Proc. 8th NZ Geothermal Workshop 1986

MASS TRANSFER DURING HYDROTHERMAL ALTERATION AT THE TAUHARA GEOTHERMAL FIELD

P K Kakimoto* and P R L Browne

Geology Department and Geothermal Institute
University of Auckland

ABSTRACT

Cores recovered from drillhole TH3 (1094m) and THMl (430m deep) in the Tauhara Geothermal Field, near Wairakei, show extensive hydrothermal alteration. The observed mineral assemblages reflect the prevailing temperatures, fluid compositions and hydrology. Minerals present include epidote, prehnite, laumontite, wairakite, heulandite, calcite, barite, sphene, leucoxene, adularia, albite, pyrite, pyrrhotite-, and rare metal-bearing phases. Clay minerals are common, comprising chlorite, smectites, interlayered illite-smectite and discrete illite; where acidic waters occur, kaolinite (and alunite) are present.

Chemical changes in the host rocks have accompanied the observed alteration: silica shows pronounced enrichment relative to the unaltered rocks but alumina has redistributed variably. Magnesium redistribution matches the presence and abundance of chlorite and smectite, and to some extent correlates with iron concentrattons in the cores. Na_2O and CaO are depleted to differing degrees whereas K20 is usually enriched in the altered rocks.

Water and sulphur have been added to most altered rocks but TiO_2, MnO and P_2O_5 are present in low abundance in all the cores with only the first showing significant variation. Sr, Rb, Ba and V are among the most mobile trace elements but, by contrast, Y, Th and Zr were relatively immobile during alteration.

The behaviour of mercury suggests that it is transported mainly in the vapour phase, being depleted in reservoir rocks that are hotter than about 225°. However, mercury has been added to rocks comprising the shallow Tauhara aquifer that contains condensed steam (and CO_2), suggesting that measuring Hg concentration in cores and cuttings from drillholes may be a method of locating zones where potentially corrosive acid sulphate and bicarbonate waters occur.

INTRODUCTION

The Tauhara geothermal field forms part of a larger Wairakei system. Cores recovered from four deep and several shallower monitor wells record evidence of extensive fluid/rock interaction. This is most obvious in their widespread hydrothermal alteration mineralogy (Kakimoto, 1983; Kakimoto and Browne, in prep.) but is also evident from the chemical changes that the host rocks have undergone. This paper describes the changes in rock chemistry that have resulted from hydrothermal alteration in cores recovered from two drillholes (TH3 and THM1).

*Present address: U R S Corporation,
150 Fourth St, San Francisco, Caltfornia, USA

STRATIGRAPHY AND HYDROTHERMAL ALTERATION

Figures 1 and 2 summarise the stratigraphy, lithology and major features of the hydrothermal alteration seen in these two wells. The sequence encountered consists of pyroclastic silicic rocks and lacustrine sediments comprisng mainly the Waiora and Huka Falls Formations. There are three aquifers: the Waiora, consisting of the Wairoa Formation itself; the Huka Falls Formation pumice breccias, and that hosted by the Wairakei Lapilli Tuff. The interbedded Huka Falls Formation sediments are much less permeable and serve as partial caps. Primary minerals present in these rocks included mainly quartz and andesine with accessory biotite, hornblende, pyroxene, ilmenite, magnetite and titanomagnetite. Glass was once widespread, and occasional lithic fragments were also present. Hydrothermal alteration has produced a suite of secondary minerals (Figures 1 and 2) that can conveniently be grouped into mineral zones that largely reflect the lithology and hydrology of their host rocks (Kakimoto, 1983; Kakimoto and Browne, in prep.).

COMPOSITION OF CORES FROM DRILLHOLES TH3 AND THMl

Methods

Whole-rock splits of 20 cores from wells TH3 and THM1, chosen to represent the different alteration zones, were analysed for major and trace elements by X-Ray fluorescence (Table 1). Structurally- bound (H_2O^+) and adsorbed (H_2O^+) water contents, particle density and porosity were also determined (Table 2). Mercury contents were measured using a Jerome Gold Film mercury detector following the method described by McNerney et al. (1972). Sb, Sn and Ag analyses were made by flame atomic adsorption. Kakimoto (1983) gives a complete account of the analytical methods used in this paper.

Mass transfer of elements between rocks and fluids is most commonly measured as changes in the amount of an element moved per unit volume of rock, relative to its initial (i.e. unaltered) composition (Steiner, 1977; Bogie and Browne, 1979; Henneberger, 1983). This method takes into account changes in rock density resulting from hydrothermal alteration either by replacement or mineral precipitation into cavities. It assumes that prior to their alteration the rocks from the same formation had the same compositions and densities. References samples of tuffs (Tables 1 and 2) are of unaltered cores from drillhole THM1-11m and Wairakei drillholes (Steiner, 1977); their compositions and densities were used to estimate net addition and removal of elements in the tuffaceous samples from wells TH3 and THMl (Table 2).

	Unaltered[b]			lH3							
				Smectite zone	Micaceous Clay zone				Calcite zone		
	THM1-11	W.Tuff	Ig.II	116 (depth m)	176	239	361	420	452	482	574
SiO_2 (wt.%)	69.77	67.7	72.4	55.26	59.63	61.06	69.32	66.83	72.08	70.42	75.08
TiO_2	0.33	0.56	0.27	0.93	0.58	0.59	0.36	0.27	0.27	0.32	0.32
Al_2O_3	13.50	15.1	14.0	23.83	16.73	17.81	15.25	14.78	14.64	13.56	12.78
Fe_2O_3[c]	2.85	3.0	2.1	1.98	4.31	6.08	2.96	2.50	1.31	2.43	2.94
MnO	0.11	0.11	0.09	0.03	0.04	0.15	0.07	0.13	0.07	0.11	0.10
MgO	0.49	0.5	0.4	0.56	0.89	2.00	1.04	0.98	0.83	0.61	1.00
CaO	2.20	2.7	1.8	0.43	3.86	4.12	1.80	0.91	1.08	2.25	0.58
Na_2O	3.81	4.2	4.0	0.27	2.97	3.12	2.06	0.78	3.45	<0.05	0.20
K_2O	2.49	2.8	3.6	1.18	1.28	1.27	1.10	0.97	1.93	3.52	2.78
P_2O_5	0.08	0.08	.03	0.04	0.09	0.11	0.10	0.04	0.08	0.08	0.10
S	0.01		trace	0.02	1.24	0.51	0.10	0.36	0.06	0.19	0.14
H_2O^+[d]	3.86	2.43	0.88	12.28	6.30	3.82	5.10	7.74	3.40	4.10	3.96
H_2O^-[e]	0.82	0.71	0.06	3.68	2.79	0.62	1.95	3.42	1.15	1.08	0.64
Total	100.32	99.89	99.63	100.49	100.71	101.26	101.21	99.71	100.35	98.77	100.62
S ≡ O	0.004			0.01	0.46	0.19	0.04	0.13	0.02	0.07	0.05
Total[f]	100.32			100.48	100.25	101.07	101.17	99.58	100.33	98.70	100.57
Rb (mg/kg)	89			48	51	51	43	64	44	213	120
Sr	172			45	261	259	136	169	141	116	80
Ba	606			273	460	418	656	376	630	825	519
V	13			215	145	130	18	38	6	14	18
Y	30			12	16	20	26	33	31	34	30
Th	9			8	5	6	10	10	10	7	7
Zr	186			292	107	129	176	195	212	180	167
Ni	2			26	17	28	nd	4	nd	nd	1
Cr	22			192	72	115	14	12	17	14	14
Cu	4			38	18	20	4	16	2	4	3
Zn	67			36	60	66	57	50	40	70	56
Pb	17			14	19	11	12	23	15	11	13
Sb[g]	<5			<5	<5	nd	nd	nd	<5	nd	nd
Sn[g]	nd			nd	nd	nd	nd	nd	nd	nd	nd
Ag[g]	nd			nd	nd	nd	nd	nd	nd	nd	nd
Au[h]										nd	
As[h]										2000	
Hg (µg/kg)[i]	1774			520	80	82	118	402	35	36	16
Rock Type	tuff	tuff	ignimbrite	sandstone	siltstone	sandstone	tuff	mudstone	tuff	tuff	tuff

	M3						THM1				
	Calcite Zone	Calc-silicate Zone				Epidote Zone	Smectite Zone		Micaceous Clay Zone	Illite Zone	Silicific Zone
Depth (m)	635	695	726	756	973	1094	63	77	200	315	390
SiO_2 (wt.%)	70.83	77.56	72.06	76.40	73.40	i4.87	60.99	67.03	73.46	62.93	82.90
TiO_2	0.35	0.21	0.41	0.22	0.28	0.25	0.42	0.25	0.36	0.56	0.18
Al_2O_3	13.93	12.20	13.76	12.27	13.47	13.20	12.78	0.86	13.80	20.50	7.97
Fe_2O_3	2.84	1.84	2.78	1.48	2.16	1.80	3.49	2.43	2.15	3.64	1.81
MnO	0.09	0.09	0.10	0.08	0.12	0.10	0.11	0.07	0.09	0.07	0.05
MgO	1.31	0.21	0.62	0.26	0.44	0.18	0.89	1.13	0.48	0.64	0.26
CaO	1.75	0.92	2.56	1.48	2.55	1.37	2.39	1.27	2.04	0.64	0.36
Na_2O	1.96	3.04	3.61	5.05	3.21	3.97	<0.05	<0.05	2.54	<0.05	1.20
K_2O	2.00	3.09	2.52	1.95	3.71	3.56	2.68	1.71	3.16	5.62	4.81
P_2O_5	0.06	0.05	0.09	0.05	0.07	0.05	0.07	0.07	0.08	0.54	0.05
S	0.17	0.19	0.10	0.19	0.03	0.06	0.27	0.63	0.05	0.59	0.26
H_2O^+	3.82	1.36	2.18	0.90	1.32	0.86	11.64	10.08	1.88	5.18	0.42
H_2O^-	0.8T	0.04	0.06	0.04	0.02	0.06	4.97	5.62	0.30	0.65	0.08
Total	100.92	100.80	100.85	100.37	100.17	100.33	100.70	100.15	100.49	101.06	100.35
S ≡ O	0.06	0.07	0.04	0.07	0.01	0.02	0.10	0.24	0.02	0.22	0.10
Total[f]	99.86	100.73	100.81	100.30	100.76	100.31	100.60	99.91	100.47	100.84	100.25
Rb (mg/kg)	61	113	93	94	131	127	133	77	110	347	198
Sr	193	128	197	110	147	143	382	131	173	25	43
Ba	556	638	512	745	810	710	687	451	712	127	310
V	36	6	28	4	12	8	46	34	19	22	5
Y	18	27	18	24	21	25	19	14	26	66	21
Th	3	10	7	10	6	9	4	4	6	17	2
Zr	143	150	178	179	169	176	176	91	174	330	96
Ni	14	2	4	3	nd	nd	8	7	1	1	1
Cr	84	29	40	30	25	27	40	36	25	9	24
Cu	5	2	4	2	nd	3	10	7	4	9	16
Zn	44	34	47	40	42	38	50	40	52	54	33
Pb	12	11	7	9	9	12	7	7	11	21	7
Sb	nd	nd	<5	<5	<5	<5	<5	nd	nd	nd	nd
Sn	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Ag	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Au						nd					
As						nd					
Hg (µg/Kg)	11	9	9	26	10	15	550	414	31	369	8
Rock Type	tuff	tuff	tuff	tuff	ignimbrite	tuff	tuff	tuff	tuff	tuff	tuff

TABLE 1: Chemical analyses of selected cores from drillholes TH3 and THM1 compared with unaltered cores from Wairakei (W. Tuff and Ig. II).

Analyses provided by XRF. unless noted. - = nor determined; nd = not detected: sample descriptions and hydrothermal mineralogy listed in Kstimoto.1983. b. Analyses for unaltered sample from Kakimoto,1983 (THM1-11), and from Steiner (1977): W. Tuff = Pumiceous and Vitric Tuff, sample No. 11; Ig.11 = Pumiceous Ignimbrite II, sample No. *30*. E. All iron reported as Fe_2O_3. d. Penfield determination. e. Loss upon drying at 110°C. f. Corrected for Sulphur = Oxygen. g. Sb, Sn and Ag analyses by flame AA method, provided by Patricia Hardman, Geology Dept., University of Auckland. h. Au. As (and Sn-detection limit = 1 mg/kg) analyses by emission spectroscopy for TH3-482, TH3-1065 (below detection limits - not shown) end TH3-1094; provided by Terry Seward, Chemistry Division, DSIR. Lower Hurt. i. Hg analyses by gold film detector.

MAJOR ELEMENTS

Enrichment and Depletion Trends

Table 2 and Figures 3 and 4 summarise the mass changes that have occurred in response to the hydrothermal alteration.

Silica shows a net gain, with the most pronounced enrichment being in the silicified zone of THMl at 390m. Silica addition mainly reflects precipitation of quartz directly from solution and, to a lesser extent, replacement of primary minerals.

Alumina redistribution is variable, with a slight net increase in the calcite zone of TH3, relative immobility in underlying calc-silicate zones and a marked (-80%) increase in the THMl illite zone (315m). Al_2O_3 is depleted in the clay-free, silicified zone of THMl. These changes result from the transformation of andesine to albite, adularia and calcite which release aluminium, probably in the form of $Al(OH_4)^-$. A typical representative reaction is:

$$An_{0.35}\,Ab_{0.65} + K^+ + 0.35\,H_4SiO_4 \rightleftharpoons KAlSi_3O_8 + 0.35\,Al(OH_4)^- + 0.65\,Na^+ + 0.35\,Ca^{2+}.$$

The alumina thus released may be fired locally, or elsewhere (e.g. in the clay'rich zones), as illite according to the reaction:

$$An_{0.35}\,Ab_{0.65} + 2H^+ + K^+ + 1.65\,Al(OH_4)^- + 0.35\,H_4SiO_4 \rightleftharpoons K\,Al\,Si_3O_{10}(OH_2) + 0.65\,Na^+ + 0.35\,Ca^{2+} + 4\,H_2O.$$

In the calc-silicate zone of TH3, alteration of andesine to calc-silicates (epidote, prehnite, wairakite) results in near isochemical transfer of alumina but whether or not it is added elsewhere depends mainly upon whether or not illite forms.

MgO is enriched in the shallow smectite zone of THMl, being incorporated into the smectite itself, but to a minor extent also into heulandite. Replacement of groundmass and some primary ferro-magnesian minerals by chlorite probably adds MgO to samples from the TH3 calcite zone but its depletion in the underlying calc-silicate zone matches the absence here of interlayered clays and scarcity of chlorite.

The behaviour of iron (expressed as Fe_2O_3 in these analyses) is variable in the two wells but it correlates, to some extent, with the pattern of MgO addition and removal. The enrichment of Fe in THMl-315m (illite zone) correlates with a local abundance of pyrite.

Na_2O and CaO are depleted to differing degrees in most altered samples whereas K20 is usually enriched. The abundance of these elements in rocks and fluids is controlled by mineral equilibria involving hydrolysis (H^+ and OH- transfer), hydration and cation-exchange reactions among primary feldspars and hydrothermal minerals.

K20 is enriched in most samples due to the formation of illite and/or adularia, for example, by the reaction:

$$2An_{0.35}\,Ab_{0.65} + 1.3\,Ca^{2+} + 0.3\,K^+ + 0.6\,Fe^{3+} + 5H_2O \rightleftharpoons \underset{\text{epidote}}{Ca(Fe_{0.6}\,Al_{2.4})\,Si_3O_{12}(OH)} + 0.3\,K\,Al\,Si_3\,O_8 + 3.4\,H^+ + 1.3\,Na^+ + 1.4\,H_4SiO_4.$$

Calcium, however, is either depleted from the rocks or is relatively immobile during alteration, being merely reshuffled during the replacement of primary andesine by calcic minerals. Samples containing abundant calcite or calc-silicate minerals (e.g. TH3-482m, 726m, 973m; THMl-66m) show CaO as being the least depleted with the near isochemical replacement of andesine.

Sodium behaviour also reflects leaching of primary plagioclase in addition to its replacement by albite. In the TH3 calcite zone, Na_2O concentrations are very low because andesine leaching is extensive; in some THMl samples, Na_2O depletion is due to replacement of andesine by smectite and illite.

By contrast, in the TH3 calc-silicate zone, little Na_2O has been removed from the rocks and, indeed, sample TH3-756m shows a net gain. This correlates with ubiquitous albite present in this zone where it occurs both in the groundmass and as a replacement mineral.

H_2O^+ is enriched in the heulandite and clay-rich THMl smectite zone samples and in the clay-rich calcite zone samples from TH3. Depletion of H_2O^+ in the hotter, TH3 calc-silicate zone may be attributed to dehydration of volcanic glass.

The addition of S during alteration is due to the widespread occurrence of iron sulphides and, more rarely, sulphates) in the altered samples.

TiO_2, MnO and P_2O_5 are present in low abundance in all of the rocks. Only Ti02 shows any significant variation, which mostly follows the pattern for MgO and Fe_2O_3 addition and removal. MnO and P_2O_5 appear to be immobile.

TRACE ELEMENTS

Sr, Rb, Ba and V are among the more mobile trace elements (Figure 3 and 4); Sr correlates closely with CaO (Kakimoto, 1983) being highest (382 mg/kg) in core from THMl-63m which contains heulandite. As expected, there is a well-defined linear relationship between Rb and K (Kakimoto, 1983) confirming their chemical similarities. However, the K/Rb ratio of an altered rock commonly reflects its intensity of alteration since adularia has a lower capacity to accommodate Rb than does illite. Thus the lowest K/Rb ratios occur in illite-rich samples such as TH3-482m (300) and THMl-315m (294) whereas samples without illite, but containing adularia, have higher K/Rb ratios, for example THMl-63m (366), 77m (403) and 390m (441).

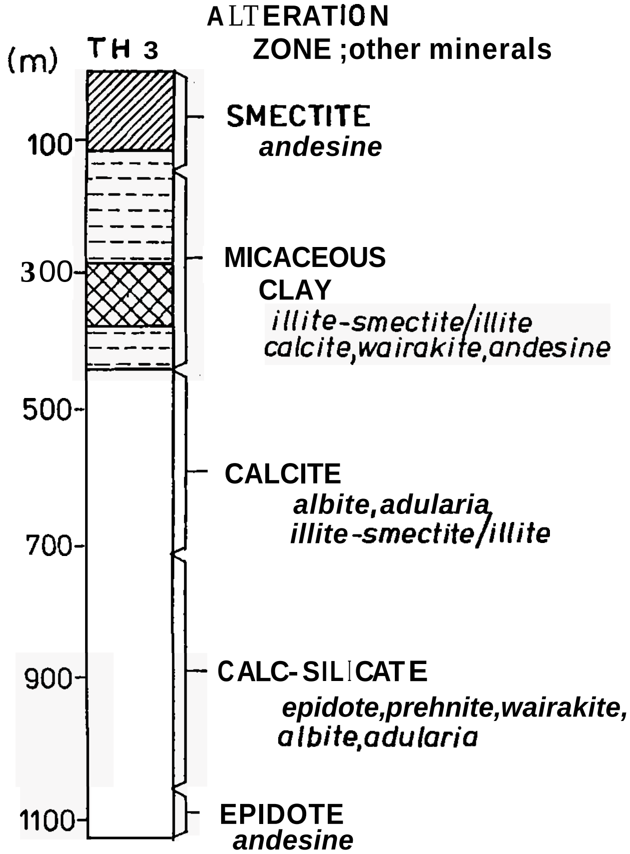
Barium is invariable enriched in the TH3 samples relative to their unaltered equivalents but THMl cores show Ba depletion at depth; in part this is due to its positive correlation with potassium for which it can substitute (Roy, 1965, 1969) but barite is also widely present as a trace mineral in many cores.

Y, Th and Zr were relatively immobile during alteration, being mainly fixed in resistate minerals'like zircon and apatite, nor do zinc and lead concentration vary significantly; neither galena nor sphalerite were seen. Despite cassiterite, silver minerals and gold being observed, the concentrations of Sn, Ag and Au are below detectable quantities. Antimony was detected in nearly half of the analysed samples but its distribution can not be related to the alteration mineralogy.

Arsenic is present in anomalously high concentrations (0.2 weight %) at the top of the calcite zone of TH3; some may be present within pyrite (up to 200 mg/kg) but an undetected separate arsenic phase is probably present here too.

MERCURY

The behaviour of Hg in many geothermal environments suggests that it is transported mainly in the vapour phase as Hg^o (e.g. Weissberg and Rhode, 1978; Cox, 1983, 1984, 1985; Lynne, 1984; Davey and Van Moort, 1986). In the Tauhara cores, Hg appears to occur predominantly as adsorbed Hg that is volatilised at temperatures above about 200 to 250°C. Mercury enrichment of an altered core should therefore indicate the presence of an Hg-transporting steam phase (or its condensate) and reservoir temperatures below 200-250°.



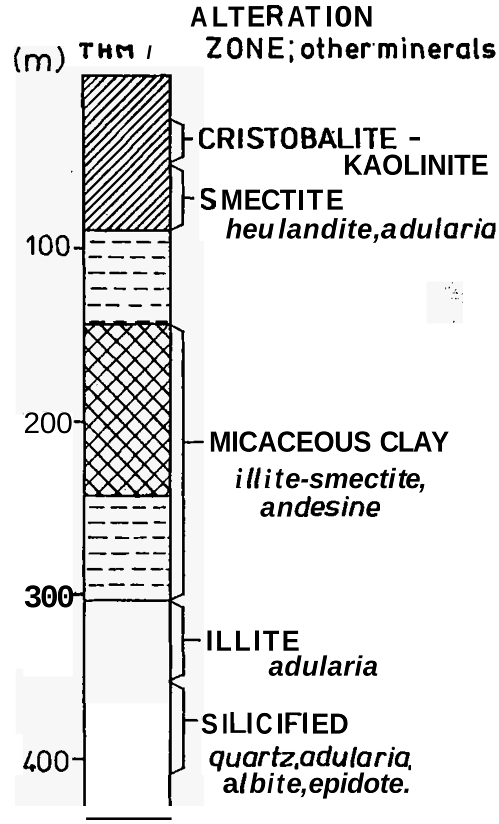


Figure 1: Summary of the distribution of major minerals in alteration zones of drillhole TH3.

Figure 2: Summary of the distribution of major minerals in the alteration zones of THM1.

	Unaltered				TH3										THM1				
Sample	THM1-11	W.Tuff	Tuff Average	Ig.11	361 (depth m)	152	482	571	615	695	726	756	971	1094	61	77	200	115	390
SiO_2 (gm/100 cm^3)	117.1	162	155	174	181.8	181.6	185.8	185.1	186.1	199.1	182.1	191.1	182.8	192.5	155.2	177.5	1117.2	171.5	211.2
TiO_2	0.7	1.1	1.0	0.65	0.95	0.68	0.84	0.79	0.92	0.51	1.0	0.55	0.70	0.61	1.1	0.66	0.92	1.5	0.16
Al_2O_3	28.6	16	12	34	40.4	16.9	36.0	11.5	16.6	11.1	11.8	30.7	11.6	11.9	32.5	16.1	15.2	56.5	20.5
Fe_2O_3	6.0	7.2	6.6	5.1	7.8	1.1	6.1	7.2	7.5	1.7	7.0	1.7	5.1	1.6	8.9	6.1	5.5	10.0	1.7
MnO	0.21	0.26	0.24	0.22	0.19	0.18	0.29	0.25	0.24	0.23	0.25	0.20	0.30	0.26	0.28	0.19	0.21	0.19	0.13
MgO	1.0	1.2	1.1	0.96	2.8	2.1	1.6	2.5	1.1	0.54	1.6	0.6	1.1	0.46	2.3	1.0	1.2	1.8	0.67
CaO	1.7	6.5	5.6	1.1	4.8	2.7	5.9	1.4	1.6	2.1	6.5	1.7	6.3	1.5	6.1	1.1	5.2	1.8	0.91
Na_2O	8.1	10	9.1	9.6	5.5	8.7	nd	0.49	5.2	7.8	9.1	12.6	8.0	10.2	nd	nd	6.7	nd	3.1
K_2O	5.1	6.7	6.0	8.6	2.9	1.9	9.1	6.8	5.1	7.9	6.1	1.9	9.2	9.2	6.8	1.5	8.0	15.5	12.4
P_2O_5	0.17	0.19	0.18	0.07	0.27	0.20	0.21	0.25	0.16	0.13	0.21	0.13	0.17	0.13	0.18	0.19	0.20	0.11	0.13
S	0.02		0.02		0.27	0.15	0.50	0.15	0.15	0.49	0.25	0.17	0.07	0.15	0.69	1.7	0.13	1.6	0.67
H_2O^+	8.3	5.8	7.05	2.1	11.5	8.6	12.2	9.8	10.0	1.5	5.5	2.2	1.1	2.2	29.6	26.7	1.8	14.3	1.8
Rb (gm/10^4 cm^3)	108				114	111	562	296	161	291	235	207	126	127	338	204	280	957	609
Sr	364				525	155	306	197	508	129	199	212	366	368	972	347	441	69	111
Ba	1283				1607	1587	2177	1280	1463	1610	1296	1640	2017	1826	1719	1194	1814	150	791
V	20				48	I5	17	44	95	I5	71	9	30	21	117	90	48	61	13
Y	61				69	78	90	71	17	69	46	53	52	61	48	17	66	182	51
Th	19				27	25	18	17	8	26	18	22	15	21	10	11	I5	17	5
Zr	391				467	514	175	412	376	386	451	1Y4	421	453	4111	241	143	910	217
Ni	1				nd	nd	nd	2	I7	5	10	7	nd	nd	20	18	1	1	3
Cr	46				I7	11	17	35	221	75	101	66	62	69	102	95	·64	25	62
Cu	8				11	5	11	7	13	5	10	1	nd	8	25	18	10	25	41
Zn	142				151	101	I85	138	168	87	119	88	105	9%	I27	106	132	149	85
Pb	36				12	38	29	12	12	28	18	20	22	31	18	18	28	58	18
K/Rb[a]	508				465	795	300	126	591	195	191	176	515	508	166	101	522	291	441
ρpart (gm/cm^3)[b]	2.10	~2.4[c]		~2.4[c]	2.60	2.19	2.61	2.15	2.61	2.57	2.51	2.5	2.19	2.57	2.12	2.5	2.54	2.71	2.57
ρdry (gm/cm^3)[d]	0.72	1.35		1.66	1.56	1.61.	1.33	1.63	1.90	1.83	2.01	2	1.98	2.26	1.28	1.0	1.36	1.19	2.46
porosity (%)	64				40	35	19	35	27	29	20	nd	21	I2	17	nd	17	49	1

a. Atomic ratio. b. Particle density. c. Estimated particle density. d. Bulk dry density.

TABLE 2: Mass densities of major and trace elements for altered and unaltered tuff samples.

The host rocks of the deep Tauhara aquifer (Figure 5) are significantly depleted in Hg compared with the overlying Huka Falls mudstones that cap it. This distribution is consistent with the high (> 225") temperatures in the deep aquifer which caused Hg to volatilise.

Mercury contents in the TH3 Huka Falls sediments correlate inversely with temperature (Figure 5). These samples are particularly enriched in Hg as it are the mudstones in cores from THM1. This may be due to the fine-grained nature of the sediment as well as the lower temperatures prevailing here (Figure 5). The high Hg levels, nonetheless, indicate the presence of condensed steam (and CO_2) in the upper Huka Falls mudstones. This conclusion is consistent with the presence of abundant vapour-rich inclusions in sulphate minerals from this zone, and indications drawn from the measured downwell temperature profiles (Kakimoto, 1983). The highest Hg contents occur in the Post Oruanui lake sediments which appear to host a vapour zone (Allis, 1983) and contain an acid alteration assemblage.

By contrast, the shallow cores from TH3 are unaltered, with low Hg contents, not having been affected by steam or steam condensate.

The distribution of Hg in samples from TH3 and THMl thus reflects reservoir conditions, in particular the location of steam condensate zones and lower reservoir temperatures.

CONCLUSIONS

Fluid/rock interaction at Tauhara has produced a suite of hydrothermal ninerals that reflect the hydrology and lithology of the reservoir. These mineralogical changes are also evident in chemical changes that the rocks have undergone. Constituents such as SiO_2, Al_2O_3, Na_2O, K_2O, CaO and H_2O^+ redistribute as a result of mineralogical changes, but others (MnO and P_2O_5) are largely immobile. Similarly, of the trace elements Sr, Rb and Ba are very mobile but Y, Th and Zr are immobile during the hydrothermal alteration processes that took place here.

Mercury shows a strong tendency to migrate depending upon local reservoir temperature and the identity of the fluid phase. It readily volatilises from its host at temperatures between 200 and 250°C, moving with the steam phase together with CO_2 and H_2S. Where the steam (and H_2S and CO_2) condenses the transported mercury is readsorbed onto adjacent rocks. Routine analysis of cores and cuttings for mercury while a well is being drilled is, therefore, probably a good way to locate corrosive waters of acid condensate or bicarbonate composition (Hedenquist and Henley, 1985).

ACKNOWLEDGEMENTS

We thank Dr R J Parker, Geology Department, University of Auckland, for his valuable help with the X-Ray Fluoresence Analyses, and Dr M E Cox for advice on mercury analysis. Ministry of Works 6 Development are thanked for allowing access to the cores and for providing drillhole information.

REFERENCES

ALLIS, R G (1983): Hydrologic changes at Tauhara geothermal field. Report 193, Geophysics Division, DSIR, Wellington.

BOGIE, I. and BROWNE, P R L (1979): Geochemistry of hydrothermal alteration of the Ohaki Rhyolite, Broadlands geothermal field. Proc NZ Geothermal Workshop, 1979, Univ. of Auckland, Part 2, 326-333.

COX, M E (1983): Summit outgassing as indicated by radon, mercury and pH mapping, Kilauea Volcano, Hawaii. Jour. Volc. Res. 16: 131-151.

COX, M E (1984): Controls on distribution of Hg in geothermal wells from Ngawha, New Zealand, and Puna, Hawaii. Proc. 6th NZ Geothermal Workshop, 145-150.

COX, M E (1985): Geochemical examination of the active hydrothermal system at Ngawha, New Zealand: Hydrochemical model, element distribution and geological setting. PhD thesis, Geology Department, University of Auckland, 385 pp.

DAVEY, H A and J C VAN MOORT (1986): Current mercury deposition at Ngawha Springs, New Zealand. Applied Geochemistry, 1, 75-93.

REDENQUIST, J W and R W HENLEY (1985): The importance of CO_2 on freezing point measurements of fluid inclusions: Evidence from active geothermal systems and implications for epithermal ore deposition. Economic Geology, 80, 1379-1406.

HENNEBERGER, R C (1983): Petrology and evolution of the Ohakuri Hydrothermal System, Taupo Volcanic Zone, New Zealand. MSc (Hons) thesis, Geology Department, University of Auckland, 141 pp.

KAKIMOTO, P K (1983): Hydrothermal alteration and fluid-rock interaction in the TH3 and THM1 drillholes, Tauhara Geothermal Field, New Zealand. M.Phil thesis, Geology Department, University of Auckland, 154 pp.

KAKIMOTO, P K and P R L BROWNE (in prep): Hydrothermal alteration and hydrology of cores from Tauhara Drillholes TH3 and THMl, New Zealand.

LYNNE, B.Y. (1984): A petrological investigation of cores and cuttings in contact with bicarbonate waters at Broadlands Geothermal Field, New Zealand. Geothermal Institute Project Report, 84.19, 71 pp.

McNERNEY, J J, BUSECK, P R and HANSON, R C (1972): Mercury detection by means of thin gold films. Science 178: 611-612.

ROY, N N (1965): The mineralogy of the potassium-barium feldspar series. I. The determination of the optical properties of natural members. Mineral. Mag. 35: 508-518.

ROY, N N (1967): The mineralogy of the potassium-barium feldspar series. 111. Studies on hydrothermally synthezised members. Mineral. Mag. 36: 43-49.

STEINER, A (1977): The Wairakei Geothermal Area, North Island, New Zealand. NZ Geol. Surv. Bull. 90, 136 pp.

WEISSBERG, B G and ROHDE, A G (1978): Mercury in some New Zealand geothermal discharges. NZ Jour. Sci. 21: 365-369.

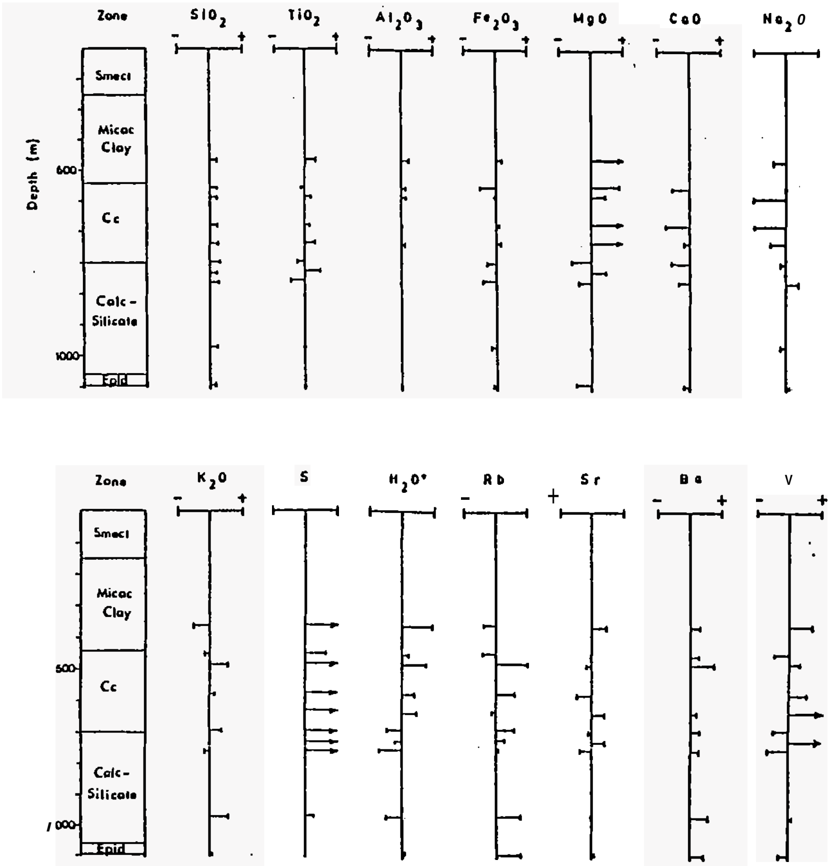


Figure 3: Tuffaceous samples from TH3: percentage change from fresh rock composition for various elements. Scale is ±100%, except for S which is ±1000%.

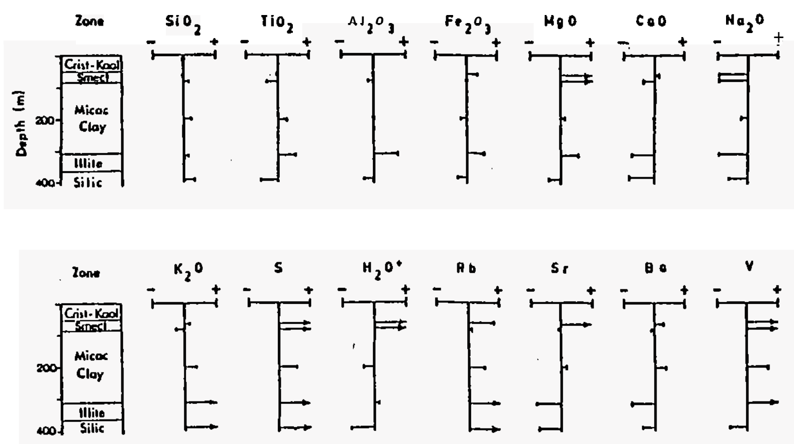


Figure 4: Tuffaceous samples from THM1: percentage change from fresh rock composition for various elements. Scale is ±100%, except for S which is ±1000%.

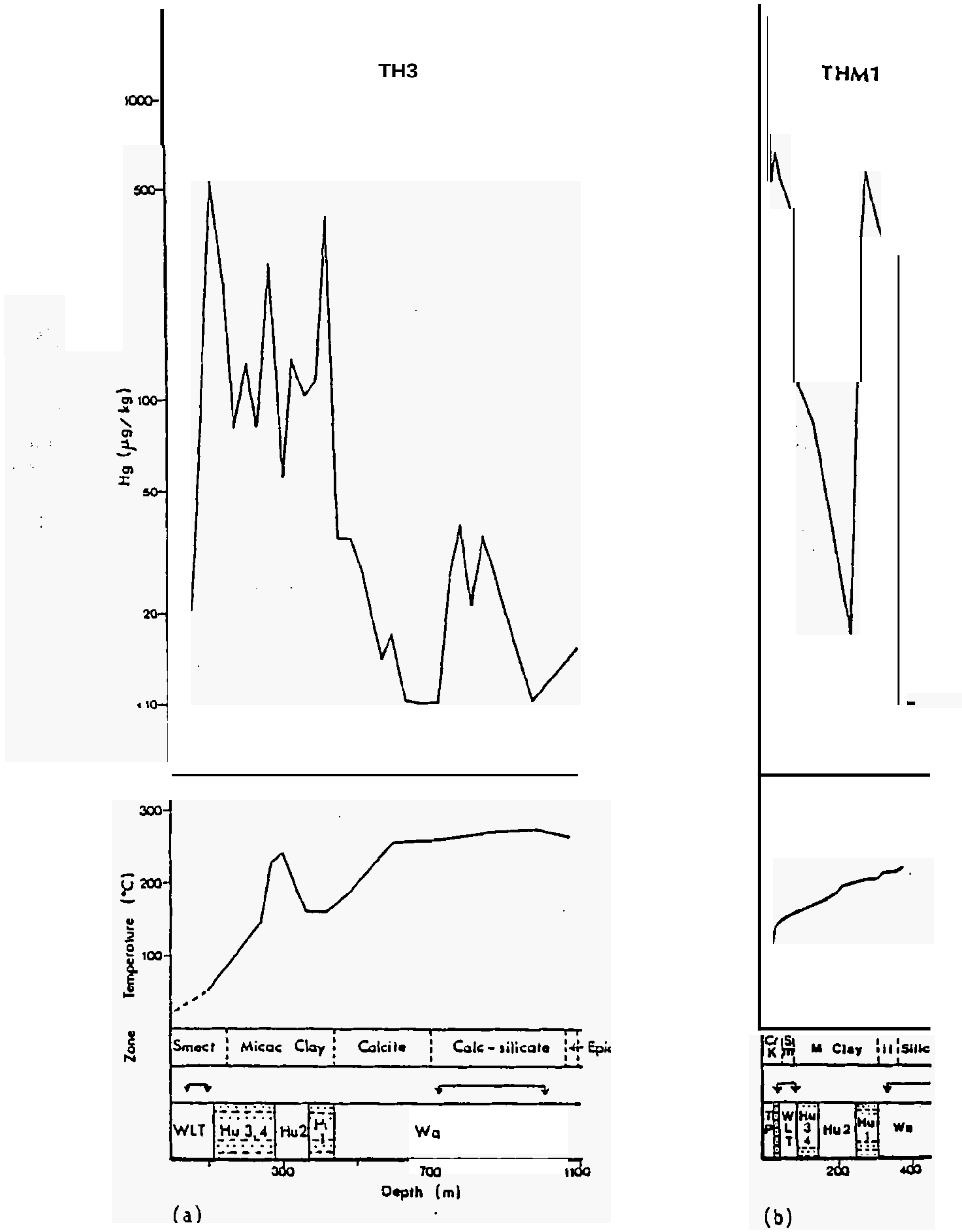


Figure 5: Distribution of Hg with depth in cores from (a) TH3, and (b) THMl; also shown are summary stratigraphy, alteration zones, drillhole temperatures and circulation losses during drilling.