FLUID INCLUSION EVIDENCE FOR THERMAL CHANGE IN THE ORAKEIKORAKO GEOTHERMAL FIELD, NEW ZEALAND

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ABSTRACT

Four wells, a distance of 1 to 1.5km apart, have been drilled at Orakeikorako, 23km NNE of Taupo. Cores recovered from below about 500m contain hydrothermal mineral assemblages that include quartz, albite, adularia, illite, chlorite, epidote, calcite, pyrite and titanite (+/- wairakite, clinozoisite, siderite, apatite and leucoxene). The distribution of secondary minerals reflects the hydrological and thermal regime which is as high as 265°C.

Temperature of homogenisation (T_h) measurements, obtained for 278 inclusions in quartz and calcite for 16 core depths, mostly match measured bore temperatures (eg. OK1, shallow levels and OK2). However, results also indicate that southern parts of the Orakeikorako field have cooled appreciably, eg. OK1 (deep levels) and OK4 (max T_{bore}=238°C, max T_h=312°C), whereas northwestern parts have heated (eg. OK6: 1113.4m, T_{bore}=261°C, T_h=210-221°C).

Freezing temperatures were obtained for 83 of the inclusions; the T_m determinations resulted in calculated apparent salinities from 0.2 to 1.8wt% NaCl equivalence. High apparent salinities in some inclusions is attributed to the presence of CO_2 in the trapped fluid..

The observations are consistent with a model whereby the hydrothermal mineralogy, fluid inclusion data, plus present surface and subsurface conditions record the evolution of the Orakeikorako system, which has clearly changed with time.

INTRODUCTION

The Orakeikorako geothermal field was investigated in the mid 1960's to assess its electrical power potential. It is located on the margin of the Maroa Volcanic Centre, about 23km NNE of Taupo (Fig1).

The surface geology in the vicinity of the geothermal area is described by Grindley (1959) and Lloyd (1972), and the subsurface stratigraphy, as revealed by drilling, is summarised by Bignall (1991). The field comprises a sequence of generally SE dipping pyroclastic rocks, pumice and crystal tuffs, lapilli tuff, tuff, ignimbrite, lacustrine tuffs and intercalated rhyolite lavas (Fig2).

Four wells were drilled in the Orakeikorako area, about 1.5km apart; OK1 (1403.6m deep), OK2 (1155.2m), OK4 (1374.6m) and OK6 (1219.8m). None reached the Mesozoic greywacke basement.

The surface hydrothermal activity at Orakeikorako, occupies an area of about 1.8km^2, intimately associated with a swarm of late Cenozoic to Recent, NE-SW trending normal faults. Surface manifestations have been described by Lloyd (1972) and consist of hot, neutral pH pools, springs and geysers, silica sinter, hydrothermal eruption craters and acid alteration.

Petrographic analysis of cores and cuttings from the wells reveal a hydrothermal mineral assemblage, below 500m depth, including quartz, albite, adularia, illite, chlorite, epidote, calcite, pyrite and titanite (+/- wairakite, clinozoisite, siderite, apatite, leucoxene).

The hydrothermal mineral studies have been supplemented by fluid inclusion measurements in 16 cores from the four drillholes. This paper establishes the relationship between rocks forming the system reservoir, their secondary mineralogy and, using the fluid inclusions results, identifies changes that have occurred in the thermal regime of the Orakeikorako field.

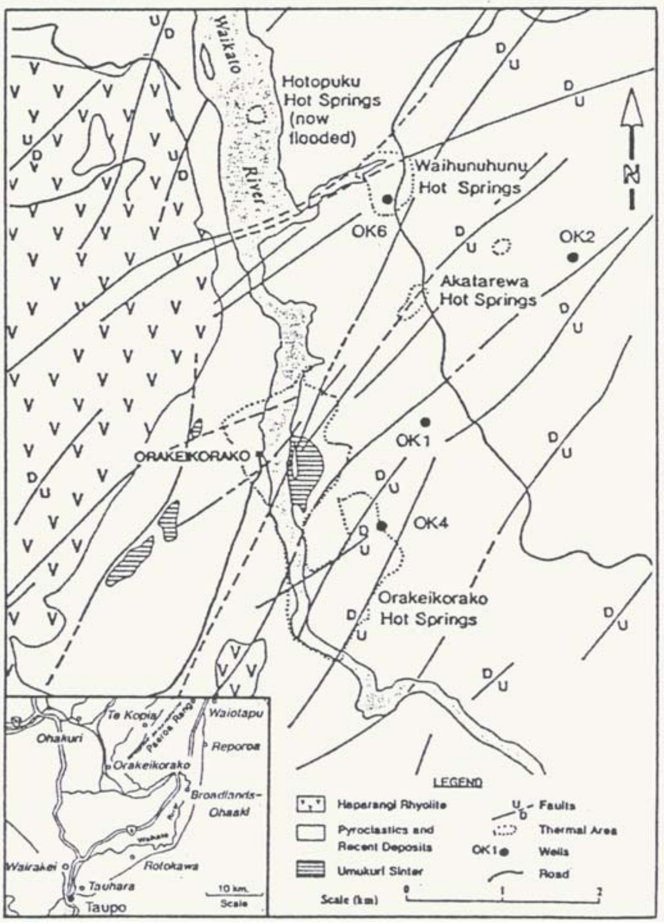

Figure 1: Location and geologic map of the Orakeikorako Geothermal Field, Taupo Volcanic Zone. From Simmons and Browne (1991).

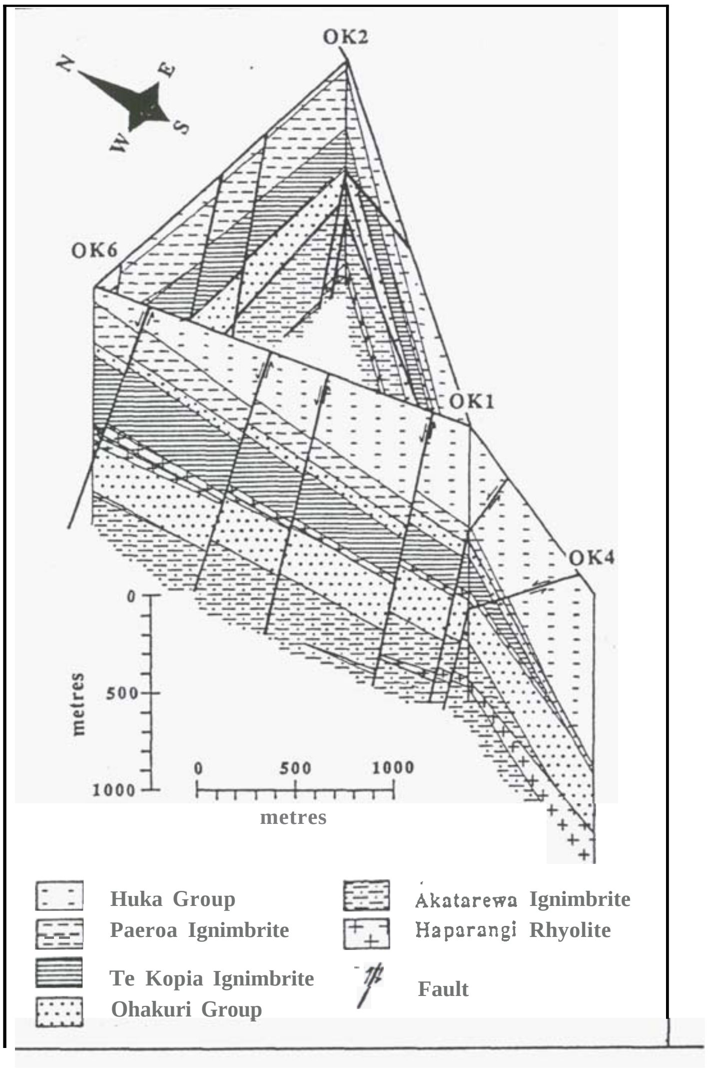

Figure 2: Panel diagram showing the subsurface stratigraphy of the Orakeikorako *area,* (Bignall, 1991).

HYDROTHERMAL MINERALOGY

The cores examined for this study are from depths below 550m **and** therefore characterise the deeper reservoir. The observed hydrothermal **minerals** (Table 1) were identified using petrographic microscopy, X-ray diffraction and **scanning** election microscope techniques. The most common hydrothermal minerals are quartz, albite, adularia, calcite, epidote, titanite (sphene), chlorite and pyrite.

The hydrothermal minerals usually **occur** replacing **primary** crystals, either directly or, typically in the *case* of calcite and illite, in altered plagioclase laths, overprinting other secondary minerals or in the groundmass. Quartz (+/- adularia), epidote and calcite veinlets are usually narrow (up to 0.5mm wide) and rare; they mainly occur below 1000m depth.

Overprinting of **quartz** and adularia-altered plagioclase laths by calcite **and/or** illite (Fig3a) implies that there have been different **stages** of hydrothermal activity in the Orakeikorako system.

The alteration minerals present **now** have a characteristic temperature stability which ranges from 210°C to above 300°C. Browne (1984) showed that hydrothermal minerals which provide information on the temperature of their formation **are** mostly those that contain, in their structure, either (OH) or nH_2O. Progressive dehydration with increasing temperature has been shown by Elders et *al* **(1984) to** produce a **sequence** of temperature dependent calc-silicate **minerals. More** recently the **use** of clays and **mixed** layer clays, **as** mineral geothermometers in the geothermal setting, **has been** reviewed by Harvey and Browne (1991), following the pioneering work by Steiner **(1968)** at the Wairakei **geothermal** field.

Harvey and Browne (1991) indicate that there are typically three ways in which clays may be used **as** geothermometers by: i) the appearance or disappearance of the clay mineral assemblage at **a** specific temperature, ii) changes in the **crystallinity** of **mixed** layer clay at a specific temperature and iii) temperature dependent changes in their composition.

It is the progressive dehydration processes **and** temperature dependence that make clay **and** calc-silicate minerals useful in the **geothermal setting as** temperature indicators.

Well	OK:1				OK:2				OK:4				OK:6			
Depth(m)	609.6	884.5	1126.8	1312.5	655.3	853.4	976.3	1136.9	580.3	884.8	1188.7	1341.1	975.4	1113.4	1141.8	1219.2
Ad		X	X	X			X	X	X	X	X	X	X	X	X	X
Alb	X			X	X		X		X	X	X	X	X	X	X	X
Cal	X	X	X	X	X	X	X	X			X	X	X	X	X	
Chl	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Ep				X	X			X	X	X	X	X				X
I		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
I-Sni	X															
Lcx					X					X	X		X			X
Py	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Qtz	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Tit	X	X	X	X	X		X	X	X	X	X		X	X	X	X
Wai			X													

TABLE 1: Occurrence of secondary minerals in selected cores **from** Orakeikorako **drillholes.** Abbreviations **used** are adularia ***(Ad),*** albite (Alb), calcite (Cal), chlorite (Chl), epidote (Ep), illite (I), interlayered illite-smectite **(I-Sm),** leucoxene (Lcx), pyrite (Py), **quartz** (Qtz), titanite (Tit) and wairakite (Wkt).

The typical temperature of formation for different clay minerals in New Zealand geothermal systems is summarised below -

Hydrothermal Mineral	Stability Temperature
Kaolinite	<120°C
Smectite	<140-150°C
Interlayered illite-smectite	140-220°C
Illite	>220°C

Clay minerals are ubiquitous in the Orakeikorako rocks. In the four wells, the clay minerals grade from smectite to interlayered illite-smectite, then to illite with increasing depth and temperatures. Chlorite is common at most depths, but particularly where temperatures exceed about 150°C. Kaolinite is common at or near the surface, in rocks which have undergone acid alteration.

The occurrence of illite deeper in the system reflects the rank of hydrothermal alteration and indicates that a lowering in the fluid pH took place at some stage during the history of the field because illite typically overprints adularia-altered plagioclace.

Epidote is a high temperature alteration mineral (>250°C) found in many geothermal fields (Browne 1978). In the Orakeikorako system it occurs below 1150m in OK1 and at depths greater than 650m in OK2, 390m in OK4 and 1170m in OK6. In the Orakeikorako drillcores epidote occurs in veinlets (Fig3b), in the rock matrix and as a replacement of plagioclase laths.

Wairakite was found in only one of the core (OK1:1126.8m), replacing plagioclase laths, although it is common in other New Zealand geothermal fields. A minimum temperature of formation for wairakite has been reported at 180°C (Kristmannsdottir, 1979), although it usually occurs above 200-210°C (Browne, 1978).

Secondary minerals indicative of low temperatures, such as cristobalite, mordenite, kaolinite and smectite occur at shallow levels in all of the Orakeikorako wells.

Ubiquitous minerals such as quartz, chlorite, calcite, adularia, albite, titanite and pyrite do not yield useful geothermometric information.

FLUID INCLUSION GEOTHERMOMETRY

Fluid inclusions can provide valuable data on subsurface temperatures and fluid conditions and may indicate whether a geothermal system is heating up or cooling.

Types of Inclusions

Examination of more than 350 thin sections of drillcores from the four exploration wells showed the presence of fluid inclusions in hydrothermal quartz and calcite. No fluid inclusions were observed in epidote.

Nineteen drillcores were collected at depths where fluid inclusion bearing grains were seen in thin section. Fluid inclusions in several samples were absent or too small to study (<2µm), however, homogenisation temperatures of 278 fluid inclusions were measured and the freezing temperatures of 83 of them were determined.

All usable fluid inclusions are liquid-rich; a few samples contain liquid and vapour-rich inclusions which are mostly interpreted as resulting from necking down. These have been excluded from this study.

Most fluid inclusions appear to have formed along healed fractures and are classified as being of secondary origin.

Figure 3a: Electromicrograph taken with SEM of illite in sample OK1:1126.8m.

Figure 3b: Electromicrograph taken with SEM of sample OK4:884.8m. Epidote crystals in vug.

None of the secondary minerals exhibit characteristics such as growth zones, indicating a primary origin for the inclusions; similarly no daughter minerals or other phases (eg. clathrate) were observed.

Analytical methods

Heating and freezing measurements were made on chips cut from doubly polished plates, prepared using the method described by Barker and Reynolds (1984).

Measurements of fluid inclusion homogenisation temperature (T_h) and final melting temperatures (T_m) were made using a microscope stage manufactured by Fluid Inc., who adapted a US Geological Survey gas-flow, heating-freezing system. The calibration of the OMEGA chromel-constantan thermocouple was checked by measuring standard synthetic inclusions. T_h measurements were corrected for small calibration errors <2°C, whilst T_m values are believed to be accurate to +/-0.1°C. Salinity is expressed in terms of Wt% NaCl equivalents (Potter and Clynne, 1978).

Crushing experiments were performed using the techniques described by Roedder (1984).

It is worthy of note that if pressure conditions at the time the fluid inclusions were trapped were similar to measured pressures in the Orakeikorako drillholes, then minimal (<5°C) temperature corrections to the T_h are necessary to obtain the trapping temperatures. Inclusions with anomalously high T_h values, which may have leaked, are removed from the data set presented here.

Fluid Inclusion Data

A summary of T_h and T_m data from Orakeikorako samples is given in Table 2.

Figs 4a-d shows the downhole temperature measurements and the boiling point curve (BPC) for pure water for each of the wells. In addition, histograms of T_h for each of the samples are superimposed on the curves. Where T_h values, at any depth, exceed the BPC and vapour inclusions are found, it *can* be assumed that boiling occured.

OK1: Homogenisation temperature measurements were obtained for 77 fluid inclusions in secondary quartz from four core samples.

At all levels in the well the measured temperatures are significantly less than the reference boiling curve (BPC), corrected for hydrostatic pressure.

The liquid-rich fluid inclusions at 609.6m and 884.5m depth all homogenised at temperatures close to the measured bore temperatures. The inclusions are secondary, show no evidence of boiling and indicate static thermal conditions since the inclusions formed.

The majority of fluid inclusions in the 1126.8m and 1312.5m core samples show T_h values significantly higher than the measured temperatures at the corresponding depth. Inclusions in 1126.8m all occur in secondary quartz, with T_h values statistically tri-modal. One group (7 inclusions) approximate present bore temperatures; another group (21 inclusions) plots close to or above the BPC; and a third group (3 inclusions) has intermediate T_h values. No vapour inclusions were found.

T_h measurements of the deepest sample in OK1, at 1312.5m depth, are statistically bi-modal. A low T_h group is consistent with "group 3" from 1126.8m, whereas the high T_h group are all liquid-rich inclusions trapped close to the boiling temperatures.

Fluid inclusions with T_h values that exceed the present measured temperatures appear to reflect a previous thermal regime that was hotter than that at present.

The apparent salinities for the three deepest samples from OK1, range from 0.35 to 1.73 wt% NaCl equivalence. Inclusions in the 609.6m sample could not be accurately measured. The T_m data (Table 2 and 3) indicates that the fluid trapped in the hydrothermal quartz was dilute, with the low T_h inclusions being less saline than higher T_h inclusions.

OK2: Heating/freezing data were obtained for 70 fluid inclusions in ignimbrite from four sample depths. All of the fluid inclusions in quartz from this drillhole occur along healed fractures and are secondary. The inclusions are liquid rich and exhibit constant liquid-vapour ratios, with none containing daughter minerals.

T_h data for the samples taken from 655.3, 853.4, 976.3 and 1135.9m in OK2 are plotted with a temperature log in Fig6b. The maximum measured temperature, at well bottom (1136.9m) is 266°C

Minimum T_h measurements from the sample depths are all close to the measured drillhole temperatures. Only the deepest sample, at 1136.9m, gave homogenisation temperatures that differed from the measured bore temperatures; with T_h values up to 20°C higher. Overall, the homogenisation temperatures indicate that the subsurface temperatures have changed little in the OK2 area since the inclusions formed. None of the samples show evidence of boiling.

T_m measurements were obtained for 27 inclusions in OK2. The data indicate that the fluid trapped in the hydrothermal quartz and calcite was a dilute, low salinity fluid, with T_m measurements ranging from 0.1 to 0.5°C which corresponds to 0.18 to 0.87 wt% NaCl equivalence.

The T_m values do not appear to vary significantly with T_h. There is no evidence from fluid inclusion analysis of OK2 samples that multiple thermal events have occurred.

Drillhole Number	Total depth (m)	Maximum drill hole temperature (°C)	Sample depth (m)	Relative depth (m)	Type of inclusion	Host Mineral	Melting temperature of ice (°C) Range (mean)	Number of homogenisation temperature measurements	Range of homogenisation temperatures (°C)	Mean homogenisation temperature (°C)	Measured bore temperature (°C)	Measured pressure (Mpa)	Range of trapping temperatures (°C) (Pressure Corrected)	Temperature difference Tbore-Tth (°C)
OK1	1403.6	228	609.6	-243.5	sec	2-quartz	am.	4	168.8-172.2	170.5	I83	5.1	170-174	- 12
			884.5	-518.4	sec	calcite	-0.4,-0.6 (-0.5)	18	218.0-248.2	235.1	224	7.4	221-251	+ 11
			1126.8	-760.7	sec	2-quartz	-0.2,-0.3 (-0.2)	7	212.1-220.9	216.6	211	8.6	216-224	+ 6
			1126.8	-760.7	sec	2-quartz	n.m.	3	253.2-257.3	254.9	211	8.6	255-259	+ 44
			1126.8	-760.7	sec	frac-quartz	-0.8,-1.0 (-0.9)	21	297.7-324.7	311.8	211	8.6	300-325	+ 101
			13125	-946.4	sec	frac-quartz	n.m.	3	2583261.1	259.3	214	10.7	262-265	• 45
			13125	-946.4	sec	frac-quartz	-0.5,-0.6 (-0.6)	21	287.5-310.9	301.3	214	10.7	291-312	• 87
OK2	11552	266	6553	-325.5	sec	frac-quartz	-0.2,-0.3 (-0.2)	13	219.9-226.2	222.8	230	6.1	223-228	- 7
			853.4	-523.6	sec	frac-quartz	-0.2,-0.4 (4.3)	21	221.9-229.2	2243	238	7.8	225-233	- 14
			976.3	-646.5	sec	2-quartz	-0.1,-0.2 (-0.2)	18	251.0-260.7	253.4	25?	8.7	254-264	4 1
			1136.9	-807.1	sec	calcite	am.	2	269.3-269.4	269.3	266	9.9	273	+ 3
			1136.9	-807.1	sa	calcite	-0.2,-0.5 (-0.3)	16	278.2-288.8	282.5	266	9.9	281-291	• 17
OK4	1374.6	235	580.3	-227.3	sec	frac-quartz	am.	11	238.9-249.5	2455	232	49	241-251	• 14
			884.8	-531.8	sec	2-quartz	-0.2,-0.4 (-0.3)	16	274.3-292.7	280.0	228	7.4	276-293	+ 54
			1188.7	-835.7	sec	frac-quartz	-0.3 (4.3)	7	230.6-235.7	2322	201	10.0	234-240	• 31
			1188.7	-835.7	sec	frac-quartz	-0.7,-1.3 (-0.9)	23	297.6-311.4	305.7	201	10.0	298-311	• 105
			1341.1	-988.1	sec	2-quartz	n.m.	3	227.3-228.1	221.7	194	11.2	233-234	*34
			1341.1	-988.1	sec	2-quartz	-0.4,-0.6 (-0.5)	9	301.8-312.4	306.9	194	11.2	304-313	• 113
OK6	1219.8	265	975.4	-676.8	sec	2-quartz	n.m.	6	215.2-216.5	215.9	259	8.6	220-221	- 42
			1113.4	-814.8	sa	frac-quartz	-0.2,-0.3 (-0.2)	11	209.8-218.7	215.2	261	9.8	215-223	- 40
			1113.4	-814.8	sec	frac-quartz	-0.4,-0.5 (-0.4)	7	247.9-253.8	251.6	261	9.8	251-257	- 3
			1141.8	-843.2	sec	2-qtz vein	-0.4,-0.5 (-0.4)	12	256.8-267.3	263.3	262	9.9	260-272	+ 9
			1219.2	-920.6	sec	2-quartz	-0.4 (-0.4)	22	.262.3-268.6	266.2	n.m.	10.5"	266-272	-
			1219.2	-920.6	sec	2-quartz	n.m.	4	290.8-292.4	291.6	n.m.	10.5"	293-295	

Table 2: Fluid inclusion data for samples fiom Orakeikorako drillholes.

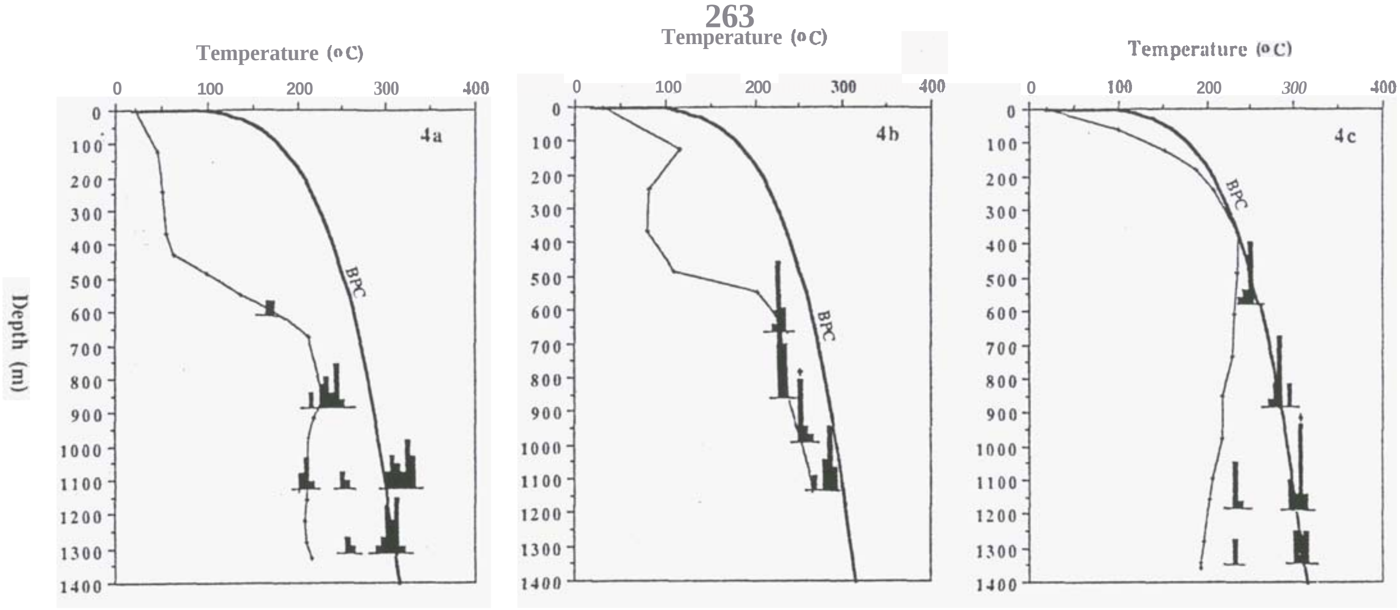

Figure 6a, b, c: Thermal profile, Boiling Point with Depth Curve for pure water (BPC) and fluid inclusion Th histograms for Orakeikorako drillholes; OK:1(a), OK:2(b) and OK:4(c).

OK3 : Homogenisation temperature measurements were obtained for 69 secondary inclusions from 4 sample depths. The fluid inclusions from 580.3m, 884.8m and most from 1188.7m and 1341.1m depths closely follow the BPC. Vapour inclusions and variable liquid-vapour ratios in some liquid-rich inclusions in OK4:580.3m indicate that boiling occurred at this depth. T_h values for the vapour inclusions have not been determined because none were optically suitable. Assuming that no necking has occurred, then the minimum T_h value for the group of inclusions indicates the boiling of the trapped fluid (Roedder and Bodnar, 1980). Therefore the minimum T_h of 239°C may be the trapping temperature of the boiling fluid at 580.3m depth.

The fluid inclusion homogenisation temperatures exceed present measured temperatures by up to 110°C (at 1341.1m) and appear to reflect a previous hotter thermal regime.

Some fluid inclusions in hydrothermal quartz from 1188.7m (7 inclusions) and 1341.1m (3 inclusions) depths exhibit T_h values up to 85°C lower than the high T_h group and are close to the maximum temperature (235°C) measured in the well, albeit still higher than present temperatures at the corresponding depths.

T_m values were obtained for 17 inclusions in three samples from OK4. The results indicate that the fluid trapped was dilute, with T_m measurements reflecting the variation in T_h values - most noticeably in OK4:1188.7 where the high T_h inclusions exhibit T_m values (-0.7 to -1.3°C) and the low T_h group with T_m values at -0.3°C. The variation in Tm measurements and hence apparent salinity (wt% NaCl equivalence), is shown in Table 3 and Fig 5.

OK6: Homogenisation temperatures were obtained on 62 fluid inclusions in 4 samples from deep levels of OK6. All of the inclusions are secondary and occur in hydrothermal quartz.

(Three groups of T_h values are indicated a low T_h group indicated in samples from 975.4m (6 inclusions), and 1113.4m (11), with homogenisation temperatures up to 50°C below measured bore temperatures. T_m values are available for only three of these inclusions (-0.2 to -0.3°C), and corresponds to 0.35 to 0.52 wt% NaCl equivalence.

Most of the inclusions in OK6 samples show close correspondence between homogenisation and the measured bore temperatures. The 'intermediate T_h' group is found in samples from 1113.4m (7 inclusions), 1141.8m (12) and 1219.2 (22). These inclusions are also secondary, occur in fractures and are usually small (<10µm). All of the liquid-rich fluid inclusions show similar liquid-vapour ratios, with no daughter minerals or evidence of boiling. T_m values for this group of inclusions range consistently between -0.4 and -0.5°C, which corresponds to 0.70 to 0.87 wt% NaCl equivalence.

A third, high T_h group is indicated by four inclusions in quartz from 1219.2m. The T_h values for these inclusions, up to 60°C higher than measured temperatures, indicate that fluids migrating through the rocks penetrated by OK6 were hotter at some time in the past than now.

DISCUSSION

The fluid inclusions analysed here come from samples below 550m depth. No samples containing fluid inclusions were found at shallower depths where cool water inflows are indicated by the temperature logs although there is no evidence of retrograde alteration at these depths.

Homogenisation temperatures for most of the 146 secondary liquid-rich inclusions studied from OK1 and OK4 drillholes range between the measured temperatures at sample depths to about 110°C hotter; close to the reference BPC. This suggests that thermal conditions at some depths in the southern Orakeikorako drillholes were warmer in the past than they are now. The occurrence of high T_h values in these two wells is entirely consistent with the presence of high temperature secondary minerals (such as illite, wairakite and epidote) which also indicate formation temperatures higher than at present.

Vapour-rich inclusions were found in one sample from OK4 (580.3m), but were too small to measure. None of the other samples show evidence of boiling, although bladed calcite occurs in OK1 at 701.4m and certainly boiling occurred here.

Measurements of fluid inclusions in samples from OK2 closely correspond to the measured bore temperatures and

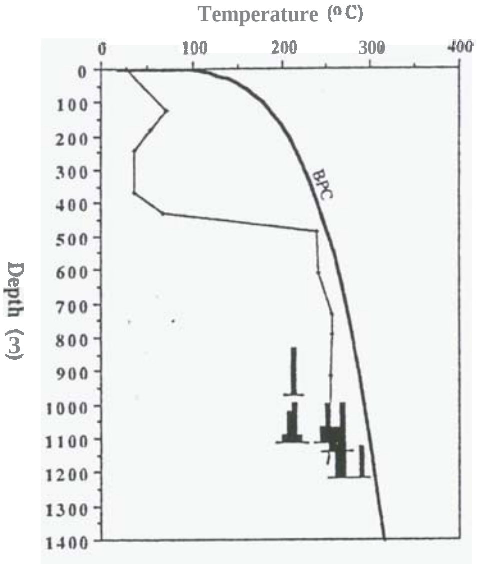

Figure 4d: Thermal profile, BPC and fluid inclusion Th histograms for OK:6

WELL	Depth (m)	Th	Tm
OK1	884.5	2327	-0.6
		231.7	4.4
		239.7	-0.6
		240.8	4.6
		2437	-0.6
		248.2	4.4
	1126.8	216.7	-0.2
		218.7	-0.3
		302.7	-0.8
		304.1	-0.9
		304.2	-0.9
		315.2	1.0
		316.7	1.0
	1312.5	287.5	-0.6
		298.1	-0.5
		298.7	-06
		303.8	-0.6
OK2	655.3	220.1	-0.2
		222.1	-0.3
		224.6	-0.2
		224.7	-0.2
	853.4	222.2	-0.2
		222.9	-0.2
		223.2	4 4
		223.7	-0.4
		229.0	-0.3
	976.3	251.0	-0.2
		251.2	-0.1
		253.2	-0.1
		253.4	-0.2
		253.9	-0.2
		260.7	-0.2
	1136.9	280.3	-0.3
		283.5	-0.3
		283.6	-0.3
		283.7	-0.2
		287.8	-0.5
		288.4	-0.4
		288.8	-0.3
OK4	884.8	2803	-0.3
		280.5	-0.4
		281.3	-0.2
		281.7	-0.2
		292.7	-02
	1188.7	231.8	-03
		232.5	9.3
		306.6	-0.8
		306.7	-0.7
		308.8	-13
	1341.1	301.8	-0.4
		302.2	-0.4
		304.9	-0.6
		310.1	4.4
		312.4	-0.5
OK6	1113.4	210.7	-0.2
		213.7	-0.2
		216.7	-0.3
		247.9	-0.4
		252.3	-0.5
		252.4	-0.4
		252.7	-a4
		253.8	-0.4
	1141.8	258.2	-0.4
		263.5	-0.4
		264.1	-0.5
		266.1	-0.4
		265.7	-0.4
		265.7	-0.4
		265.8	-0.5
	1219.2	266.9	4 4
		261.1	-0.4
		268.6	-0.4

Table 3: Freezing measurements (Tm) and Th data for individual fluid inclusions in Orakeikorako samples.

may indicate a more stable thermal environment in the central and NE part of the field. Temperature dependent calc-silicate and clay minerals also closely reflect the OK2 thermal profile.

Fluid inclusions in OK6 indicate that the NW part of the Orakeikorako field may be heating up. Homogenisation temperatures for secondary inclusions in three of the sample depths are as much as 40°C lower than present temperatures. The low T_h measurements are not due to necking; in some samples variable phase ratios and necked inclusions are evident and this may account for some scatter in the data.

Samples analysed from **OK6** contain secondary minerals with formation temperatures up to and exceeding 220°C. However, no epidote, generally indicative of temperatures greater than about 250°C, is found in these samples despite measured temperatures exceeding 260°C. The absence of epidote may be due to a higher the CO_2 content in the fluid migrating through the rocks penetrated by OK6. This may also be indicated by pools and springs in the northern part of the Orakeikorako field in which bicarbonate is the dominant anion, compared to chloride-dominant pools in the south (Sheppard and Lyon, 1984). Epidote does occur in the deepest (1219.2m deep) sample from OK6, where some T_h values exceed measured bore temperatures.

83 T_m measurements were made on Orakeikorako fluid inclusion samples; the melting temperatures indicate calculated apparent salinities ranging from about 0.18 to 1.73wt%NaCl equivalence.

The higher calculated fluid inclusion salinities in some samples may be due to the presence of dissolved CO_2 in the fluid, as suggested by studies of Hedenquist and Henley (1985), and indicated by crushing studies undertaken here. The lowest values for the apparent salinity was observed in the sample from OK2 (976.3m depth). A shallower sample from the same well has fluid inclusions with lower homogenisation temperatures, yet records an increase in apparent salinity, this is most probably related to a slight increase in dissolved salt concentration which accompanied minor vapour loss.

Over the entire field, the main trend since inclusions formed is one of cooling in the southern part of the field and heating in the north-west. Orakeikorako is not the only geothermal system in New Zealand where fluid inclusions record the thermal evolution of the field.

CONCLUSIONS

- Cores recovered from below about **500m** contain hydrothermal mineral assemblages that include **quartz,** albite, adularia, illite, chlorite, epidote, calcite, pyrite and titanite (+/- wairakite, clinozoisite, siderite, apatite and leucoxene).

- The T_h values of secondary inclusions from 16 different depths mostly match measured bore temperatures (eg. OK2), but also indicate that the southern part of the Orakeikorako system has cooled (eg. OK4, maximum T_{bore}=230°C, maximum T_h=312°C) whereas the northwestern part may have heated (eg. OK6: 1113.4m, T_{bore}=261°C, T_h=210-221°C) since inclusions formed.

- Some secondary calc-silicate and clay minerals match the changes that have occurred in the thermal regime of the field and are consistent with the fluid inclusion results.

- The apparent salinities are from 0.2 to 1.8wt% NaCl equivalent, compared to surface discharges of 400mg/kg and deep fluids up to 546mg/kg. However, some of the variation in fluid inclusion indicated salinities may be due to the presence of dissolved CO_2.

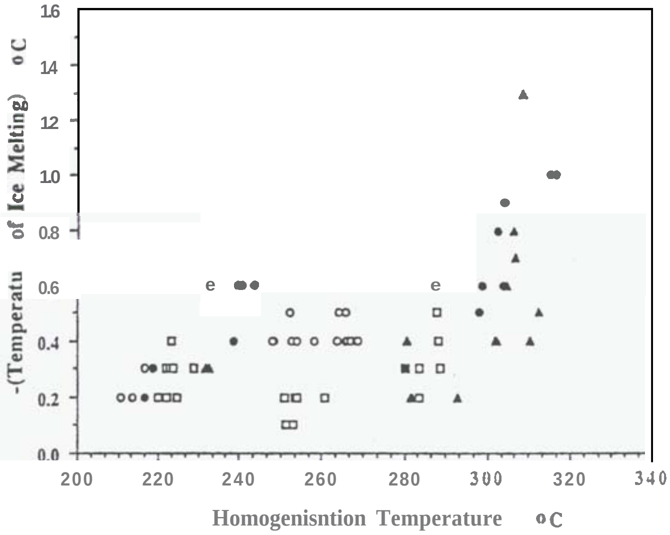

Figure 5: Homogenisation temperature data versus temperature of ice melting for inclusions from Orakeikorako samples. (● OK:1, □ OK:2, ▲ OK:4 and ○ OK:6).

- This paper emphasises the usefulness of fluid inclusion studies in understanding the hydrology of geothermal systems, past and present; and as a tool in planning the development of a geothermal field. Fluid inclusion results can be compared to the distribution of temperature dependent secondary minerals and measured thermal profiles and may indicate whether heating or cooling is occurring.

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