silica, calcite, pyrite and wairakite occur and other hydrothermal minerals present are illite, chlorite, leucoxene and sphene.
731-733	(2408-2414)	Tuffaceous siltstone. A thinly-bedded, pale grey rock with occasional larger quartz crystals. Veinlets, parallel and normal to bedding, contain pyrite, calcite, quartz and wairakite. Illite is also present.
795-796	(2618-2623)	Lithic lapilli tuff. A white, poorly-sorted rock containing fragments of vitric tuff, altered pumice and sub-angular crystals of quartz and altered feldspar. Vague vitroclastic texture. Hydrothermal minerals present are quartz, illite, adularia, calcite, pyrite, chlorite and minor albite.

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*Gd = Core depth below ground surface

**KD = Core depth below Kelly drive

Metres Gd*	Feet KD**	
850-852	(2800-2805)	Lithic lapilli tuff. A poorly-sorted, white rock containing fragments of dacite, vitric tuff, spherulitic rhyolite, silicified pumice and subangular crystals of quartz and feldspar. Albite, adularia, pyrite, calcite, sphene, quartz and chlorite are the hydrothermal minerals present.
873-875	(2874-2879)	Coarse lithic tuff. A poorly-sorted rock composed of argillite, siltstone, vitric tuff and silicified pumice fragments with angular quartz and feldspar crystals. Hydrothermal minerals present are quartz, albite, adularia, calcite, chlorite, pyrite and minor epidote.
933-934	(3072-3074)	Crystal-lithic tuff. Also poorly-sorted this rock is partly composed of fine-grained siltstone and fragments of vitric tuff and silicified pumice. Also present are subangular crystals of quartz and feldspar and the hydrothermal minerals illite, calcite, albite, chlorite and minor adularia.
998-999	(3284-3289)	Lithic-crystal tuff. Poorly-sorted and containing fragments of welded vitric-tuff with quartz and feldspar crystals. Adularia, albite, illite, quartz, calcite, chlorite and pyrite are the hydrothermal minerals present.
1061-1063	(3492-3496)	Welded crystal-vitric tuff. A dense rock containing large crystals of corroded quartz and subhedral feldspar. Hydrothermal minerals present are illite, chlorite, calcite and albite, but some andesine remains unaltered.
1122-1123	(3691-3693)	Welded crystal-vitric tuff. A dense, hard, pale-green rock containing crystals of strongly resorbed quartz and partly altered andesine in a vitroclastic, part spherulitic, microcrystalline groundmass. Also present are the hydrothermal minerals quartz, calcite, epidote, chlorite, pyrite and traces of adularia and illite.

SUMMARY LOG

Metres	
3-131	Huka Falls Formation
131-482	Ohaki Rhyolite
482-509	Huka Falls Formation
509-652	Upper Waiora Formation
652-722	Broadlands Dacite
722-756	Lower Siltstone
756-c972	Rautawiri Breccia
c972-1123	Rangitaiki-type Ignimbrite

DRILLHOLE BR 22

Grid Ref: 76,806 S R.L. 299.36
44,883 W

Metres Gd*	Feet KD**	
192-194	(640-645)	Rhyolite. White rhyolite containing unaltered phenocrysts of plagioclase and quartz. Traces of hornblende are present but biotite has been partly oxidised and replaced by quartz and opaques. The groundmass is dominantly pumiceous but locally spherulitic and contains abundant mordenite and a trace of calcite and siderite.
430-432	(1422-1427)	Rhyolite. Biotite has been replaced by well-cyrstallised mica and the andesine phenocrysts partly by calcite. The groundmass has variable crystallinity and contains hydrothermal quartz and calcite.
		Junk Basket sample from 485-487m(1601-1607 ft). Dark grey, poorly sorted mudstone, mainly composed of quartz and illite.
548-550	(1809-1814)	Water-laid pumice tuff. A pale grey, poorly-sorted rock containing a few slightly flattened pumice fragments, rarer greywacke and argillite, angular quartz grains and small rosettes of pyrite. Some hydrothermal illite present.
612-614	(2018-2023)	Water-laid pumice lapilli tuff. A pale-grey coloured, poorly sorted rock containing flattened lapilli of altered pumice and occasional larger angular fragments of older tuff. Small rare quartz crystals are also present and the hydrothermal minerals are illite, pyrite, quartz, and calcite.
668-670	(2202-2207)	Dacite. Hard, pale-green and white-coloured rock in which the plagioclase phenocrysts and the groundmass have been replaced by quartz, chlorite, illite, sphene and pyrite. Small veinlets and vugs are filled with opaline quartz and calcite. Wairakite is also present.
729-730	(2400-2404)	Siltstone. Thinly-bedded, well-sorted, fine-grained siltstone varying from white to dark-brown in colour. Mainly composed of quartz and illite but some wairakite, calcite and pyrite are also present. Pyrite is more abundant and forms largest crystals in the darker sediments where there has apparently been some organic material.

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*Gd = Core depth below ground surface
**KD = Core depth below Kelly drive

Metres Gd*	Feet KD**	
788-789	(2595-2600)	Coarse lithic tuff. A poorly-sorted rock containing fragments of silicified pumice, vitric tuff, andesite, rhyolite and spherulitic rhyolite. Subhedral crystals of altered feldspar and a few smaller angular grains of quartz are also present and the hydrothermal minerals are calcite, albite, adularia, illite, quartz, chlorite and pyrite.
852-854	(2806-2811)	Soft, unconsolidated tuffaceous and sedimentary material which has apparently fallen down the drillhole from shallower levels.
917-918	(3017-3022)	Lithic-crystal lapilli tuff. A poorly-sorted rock with fragments of silicified pumice, tuff, banded and spherulitic rhyolite. Some crystals of euhedral plagioclase and smaller rare ones of quartz are present and the hydrothermal minerals are albite, adularia, quartz, calcite, chlorite ~~an~~ and pyrite.
1017-1018	(3346-3351)	Lithic-crystal lapilli tuff. Composed of numerous phenocrysts of euhedral and subhedral feldspar and large corroded quartz crystals in a groundmass with a vague, slightly welded vitroclastic texture. Subangular fragments of silicified pumice, vitric tuff, rhyolite and older welded tuff are also present, as are the hydrothermal minerals calcite, quartz, chlorite, albite, minor adularia, pyrite and a trace of illite.

SUMMARY LOG

Metres	
3-90	Huka Falls Formation
90-483	Ohaki Rhyolite
483-578	Huka Falls Formation
578-661	Upper Waiora Formation
661-722	Broadlands Dacite
722-759	Lower Siltstone
759-c908	Rautawiri Breccia

No cuttings below 908 m but the core 917-918 m is correlated with the Rautawiri Breccia and the core 1017-1018 m with the Rangitaiki-type Ignimbrite

DRILLHOLE BR 23

Grid Ref. 78,925 S R.L. 293.33
45,214 W

Metres Gd*	Feet KD**	
180-181	(600-605)	Claystone. A soft, white and cream, horizontally bedded rock mainly composed of montmorillonite and quartz, but some allophane calcite and minor andesine are also present.
437-439	(1445-1451)	Rhyolite. Partly spherulitic lava with fresh andesine and biotite. The groundmass contains tridymite, minor siderite and montmorillonite.
483-485	(1594-1600)	Tuffaceous sandstone. A white and grey patchy coloured rock composed of quartz, ~~illite~~, pyrite and minor calcite and montmorillonite.
646-648	(2130-2135)	Dacite breccia. A dense, pale green and white coloured rock containing angular fragments of altered dacite. Feldspar phenocrysts have altered to quartz, calcite and illite and there is also some vein quartz and calcite present. The groundmass contains quartz, pyrite, chlorite and albite.
704-706	(2320-2325)	Dacite breccia. Feldspar and groundmass have altered to illite and quartz and the rock is characterised by abundant pyrite. Veins contain quartz, calcite, pyrite and wairakite.
797-799	(2626-2631)	Coarse lithic tuff. A poorly-sorted rock containing subangular fragments of silicified pumice and tuff with minor small quartz crystals. Plagioclase has been replaced by adularia, calcite and a trace of albite. Other hydrothermal minerals present are quartz, pyrite, illite and chlorite.
861-862	(2833-2838)	Coarse lithic-crystal tuff. A pale grey, poorly-sorted rock containing subhedral crystals of plagioclase and rarer smaller angular quartz grains. Lithic fragments present include pumice, a few pieces of vitric tuff and obsidian; and the hydrothermal minerals present are adularia, albite, quartz, chlorite, pyrite and illite.

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*Gd = Core depth below ground surface
**KD = Core depth below Kelly drive

Metres Gd*	Feet KD**	
916-917	(3014-3020)	Lithic lapilli tuff. A friable cream and green coloured, poorly-sorted rock containing lapilli of silicified pumice, spherulitic rhyolite, argillite and crystals of subhedral feldspar and small quartz grains. The rock has a vague vitroclastic texture. Hydrothermal minerals present are albite, adularia, quartz, calcite, chlorite, pyrite, and a trace of illite.
941-942	(3098-3102)	Lithic lapilli tuff. A hard, poorly-sorted rock containing lapilli of dacite, silicified pumice, argillite and tuff. Subhedral feldspars and occasional corroded quartz crystals up to 1½mm long are also present and the hydrothermal minerals are quartz, calcite, chlorite, albite, adularia and pyrite.
1008-1009	(3316-3321)	Welded coarse lithic-crystal tuff. A crystal-rich rock composed of numerous anhedral and subhedral feldspar crystals and a few corroded quartz grains up to 2 mm in diameter. Rock fragments present include dacite, rhyolite, spherulitic rhyolite, and the hydrothermal minerals are calcite, albite, adularia, chlorite, illite and pyrite.
1098	(3614-3616)	Welded crystal tuff. A hard, dense, crystal-rich rock composed of abundant subhedral and euhedral feldspar and strongly corroded quartz crystals, the latter up to 5 mm in diameter. Some feldspar remains unaltered but adularia is present and the other hydrothermal minerals are calcite, illite, chlorite and pyrite.

SUMMARY LOG

Metres	
61-256	Huka Falls Formation
256-479	Ohaki Rhyolite
479-518	Huka Falls Formation
518-613	Upper Waiora Formation
613-750	Broadlands Dacite
750-768	Lower Siltstone
768-954	Rautawiri Breccia
954-1015	Rangitaiki-type Ignimbrite

No cuttings recovered from below 1015 m but the core from 1098 m is also correlated with the Rangitaiki-type Ignimbrite.

DRILLHOLE BR 24

Grid Ref. 80,022 S   R.L. 295.32
43,979 W

Metres Gd*	Feet KD**	
159-161	(530-537)	Water-laid tuff. A grey-green, vaguely bedded, crystal-rich, poorly-sorted rock containing angular crystals of quartz, andesine and fragments of greywacke, rhyolite, andesite, pumice and devitrified obsidian. Chlorite and calcite are the hydrothermal minerals present.
305-306	(1009-1014)	Rhyolite. Andesine is mainly fresh but ferromagnesian minerals have altered to quartz and chlorite. The devitrified, partly pumiceous groundmass contains illite-montmorillonite and pyrite.
362-363	(1196-1201)	Rhyolite. Andesine fresh, but biotite has partly and amphibole completely altered. Some hydrothermal quartz and well-crystallised chlorite are present.
426-428	(1409-1414)	Rhyolite ash. Andesine fresh, biotite partly altered and the rock also contains a few fragments of vitric tuff. Illite, calcite and chlorite are present in the groundmass.
611	(2013-2016)	Dacite. A hard, grey rock containing plagioclase crystals which have been completely replaced by illite and quartz. Some vein pyrite, chlorite and a trace of albite are also present.
651	(2145-2147)	Andesite. A grey-green, hard rock which contains mainly fresh andesine and partly-altered hornblende. Hydrothermal minerals present are calcite, chlorite and quartz.
704-706	(2320-2325)	Dacite. A grey-green coloured rock in which feldspars have been completely replaced by illite, calcite and quartz. Quartz, illite and pyrite also form thin veins and chlorite and a trace of albite are also present in the groundmass.
769-771	(2533-2538)	Coarse lithic tuff. A white rock mainly composed of silicified pumice and quartz grains in a microcrystalline matrix. Quartz, illite, calcite and pyrite are the hydrothermal minerals present, the calcite as thin veins.

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* Gd = Core depth below ground surface

** KD = Core depth below Kelly drive

Metres Gd*	Feet KD**	
825-827	(2717-2722)	Coarse lithic tuff. A white, poorly-sorted rock containing angular and subangular crystals of quartz and feldspar. Lithic fragments present include pumiceous rhyolite and the hydrothermal minerals and adularia, albite, illite, quartz, chlorite, calcite and pyrite .
880-882	(2898-2902)	Lithic lapilli tuff. A poorly-sorted rock containing subangular crystals of quartz and feldspar and lapilli of pumice, vitric tuff, greywacke and rhyolite. The groundmass has a part vitroclastic texture and hydrothermal minerals present are quartz, albite, pyrite, chlorite, large calcite crystals and minor adularia.
945-947	(3111-3116)	Crystal-lithic lapilli tuff. A very poorly-sorted rock composed of numerous angular fragments of pale green rhyolite and minor spherulitic rhyolite. Numerous subangular quartz and feldspar crystals are also present and the hydrothermal minerals are chlorite, albite, calcite, illite, quartz and minor adularia.
1010-1011	(3323-3328)	Crystal-lithic lapilli tuff. Similar to core from 945-947 m but also present are tuff,greywacke and siltstone lapilli. Hydrothermal minerals present are albite, illite, chlorite, calcite, quartz and adularia.
1074-1075	(3533-3538)	Coarse lithic tuff. Poorly-sorted and composed of rounded greywacke and silicified pumice fragments. A few larger quartz crystals are also present and secondary minerals are quartz, Mg-chlorite, pyrite calcite and illite.
1135-1137	(3735-3740)	Siltstone. A dark grey-brown,fine-grained thinly bedded rock mainly composed of quartz and illite, minor organic material, albite, chlorite and calcite. Vague plant fossils visible.
1194-1195	(3927-3932)	Coarse water-laid tuff. Poorly-sorted but with graded bedding, this rock contains quartz, feldspar and fragments of greywacke, basalt, argillite, tuff, and rhyolite. Hydrothermal minerals present are illite, calcite, albite and chlorite.

Metres Gd*	Feet KD**	
1249-1251	(4109-4114)	Conglomerate. A poorly-sorted rock composed of rounded and subrounded pebbles of argillite and greywacke plus a few large crystals of quartz and pumice fragments in a chlorite matrix. Quartz, calcite and illite, and a trace of wairakite are the hydrothermal minerals present.

SUMMARY LOG

Metres	
33-241	Huka Falls Formation
241-453	Ohaki Rhyolite
453-497	Huka Falls Formation
497-607	Upper Waiora Formation
607-729	Broadlands Dacite
729-1056	Rautawiri Breccia
1056-1171	Upper Waikora Formation
1171-1241	Lower Waiora Formation
1241-1251	Lower Waikora Formation

DRILLHOLE BR 25

Grid Ref. 81,673 S R.L. 302.38
44,125 W

Metres Gd*	Feet KD**	
157-159	(525-531)	Tuffaceous sandstone and siltstone. A grey-brown, poorly-sorted rock composed of angular crystals of andesine, rarer quartz, and a few small rock fragments. The dark matrix contains siderite, illite, chlorite, calcite and montmorillonite.
306-308	(1015-1020)	Rhyolite. A soft, white rhyolite containing unaltered primary quartz. Biotite, amphibole and the pumiceous groundmass have altered to illite and plagioclase to illite-montmorillonite, calcite and wairakite. Some hydrothermal chlorite, pyrite and quartz are present.

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*Gd = Core depth below ground surface

**KD = Core depth below Kelly drive

Metres Gd*	Feet KD**	
363-364	(1200-1205)	Sandstone. A grey, massive, comparatively well-sorted sandstone mainly composed of angular quartz, illite-montmorillonite, biotite and chlorite.
423-425	(1399-1405)	(a) Mudstone. Dark-brown, bedded rock composed of illite, pyrite and traces of chlorite, epidote, sphene and calcite. (b) Pumice tuff. A cream-coloured, soft rock composed of fragments of altered pumice, rhyolite and biotite crystals. Abundant illite, minor pyrite and chlorite are the hydrothermal minerals present.
488-490	(1611-1616)	Vitric-lithic lapilli tuff. A grey, poorly-sorted rock composed of subrounded to subangular lapilli of rhyolite, silicified pumice, perlitic and spherulitic rhyolite, dacite, tuffaceous siltstone and a few small quartz and feldspar crystals. Secondary quartz, adularia, calcite and pyrite.
543-544	(1792-1796)	Lithic lapilli tuff. A poorly-sorted, cemented rock composed of lapilli of basalt, bedded siltstone, sandstone, silicified pumice, rhyolite, and a few crystals of quartz and altered feldspar. The hydrothermal minerals present are pyrite, chlorite, calcite, and abundant quartz and adularia.
607-608	(2001-2004)	Vitric-lithic lapilli tuff. A hard, silicified, poorly-sorted rock containing fragments of welded tuff, argillite, silicified pumice, mudstone and rhyolite. Also present are a few crystals of quartz and altered feldspar and the hydrothermal minerals chlorite, quartz, adularia and traces of illite, pyrite and calcite,
667-668	(2199-2203)	Breccia. A hard, dense rock composed of angular fragments of altered dacite intermixed with dark brown tuffaceous mudstone. Hydrothermal minerals present are quartz, pyrite, illite, adularia, chlorite and leucoxene.
692-694	(2281-2286)	Dacite breccia. A hard, dense, pale-green rock containing dacite fragments which themselves contain small mudstone xenoliths. Quartz, pyrite, chlorite, illite, albite and adularia are the hydrothermal minerals present.

Metres Gd*	Feet KD**	
759-761	(2501-2508)	(a) Dacite breccia. Similar to core from 692-694 m, but xenoliths are absent. Hydrothermal calcite, sphene, adularia, albite, quartz, chlorite and pyrite are present. (b) Coarse lithic tuff. A pale green, poorly-sorted rock containing subrounded fragments of vitric tuff, partly silicified pumice, and rhyolite together with crystals of quartz and subhedral plagioclase. The groundmass has a vitroclastic texture and contains the hydrothermal minerals quartz, chlorite, adularia and pyrite.
820-821	(2700-2705)	Lithic-vitric lapilli tuff. Hard and silicified this rock has a good vitro-clastic texture and contains lapilli of tuffaceous siltstone and crystals of subhedral and anhedral feldspar. Quartz is rare as a primary mineral but is abundant as a hydrothermal product, commonly forming veins. Other hydrothermal minerals present are pyrite, calcite, adularia, chlorite and a trace of illite.
879-881	(2895-2900)	Welded lithic-vitric tuff. A hard, poorly-sorted rock composed of rounded fragments of tuffaceous siltstone, silicified flattened pumice, and argillite together with crystals of euhedral feldspar, corroded quartz and replaced biotite. The rock has a good vitroclastic texture and contains the hydrothermal minerals adularia, quartz, pyrite, calcite, chlorite plus traces of illite and epidote.
939-940	(3090-3095)	Welded coarse lithic-crystal tuff. Similar to core from 879-881 m. Fragments of silicified pumice, rhyolite, spherulitic rhyolite and greywacke are present and the hydrothermal minerals are chlorite, quartz, adularia, pyrite and a trace of illite.
1003-1004	(3300-3305)	Lithic lapilli tuff. A hard, dense rock composed of greywacke lapilli up to 5 cm in diameter with other inclusions of vitric tuff, rhyolite and spherulitic rhyolite. Crystals of anhedral and subhedral feldspar and angular quartz are present and the hydrothermal minerals are adularia, chlorite, quartz, calcite, illite and pyrite.

Metres Gd*	Feet KD**	
1064-1065	(3500-3505)	Conglomerate. A poorly-sorted rock composed of round pebbles and granules of greywacke and argillite in a matrix of quartz and chlorite. Calcite and sphene are also present.
1125-1126	(3700-3705)	Vitric-crystal tuff. A hard, pale green rock with a comparatively low crystal content but containing variable sized phenocrysts of euhedral feldspar and angular corroded quartz. Lithic fragments present include rhyolite, spherulitic rhyolite and greywacke and the hydrothermal minerals are adularia, illite, quartz, chlorite, pyrite, sphene and calcite. Vitroclastic texture.
1184-1185	(3894-3899)	Conglomerate. A poorly-sorted rock composed of rounded pebbles and granules of greywacke, argillite and rare pumice in a matrix containing hydrothermal quartz, chlorite, adularia, albite, illite and rare sphene.
1256-1258	(4131-4136)	(a) Conglomerate. Greywacke and argillite conglomerate similar to core from 1184-1185 m. Hydrothermal quartz, illite, calcite, chlorite, adularia and sphene are present. (b) Tuff. Consists of poorly sorted crystals of quartz and fragments of rhyolite and quartzite in a matrix with vague vitroclastic texture. The hydrothermal minerals present are calcite, epidote, pyrite, chlorite, quartz and illite.

SUMMARY LOG

Metres	
98-293	Huka Falls Formation
293-363	Ohaki Rhyolite
363-469	Huka Falls Formation
469-668	Upper Waiora Formation
668-c761	Broadlands Dacite

No cuttings were recovered below 716 m but cores are correlated as follows -

820-1004 m with the Rangitaiki-type Ignimbrite
1064-1065 m with the Upper Waikora Formation
1125-1126 m with the Lower Waiora Formation
1184-1258 m with the Lower Waikora Formation

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APPENDIX B - LOG OF DRILLHOLE PH 1A

metres	
1-1.2	Weathered, poorly-sorted, subangular to subrounded, creamy, vesicular, pumice fragments (some up to lapilli size) mixed with soil and smaller angular grains of black and red volcanic rocks.
1.2-2.1	A poorly-sorted mixture of pumice fragments up to 10 mm diameter, rounded quartz crystals and subrounded to subangular grains of black rhyolite cemented by fine-grained, pale brown mud.
2.1-2.7	Soft, friable, well-sorted, cream-coloured tuffaceous silts. Occasional flecks of black organic matter and rounded rhyolite grains (up to 3 mm diameter) are present and the proportion of larger pumice fragments increases as this grades into -
2.7-3.4	Pale fawn, poorly-sorted silts with vesicular pumice up to lapilli size at 2.9 m, but smaller at 3.4m. Occasional small dark volcanic rock fragments.
3.4-3.7	Poorly- sorted pumice lapilli tuff, in places weathered.
3.7-4.4	Moderately-sorted, cream-grey pumice lapilli with little matrix and occasional small charcoal fragments.
4.4-4.9	Water-laid pumice ash and lapilli containing poorly-sorted, round to angular grains of pumice, obsidian, rhyolite and occasional mudstone.
4.9-5.2	Similar, but pumice up to lapilli size and less matrix.
5.2-5.5	White, poorly-sorted, water-laid ash containing mainly pumice and rarer rhyolite grains.
5.5-5.6	Pumice Lapilli.
5.6-6.4	Fawn-coloured, water-laid, poorly sorted, pumice ash containing grains of pumice, rare obsidian, round dark rhyolite, mudstone, rare charcoal and twigs of wood.
6.4-6.6	Loose pumice lapilli, small dark angular grains of volcanic rock and angular quartz crystals.
6.6-6.7	Tuffaceous grit. Poorly-sorted, mainly uncemented angular to round grains of dark rhyolite and pumice up to 35 mm in diameter.
6.7-7.0	Fawn-coloured, friable, comparatively well-sorted, fine-grained water-laid ash. Occasional patches of leaves and needles present.
7.0-7.2	Water-laid pumice ash. Soft, friable, with pumice up to lapilli size in a fine-grained pumice matrix. Some leafy material present.
7.2-7.6	Off-white, thin bedded, well-sorted, water-laid ash containing organic-rich patches.
7.6-9.1	Pale brown, subrounded to rounded loose pumice pieces,

Metres	
	varying in size between 1 and 25 mm, mixed with darker, rare, angular rhyolite grains.
9.1-10.1	Thin irregular beds of pumice lapilli (50 mm); fine ash (50 mm); rhyolite grit (25 mm); coarse water-deposited pumice (25 mm) tuff; fawny-brown, poorly-sorted water-laid tuff (50 mm); thin leafy bands and tuffaceous sand containing angular uncemented grains of rhyolite, quartz and pumice.
10.1-11.0	Pale grey, round, pumice lapilli.
11.0-11.3	Rounded, white pumice lapilli smaller than in 10.1-11.0, and dark tuffaceous, rhyolitic grit.
11.3-11.9	Unconsolidated, poorly-sorted, water-laid pumice and with quartz and plagioclase crystals and rare, dark, angular andesite grains.
11.9-13.1	0.15 m of white, round and subround, unconsolidated, occasionally banded pumice lapilli up to 25 mm in diameter grading into poorly-sorted, smaller grey pumice. Rare plant material and dark andesite also present.
13.1-13.3	Mottled grey-coloured pumice lapilli.
13.3-13.9	Unconsolidated, angular, poorly-sorted rhyolite and pumice grits, with a few small crystals of quartz and plagioclase.
13.4-13.6	White pumice lapilli.
13.6-14.6	Muddy brown, mottled, light, part peaty, part pumice material.
14.6-15.2	Wood.
15.2-16.8	One pumice lapillus and pale-brown, peaty and tuffaceous mudstone with pieces of bark grading into mudstone and pale brown-grey, well-sorted tuffaceous siltstone.
16.8-18,3	Peaty brown mudstone containing bark fragments and small grains of pumice and dark rhyolite grading into green-grey and brown, well-sorted, friable, tuffaceous sandstone and siltstone. This contains a few pumice grains and flecks of flattened organic matter. Crude stratification of black organic matter.
18.3-19.8	Grey-brown, friable, poorly-sorted tuffaceous sandstone containing small (up to 2 mm diameter), angular rhyolite grains and pieces of wood. Very crude bedding with lenses of coarser, unconsolidated grains and layers of black organic matter.
19.8-20.6	Grey-brown, poorly-sorted pumiceous sandstone mixed with wood fragments. At 20.6 m there are several thin layers of black organic matter.
20.6-21.3	Crudely graded, bedded, tuffaceous grits and sands containing grains of pumice and crystals of quartz and feldspar. Patchy weathering. Also present are a few volcanic rock fragments.

Metres	
21.3-22.6	Similar, but coarser-grained, composed of unbedded tuffaceous material, mainly poorly-sorted, coarse-grained sands. Includes grains of part weathered pumice, rounded quartz, small andesine and rare biotite crystals.
22.6-22.9	Pale cream-brown, well-sorted, friable, tuffaceous siltstone.
22.9-24.3	0.3 m of core only consisting of pale orange-cream, poorly-sorted, coarse tuffaceous sandstone containing grains of part weathered pumice and rhyolite and quartz and plagioclase crystals.
24.3-24.7	Pale, grey-brown, unconsolidated, poorly-sorted, coarse tuffaceous sandstone.
24.7-24.8	Conglomerate containing loosely cemented, round and sub-round grains of rhyolite, pumice and quartz.
24.8-25.9	Pale grey-brown, poorly-sorted, loosely consolidated tuffaceous sandstone and coarse sandstone containing quartz and plagioclase crystals and grains of pumice and rhyolite.
25.9-27.1	Pale brown-grey, irregularly interbedded tuffaceous conglomerate, coarse tuffaceous sand and sandstone. Pumice and rhyolite fragments common. Pebbles more common at 26.2 m.
27.1-27.4	Subrounded to rounded pebbles, up to 25 mm in diameter, of dark grey, hard volcanic rock.
27.4-28.0	Subrounded to subangular pebbles of greywacke, tuffaceous sandstone and hydrothermally altered crystal tuff.
28.0-28.7	Pale grey-brown tuffaceous sandstone and siltstone containing pumice and rhyolite grains.
28.7-29.0	Subrounded and subangular pebbles, up to 35 mm diameter, of rhyolite, tuff, tuffaceous sandstone, and andesite.
29.0-29.6	Pale grey, loosely consolidated, poorly-sorted, coarse tuffaceous sandstone, containing crystals of quartz, plagioclase and grains of pumice and rhyolite, interbedded with creamy, soft, poorly-sorted siltstone.