ALTERATION MINERALOGY OF SEDIMENTS IN THE HUKA FALLS FORMATION OF THE TE MIHI AREA, WAIRAKEI

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SUMMARY The Huka Falls Formation (HFF) in the Te Mihi area of the Wairakei geothermal system comprises hydrothermal eruption breccias and lacustrine sediments locally up to 230m thick. Sixty core samples recovered from drillholes WK201, 202, 206, 207, 219 and 222 contain hydrothermal minerals grouped into 3 zones; smectite, adularia-calcite-chlorite and adularia-illite, that reflect the prevailing thermal regime. Smectites occur in the sediments where measured well temperatures are below 90° and adularia-calcite-chlorite between 90° and 220°C. End member illite occurs where temperatures exceed 180° with interlayered illite-smectite having increasing proportions of illite at higher temperatures.

INTRODUCTION

The Huka Falls Formation (HFF) is the most widespread sedimentary formation in the Taupo Volcanic Zone. It is hydrologically important at Wairakei (Figure 1), where it occurs at shallow depths between the top of the dominantly volcanic Waiora Formation (WF) and the base of the 22,7Ka year old Wairakei Breccia (WB) (Grindley, 1965; Steiner, 1977).

In the Te Mihi area (Figure 2) the HFF includes hydrothermal emption breccias and lacustrine sediments that comprise bedded mudstones and coarse tuffaceous mudstones totally 180 to 230m in thickness (Figure 3).

The hydrothermal alteration of the HFF is not so obvious as it is in the more reactive underlying volcanic rocks (Steiner, 1977), but the lacustrine sediments have indeed also responded to the geothermal environment by interacting with the hot thermal fluids (Figure 4). The purpose of this paper is to describe progress on the study of the alteration of these sediments and to demonstrate that their secondary mineralogy also reflects the thermal region prevailing in the Te Mihi area

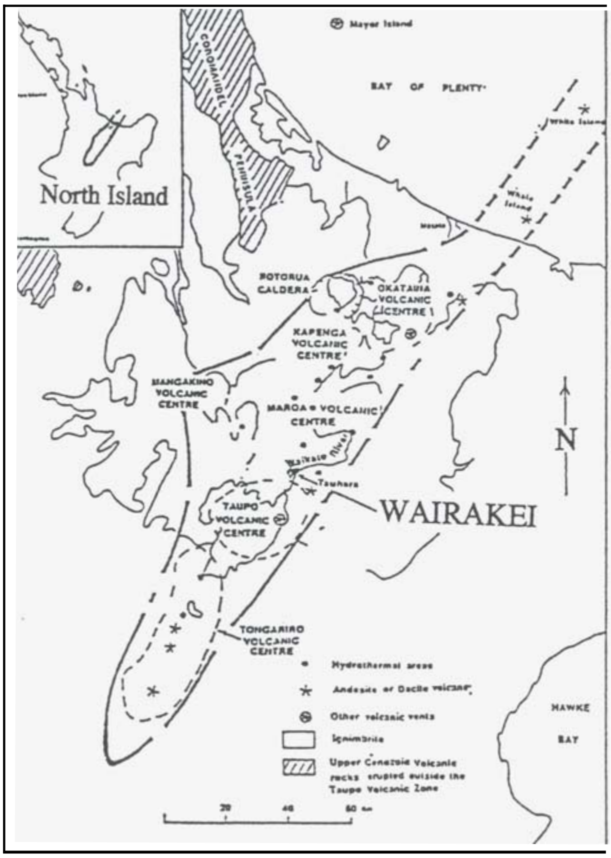

Figure 1. Location of the Wairakei geothermal system in the Taupo Volcanic Zone, North Island, New Zealand.

Our study is based an examination of more than 60 core samples recovered from the shallow parts of drillholes WK201, 202, 206, 207, 219 and 222 (Figure 2).

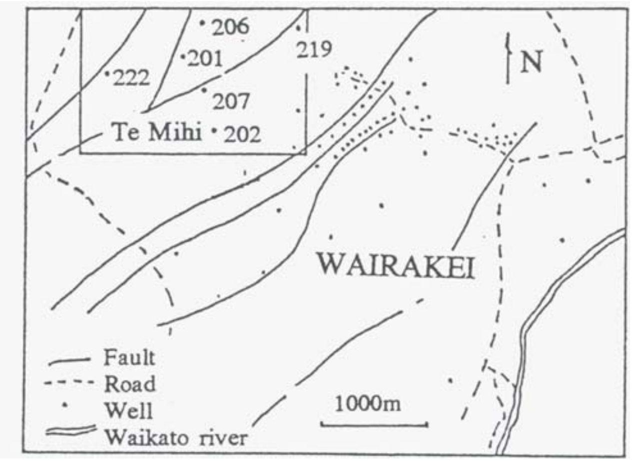

Figure 2. Location of the Te Mihi sector of Wairakei and well locations (from Grindley, 1965).

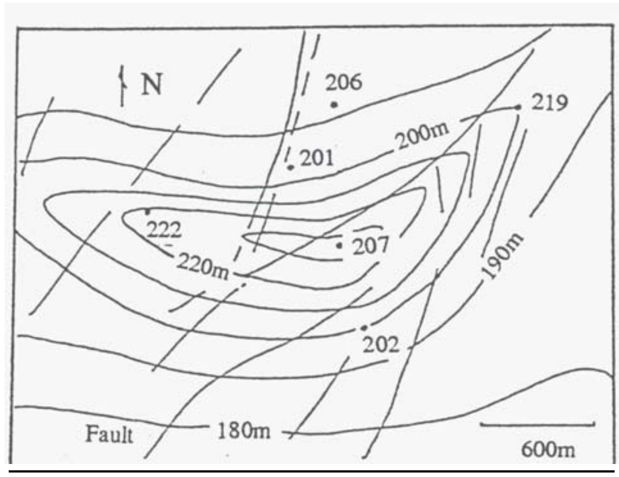

Figure 3. Isopach map of the HFF in the Te Mihi sector (modified from Grindley, 1965).

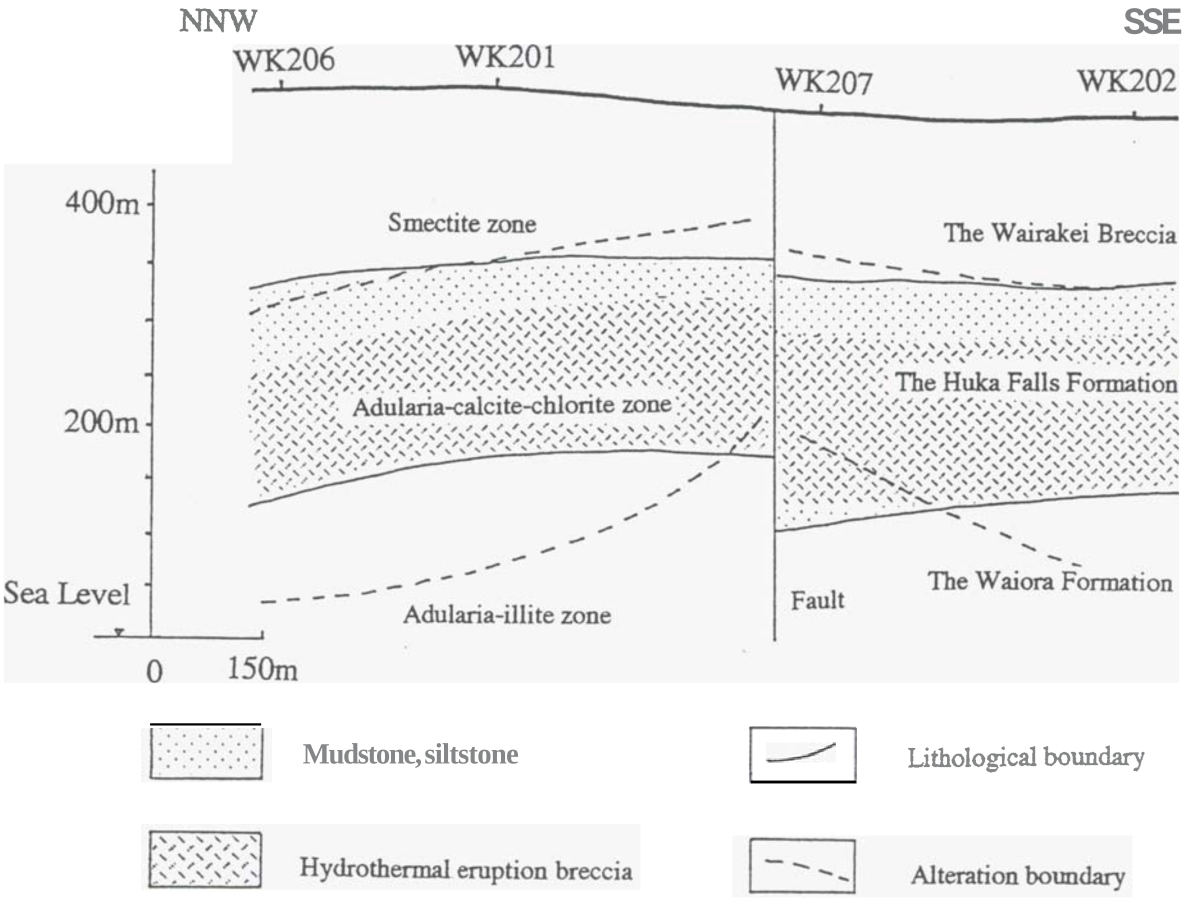

Figure 4. Cross section through the Te Mihi sector showing lithology and alteration zones

METHODS

The mineralogy of the cores was determined mainly using thin section petrography and X-Diffraction analysis, including glycolation and heat treatment of clay separates.

Oriented clay samples were prepared by pipetting a clay slurry onto a glass slide. All samples were run on a Phillips X-ray diffractometer (in the Geology Department, University of Auckland) using CuKα (1.5418Å) radiation and a scanning speed of 3°/min, from 2 to 30 degrees.

X-ray identifications of the clay minerals were made by using the JCPDS file and the data of Brindley and Brown (1980); the compositions of the mixed-layer clay minerals were determined by comparison of the saturated ethylene glycol sample patterns with the data of Reynolds, et al (1970, 1980).

PRIMARY MINERALOGY

The primary minerals decrease in abundance with depth in the Huka Falls Formation (Figure 5). They include quartz, plagioclase, volcanic glass, minor apatite and zircon, rare hornblende and biotite, magnetite, titanomagnetite and occasional lithic fragments.

Detrital quartz occurs in samples from all depths, comprising <15 vol.%; it is present as 0.01-1.5mm diameter, subhedral, embayed crystals, some with shatter cracks. Plagioclase (5-15 vol.%) occurs as subhedral-anhedral, 0.05-2mm diameter crystals of about An25 composition. Glass shards remain in a few cores but most have altered entirely.

The order of increasing stability of the primary constituents in the Te Mihi cores is: glass, magnetite, hornblende, biotite, plagioclase. This is the same sequence as that determined by Steiner (1977).

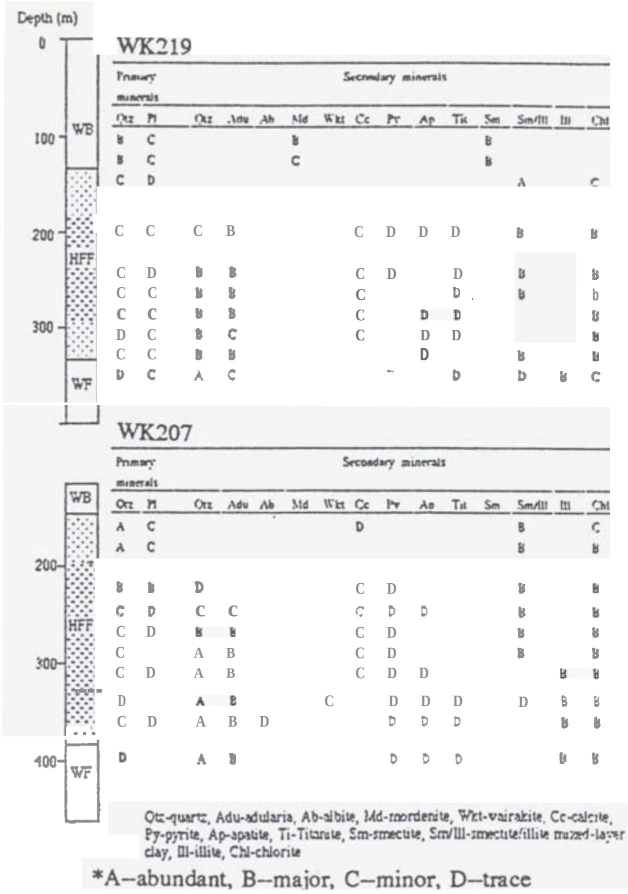

Figure 5. Distribution of the primary and alteration minerals in cores from drillholes WK219 and WK207.

ALTERATION MINERALOGY

Several associations of hydrothermal minerals are recognized and their distributions are shown in Figures 4 and 5.

Quartz is the most common secondary mineral in the HFF, occurring as a recrystallization product of glass shards present in the tuffaceous material and pumice. The abundance of secondary quartz increases with depth in the HFF. Quartz veins have developed locally and quartz is also present in vugs at several depths (e.g. 274-282m depth WK207)

Adularia is locally abundant being distributed over a very wide range of depths. It replaces plagioclase, sometimes accompanied by albite, calcite and wairakite. Albite is not common, occurring in the groundmass and as a replacement of plagioclase, usually together with adularia, at lower depths in the HFF (e.g. WK207, 250m, 360m). No albite was found in cores from shallow depths.

Mordenite occurs in the upper part of the HFF and the Wairakei Breccia. It is usually present together with smectite (Table 1). Wairakite only occurs below 335m depth in WK207 as an alteration product of both plagioclase and the groundmass.

Calcite is a very common minor hydrothermal mineral, replacing primary plagioclase both alone and together with adularia. Calcite also replaces the groundmass, fills interstices and veinlets, and lines the walls of fractures. The vertical distribution of calcite in the HFF indicates it formed over a wide temperature range. Large bladed calcite crystals indicate boiling occurred in the lower part of the HFF, e.g. at 275m, WK207.

Pyrite is a common trace mineral present over a wide temperature range. It occurs as small anhedral clots to subhedral rhombs throughout the groundmass, usually as a replacement of magnetite and mafic minerals. It commonly forms minute cubes, or rarely octahedra. Titanite (sphene) is also a common trace or minor mineral which is present as brownish, fine-grained, cloudy aggregates in the groundmass. Apatite occurs as small euhedral crystals in the groundmass but never in more than *trace* amounts.

Zonation of Hydrothermal Minerals

Alteration zonation in the HFF at Te Mihi is marked by both rank and intensity variations Three zones are recognised: i.e. smectite, adularia-calcite-chlorite and adularia-illite. These are shown on Figures 4 and 5.

Table 1. Representative clay mineralogy of cores from drillholes WK202 and WK219.

WK202

Depth (m)	Elevation R.S.L.(m)	Unit	Lithology	Measured T (°C)	2-0.2 Micron Fraction	<0.2 Micron Fraction
152	345	WB	lapilli tuff	89	Sm + Md	Sm + Md(m)
155	342	HFF	siltstone	90	Chl + Md	Chl+70%Ill/Sm(m)+Md (m)
183	314.	HFF	tuff	109	Chl + Md	95%Chl/Sm + Md
215	282	HFF	breccia	140	Chl + 80%Ill/Sm	Chl + 75%Ill/Sm
244	253	HFF	breccia	160	Chl + 90%Ill/Sm	Chl + 90%Ill/Sm
274	223	HFF	breccia	182	Chl + 90%Ill/Sm	Chl + 80%Ill/Sm
290	207	HFF	breccia	192	Chl(m) + 90%Ill/Sm	Chl(m) + 85%Ill/Sm
305	192	HFF	breccia	202	Chl + 90%Ill/Sm	Chl + 80%Ill/Sm
399	98	HFF	lapilli tuff	216	Chl(m) + 80%Ill/Sm	95%Chl/Sm(m) +90%Ill/Sm
430	67	WF	ruff	221	Chl(m) + 95%Ill/Sm	Chl(m) + Illite
433-457	64-40	WF	tuff	221-228	Chl(m) + Illite	Chl(m) + Illite

WK219

Depth (m)	Elevation R.S.L.(m)	Unit	Lithology	Measured T (°C)	2-0.2 Micron Fraction	<0.2 Micron Fraction
116	356	WB	lapilliruff		Md	Sm + Chl(m) + Md
143	329	HFF	mudstone		Sm	Sm + 10%Ill/Sm + Chl(m)
154	318	HFF	mudstone		Chl + 60%Ill/Sm	Chl(m) + 55%Ill/Sm
188	284	HFF	breccia		Sm + 70%Ill/Sm	Chl + 80%Ill/Sm
259	213	HFF	breccia		Chl + 90%Ill/Sm	Chl + 80%Ill/Sm
274-276	198-196	HFF	breccia		Chl + 95%Ill/Sm	Chl + 90%Ill/Sm
290-291	182-181	HFF	breccia		Chl + 90%Ill/Sm	Chl(m) + 90%Ill/Sm(m)
305	167	HFF	siltstone		Chl + 85%Ill/Sm	Chl + 70%Ill/Sm
320-322	152-150	HFF	silt-mudstone		Chl	Chl
335	137	HFF	mudstone		Chl + 85%Ill/Sm	Chl + 80%Ill/Sm
366	106	WF	crystal tuff		Chl + 90%Ill/Sm(m)	Chl + Illite

* (m)--minor, Sm--smectite, Md--mordenite, Chl-chlorite, Ill/Sm--illite/smectite mixed-layer clay

* Temperatures data from Grindley, 1965

The smectite zone is a low rank and low intensity alteration zone, which occurs in the Wairakei Breccia **and** locally in **the** upper part of the Huka Falls Formation. It is characterised by abundant smectites and mordenite. In addition, minor calcite, adularia and traces of pyrite occur locally. Chlorites are rare. The smectite zone is poorly permeable; **The adularia-calcite-chlorite zone** is of low to intermediate rank and alteration intensity hosted by the HFF and the upper parts of the Waiora Formation. This zone is distinguished by the presence of adularia, calcite, chlorite and mixed-layer clays (illite-smectite). Secondary quartz is **also** common and increases in abundance with increasing depth. This zone is interpreted to a boiling horizon, **as** shown by the Occurrence of platy calcite (e.g. WK207, 275m). Its permeability is much higher than that of the smectite zone **as** is indicated by the occurrence here of adularia. The **adularia-illite** zone **, of** intermediate **rank** and high intensity alteration, is located in the Waiora Formation **and** locally in the lower part of the HFF, e.g. WK207 (Figure **4).** This zone is distinguished by the presence of illite and abundant adularia. Chlorite distribution is **irregular.**

Clay mineralogy

Smectites **occur** at temperatures below 90°C within the WB and locally near the top of HFF (Table 1). Chlorites **are** present in the HFF and the WF, covering a range of temperatures from 90°C to above 220°C. Locally chlorites have about **5%** smectite layers in their structures, thus forming chlorite-smectite mixed-layer clays. The illite-smectite mixed-layer clays occur in the HFF and the upper part of the WF; the interlayer occupancy of the illite component increases regularly with temperature. End member illite appears **at** temperatures above **180°C,** in the WF and locally the lower part of the HFF. Table 1 shows the distribution and identity of the clay mineral present in cores from two representative drillholes, WK219 and **WK207.**

An empirical relationship between the illite-smectite mixed-layer clays and their formation temperatures **was** calibrated from 90° to **230°C.(Figure 6),** based on **data** from drillholes **WK202 (Table** 1), WK207 and WK210 (Harvey and Browne, 1991).

The relationship is : $Y=0.34+2.74*10^{-3}T$

Y is the proportion of illite present in the illite-smectite mixed-layer, T is **the** appropriate measured downhole temperature (Grindley, 1965).

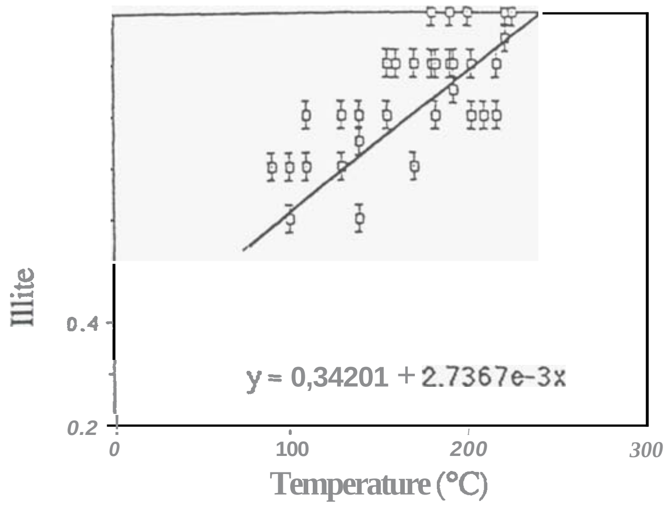

Figure 6. Relationship between the Ill/Sm mixed-layer clays and **measured** temperatures ***(see*** text)

The expandibility of the basal layer of the Ill/Sm mixed-layer clays decreases with increasing downhole temperature and depth. The basal d-spacing of air-dried clays decreases, **and** that of the glycolated samples increases with increasing temperature and depth (e.g. ***see*** Figure 7).

The half **peak** height widths (Kubler Index, $\Delta°2\theta$) of the mixed-layer clays and basal spacing of chlorite were used as **a** measure of their crystallinity. The 'illite crystallinity' of **the** illite-smectite mixed-layer clays increases with increasing temperature and depth, **as** shown by their Kubler Index values. However, chlorite crystallinity changes only slightly with temperature, showing a high degree of crystallinity throughout (average $\Delta°2\theta$ = 0.28) (Figure 8). The Kubler Index of the illites is from 0.35 to 0.44.

The chlorites are all of iron rich trioctohedral type with their 7Å and 3.54Å peaks being much higher than those at 14A and 4.7Å. There is no clear relationship between their Al^{IV}, Fe^{II} contents and temperature. This suggests that variations are partly influenced by temperature, but also depend on permeability of the host rocks and the composition of the reacting fluid.

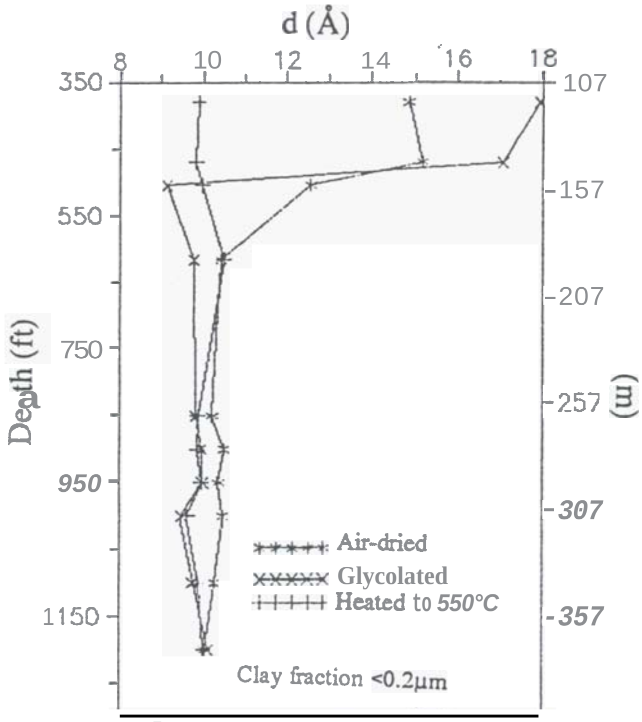

Figure 7. Basal d-spacing values of clays vs depth for cores from drillhole WK219

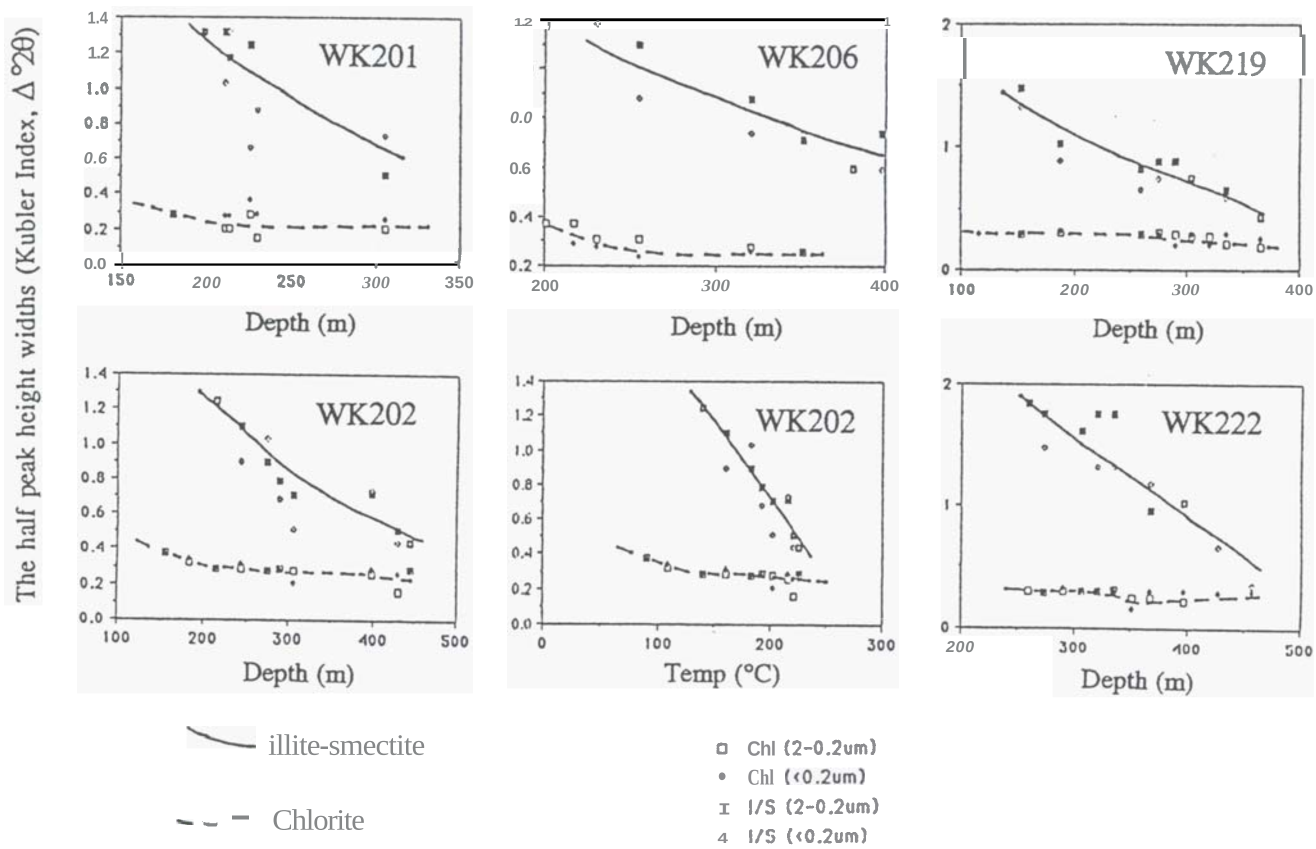

Figure 8. Relationship between 'illite crystallinity' of Ill/Sm mixed-layer clays, chlorite crystallinity, core depth and measured drillhole temperatures (temperatures data fom Grindley, 1965).

CONCLUSIONS

(1) Hydrothermal alteration in the HFF generally increases in intensity and rank with increasing temperature and depth. Based on the secondary mineralogy, 3 alteration zones are recognized: smectite, adularia-calcite-chlorite and adularia-illite.

(2) The alteration m i n d assemblages differ regularly with depth at shallow levels in the Te Mihi sector of the Wairakei field. There are no differences in the mineral assemblages present in the HFF, the WB or the WF, that can be attributed only to lithological control.

(3) In different parts of the Te Mihi sector, the HFF, especially in its upper levels, shows differences in alteration, both inintensity and rank. This reflects variations in the thermal regime.

(4) The major factors controlling alteration are temperature, fluid composition and permeability. Smectites occur at less than 90°C, but chlorites cover a range of formation temperatures, from 90°C to above 220°C. The illite-smectite mixed-layer clays have developed with the interlayer occupancy of the illite component increasing regularly with temperature. End member illite occurs at temperature above 180°C.

(5) The 'illite crystallinity' of the illite-smectite mixed-layer clays increases with temperature and depth. However, chlorite crystallinity increases only slightly with temperature, showing a high degree of crystallinity throughout. The Kubler Index ($\Delta °2\theta$) of the illites is from 0.35 to 0.44.

(6) The chlorites are all iron rich. Compositional variations, such as the amount of Al^{IV} present in the tetrahedral site and their Fe contents, are partly influenced by temperature, but also depend on permeability of the host rocks and the composition of the reacting fluid.

(7) An empirical relationship between the illite-smectite mixed-layer clays and temperature was established from 90° to 230°C. The clay geothermometers provide tools for estimating the formation temperature of clays present in extinct geothermal systems and metamorphic rocks formed at low temperatures.

ACKNOWLEDGEMENTS

We thank Dr Colin Harvey for his advice and suggestions and Electricorp Production, Wairakei for allowing us access to the cores.

This paper is dedicated to a mineralogist : Ma Jingde (1939-1991)

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