

FC-199

0/158

William A.

THE CHEMISTRY OF THE BROADLANDS GEOTHERMAL AREA NEW ZEALAND

WILLIAM A. J. MAHON and JAMES B. FINLAYSON*

GL03508

Chemistry Division, Department of Scientific and Industrial Research, Private Bag, Petone, New Zealand

ABSTRACT. Broadlands is a hydrothermal area in the Taupo Volcanic Zone of the North Island of New Zealand. The surface activity is limited in extent, and the natural heat flow from the area, 17,500 kcals/sec, is small compared with other areas in the zone. Scientific investigations and later drilling, however, have shown that the area of the deep hot water system (9km²) is comparable to that at Wairakei.

Hot water at temperatures up to about 300°C but usually tapped by drillholes at 260° to 270°C contains in approximate quantities, NaCl (1625 ppm), KCl (265 ppm), boron (32 ppm), and silica as major constituents and occurs at depths down to approximately 2420 meters. Dissolved gas in the water is mainly carbon dioxide, at a concentration level near 0.14 molal. Concentrations of heavy metals in the water are low, but precipitates and sinters derived from the water contain high concentrations of arsenic, antimony, and heavy metals. D/H values in the water are similar to those present in local streams to the east, indicating that a high proportion of the hot water is derived from a meteoric source.

Trends in the chemistry of drillhole fluids with time provide a clearer picture of the physical conditions existing in the underground system, before and during exploitation. Slight deposition of calcite occurs in the casing of a drillhole, as originally predicted from the early chemistry of the water discharges.

INTRODUCTION

Following successful geothermal power developments at Wairakei large-scale drilling was carried out at Broadlands to determine the extent and characteristics of the deep high temperature water. This was preceded by a Wenner resistivity survey across the area which delineated a zone of low resistivity, to depths of approximately 550 m, of size comparable to the Wairakei geothermal field. The results from subsequent geochemical, geophysical, and geological investigations were used to locate sites for exploratory drillholes. To date nineteen holes ranging in depth from 762 to 2420 m have been drilled in an area of some 9 km². This paper discusses the chemistry of the fluids discharged from the hot springs and drillholes and correlates the results with the geology and physical conditions at depth in the field.

The locality of Broadlands with respect to other geothermal areas in the Taupo Volcanic Zone is shown as an inset in figure 1. The field extends some 3.6 km along both sides of the Waikato River in the Taupo-Reporoa Basin, some 27 km northeast of Taupo. The natural activity is limited to a few hot springs and hot water seepage into the Waikato River and minor areas of mudpools and steaming ground. The natural heat flow was estimated by Dickinson (ms) as 17,500 kcal/sec which can be compared with 101,000 kcal/sec for the Wairakei area (Dawson and Dickinson, 1970).

The major surface activity in the northern part of the field was Ohaki Pool (fig. 1) a hot spring that covered an area of 850 m² and discharged 10 l/sec of hot water at 98°C before the area was drilled. In addition there was a smaller spring close by and scattered zones of

* Present address: Hilo Campus, University of Hawaii, Hilo, Hawaii 96720

hot water seepage into the of the Ohaki Pool (see w hot springs occurred 3 km of mud pools and dark km southwest of Ohaki P. two latter areas was below less than 70°C.

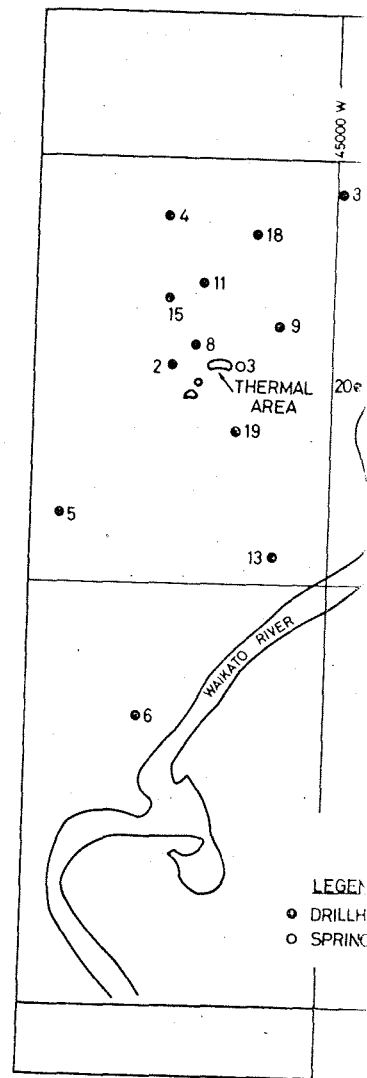


Fig. 1. Locality of the springs position of Broadlands within the Taupo Volcanic Zone.

UNIVERSITY OF UTAH
RESEARCH INSTITUTE
EARTH SCIENCE LAB.

**LANDS
LAND**

FINLAYSON*

ific and
w Zealand

upo Volcanic Zone of
ted in extent, and the
pared with other areas
ver, have shown that
t at Wairakei.

y tapped by drillholes
(1625 ppm), KCl (265
occurs at depths down
mainly carbon dioxide,
heavy metals in the
e water contain high
values in the water
indicating that a high

vide a clearer picture
n, before and during
g of a drillhole, as
discharges.

ments at Wairakei
determine the ex-
e water. This was
area which delin-
imately 550 m, of
The results from
investigations were
ate nineteen holes
lled in an area of
e fluids discharged
e results with the

r geothermal areas
figure 1. The field
kato River in the
upo. The natural
r seepage into the
ming ground. The
s 17,500 kcal/sec
the Wairakei area

t of the field was
ea of 850 m² and
e area was drilled.
scattered zones of

Hawaii 96720

hot water seepage into the Waikato River 1.2 km to the east and south of the Ohaki Pool (see water compositions, table 1). A smaller area of hot springs occurred 3 km south-southwest of Ohaki Pool, and a number of mud pools and dark colored thermal pools lay approximately 1.0 km southwest of Ohaki Pool. The flow from individual springs in the two latter areas was below 1 l/sec, and temperatures were in all cases less than 70°C.

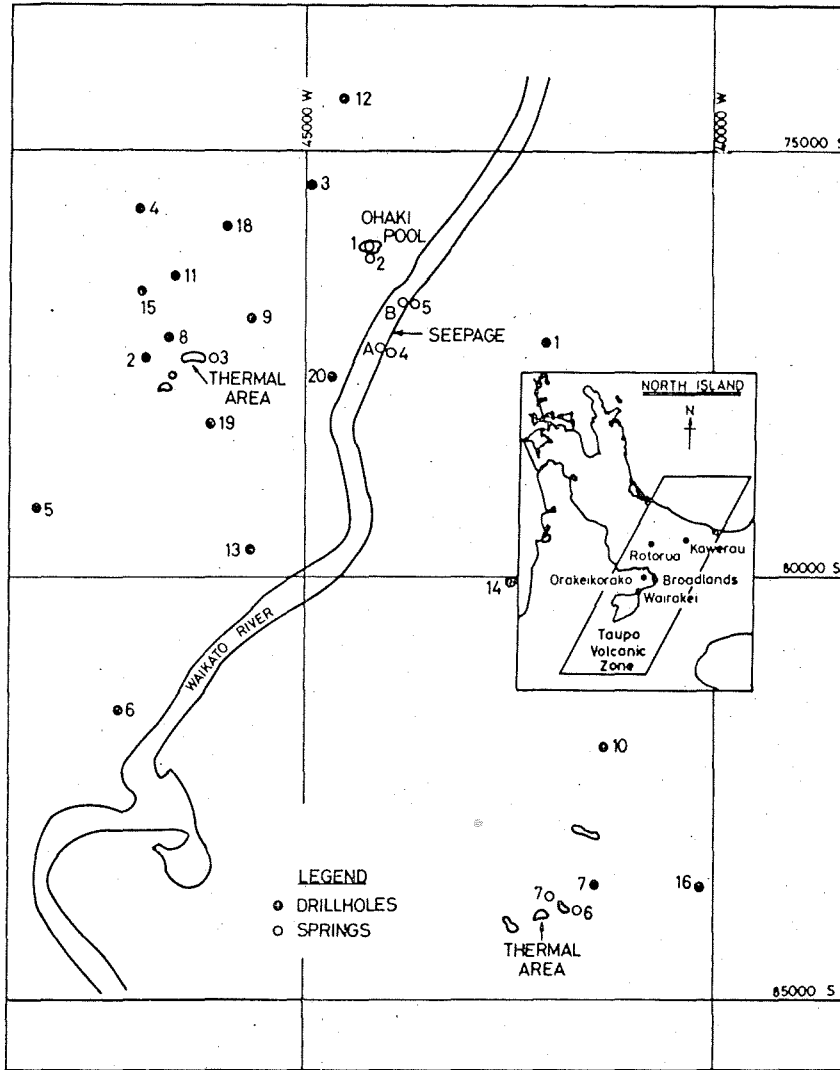


Fig. 1. Locality of the springs and drillholes at Broadlands. Inset shows the position of Broadlands within the Taupo Volcanic Zone.

During the early chemical survey work in the area, the extent of hot water seepage and runoff from Broadlands was measured. Water samples were collected from cold streams within the area and from the Waikato River upstream and downstream of the visible surface activity to check on high chloride water flows. The survey showed that little more than 30 to 35 l/sec of hot chloride water appeared at the surface.

Studies of the surface and subsurface geology at Broadlands and the mineralogy and hydrothermal alteration of rock cores taken during drilling were made by Grindley and Browne (ms) and Browne and Ellis (1970). A generalized stratigraphic sequence of the rocks, taken from Grindley and Browne (ms), is shown opposite.

Holes drilled in the eastern side of the field, at the deepest level, penetrated basement argillite and graywacke, as did the deepest hole in the field, hole 15 in the west. Most of the other holes drilled in the west terminated in ignimbrite. The porosity of the formations was in the range 10 to 40 percent, but where there was extensive hydrothermal alteration, it was considerably reduced.

Table 4 shows data for the 19 holes drilled and discharged at Broadlands. Most of the holes were drilled to depths between approximately 750 and 1400 m except hole 15 which was drilled to 2418 m. Downhole temperatures were high and in the range 260° to 300°C, while pressures at deeper levels in the holes, before discharge, approximated to hot hydrostatic pressure and were higher than the vapor pressure of the water at any particular depth.

The highest temperature in most holes was near the hole bottom, but those having high mass outputs reached near maximum temperature (within 20° to 30°C) between 427 and 610 m. Poor production holes had a more gradual or erratic temperature increase throughout their length, while holes 4 and 13 had a temperature inversion at deeper levels.

The discharge enthalpies of many holes, after continuous discharge, were higher than the supply water at maximum measured temperatures. These holes were supplied by a steam/water mixture rather than a single hot water phase. Significant pressure falls occurred in the drill-holes after continuous discharge, and pressures measured in some drill-holes indicated the presence of a fluid less dense than water at the respective temperatures (vapor/water mixture). Many holes after drilling and standing closed for a few days built up high gas pressures at the wellhead as a result of accumulation of gas in the holes and consequent depression of the water levels.

The permeability of the rocks penetrated by many drillholes at Broadlands is apparently too low to allow steady state production. Drawdown of hot water levels in holes during production allows hydrostatic pressures to fall to the vapor pressures at the producing horizons. Boiling and the formation of steam within the system are induced and propagated by the lowering of pressures and the consequent transfer of heat from rock to water.

Stratigraphic sequence of rocks at Broadlands

Formation	Content	Thickness	
		Fcct	Meters
Taupo Pumice Haparangi Pumice Wairakei Breccia (Lapilli Tuff)	Pumice alluvium and ash showers. Pumiceous sands, rhyolitic gravel, and sand. Pisolitic, pumice-rhyolite lapilli tuff, and breccia.	100-300	30-91
Huka Falls Formation	Alternating thick beds of lacustrine siltstone, locally diatomaceous, with pumiceous sandstone, grit, and tuff.	100-1000	30-305
Ohaki Rhyolite	Crystal rich, biotite-hornblende quartz-plagioclase rhyolite. Commonly pumiceous and spherulitic, locally brecciated.	0-1400	0-427
Upper Waioira Formation	Tuff-breccia with pumice and rhyolite lapilli; siltstone underlain by sedimentary pumice tuffs.	600-900	183-274
Broadlands Rhyolite	Dense, flowbanded, plagioclase, rhyolite, locally perlitic or glassy. Upper (2) and lower (1) flow units.	0-1500(2) 0-750 (1)	457 229
Rautawiri Breccia	Coarse, crystal-vitric-lithic breccias with fragments of pumice rhyolite, ignimbrite, siltstone, and argillite.	500-900	152-274
Rangataiki Ignimbrite	Crystal-rich, quartz-plagioclase ignimbrite, locally lenticulitic, passing up into unwelded crystal-vitric tuff.	100-1400	30-427
Upper Waikora Formation	Thin-bedded, non-volcanic sandstone, siltstone, grit. Conglomerate beds with argillite and minor pumice pebbles.	0-200	0-61
Lower Waioira Formation	Pale gray, coarse crystal-vitric tuff with quartz (possibly unwelded upper part of ignimbrite sheet).	0-350	0-107
Lower Waikora Formation	Thin-bedded, non-volcanic sandstone, siltstone, grit, conglomerate beds with argillite pebbles.	0-300	0-91
Wairakei Ignimbrite	Crystal rich, quartz-plagioclase ignimbrite, locally lenticulitic, small graywacke inclusions.	150+	46+
Graywacke basement	Dense, indurated, massive graywacke and dark fractured, vein argillite with poor bedding.		

CHEMISTRY OF THE NATURAL ACTIVITY AT BROADLANDS

Table 1 lists the chemical compositions of waters discharged from springs at Broadlands. As the number of near boiling springs in the area was small, the extent to which surface chemistry could be used for predicting underground water compositions and temperatures was limited. However, the presence of a major feature such as Ohaki Pool,

TABLE 1
Analysis of a representative group of springs at Broadlands

Spring No.	Date of colln. Flow		Concentration in water (ppm)													
	1965	l/sec	T°C	pH	Li	Na	K	Rb	Cs	Ca	Mg	F	Cl	Br	I	SO ₄
1	16.6	10	98	7.0	7.4	860	82	0.1	1.2	8.5	0.215	5.2	1040	3.0	0.6	100
3	16.6	Nil	25	2.6	4.6	440	43.5	—	—	33	—	—	681	—	0.3	530
4	16.6	0.3	75	8.0	3.6	430	31.5	—	—	28	—	2.2	525	—	—	132
5	16.6	0.3	57	8.7	2.6	374	28	—	—	16.2	—	2.2	362	—	0.2	52
6	17.6	0.3	19	2.8	3.35	410	22	—	—	5.7	—	—	539	1.5	0.3	347
7	17.6	Nil	42	7.3	3.95	500	21	—	—	7.0	—	4.2	638	1.7	0.3	185
A*	16.6	0.5	61	7.9	3.6	415	30.5	—	—	46	—	2.4	492	—	—	162
B*	16.6	0.3	66	7.9	3.3	410	31	—	—	15.3	—	2.4	443	—	—	82

Spring 1 is Ohaki Pool

Analysis of spring 2 (Fig. 1) is identical to analysis of spring 1.

* A and B are samples collected from seepage into the Waikato River

(table 1) with a high temperature and large flow, enabled certain predictions to be made.

The hot waters discharged from springs in the Broadlands area were mainly of the neutral pH, chloride-bicarbonate type. Chloride concentrations ranged from approximately 300 to 1000 ppm, and 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. Acid pools, with little or no overflow, had similar constituent ratios to the near neutral pH springs.

Cl/B ratios in the waters ranged from 8 to 11 which were low compared with values found in rhyolitic areas such as Wairakei, Waiotapu, Orakei-Korako, and Rotorua. Low to very low ratios were found also at Kawerau (Mahon, 1962b), Tokaanu (Mahon and Klyen, 1968), and Ngawha (Ellis and Mahon, 1966), where the rocks are either andesitic or sedimentary. The Na/Li ratios and rather high ammonia concentrations at Broadlands were similar to those for the Kawerau waters.

High sulphate and ammonia concentrations in the lower pH spring waters and the presence of sulphur on sinter and in areas of steaming ground suggested that some steam heating of surface waters occurred. Concentrations of minor elements such as rubidium, caesium, fluoride, bromide, iodine, calcium, and magnesium were of the same order as found in hot waters at Wairakei, and ratios of these elements to either chloride or sodium were also similar to those at Wairakei. Cl/Br and Cl/As ratios at Broadlands for example were approximately 800 and 820 respectively compared with ratios of 850 and 1000 at Wairakei.

TABLE 1 (continued)

Concentration in water (ppm)							Molecular ratio							
B	SiO ₂	As	NH ₃	HCO ₃	H ₂ S	CO ₂ as to	of chloride to				of sodium to			
							B	F	As	Br	SO ₄	Cs	Li	K
32.1	338	1.5	3.8	680	1.0	9.9	107	560	780	28.1	3250	35	17.8	176
18.9	280	—	5.8	Nil	1.0	11.0	—	—	—	3.5	—	29	17.2	23.2
14.8	280	—	0.1	322	1.0	10.8	128	—	—	10.8	—	36	23.2	26.8
11.0	207	—	1.9	430	1.0	10.8	88	—	—	18.8	—	43	22.7	40.2
20.6	250	1.2	1.6	CO ₂	1.0	8.0	—	950	810	4.2	—	37	31.7	125
23.7	232	1.4	1.1	188	1.0	8.2	81	962	846	9.3	—	38	40.5	124
13.6	214	—	2.8	307	1.0	11.0	110	—	—	8.2	—	35	23.1	15.7
13.1	225	—	2.3	385	1.0	10.3	99	—	—	14.6	—	38	22.5	46.6

Silica concentrations of between 280 and 340 ppm in the spring waters would correspond to an underground water temperature of between 190° to 200°C. This assumes that the deep waters were just saturated with respect to quartz and were not affected by dilution or loss of SiO₂ on route to the surface, and decrease in temperature resulted from boiling with no loss of heat by conduction. (Mahon, 1966; Fournier and Rowe, 1966). The Na/K ratios of between 17 and 23 corresponded to underground equilibration temperatures of about 200°C between rock minerals and water (Ellis and Mahon, 1967).

The low concentrations of constituents such as calcium, magnesium, and fluoride, which at high temperature are controlled at a low level by mineral equilibria, indicated high temperatures at deeper levels and substantiated the impressions obtained from the silica concentrations and Na/K ratios.

Estimates of the carbon dioxide concentration in the deep water from surface chemistry, using the methods of Ellis (1970), gave values ranging from 1.6×10^{-3} to 3.25×10^{-1} molal. The low concentration was obtained for a deep water temperature of 200°C, while the high value corresponded to a deep temperature of 250°C. (At Wairakei, Waiotapu, and Orakeikorako experience showed that estimates of minimal underground temperatures from SiO₂ concentrations and Na/K ratios were approximately 50° to 60°C lower than those found on drilling.) The higher value was of the same order as carbon dioxide concentrations found in steam discharged from two areas of steaming ground (0.6 molal).

TABLE 2
Analyses of water in drillholes at Broadlands

Hole	Date	pH 20°C	Concentration in water (ppm)												
			Li	Na	K	Rb	Cs	Ca	Mg	F	Cl	Br	I	SO ₄	
1	1. 2.66	8.3	10.9	1065	152	0.6	0.6	4.6	—	6.7	1701	—	1.4	43	
2	23. 8.66	8.3	11.7	1050	224	2.2	1.7	2.2	0.08	7.3	1743	6.4	0.8	8	
3	28. 4.67	8.0	12.2	1015	213	1.8	1.8	3.0	0.80	6.1	1801	6.6	—	6	
4	6. 9.67	8.35	11.8	1075	218	2.0	1.4	3.0	0.02	4.5	1851	6.7	1.3	29	
5	14.11.67	9.1	4.9	1400	146	—	—	—	—	—	1142	—	—	—	
6	4.12.67	7.4	1.2	435	39	—	—	260	—	—	28	—	—	—	
7	14. 5.68	8.55	15.0	1300	234	2.4	1.8	1.4	0.013	—	1823	5.2	0.35	15	
8	29. 2.68	7.9	11.4	975	232	2.9	1.6	3.0	0.1	8.4	1858	6.3	0.6	6	
9	14. 5.68	8.45	12.7	930	203	2.4	1.5	2.0	0.36	8.0	1709	5.9	0.4	3.5	
10	18.10.68	8.6	9.5	910	142.5	1.1	1.4	1.1	0.05	6.2	1244	3.6	0.1	4.0	
11	22. 8.68	8.25	12.2	1020	218.5	1.7	1.4	7.3	0.92	6.4	1794	7.0	0.1	11.5	
12	13.12.68	8.51	10.0	1510	198	0.95	1.25	2.8	0.13	3.2	1546	5.1	0.5	10	
13	10.10.68	8.6	12.6	980	200	2.2	1.3	2.4	0.015	4.5	1668	5.25	0.1	25	
14	6. 2.69	8.5	10.5	880	175	0.9	1.5	2.0	0.7	3.2	1482	4.2	0.7	6.5	
15	3. 4.70	8.25	11.5	1066	207	1.8	1.55	5.7	0.13	6.8	1750	5.8	0.4	6.0	
16	16. 1.70	8.25	6.25	570	85	0.51	0.47	8.55	7.46	6.05	528	1.6	0.30	7.1	
17	24. 4.70	8.15	10.0	1000	224	1.86	1.88	4.82	0.007	8.6	1778	4.5	0.25	45	
18	24. 4.70	7.83	11.2	1110	237	1.84	1.86	9.0	0.18	3.9	1985	6.4	0.35	5.5	
19	2. 4.70	8.25	11.8	950	206.5	1.6	1.7	2.5	0.05	7.4	1720	4.6	0.65	4.0	
Wairakei															
27	1965	8.5	13.2	1200	200	3.0	2.7	17.5	0.05	8.1	2156	5.9	0.6	20.6	
44	1965	8.6	14.2	1320	225	2.8	2.5	17.5	0.035	8.3	2260	6.0	0.3	25	
Kawerau															
8	1969	9.0	5.5	740	130	0.9	0.5	1.1	0.39	5.2	1262	6.2	0.2	36	
16	1969	8.0	5.6	720	131	0.55	0.48	3.2	0.31	3.0	1233	5.4	0.2	10.5	
														14.0	

CHEMISTRY OF THE FLUIDS DISCHARGED FROM DRILLHOLES AT BROADLANDS

Chemical results.—The analyses of the water and steam discharged from drillholes during initial discharge are shown in tables 2 and 3. Concentrations in the water are given in parts per million parts of water, for waters separated from the discharge at boiling point and atmospheric pressure. Chloride concentrations are given for atmospheric pressure separation and for the original deep water. Gas concentrations are given as either millimoles per 100 moles steam condensate or as a weight percentage. For comparison, the analyses of waters discharged from deep drillholes in the Wairakei and Kawerau Geothermal Fields are listed.

General comments on results.—The waters discharged from the Broadlands drillholes were lower in mineral content than the deep Wairakei waters but similar to that of the deep waters at Kawerau and Waiotapu. Atmospheric pressure chloride concentrations ranged from approximately 1200 to 2000 ppm, except for hole 6 which discharged water at a temperature well below boiling point, containing approximately 30 ppm chloride.

At depth the waters were saturated with silica in equilibrium with quartz at the water temperatures and near to saturation with calcite.

TABLE 2 (continued)

B	Concentration in water (ppm)				Cl in deep water	Molecular ratio									
	SiO ₂	As	* Total NH ₃	** Total HCO ₃		of chloride to				of sodium to					
						B	F	As	Br	SO ₄	Cs	Li	K	Rb	Ca
48.1	565	—	12.0	230	1233	10.8	136	—	—	109	10625	30	11.9	6595	405
48.4	805	5.7	2.1	178	1177	11.0	128	650	615	590	3840	27	8.0	1775	830
55.3	725	4.0	4.0	174	1245	9.9	160	951	615	800	3750	26	8.3	2155	605
56.5	880	5.7	2.3	282	1150	10.0	220	685	622	170	4955	28	8.4	1995	625
23.4	—	—	1.5	1410	1000	14.8	—	—	—	—	—	86	16.3	—	—
1.2	180	—	1.1	2284	25	6.9	—	—	—	5.1	—	110	19.0	—	2.9
82.7	1000	—	1.0	910	1002	6.7	—	—	790	825	3795	26.2	9.4	2010	1620
52.6	796	5.7	2.3	157	1220	11.0	114	690	665	1440	4350	25.8	7.1	1250	565
43.95	805	4.5	—	134	1147	11.9	114	800	650	1155	4270	22	7.8	1440	810
54.8	635	4.1	1.2	533	891	6.9	107	640	780	295	3330	28.9	10.85	3075	1440
48.9	805	5.5	1.35	78	1213	11.2	150	690	575	485	4800	25.2	7.9	2230	245
48.7	400	1.0	2.4	1820	1196	10.8	258	3265	680	165	4635	45.5	13.0	5905	940
48.0	750	3.2	1.9	162	1144	10.6	199	1100	715	695	4810	23.5	8.3	1655	710
47.4	844	5.7	1.45	218	961	9.6	248	550	795	670	3700	25.3	8.5	3635	765
37.5	1126	—	2.0	310	1150	14.2	138	—	680	665	4230	27.8	8.7	2190	325
40.6	265	—	12.0	555	441	4.0	47	—	744	32	4210	30.2	11.4	4155	115
46.0	765	—	1.9	115	1215	11.8	111	—	890	875	3544	30.2	7.6	2000	360
58.5	635	—	3.05	250	1367	10.3	273	—	699	1345	4135	29.9	8.0	2240	215
48.2	875	—	1.9	175.5	1150	10.9	124	—	844	225	3775	25.0	7.8	2205	660
28.4	660	4.7	0.15	23	1528	23.2	145	970	820	235	2990	27.4	10.2	1490	120
28.9	650	—	0.15	19	1600	23.8	145	—	850	170	3385	28.0	10.0	1750	130
61.2	815	—	0.5	24	860	6.3	130	—	460	325	9455	41.0	9.7	3055	1170
58.8	800	—	1.3	138	840	6.4	220	—	515	240	9625	39	9.3	4865	390

* Total NH₃ + NH₄ expressed at NH₃.

** Total HCO₃ means CO₂ + HCO₃⁻ + CO₃²⁻ expressed as HCO₃.

The waters were chemically similar to the spring waters. Lower bicarbonate contents in the deep waters resulted from the higher temperatures and smaller extent of rock/water interaction, and the low oxygen fugacity at depth accounted for the low sulfate concentrations.

The deep waters had a high total gas content, the carbon dioxide concentration of approximately 0.14 molal being ten times greater than found at Wairakei. The gas concentration was between that found in New Zealand hydrothermal areas in a mainly volcanic rock environment, for example, Wairakei and Orakeikorako (0.005-0.028 molal), and in a sedimentary rock environment, for example Ngawha (3.5 molal). The weight percentage of carbon dioxide plus hydrogen sulfide in steam separated from the discharges at 125 psig (PSI gauge) varied from about 2 to 12 percent.

Within the Broadlands Field the chemistry of the deep waters was similar. Some variation occurred in the concentration of constituents, but constituent ratios such as Na/Li, Cl/Br, Cl/As, Na/Rb, and Cl/Cs were similar, suggesting a common water supply.

TABLE 3
Gas concentrations in drillholes at Broadlands

Hole no.	Date	W.H.P. psig	S.P. psig	E BTU/lb	Gas as analyzed		Gas in total discharge		Gas in steam at 0 psig		% by wt of gas in total discharge		% by wt of gas in steam at 0 psig		CO ₂ /H ₂ S	
					CO ₂	H ₂ S	CO ₂	H ₂ S	CO ₂	H ₂ S	CO ₂	H ₂ S	CO ₂	H ₂ S		CO ₂
1	28. 2.66	45	20	1150	2770	7	2770	7	7	2770	7	6.7	0.013	6.8	0.013	395
2	30. 9.66	445	60	530	918	25.5	256	7.1	7.1	711	19.7	0.62	0.013	1.7	0.037	36.0
2	19. 1.68	198	192	793	2738	49.1	593	13.7	13.7	1795	32.2	1.86	0.026	4.4	0.060	55.8
3	28. 4.67	260	220	570	5050	60.0	1213	14.3	14.3	3019	35.9	2.96	0.027	7.4	0.067	85.0
3	1. 3.68	167	125	730	5749	39.3	2680	27.9	27.9	4735	49.2	6.54	0.053	11.6	0.093	96.1
4	29. 2.68	92	46	795	2133	33.8	1240	19.3	19.3	1955	30.5	3.02	0.036	4.8	0.058	61.0
4	26. 3.68	138	34	770	1988	31.5	1120	17.7	17.7	1810	29.2	2.73	0.033	4.5	0.055	63.1
7	2. 4.68	245	240	1028	2615	21.0	2060	16.5	16.5	2360	18.9	5.03	0.031	5.8	0.036	124
7	15. 5.68	175	44	983	2463	20.0	2095	15.7	15.7	2535	19.0	5.11	0.030	6.2	0.036	133
8	15. 1.68	155	90	663	1952	38.4	795	15.6	15.6	1595	31.4	1.91	0.029	3.9	0.059	50.8
8*	26. 3.68	160	100	722	2070	38.2	924	17.9	17.9	1735	32.0	2.37	0.034	4.2	0.060	54.2
9	22. 4.68	110	70	550	924	18.5	270	5.4	5.4	710	14.2	0.66	0.010	1.7	0.027	50.0
9	22. 4.68	110	40	550	691	14.5	220	4.6	4.6	580	12.1	0.54	0.009	1.4	0.022	47.6
9	15. 5.68	190	110	642	1700	31.0	635	11.5	11.5	1330	24.3	1.55	0.022	3.2	0.016	54.8
10	11. 5.68	123	123	470	3091	24.3	522	4.1	4.1	1750	13.8	4.27	0.008	4.3	0.026	127
10	18.10.68	120	120	476	3058	22.4	541	4.0	4.0	1775	13.0	1.3	0.007	4.3	0.024	136
11	29. 8.68	220	170	525	1065	22.5	208	4.7	4.7	585	13.1	0.51	0.009	1.4	0.025	44.7
11	4. 9.68	250	160	518	1388	26.9	283.5	5.6	5.6	814	15.8	1.99	0.010	2.0	0.030	51.5
11	17. 9.68	222	164	532	1020	24.1	222.5	5.2	5.2	614	14.5	0.54	0.010	1.5	0.027	42.3
12	18.10.68	225	60	400*	11500	53.7	1563	7.3	4.65	6903	32.2	3.81	0.014	16.8	0.060	214
13	6. 2.69	238	218	523	1420	25.4	261	20.8	4.65	739	13.2	0.61	0.009	1.8	0.025	55.9
14	6. 2.69	238	205	750	3835	45.2	1769	8.6	8.6	3013	35.5	4.32	0.039	7.35	0.067	81.9
14	12. 5.69	176	173	635	1870	25.6	623	8.6	8.6	1329	18.2	1.52	0.016	3.2	0.034	73.0
15	15.12.69	230	230	500	714	18.6	108.5	2.8	2.8	329	8.6	0.26	0.005	0.8	0.016	38.4
15	16.12.69	108	105	942	1078	15.0	773	10.7	10.7	981	13.7	1.89	0.020	2.4	0.026	71.9
17	2. 2.70	165	158	648	1269	27.3	452	9.7	9.7	938	20.2	1.10	0.018	2.3	0.038	46.5
17	2. 3.70	328	325	599	1703	34.8	411	8.4	8.4	952	19.4	1.60	0.016	2.3	0.036	49.0
18	31. 3.70	177	166	826	3209	37.0	1808	20.8	20.8	2717	31.3	4.41	0.039	6.6	0.059	86.7
18	7. 4.70	128	122	762	3640	45.3	1840	22.9	22.9	3062	38.1	4.49	0.043	7.5	0.072	80.3
19	2. 4.70	163	163	500	1317	24.1	239	4.4	4.4	726	13.3	0.58	0.008	1.8	0.025	54.5
19	2. 4.70	163	163	500	1461	26.5	265	4.8	4.8	806	14.6	0.65	0.009	2.0	0.027	55.2

NOTE: W.H.P. is wellhead pressure; S.P., sampling pressure; E, enthalpy; psig, pounds per square inch gauge.
* Estimated, not measured.

TABLE 4

Hole no.	Drilled depth		Solid cased to		Maximum temperature after drilling and stabilization		
	Meters	Feet	Meters	Feet	°C	Meters	Feet
1	1397	4583	607	1992	278	1378	4550
2	1034	3392	417	1368	287	1021	3350
3	912	2992	469	1539	281	905	2969
4	1019	3343	517	1696	273	915	3002
5	1351	4432	842	2762	244	1265	4150
6	1083	3553	653	2142	143	960	3149
7	1119	3671	538	1765	279	1067	3501
8	776	2546	444	1457	273	771	2529
9	1368	4488	500	1640	294	1341	4399
10	1087	3566	497	1630	280	1082	3530
11	760	2493	484	1588	271	756	2480
12	1369	4491	656	2152	274	1341	4399
13	1080	3543	806	2644	276	823	2700
14	1282	4206	588	1929	297	1250	4101
15	2418	7933	1547	5075	298	2165	7103
16	1404	4606	623	2044	277	1387	4530
17	1082	3550	576	1890	291	1036	3399
18	1215	3986	538	1765	290	1195	3920
19	1078	3537	527	1729	272	744	2441

Deep chloride values for waters were calculated from chloride concentrations in waters flashed to atmospheric pressure, knowing the enthalpy of the discharge and the deep water temperature (SiO₂ concentrations). Deep chloride concentrations fell into two categories. Holes on the northwest side of the field (2, 3, 4, 8, 9, 11, 12, 13, 15, 17, 18, and 19) and hole 1 in the northeast produced from hot water containing 1150 to 1250 ppm chloride while holes on the southeast side of the field (7, 10, and 14) were supplied by hot water of 800 to 1000 ppm chloride.

The Cl/B ratios showed a trend across the field. Significant changes were apparent between holes 5 and 15 and the remainder of the northwestern holes and between holes in the west and southeast of the field. The low ratios of between 4 and 7 in the latter area probably resulted from the association with basement argillites and graywackes which generally have a higher boron content than the igneous rocks. The graywacke did not show a high grade of hydrothermal alteration, but the type and degree of alteration expected from contact of this rock with 270°C water has not been established.

The ratio of 9.6 in hole 14 (this hole did not penetrate into graywacke) was between the values found in the west and southeast, and the basement graywacke appears to be close enough to the hole to influence water compositions. The Cl/B ratios of between 14 and 15 in holes 5 and 15, which produced from ignimbrite, were the highest in the field. Hot waters associated with ignimbrite in other Taupo Volcanic Zone hydrothermal areas are known to have relatively high Cl/B ratios, and for example, waters from Orakeikorako drillholes had ratios varying from 25 to 35. Holes 9 and 17, which obtained most of their water supply

from the Rautawiri Breccia (Browne and Ellis, 1970), had ratios of approximately 11.8 to 12, while holes drawing from a shallow level within the Ohaki Rhyolite and Upper Waiora Formation such as 3, 4, and 18 had ratios of between 9.9 and 10.3. Holes 2, 8, 11, 12, and 19 which could draw water from both the Ohaki Rhyolite and Rautawiri Breccia had intermediate ratios of around 11.

Constituent ratios such as Na/Li, Na/Rb, Cl/F, Cl/Cs, Cl/Br, and Cl/As were remarkably similar to those at Wairakei, illustrating the overall similarity of volcanic rock compositions in the two areas. The higher values of the ratios Cl/SO₄, Na/Ca, and the silica concentrations and the lower ratios of Na/K at Broadlands reflect the higher temperatures in this area. The high boron, ammonia, carbon dioxide, and bicarbonate concentrations at Broadlands are likely to result from the sediments interbedded with the volcanic rocks and the relatively shallow sedimentary basement in this area.

Base metal sulfides (Pb, Zn, Cu) were found in cores taken from holes 7, 10, 14, 15, and 16 (Browne and Ellis, 1970). Apart from 14, these holes penetrated the argillite-graywacke basement, the holes on the southeast at a depth of 914 to 1219 m and hole 15 at around 2286 m. Hole 14 was apparently also close to the basement.

Most of the sulfide mineralization in the southeast occurred close to or in the sediments, while in hole 15 it occurred at a depth considerably deeper than the majority of the other northwestern holes. The close association of the metal deposits with the basement sediments indicated that sulfide mineralization was influenced to some extent by these rocks.

Supply water temperatures.—The silica concentrations (Mahon, 1966) and the Na/K ratios (Ellis, 1967) in the drillhole waters were used to assess the temperature conditions in the deep aquifers.

Table 5 shows the maximum temperatures recorded in the drill-holes by engineers of the New Zealand Ministry of Works, with a geothermograph or a resistance thermometer, and the temperatures calculated from Na/K ratios and silica concentrations. The latter results were obtained after the holes had been opened for a short period and water compositions had become constant. The maximum temperatures measured by physical methods were not necessarily recorded in permeable zones in the rock formations. The maximum temperatures in these zones ranged from 260° to 285°C.

The temperatures estimated from the Na/K ratios were in most cases closer to the measured maximum temperatures than were the silica temperatures.

It appeared that water of 270° to 280°C rose up through the country rock from below 1220 m and lost steam close to the production zones. Due to the rapidity of water movement and the slow readjustment of the Na/K ratio to an equilibrium value at a new temperature, the ratios in the discharges did not represent the temperature conditions at the production depth. The possibility the drillholes drew water up

TABLE 5

A comparison of temperatures estimated from silica concentrations and Na/K ratios in waters, with maximum temperatures measured down drillholes

Hole no.	Physical measurement*	Temperature °C	
		Na/K	SiO ₂
1	278	230	236
2	287	278-292	262
3	281	277-288	252
4	273	268-280	260
5	244	197-200	—
6	143	192	—
7	279	252-260	270-280**
8	273	300	255.5
9	294	292	259-261
10	280	240-242	244.5
11	271	290	261
12	274	220	212
13	276	282	255
14	297	277	259.5
15	298	273	290**
16	277	234	184
17	291	298	255.5
18	290	288	240.5
19	272	292	267

* Measurements made by Ministry of Works, Wairakei.

** Results suspect or unreliable.

Silica concentrations and temperatures have been corrected for enthalpy variations.

from deeper levels was also suggested by the low Cl/B ratio in holes 7 and 10.

The silica supply water temperatures of holes 2, 3, 4, 8, 9, 11, 13, 14, 17, and 19, of between 252° and 267°C were remarkably similar. Supply water temperatures in the eastern field were generally lower than those in the northwest, for example, holes 1, 10, and 16 were supplied by water of temperature less than approximately 245°C, while holes 7 and 14 had supply water temperatures between 250° and 260°C. Comparison of these temperatures, with measured temperatures and corresponding pressures in the field, indicated that the Ohaki Rhyolite, Broadlands Rhyolite, and Rautawiri Breccias in the west of the field and the Broadlands Rhyolite in the east were major aquifers. The rhyolites at Broadlands appear to play an important role both in the storage of fluids and in determining the migration paths.

Gases.—Table 3 shows the concentrations of carbon dioxide and hydrogen sulfide in the Broadlands drillholes. During the initial discharge period of the drillholes the carbon dioxide and hydrogen sulfide concentrations in total discharge ranged from 108 to 2770 and 2.8 to 20.8 millimoles/100 moles water respectively. These concentrations may be compared with those of 20 and 0.6 millimoles/100 moles water of carbon dioxide and hydrogen sulfide originally present in the deep Wairakei waters. The ratio of CO₂/H₂S in the different discharges

TABLE 6
Analysis of gases in drillhole discharges at Broadlands

Hole no.	Gas; volume percent				HC	NH ₃ (ppm) in total discharge	Mole ratios		
	CO ₂	H ₂ S	H ₂	N ₂			N ₂ /H ₂	HC/H ₂	H ₂ S/H ₂
2*	94.2	1.6	0.17	1.8	2.25	9.9	10.4	13.2	9.3
3*	97.4	0.94	0.054	0.62	1.0	11.8	11.4	18.3	17.4
4*	94.5	1.1	0.25	1.45	2.72	10.1	5.8	10.9	4.4
7*	96.6	0.81	0.22	0.86	1.4	10.7	4.0	6.7	3.7
8*	94.8	1.57	0.23	1.14	2.32	11.2	4.9	10.1	6.8
9	91.5	1.75	0.28	1.94	4.57	5.5	7.0	16.4	6.3
10	96.6	0.8	0.24	0.87	1.45	4.8	3.6	6.1	3.3
11	95.6	2.13	0.19	0.84	1.23	5.0	4.5	6.5	11.3
12	93.9	0.43	0.18	1.84	3.65	6.2	10.0	19.9	2.4
13	96.4	2.82	0.041	0.27	0.51	4.8	6.6	12.2	68.0
Wairakei									
27	90.0	4.1	0.5	2.4	2.1	1.30	4.8	4.2	8.2
67	90.3	4.7	0.4	2.5	2.1	1.05	6.2	5.2	11.7
Waiotapu									
6	88.0	10.3	1.0	0.5	0.2	—	0.5	0.2	10.3
7	92.2	5.3	2.0	—	0.5	—	—	0.25	2.6
Kawerau									
8	94.0	2.6	0.3	1.0	2.1	5.5	3.3	7.0	8.7
10	94.6	2.5	0.1	0.9	1.9	8.0	9.0	19.0	25.0

* Holes had a high discharge enthalpy at time of sampling.
HC = Total hydrocarbons, mainly methane.

ranged from approximately 36 to 395, the highest values being found on the east side of the river.

The best assessment of the gas concentration in the deep water in the undisturbed system was made from the concentration in holes which, initially at least, discharged a steam and water mixture of enthalpy similar to that of the supply water, for example, holes 2, 9, 11, 13, and 19. The average result from the five drillholes was 250 millimoles/100 moles of carbon dioxide and 5.1 millimoles/100 moles hydrogen sulfide with a CO₂/H₂S ratio of 49.3. In the eastern field only hole 10 had a discharge enthalpy approximating the downhole temperature, and the carbon dioxide concentration in total discharge was approximately twice that found in the western field.

Before the Broadlands holes were discharged the downhole pressures, measured at various depth in the "liquid phase", were found to be approximately 100 to 200 psig higher than the water vapor pressure. In one particular case (hole 7) a value of 370 psig above water vapor pressure was recorded. For a carbon dioxide concentration of 250 millimoles/100 moles water to exist entirely in a liquid phase at 260° to 270°C would require that the hydrostatic pressure exceed water vapor pressure by 185 psig (Ellis and Golding, 1963). Conditions at depth at Broadlands were initially close to a state where separation of a gas-rich steam phase could occur.

Analyses of the total gases present in the Broadlands drillholes are shown in table 6. Results for drillholes at Wairakei, Waiotapu, and Kawerau are shown for comparison.

There are no large differences between the gas composition at Broadlands and those in other geothermal areas in the Taupo Volcanic Zone. A close similarity existed between the compositions at Broadlands and Kawerau, whereas at Wairakei and Waiotapu the volume percent of hydrogen sulfide was somewhat higher and the carbon dioxide percent a little lower.

There were fluctuations in the molar gas ratios, but no obvious trends that could be correlated with depth or geology were apparent. Holes 3 and 13 (the latter hole thought to produce mainly from ignimbrite) contained relatively low hydrogen concentrations while hole 12, which was drilled into highly impermeable formations, had a rather high hydrocarbon content. There was a close similarity in gas compositions and ratios of holes 7 and 10 on the east side and those in the western sector of the field.

The partial pressures of various gases in the deep water at Broadlands were calculated (Ellis, 1967) and are shown in table 7. Also listed are results from Wairakei and other geothermal fields in different parts of the world.

TABLE 7
Calculated partial pressures of gases in underground systems

Area	Pressures in atmospheres						Temp °C
	pCO ₂	pH ₂ S	pH ₂	pN ₂	pNH ₃	pCH ₄	
Broadlands†	9.0	0.1	0.11	0.95	0.0016	0.7	260
Wairakei†	0.9	0.02	0.09	0.02	0.0003	0.08	260
Hveragerdi*	0.02	0.0002	0.08	0.23	—	—	216
Larderello*	0.4	0.01	0.01	0.003	0.008	—	220
The Geysers*	0.04	0.002	0.007	0.0009	0.0009	—	190

† Results are an average from several drillholes

* Results from Ellis (1967)

In most cases the partial pressures of gases at Broadlands were an order of 5 to 10 times greater than at Wairakei, the main exception being the hydrogen pressure which was similar in both areas. The higher gas content at Broadlands was thought to originate from the greater volumes of sedimentary rock in that system.

Water pH and mineral deposition.—Ellis (1970) discussed the pH of hot waters in hydrothermal systems and the influence of pH on mineral deposition. At Wairakei and Broadlands the main secondary alteration minerals controlling solution pH at highest rock and water temperatures were sodium-potassium feldspars and mica.

Hemley (1959) determined by experiment the ratio K⁺/H⁺ for the K-mica, K-feldspar equilibrium over a wide range of temperature. Substituting an average value of the potassium concentration in the deep 260°C water at Broadlands into Hemley's results gave a pH of 6.4. For comparison pH neutral at 260°C is 5.7. At Wairakei deep water pH's obtained by the same process of substitution were in the range 6.0 to 6.6.

The pH of the deep water can also be estimated from the chemical analyses of the steam and water discharged from drillholes (Ellis, 1967). The complete discharge composition of individual holes is required. Estimates made from total discharge results from holes 2, 9, 11, and 19 when they were first discharged and when the enthalpies were similar to that of water at the supply temperatures gave values of between 6 and 6.2.

Browne and Ellis (1970) discussed the significance of solution pH and the concentration of carbon dioxide on the stability and presence of different minerals, particularly calcite, in hydrothermally altered rocks at Broadlands. Experimental information available on calcite solubility in salt solutions at temperatures of 200° to 300°C (Ellis, 1963, 1970) was used to show that the maximum underground pH at Broadlands which could exist before calcite was precipitated from solution was approximately 6.5. Comparison of this value with the calculated deep water value of approximately 6 to 6.4 indicated that the Broadlands waters were close to saturation with this mineral.

The high discharge enthalpy of many of the Broadlands drillholes favors the deposition of calcite within the system. The removal of steam and gas (CO₂ and H₂S) from the deep water raises the water pH allowing calcite to precipitate. Calcite was recently found to be depositing in the steel casing of hole 11, resulting in a rapid decrease in mass output of the hole from 500 to 260 k lb/hr.

Precipitates and heavy metals.—High concentrations of gold, silver, and thallium occur in antimony and arsenic sulfide precipitates, formed from springs and drillholes at Broadlands (Weissberg 1969). Analyses of arsenic in the drillhole waters gave concentrations of around 5 to 6 ppm which were generally higher than found in Ohaki Pool (1.5-3.9 ppm). The concentration of arsenic in the pool varied considerably over a monitoring period of several years. It appeared that arsenic was being transported from depth and deposited in the surface rocks and sinters. The effect of chloride concentration in controlling the concentration of these metals was recently pointed out by Ellis (1968).

The concentrations of iron and aluminum in the deep water at Broadlands, 0.36 and 0.34 ppm respectively, were approximately ten times higher than at Wairakei. Preliminary results of trace metal concentrations (Cu, Zn, Pb) in the deep waters, obtained by one of the present authors (J. B. Finlayson), showed them to be very low (0.05-4 ppb).

Isotope studies.—Preliminary isotopic studies have been made on the steam and water discharged from Broadlands drillholes. Deuterium concentrations were similar to those present in streams to the east of Broadlands but lower than the concentrations in the Waikato River or Lake Taupo water (Giggenbach, 1971). These data are best explained if the hot water at Broadlands originated from local precipitation, probably in the highlands to the east, with Waikato River-Lake Taupo waters being enriched in deuterium by evaporation.

Lyon and Hulston (ms) calculated deep water temperatures from the C¹³/C¹² ratios in carbon dioxide and methane, on the assumption that isotopic equilibrium had been attained in the reaction CH₄ + H₂O = CO₂ + 4H₂. From calculations used by Craig (1953) they obtained temperatures ranging from 325° to 345°C. These temperatures were higher than those obtained from Na/K ratios and silica concentrations. From the composition of the residual gases at Broadlands, Lyon and Hulston also calculated temperatures using the CH₄ + H₂O = CO₂ + 4H₂ equilibrium. Values were similar to those obtained from the C¹³/C¹² ratio except for holes 11 and 13. The chemical equilibrium temperatures for these holes were 290° and 310°C, compared with the Na/K ratio temperatures of 290° and 282°C. At the time of Lyon and Hulston's survey 11 and 13 were the only holes that had discharge enthalpies similar to that of water at the supply temperatures. The remaining holes discharged a mixture enriched in steam and gas. Since the gas equilibrium method assumes that the sample is representative of the underground fluid, that is, there has been no enrichment or depletion of gas due to steam separation, the gas equilibrium temperatures calculated for holes 11 and 13 are likely to be the most accurate.

CHANGES IN DRILLHOLE CHEMISTRY WITH TIME

The changes in both water and steam chemistry of a selected number of holes at Broadlands are shown graphically in figures 2, 3, and

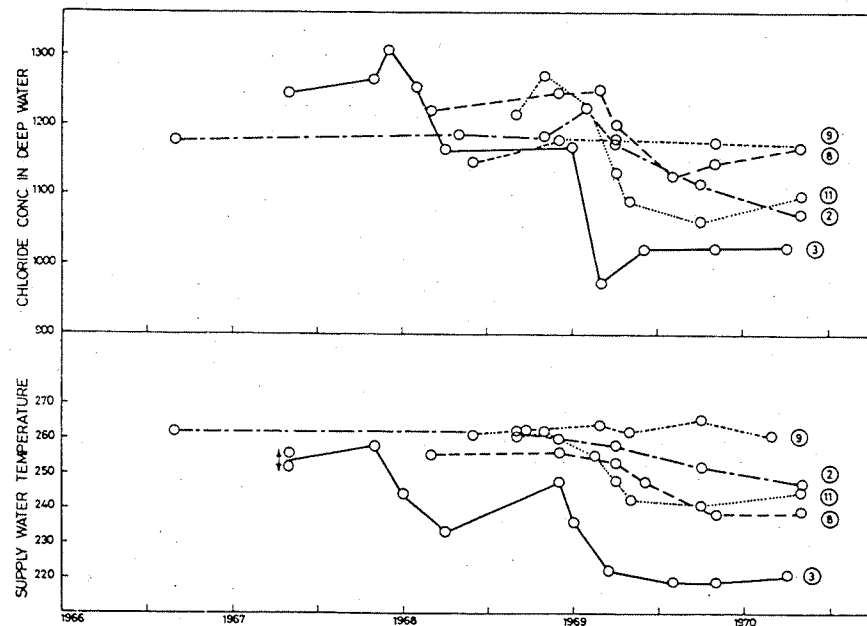


Fig. 2. Trends in the deep chloride concentrations in drillholes at Broadlands between 1966 and 1970.

4. The chloride concentrations used for interhole comparison and for the present discussion are those present in the deep water. Silica supply water temperatures are shown on figure 2. The gas concentrations are given on a total discharge basis and represent the gas concentrations in the integrated mass of steam and water discharged from a drillhole.

Water chemistry.—The decreases in solute concentrations, discharge enthalpies, and supply water temperatures in many Broadlands drill-holes since 1969 may have resulted from dilution, by lower temperature, lower chloride water in the system, and/or by loss of heat, originally available conductively from the aquifer rocks.

Waters of lower temperature and chloride content than the main body of hot water in the system are known to occur above and below the major aquifers at Broadlands. Ohaki Pool was originally supplied by 200°C water containing 840 ppm of chloride from a depth of approximately 305 m. Hole 20, a deep hole completed during the preparation of this paper, passed through a temperature inversion at 1065 m (this inversion was present in a number of other holes). The temperature and

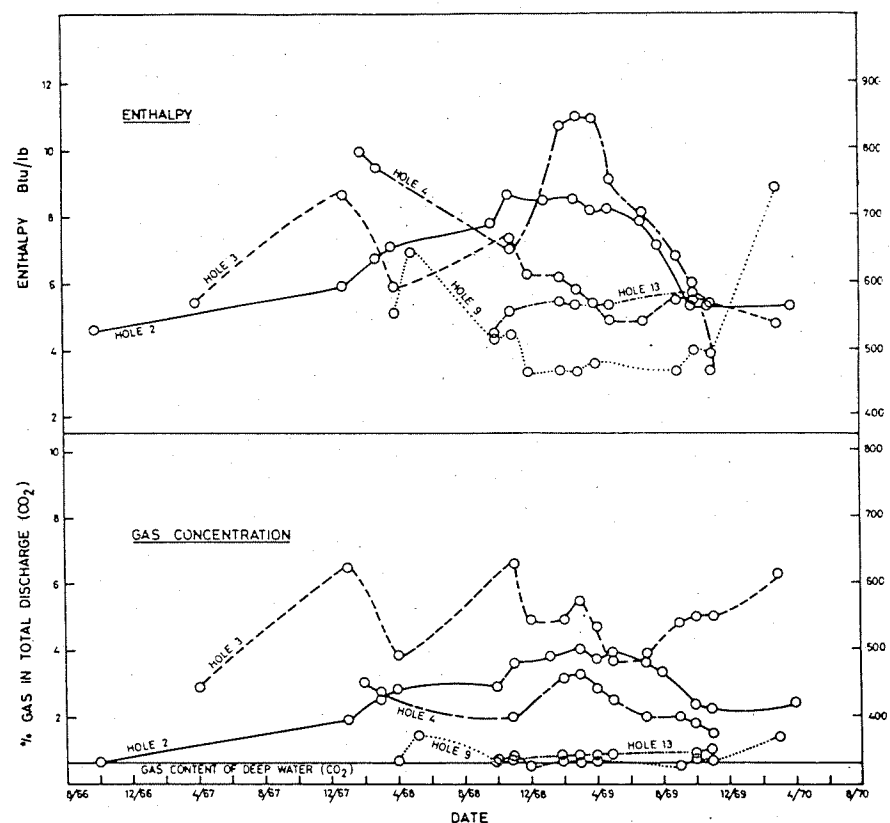


Fig. 3. Trends in the carbon dioxide concentrations in drillholes at Broadlands between 1966 and 1970.

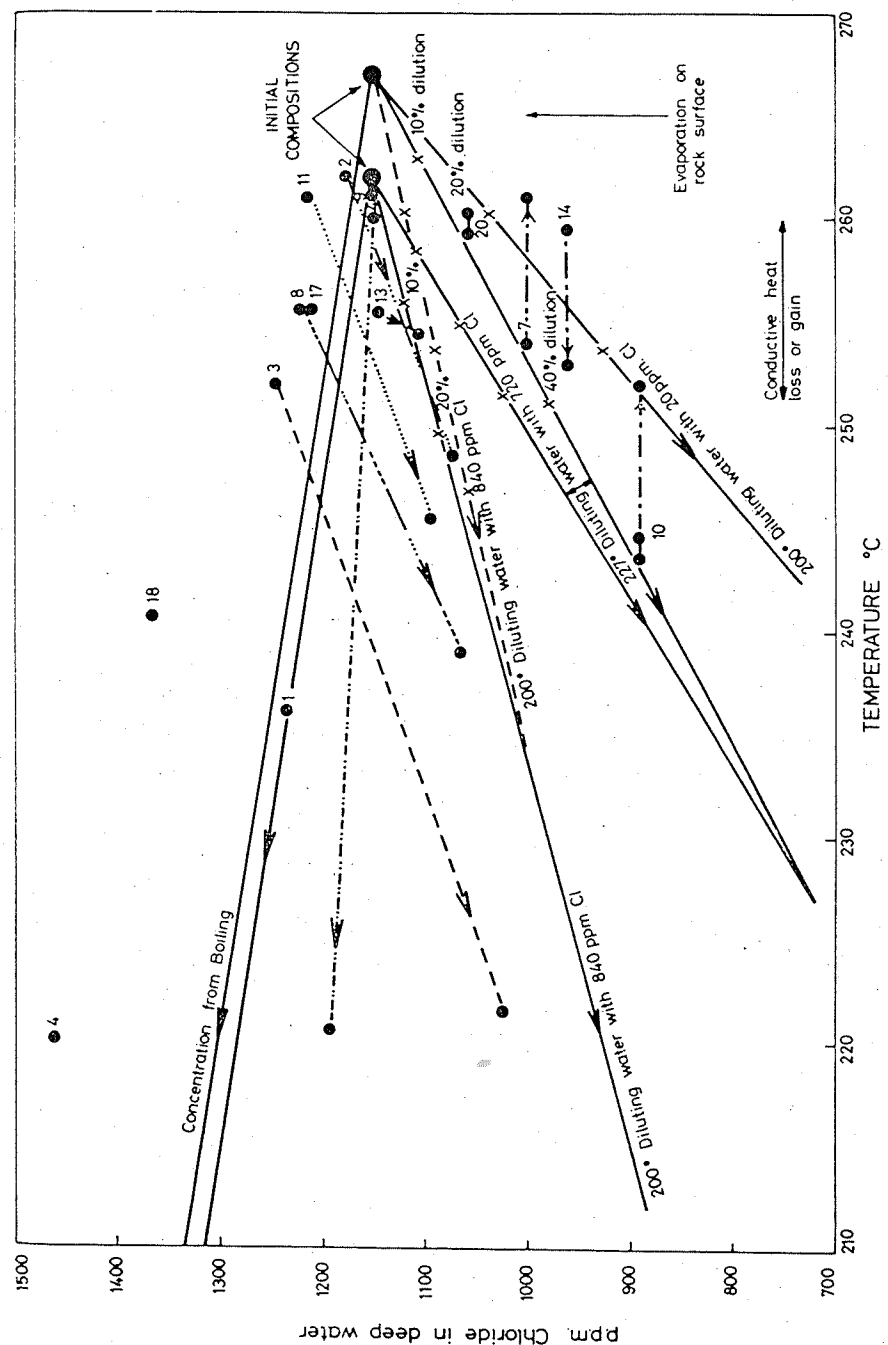


Fig. 4. Physical changes in the underground hot water correlated with trends in water chemistry of drillhole discharges at Broadlands.

chloride content of water sampled from this zone were 227°C and 720 ppm respectively.

Figure 4 shows how the chemistry of the deep water could be affected by physical changes in the system. The range of possible starting compositions of the primary hot water is shown between two large solid points in the diagram. Only one hole to date has discharged water of original temperature 267°C and chloride concentration 1150 ppm. This hole (hole 19), however, had such a large output (500 tons/hr) that the temperature was regarded as representing that present in a major upflow zone. A temperature of 262°C with a similar chloride concentration was more representative of many high production drillholes in the northwestern part of the field. Lines are drawn showing the changes that occur when the primary water is diluted.

The earliest compositions of holes 7, 10, and 20 fall close to the line corresponding to dilution of 267°C water with the colder water that occurs at depth in hole 20. In the formative stages of the Broadlands system, it seems possible that water from the western part of the field, at 267°C and containing 1150 ppm chloride, flowed out to the southeast, undergoing dilution in transit.

During exploitation the chemistry of the eastern holes have shown little permanent change. Fluctuations of the chloride concentration in hole 7 could be caused by evaporation on rock surfaces. Increasing supply water temperatures in holes 7 and 10 and decreasing values in hole 14 indicate that transfer of heat between rock and water by conduction could be important. These trends suggest that the eastern holes are producing from porous medium rather than fractures or faults.

The early compositions of the discharges of many of the western holes suggest a rather complex history of water migration before and during production. Waters at holes 3, 4, 8, 11, 17, and 18 appear to have been concentrated by both boiling and evaporation on rock surfaces. With the exception of hole 4, the average trend for these holes after 2 years corresponds to dilution. The trend line for hole 4 suggests loss of heat by conduction, but the slope of short term changes is probably explained by evaporation on rock surfaces combined with dilution.

The initial water discharged from hole 13 had lost heat conductively. Under exploitation conductive heat loss as well as boiling was apparent. The initial water composition and temperature of hole 1 suggested that the water reaching the northeast of the field had lost steam by boiling.

Since the beginning of 1970 the rate of fall of chloride concentrations and temperatures in most holes decreased, and in some cases, for example, in holes 8 and 11, values became constant. The apparent stable values attained by several of the drillholes were above those assumed to be present in the diluting water and could thus represent only a temporary condition. However it may also mark a limit to the extent of inflow of diluting water.

TABLE 8

Changes in the ratio of Na/K in drillholes over the discharge period

Hole no.	Date	Na/K	Temp °C	Date	Na/K	T °C
2	23. 8.66	8.0	288	7. 4.70	9.3	262
3	28. 4.67	8.3	281	25. 3.70	12.0	228
4	6. 9.67	8.4	280	16. 2.70	9.5	260
7	14. 5.67	9.4	261	28.11.69	9.1	266
8	29. 2.68	7.5	300	20. 4.70	8.9	270
9	14. 5.68	7.8	293	24. 4.70	8.1	286
10	18.10.68	10.85	240	24. 7.69	9.8	268
11	22. 8.68	7.9	290	28. 4.70	9.0	268
13	10.10.68	8.3	282	4. 5.70	7.9	290

Changes of the Na/K ratios and chemical equilibration temperature are shown in table 8.

With the exception of holes 7, 10, and 13 the Na/K ratios have increased in the discharges of holes that have decreased in chloride concentration and temperature. The temperature corresponding to equilibration at the new values did not correspond closely with the silica temperatures, variations being of the order of 10° to 30°C. It is possible that the high gas content at Broadlands influences the Na/K ratios.

Gases.—Changes in gas concentrations (carbon dioxide and hydrogen sulfide) in drillholes can be correlated with changes in discharge enthalpies (fig. 3). Increasing gas concentrations occurred in holes that increased in steam fraction. The CO₂/H₂S ratios also increased indicating that the added steam was derived from water boiling close to the production zones.

In recent months decreasing supply water temperatures have been accompanied by decreasing discharge enthalpies and gas concentrations. The gas concentrations, in total discharge, however, have not fallen below the value present in the deep water, nor have the enthalpies decreased to the temperatures of the supply water.

The trends in gas concentrations at Broadlands are similar to those seen for high enthalpy drillholes at Wairakei, (Mahon, 1962a; Ellis, 1962; Glover, 1970). With the present pressure and temperature trends in the system it is apparent that carbon dioxide and hydrogen sulfide concentrations and the ratio CO₂/H₂S will decrease with time (Ellis, 1962).

ACKNOWLEDGMENTS

Special thanks are offered to Dr. R. B. Glover and Mrs. R. Jans for some of the analytical work carried out on the Broadlands samples and to Mr. L. Klyen for a high proportion of the field work. Thanks are also expressed to the Ministry of Works, Wairakei, for supplying the results of downhole measurements.

REFERENCES

- Browne, P. R. L., and Ellis, A. J., 1970, The Ohaki-Broadlands hydrothermal area, New Zealand: mineralogy and related geochemistry: *Am. Jour. Sci.*, v. 269, p. 97-131.
- Craig, Harmon, 1953, Geochemistry of carbon isotopes: *Geochim. et Cosmochim. Acta*, v. 3, p. 53-92.
- 1963, The isotopic geochemistry of water and carbon in geothermal areas, in Tongiorgi, E., ed., *Nuclear Geology in Geothermal Areas: Italy, Consiglio Nazionale della Ricerca*.
- Dawson, G. B., and Dickinson, D. J., 1970, Heat flow studies in thermal areas of the North Island of New Zealand: United Nations Conf. Devel. Utilization Geothermal Resources, Pisa, Italy, Sept. 1970, Proc., in press.
- Dickinson, D. J., ms, 1968, Geophysical Report on Broadlands geothermal field: New Zealand Geophys. Div. Rept. 49 (unpub. open file rept.)
- Ellis, A. J., 1962, Interpretation of gas analysis from the Wairakei hydrothermal area: *New Zealand Jour. Sci.*, v. 5, p. 434-452.
- 1963, The solubility of calcite in sodium chloride solutions at high temperatures: *Am. Jour. Sci.*, v. 261, p. 259-267.
- 1967, The chemistry of some explored hydrothermal systems, in Barnes, H. L., ed., *Geochemistry of hydrothermal ore deposits: New York, Holt, Rinehart and Winston*, p. 465-514.
- 1968, Natural hydrothermal systems and experimental hot water/rock interaction: Reactions of NaCl solutions and trace metal extractions: *Geochim. et Cosmochim. Acta*, v. 32, p. 1356-1363.
- 1969, Present-day hydrothermal systems and mineral deposition: Commonwealth Mining and Metallurgy Conf., 9th, London 1969, Mining and Petroleum Geology Sec., Paper 7, p. 1-30.
- 1970, Quantitative interpretation of chemical characteristics of hydrothermal systems: United Nations Conf. Devel. Utilization Geothermal Resources, Pisa, Italy, Sept. 1970, Proc., in press.
- Ellis, A. J., and Golding, R. M., 1963, The solubility of carbon dioxide above 100°C in water and in sodium chloride solutions: *Am. Jour. Sci.*, v. 261, p. 47-60.
- Ellis, A. J., and Mahon, W. A. J., 1966, Geochemistry of the Ngawha Hydrothermal Area: *New Zealand Jour. Sci.*, v. 9, p. 440-456.
- 1967, Natural hydrothermal systems and experimental hot water/rock interactions (Pt. 11): *Geochim. et Cosmochim. Acta*, v. 3, p. 519-538.
- Fournier, R. O., and Rowe, J. J., 1966, Estimation of underground temperatures from the silica content of water from hot springs and wet steam wells: *Am. Jour. Sci.*, v. 264, p. 685-697.
- Giggenbach, W. E., 1971, Isotopic composition of waters of the Broadlands Geothermal Field: *New Zealand Jour. Sci.*, in press.
- Glover, R. B., 1970, Interpretation of gas compositions from the Wairakei Field over ten years: United Nations Conf. Devel. Utilization Geothermal Resources, Pisa, Italy, Sept. 1970, Proc., in press.
- Grindley, G. W., and Browne, P. R. L., ms, 1968, The sub-surface geology of the Broadlands geothermal field: *New Zealand Geol. Survey Rept. 34* (unpub. open file rept.).
- Hemley, J. J., 1959, Some mineralogical equilibria in the system $K_2O-Al_2O_3-SiO_2-H_2O$: *Am. Jour. Sci.*, v. 257, p. 241-270.
- Lyon, G. L., and Hulston, J. R., ms, 1970, Recent carbon isotope and residual gas measurements in relation to geothermal temperatures: *New Zealand Inst. Nuclear Sci. Rept.* (unpub. open file rept.).
- Mahon, W. A. J., 1962a, The CO_2 and H_2S contents of steam from drillholes at Wairakei: *New Zealand Jour. Sci.*, v. 5, p. 85-98.
- 1962b, A chemical survey of the steam and water discharged from drillholes and hot springs at Kawerau, New Zealand: *New Zealand Jour. Sci.*, v. 5, p. 417-433.
- 1966, Silica in hot water discharged from drillholes at Wairakei, New Zealand: *New Zealand Jour. Sci.*, v. 9, p. 135-144.
- Mahon, W. A. J., and Klyen, L. E., 1968, Chemistry of the Tokaanu-Waihi hydrothermal area: *New Zealand Jour. Sci.*, v. 2, p. 140-158.
- Weissberg, B. G., 1969, Gold-silver ore-grade precipitates from New Zealand thermal waters: *Econ. Geology*, v. 64, p. 95-108.

Geophysical

ABSTRACT. Korzhinskii (1966) in light of chromatographic process is identical. Shape and velocity of column depend on position of component relative to the $C_{1,t}$ axis. The velocity $dC_{1,t}/dC_{1,s}$. The velocity of the chord connecting the two points is equal to the velocity of the component.

The theory is based on the fact that infiltrating fluids result in a leading edge followed by a self-sharpening front. Or at which the Na) ratio of the infiltrating fluid is constant.

Extension of this theory to the case of a component gives rise to a sharp front which can be caused by solubility differences.

The presence of a sharp front rather than diffusion in one direction only results in plateaus in solid solution composition at the sharp front; and the elements such as Li, B, and Cs are concentrated at the placement fronts.

The study of the theoretical work of Korzhinskii (1966) has been approached from a different concept of local equilibrium that is useful in the study of fluid transport (Thompson, 1959; Thompson, 1969). The transport equation in a "metasomatic" treatment has solutions that show a sharp front, even though formation beyond the front is possible. Korzhinskii's (1966) theoretical work on metafluid transport equation is an extreme type of non-equilibrium "material is transported."

¹This approach is based on the work of Korzhinskii (1966), which is discussed in the text. The concept of local equilibrium is