SUBSURFACE ALTERATION AT THE NGAWHA GEOTHERMAL FIELD: A PROGRESS REPORT

P.R.L. Browne and M.W. Gardner

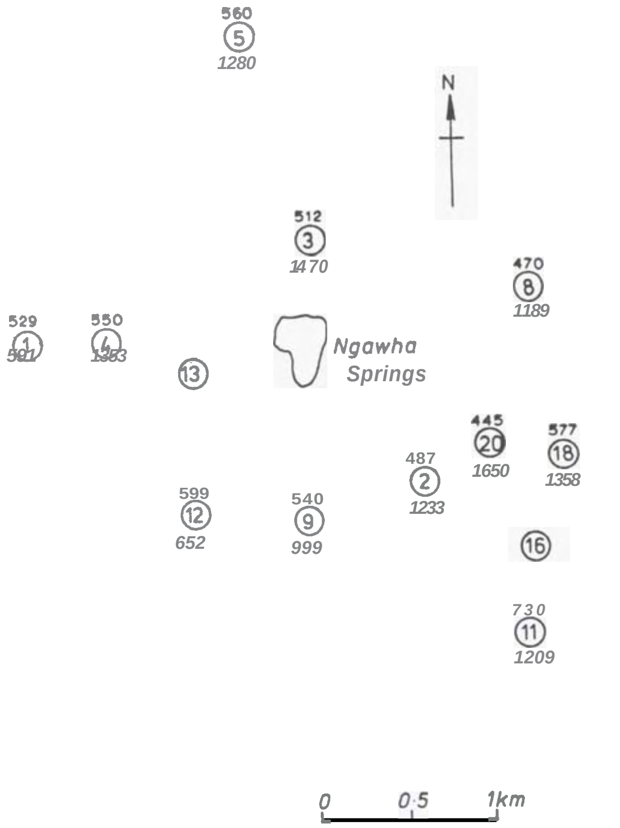
Geothermal Institute, University of Auckland;
NZ Geological Survey, Lower Hutt..

ABSTRACT

Twelve wells drilled by the Ministry of Works and Development at the Ngawha geothermal field, Northland, penetrated a 445-730 m thick sequence of deformed, sheared and brecciated Cretaceous-Tertiary siltstones, sandstones, claystones, limestones, and argillaceous limestones; these rocks are locally overlain by thin (< 40 m) basalt flows and lake beds. Fine-grained sandstones and argillites belonging to the Waipapa Group of Permian to Jurassic age, unconformably underlie the younger sediments and are of great, but unknown, thickness. The two groups of sediments contrast in their hydrology. The Cretaceous-Tertiary rocks are generally soft, incompetent and contain abundant montmorillonite, illite and minor, but widespread, kaolin and chlorite. These rocks do not allow the deep, near neutral, alkali chloride water to reach the surface, only steam and gas, mainly CO_2. Consequently, heat moves through these rocks mainly by conduction. The Waipapa Group rocks are of very low inherent porosity but can act as the reservoir because of locally high permeability due to the presence of numerous closely spaced joints, and faults. These controls on hydrology are reflected in the nature of the resultant hydrothermal alteration; the Cretaceous-Tertiary rocks record movement of CO_2 by the presence of recrystallised calcite; local steam condensation produced minor kaolin and heat transfer by changes in the hydration characteristics and crystallinity of the other clay minerals. These alteration features are best seen by X-Ray Diffraction and Differential Thermal Analysis. Veins of different ages occur in great abundance in the Waipapa Group greywackes and argillites; the formation of many of the veins clearly predated the onset of the present geothermal activity, but the youngest (e.g. calcite, quartz, pyrrhotite and pyrite) are probably 'modern'. However, other secondary minerals present in the rocks, both in the matrix and forming veins, probably determine, in some measure, the composition of the circulating reservoir fluid. These minerals include illite, epidote, chlorite, clinozoisite, pumpellyite, prehnite and hematite.

INTRODUCTION

The Ngawha geothermal field, Northland, has been the subject of intensive investigation and research since drilling by the NZ Ministry of Works and Development resumed in 1978; since that date 11 more wells, between 652 to 1650 m deep (Fig. 1) have been drilled. The most comprehensive recent survey of the field is a multidisciplinary report by DSIR (1981), which includes an account of subsurface hydrothermal alteration with summary descriptions of the alteration of cores and cuttings from drillholes Ng 1,2,4,5,7 & 9 (Browne, 1981). In this present paper we report progress on hydrothermal alteration studies of samples from some of the more recent drillholes.



610
7
1316

FIG. 1. Location of Ngawha drillholes; wellhead elevations vary from 116m (Ng7) to 272m (Ng20)
Key
540 - Depth to Waipapa Group rocks
9 - drillhole number
999 - depth of drillhole

GEOLOGY, STRUCTURE AND HYDROLOGY

The reservoir rocks of the Ngawha geothermal field, first encountered at depths below 445 to 730 m, consist of fine-grained greywackes and argillites belonging to the Waipapa Group of probable Permian to Jurassic age (Skinner, 1981). These rocks are of unknown thickness and are overlain by generally highly deformed Cretaceous-Tertiary siltstones, limestones, sandstones, argillaceous limestones and claystones. The youngest rocks in the field are localised, thin (210 m) Quaternary lake beds and basalt flows (~ 40 m thick). Near the probable northern margin of the Ngawha field, youthful, but extinct alkaline rhyolite, andesite and basalt volcanoes occur. It is probable that cooling magma of rhyolitic composition underlies the field, possibly at a depth as shallow as 3 km (Suprijadi, 1981). Numerous old and some probably active normal (and transcurrent) faults have been mapped in the area (Skinner, 1981; Grindley, 1981) and some of these have been intersected by drill-holes (e.g. Ng 4,9,18). Although these faults have generated permeable zones within the reservoir greywacke and argillite, nowhere do they allow unmodified fluid to migrate to the surface. This is because of the high clay content and incompetent nature of the overlying Cretaceous-Tertiary sediments; however, steam and gas, dominantly CO_2, separated from the deeper fluid does ascend, probably very slowly, through these rocks and mixes with local groundwater at the surface (Sheppard and Lyon, 1981). Total natural discharge of water from the main Ngawha area is possibly as little as 1 litre/second (Sheppard and Lyon, 1981).

Because of this very low porosity (< 3%) and high competency of the greywackes and argillites fluid mostly moves through these rocks in zones of closely spaced narrow joints many probably generated by faulting (Browne, 1980).

HYDROTHERMAL ALTERATION

It is difficult to be sure which minerals are presently forming by fluid/rock interaction or depositing from the thermal fluids now circulating; nevertheless, these processes are taking place in response to heat and fluid transfer within the Ngawha system. The dominant thermal process in these rocks is heat transfer by conduction and minor movement of steam and gases, mainly CO_2.

Alteration of Cretaceous-Tertiary Rocks

Only occasionally do core and cuttings samples from the base of the impermeable cover show the effects of water/rock interaction. For example, euhedral quartz crystals were recovered in cuttings from Ng.4 from 500 m depth and bright green glauconite-pyritic sandstone were found in Ng 5 material.

Typically, alteration of the Cretaceous-Tertiary rocks consist of recrystallisation and redistribution of calcite plus deposition of pyrite, rare pyrrhotite and changes in hydration characteristics of the phyllosilicates. Nearly all rocks composing this group are fine-grained or very fine-grained; almost all contain quartz, many also contain calcite plus lesser amounts of feldspar. Detrital clay minerals, however, are both abundant and widespread; montmorillonite is the most common but illite, chlorite, kaolin, interlayered illite-montmorillonite and rare biotite also occur. Although there is some microscopic evidence that kaolin and montmorillonite locally replace detrital feldspar in many places, these clays appear to have changed their hydration and crystallinity characteristics in response to the prevailing geothermal conditions. These changes are not obvious under the microscope but are, in places, apparent using X-Ray Diffraction (XRD) and Differential Thermal Analysis (DTA) methods. Although we have insufficient data to know the full range of their inherited hydration and crystallinity properties our data based upon cuttings from some recent wells, particularly Ng 8 and 18, show that with increasing depth and temperature:

1. The magnitude of the low temperature endothermic peak (montmorillonite and interlayered montmorillonite-illite) decreases with respect to the magnitude of the higher temperature endothermic peak (i.e. inversely related) (Browne and Gardner, 1981);
2. The temperature at which the low temperature endothermic reaction is at its maximum increases with depth; thus in cuttings from a depth of 25 m in Ng 18, it occurs at about 125° whereas at a depth of 465 m it takes place at about 170". However, there are exceptions to this and we suspect that some rehydration of montmorillonite may take place by absorbing drilling water (e.g. Ng 18, 545 and 565 m and Ng 11, 614 m);
3. The unexpanded (001) reflection of smectite decreases, from being commonly about 14.0 to 15.0 Å in cuttings down to a depth of about 150 m, to 12.0 to 14.0 Å in samples from below this. There are local reversals to this general observation, and on treatment with glycol the (001) reflection usually increases to between 16.7 and 17.0 Å irrespective of the depth of the samples;
4. The crystallinity of the smectites, as revealed by the sharpness of their (001) reflection varies but not as regularly as that described by Browne (1981) for samples from the early wells. Thus very poorly-crystalline smectite can persist below 200 m (Mg 11) whereas moderately well-crystallised types sometimes occur as shallow as 100 m (Ng 8 and 18). Perhaps in the latter case, as well as elsewhere, the crystallinity of the clays has not changed in response to the prevailing geothermal environment.

By contrast with some earlier wells, interlayered montmorillonite-illite is rare but a 7 Å clay is common; in most cuttings this is not accompanied by a 14 Å reflection but the

7 Å reflection is destroyed on heating above 550°C. This indicates that this clay is most probably kaolin, an identification consistent with a generally broad endothermic peak showing on the DTA at about 580°C. However, in some thin sections chlorite is also occasionally seen, so that in places both kaolin and chlorite are thought to occur. Limited data further suggest that the crystallinity of the 7 Å clay increases with both depth and temperature.

Alteration of the Waipapa Group Greywackes and Argillites

Veins are extremely common in these rocks and every cutting chip seems to contain at least one vein and many contain several. This contrasts with reservoir rocks of geothemal systems in the Taupo Volcanic Zone where veins are far fewer and fluid movement is largely within pore spaces in the rocks. Many of the veins in the Ngawha reservoir rocks, however, probably formed prior to the onset of geothermal activity and this is shown by comparing their textural relationships with veins seen in greywackes and argillites exposed by quarrying about 20 km away (Browne, 1980). Veins in both reservoir samples and those exposed in the quarry are usually narrower than 1 mm but occasionally exceed 10 mm. They are composed of quartz often with undulose extinction; and calcite with curved cleavage: features which are evidence for strong deformation. The youngest veins in reservoir rocks are composed of calcite so that it seems most likely that these, plus occasional lenses and veins of quartz and pyrrhotite have been deposited in response to present geothermal conditions. Other vein minerals, in places zonally distributed, include illite, pyrite, hematite, prehnite, chlorite, epidote, clinozoisite and pumpellyite. Calcite veins, however, seem to be most abundant in shallow parts of the greywacke and argillite rocks (500 to 1000 m below ground surface) and there is a suggestion that epidote veins become more common with increasing depth. Neither trend, however, is invariably the case.

Epidote, chlorite, illite, quartz, calcite, hematite, prehnite and pyrite also occur in the matrix of these rocks but formation of most phases undoubtedly predates that of the present geothermal activity. Illite does, however, replace detrital feldspar in some samples and hydrothermal biotite occurs in at least one (Ng 11, 896 m). The other listed minerals appear to be stable in the present environment and, indeed, it seems highly probable that their presence acts as a buffer for sodium, potassium, hydrogen, calcium and iron as well as serving as a control on the composition of the circulating fluid. Thus except for the presence of high concentrations of boron the composition of the Ngawha reservoir water is very similar to that of geothermal fluids occurring in fields of the Taupo Volcanic Zones (Sheppard and Lyon, 1981).

OUTLINE OF SECONDARY MINERAL DISTRIBUTIONS IN DRILLHOLES

Ng 8 Greywackes and argillites were reached at a depth of 470 m; the overlying Cretaceous-Tertiary sediments contain abundant clay minerals (Table 1), recrystallised calcite, hematite and minor pyrite. Montmorillonite is present in all cuttings examined by X-Ray Diffraction but only below 375 m is it interlayered with minor illite. The sharpness of the (001) montmorillonite reflections vary but most are broad, indicating poor crystallinity. Montmorillonite from above 170 m shows reflections with a basal spacing greater than 14.0 Å. However, glycol treatment typically expands this reflection to between 16 and 17.7 Å. Chlorite occurs in some samples but small amounts of kaolin are common in most; discrete illite, mainly poor to very poorly crystalline, is present above 350 m but is rarely abundant. Montmorillonite does not occur in the greywacke-argillite samples, however, although illite and chlorite are almost ubiquitous in the core from 490 m, for examples, needles and flakes up to 0.07 mm long of both minerals are present and very well-crystallised. Epidote occurs in patches in core from 826.8 m and forms veins in many of the deeper samples although it is absent in places (e.g. cuttings from 1015 m). Veins of calcite post-date both quartz veins as well as periods of brecciation and deformation; pumpellyite is locally abundant, forming lenses and veins. Poorly crystalline, dusty sphene crystals are disseminated throughout many samples.

Ng 11 Montmorillonite is widespread and abundant in all samples of the Cretaceous-Tertiary rocks down to 730 m and in the very curious 4 m thick inlier of the same rocks at 897 m. It is very poorly crystalline but only in a few samples (e.g. 290 m) is it interlayered with minor illite; the montmorillonite expands upon treatment with glycol but the 'starting' (001) reflection varies between 11.1 Å (897 m) to 14.7 Å (25 m). Discrete, very poor to moderately well-crystallised illite occurs in almost all samples of both the Cretaceous-Tertiary and Waipapa Group rocks down to 915 m, but below this depth is much better crystallised. Prehnite forms veins in a core of siltstone from 614 m, as does quartz, and both minerals also occur in deep cuttings. Epidote is present in cuttings from 1025 m and in some deeper cores (e.g. 1216 m); weakly pleochroic biotite is present in a core of brecciated argillite from 896 m where it appears to be of hydrothermal origin. Calcite is a common vein mineral in many samples from this well and pyrite occurs locally.

Ng 12 Work on samples from this well is far from complete but petrographic examination shows that many of the cuttings are brecciated and silicified. This well only reached a depth of 652 m, about 53 m into the Waipapa Group rocks. At

TABLE 1: **Summary** of DTA and XRD results of cuttings of Cretaceous-Tertiary rocks, Well Ng 8. Mineral abundances are estimates on an arbitrary scale of 0 - 5.

Depth (m)	Quartz Abundance	Feldspar Abundance	Calcite Abundance	Calcite DTA Peak °C	Illite Abundance	Illite Crystallinity
5	5	0	0	nr	0.5	very poor
25	5	0	0	nr	0.5	very poor
50	5	0.5	0.5	nr	2	moderate
75	4	0	4	nr	2	moderate
100	4	0	2	nr	2	very poor
125	4	0	1.5	nr	3	poor
150	4	0	1	nr	3	poor
175	4	0	2	880	1.5	poor
200	4	0	1	840	3	poor
225	4	4	4	880	3	very poor
250	5	0	4	880	3	very poor
275	5	1	3	930	3	very poor
300	5	1	3	870	3	poor
325	5	0	3	920	1	very poor
350	5	1	1	870	2	very poor
375	?	3	3	880	0	-
400	4	2	2	860	0	-
450	5	0	5	900	0	-
475	4	1	1	860	2	well

Depth (m)	Montmorillonite and Interlayered i/m Abundance	Crystallinity	Swelling Å	Swelling Å	DTA Peaks °C	7Å Clay Abundance	Sulphate Abundance
5	1.5	poor	16.7	17.3	nr	absent	-
25	0.5	very poor	15.0	18.4	nr	trace-chlorite	-
50	5	poor	14.7	17.0	nr	trace	-
75	3	poor	14.3	16.4	nr	0.5 kaolin	-
100	2.5	moderate	14.5	17.0	nr	0.5 kaolin	-
125	5	moderate	14.0	17.0	nr	0.5 kaolin	-
150	4	moderate	14.7	16.7	nr	2 kaolin	-
175	2.5	poor	13.8	16.1	140,580	0.5 kaolin	absent
200	4	very poor	13.4	13.4	150,120	4 kaolin(590)	absent
225	4	very poor	13.4	16.4	150,120	2 kaolin(570)	trace
250	4	very poor	13.6	15.8	130	2 kaolin	absent
275	4	poor	13.4	17.7	160	1 kaolin(600)	1
300	4	poor	14	~19	120,140	1 kaolin(580)	0.5
325	3	very poor	13.4	17	130,150	1 kaolin(580)	absent
350	4	poor	12.6	16.4	160	1 kaolin(580)	0.5
375	4	moderate.(i/m)	13	16.7	150	1 'kaolin(560)	0.5
400	3	poor (i/m)	12.6	17	-	1 kaolin(560)	absent
450	4	poor (i/m)	13.4	16.7	-	1 kaolin(560)	2
475	absent	-	-	-	-	2 .chlorite	0.5

nr = not recorded

TABLE 2: Summary of Differential Thermal Analysis : Results of cuttings from Ng 18. Waipapa Group rocks were reached at 579 m.

Depth (m) (KD)		Montmorillonite and interlayered llite/montmorillonite Relative abundance	Low temp endothermic peak (°C±5)	High temp endothermic peak (°C)	Pyrite Relative abundance	Calcite Relative abundance	Endothermic peak (°C)
25		major	125	-	trace	-	-
45		major	125	-	trace	trace	-
65		minor	142	-	trace	minor	905
85		minor	unclear	-	trace	trace	825
105		minor	140	-	trace	trace	880
125		minor	160	-	-	abundant	920
145		minor	155	-	-	minor	910
165		minor	158	-	-	minor	865
185		minor	135	562	trace	minor	840
205		major	142	590	-	trace	830
225		minor	140	580	-	minor	840
245		minor	145	560	trace	minor	845
265		major(doublet)	150	590	minor	trace	810
285		major	158	620 (broad)	-	minor	835
305		major	145	580 (broad)	trace	major	850
325		minor	153	broad	trace	dominant	945
345		minor	160	590 (broad)	trace	dominant	910
365		major	150	570 (broad)	trace	dominant	905
385		major	162	broad	trace	major	910
405		major(doublet)	170	605 (broad)	trace	dominant	960
425		major	160	600 (v. broad)	none	minor	830
445		major(doublet)	160	600 (v. broad)	trace	major	825
465		major(doublet)	175	590	sl.trace	minor	885
485		major(doublet)	160	560	none	slight trace	~840
505		minor	155	580 (broad)	none	none	-
525		major(doublet)	160	600 (v.broad)	sl.trace	minor	880
545		minor	150	580 (v. broad)	sl.trace	minor	850
565		minor(doublet)	140	580 (broad)	minor	minor	895
585	?	v. minor(broad)	130	590 (v.broad)	none	trace	855
605		none	-	580 (broad)	none	slight trace	900
625		slight	180	590	none	slight trace	820
645		none	-	590	none	slight trace	810
665		none	-	585 (broad)	none	none	-
685	?	v. minor(broad)	130	580	sl.trace	minor	860
705		none	-	600 (v.broad)	sl.trace	slight trace	835
725		none	-	580 (v.broad)	sl.trace	minor	830
765		none		580 (v broad)	none	trace	840
785		none	-	600 (v. broad)	none	trace	810
805		none	-	570 (v.broad)	none	slight trace	810
825		none	-	580 (broad)	trace	trace	890
845		none	-	600 (v.broad)	none	minor(?)dolomite	810 & 930
865		none	-	590 (v.broad)	trace	none	-
885		none	-	? 570 (v.broad	v.sl.trace	slight trace	900
925		none	-	570 (broad)	none	?minor dolomite	830 & 925
985		none	-	590 (v.broad)	none	none	-
1005		none	-	none	tr.pyrrhotite	very slight trace	890
1025		none	-	? 580 (v.broad)	none	slight trace	800 & 910
1045		none	-	? 580 (v. broad)	none	trace	890
1965		none	-	-	none	trace	930
1085		none	-	570 (v.broad)	none	trace(?)dolomite	795 & 920
1100		none		-	none	trace	895

that depth they locally contain irregular veins of pumpellyite and lenses of calcite, ancient but also some modern quartz and, in places, both pyrite and pyrrhotite. Calcite, as crystals up to 4 mm long, from 645.6 to 648.5 m depth has a bladed morphology suggesting that boiling has taken place near here. Epidote occurs in a few chips but its deposition predated that of the enclosing quartz.

Ng 18 Differential Thermal Analysis results (Table 2) show that montmorillonite occurs in all samples analysed to a depth of 585 m and also occasionally in trace amounts below this. In many cuttings it is abundant with prominant low temperature endothermic peaks; these have a double peak in some samples, and there is a progressive, but not regular, increase in the temperature at which the main reaction occurs. Therefore, shallow samples (25 and 45 m) have endothermic peaks at 125° but in a sample from 625 m depth this peak shifts to a temperature of 180°. However, the occasional deep sample (e.g. 685 m), which shows a lower temperature (130°) endothermic reaction is interpreted as resulting from a rehydration of the clay by absorbing drilling water. Higher temperature (generally between 560 and 600") endothermic peaks occur in many samples from below 200 m depth; it is difficult to assign it to a particular mineral as it is typically broad, but in shallow samples it is probably caused by either montmorillonite or kaolin and in the deeper sample it is probably produced by illite and chlorite.

Many cuttings and some cores from this well are strongly brecciated, e.g. core from 574 - 576 m is markedly sheared and evidently derived from a fault zone (D.N.B. Skinner, pers. comm.). However, calcite forms irregular veins in the core and these formed after most shearing ceased. Cores of Waipapa Group rocks contain abundant quartz, chlorite and calcite plus irregularly distributed clinozoisite, hematite, disseminated sphene and variable amounts of epidote, most abundant at a depth of about 1220 m.

GENERAL COMMENTS

The observed subsurface alteration at Ngawha is consistent with a model whereby ascending alkali-chloride water of near neutral pH moves through a myriad of closely spaced, narrow joints whose permeability varies in response to sealing and regeneration, the latter, perhaps by faulting. This fluid contains carbon dioxide which is mostly lost above a depth of about 700 m. The CO_2 plus separated steam and other gases, ascends rather slowly through the covering Cretaceous-Tertiary rocks, condensing in places to produce kaolin, but with some gas reaching the surface. The alkali-chloride water itself remains trapped below these overlying lithologies but can migrate laterally within joints in the argillites and greywackes. Fluid inclusion homogenisation temperatures, measured by Ml A. Christie, Victoria University of Wellington (Browne,1981) show that thermal changes have occurred during the life of the Ngawha field; for example, in the northern part of the area drilled (Ng 5) there is evidence of heating, whereas the central part seems to have been more thermally stable.

ACKNOWLEDGEMENTS

We thank Janet Ashcroft for making many X-Ray Diffraction Analyses of cuttings; the University Grants Committee for travel support and the Lottery Board for providing funds for a petrographic microscope. Malcolm Cox offered helpful suggestions.

REFERENCES

Browne, P.R.L., 1980: Joint channels in reservoir rocks of the Ngawha Geothermal field, Northland. Proceedings of the New Zealand Geothermal Workshop, 1980, Auckland Uni., 81-89.

Browne, P.R.L., 1981: Hydrothermal alteration at Ngawha. in DSIR Report, No.7, 87-94.

Browne, P.R.L. and M.W. Gardner, 1981: Differential thermal analysis as an aid in geothermal petrology. Proceedings of NZ Geothermal Workshop 1981, Auckland Uni., 209-218.

DSIR, 1981: The Ngawha geothermal area. Geothermal Report, No.7, DSIR Wellington, 167 pp.

Grindley, G.W., 1981: Geological history and structure of the Ngawha area. in DSIR Report No.7, 7-13.

Sheppard, D.S. and G.L. Lyon, 1981: Chemistry of the Ngawha thermal area. in DSIR Geothermal Report No. 7, 95-128.

Skinner, D.N.B., 1981: Geological setting and sub-surface geology of Ngawha. in DSIR Geothermal Report, No.7, 14-35.

Suprijadi, 1981: 3D gravity modelling of Ngawha. Geothermal Institute Project.