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Use of Illite Crystallinity as a Temperature Indicator in the Orakei Korako Geothermal System, New Zealand

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Keywords

Illite crystallinity, geothermometry, fluid inclusion geothermometry, Orakei Korako

ABSTRACT

An empirical relationship between the measured downhole temperatures and Kubler Indices, based on drillhole data and mineralogical evidence from a thermally stable part of the Orakei Korako geothermal system (New Zealand), is $T_{\text{bore}}(^{\circ}\text{C}) = 300 - 88.4 \times K$, where K is the Kubler Index (half peak height width, or $^{\circ}\Delta 2\theta$) of the (001) illite peak and T_{bore} is the measured downhole temperature. Illite crystallinity (IC) data, fluid inclusion geothermometry, and T_{bore} values indicate stable thermal conditions in the Te Kapua (Drillhole OK-2) area, but the southern part of the system is now cooler (by at least 120 $^{\circ}\text{C}$) than it was in the past.

Introduction

The Orakei Korako geothermal area (Figure 1) was investigated in the mid-1960's by drilling four vertical wells to a maximum depth of 1403.6m. The area comprises a sequence of generally SE-dipping, Quaternary ignimbrites, airfall and lacustrine tuffs, hydrothermal eruption breccias and intercalated rhyolite lava flows (Lloyd, 1972; Bignall, 1994). A feature of the geothermal field is its vertical permeability, provided by faults, indicated by slickensided cores, with associated joints and breccia zones and intense hydrothermal alteration. The hydrothermal minerals present include widespread illite whose crystallinity (IC) varies spatially. This paper reports the thermal significance of the IC variations. We also compare the measured drillhole temperatures with those inferred from chemical geothermometry, fluid inclusion geothermometry and the stability ranges at which temperature-dependent secondary minerals usually form. This comparison, therefore, tests the usefulness of illite crystallinity as a temperature indicator in a hydrothermal system.

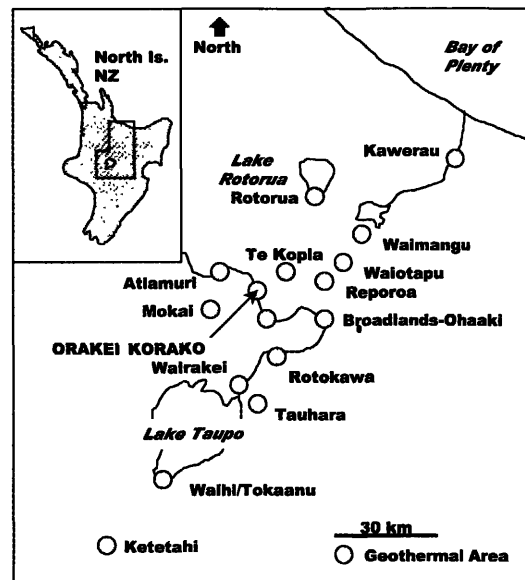


Figure 1. Location of major geothermal areas in the Taupo Volcanic Zone, New Zealand.

Geothermal Activity and Fluid Chemistry

The presently active thermal area at Orakei Korako covers ~1.8km² (Figure 2). The locations of many hot springs, pools and geysers are associated with several SW-NE trending faults, which channel hot, neutral pH alkali chloride-bicarbonate water to the surface. Spring waters are characterized by chloride contents of 250-400mg/kg, bicarbonate contents of 100-300mg/kg, sulfate contents of 50-250mg/kg and pH values ranging from 7.5 to 9.0 (Sheppard and Lyon, 1984; Bignall, 1994).

Chemical and isotope geothermometry (Sheppard and Lyon, 1984) indicate a reservoir hotter than 245 $^{\circ}\text{C}$ supplies the surface features. The T_{NaCaK} geothermometer indicates even higher temperatures, up to 260 $^{\circ}\text{C}$, which match the maximum measured drillhole temperature of 265 $^{\circ}\text{C}$ (in drillhole OK-2). Fluid discharged from OK-2 indicates water in the reservoir has a chloride content of ~385mg/kg, although this is likely to be a

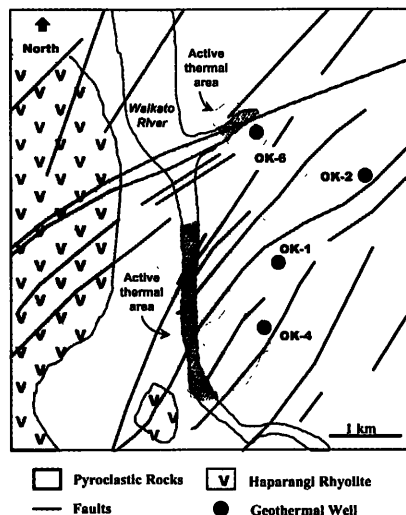
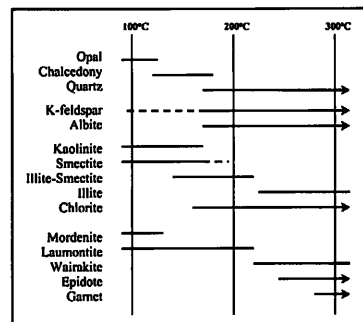


Figure 2. Location of active thermal areas, geothermal drillholes, and surface geology at the Orakei Korako geothermal field, Taupo Volcanic Zone, New Zealand (after Bignall, 1994).

minimum value since it may be diluted with ground water. Sheppard and Lyon (1984) suggest that the deep water contains ~430mg/kg chloride.

The most conspicuous thermal deposit is the Umukuri Sinter (~1km², which is up to 18m thick (Lloyd, 1972; Campbell *et al*, in press) but mud pools and warm ground east of the main hot spring area contain cristobalite, alunite, native sulfur and kaolin.

Table 1. Thermal stabilities for common hydrothermal minerals in active geothermal systems of the Taupo Volcanic Zone, New Zealand (after Simmons *et al.*, 1992).



Hydrothermal Alteration and Reservoir Conditions.

Fluid-rock interactions at Orakei Korako have produced an assemblage of secondary minerals, below ~500m, that includes adularia, albite, calcite, chlorite, epidote, illite and quartz, +/- pyrite, titanite, leucoxene, wairakite and almandine (Figure 3), with characteristic temperature stabilities that range from ~210°C to >280°C (Table 1). The secondary mineral assemblages, and their textures, indicate that fluids in the Orakei Korako system are not everywhere in equilibrium with the rocks through which they pass, although they do indicate the direction of the reactions.

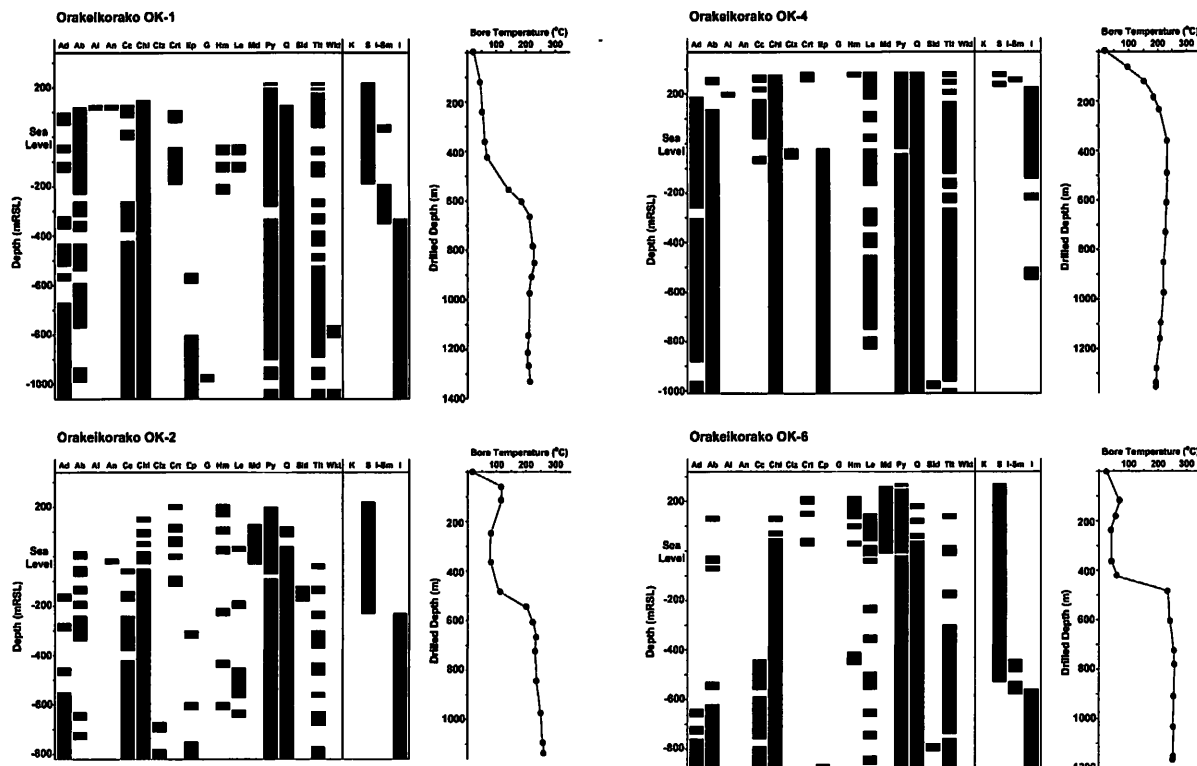


Figure 3. Distribution of secondary minerals and clays in Orakei Korako drillholes (Ad adularia, Ab albite, Al alunite, An anhydrite, Ca calcite, Chl chlorite, Clz clinozoisite, Crt cristobalite, Ep epidote, G garnet, Hm hematite, Le leucoxene, Md mordenite, Py pyrite, Q quartz, Sid siderite, Tit titanite, Wkt wairakite, K kaolinite, Sm smectite, I-Sm illite-smectite, I illite).

Table 2. Summary data of T_{IC} , T_{bore} , fluid inclusion (mean T_h) and mineral inferred temperatures ($T_{mineral}$) for Orakei Korako drillcores. T_{IC} values were calculated following the procedure described in the text.

| Sample (Drilled Depth, m) | Meas. T_{bore} (°C) | Fluid Inclusion Mineral | No. T_h Meas. | T_h (°C) Range (mean) | $T_{bore} - T_h$ (°C) | IC ($^{\circ}\Delta 2\theta$) | $T_{(min)}$ (°C) | $T_{(IC)}$ (°C) | $T_{bore} - T_{(IC)}$ (°C) | $T_{(IC)} - T_h$ and/or match $T_{(min)}$? |
|---------------------------|-----------------------|-------------------------|-----------------|---|-----------------------|---------------------------------|------------------|-----------------|----------------------------|--|
| OK1:609.6 | 182 | Quartz | 4 | 169 - 172 (170.5) | 12 | - | 160 - 210 | - | - | - |
| OK1:731.5 | 218 | - | - | - | - | 0.65 | 210 - 250 | 243 | -25 | (match) |
| OK1:791.3 | 224 | - | - | - | - | 0.62 | 210 - 250 | 245 | -21 | (match) |
| OK1:884.5 | 224 | Calcite | 18 | 218 - 248 (235.1) | -11 | 0.56 | 210 - 250 | 250 | -26 | +15 (match) |
| OK1:914.4 | 220 | - | - | - | - | 0.56 | > 250 | 250 | -30 | (match) |
| OK1:944.9 | 216 | - | - | - | - | 0.46 | > 250 | 259 | -43 | (match) |
| OK1:1006.4 | 211 | - | - | - | - | 0.40 | 210 - 250 | 265 | -54 | (too high) |
| OK1:1066.8 | 211 | - | - | - | - | 0.33 | 210 - 250 | 271 | -60 | (too high) |
| OK1:1126.8 | 210 | Quartz | 7 3 21 | 212 - 221 (216.6) 253 - 257 (254.9) 298 - 325 (311.8) | -7 -45 -102 | 0.48 | 210 - 250 | 258 | -48 | 41 (too high) +3 (match) -54 (too low) |
| OK1:1219.2 | 209 | - | - | - | - | 0.42 | > 250 | 263 | -52 | (match) |
| OK1:1280.2 | 211 | - | - | - | - | 0.30 | > 250 | 273 | -62 | (match) |
| OK1:1312.5 | 214 | Quartz | 3 21 | 258 - 261 (259.3) 288 - 311 (301.3) | -45 | 0.28 | > 280 | 275 | -61 | +16 (match) -26 (too low) |
| OK2:595.3 | 218 | - | - | - | - | 0.67 | 210 - 250 | 241 | -23 | (match) |
| OK2:624.8 | 225 | - | - | - | - | 0.62 | 210 - 250 | 245 | -20 | (match) |
| OK2:655.3 | 230 | Quartz | 13 | 220 - 226 (222.8) | +7 | 0.79 | 210 - 250 | 230 | 0 | +7 (match) |
| OK2:682.8 | 231 | - | - | - | - | 0.74 | 210 - 250 | 235 | -4 | (match) |
| OK2:816.9 | 234 | - | - | - | - | 0.76 | 210 - 250 | 233 | +1 | (match) |
| OK2:853.4 | 238 | Quartz | 21 | 222 - 229 (224.3) | -14 | 0.70 | 210 - 250 | 238 | 0 | +14 (match) |
| OK2:914.4 | 244 | - | - | - | - | 0.76 | 210 - 250 | 233 | -11 | (match) |
| OK2:945.5 | 247 | - | - | - | - | 0.48 | 210 - 250 | 258 | -11 | (little high) |
| OK2:976.3 | 252 | Quartz | 18 | 251 - 261 (253.4) | -1 | 0.59 | > 250 | 248 | 14 | +5 (match) |
| OK2:1004.0 | 254 | - | - | - | - | 0.62 | 210 - 250 | 245 | 11 | (match) |
| OK2:1036.3 | 257 | - | - | - | - | 0.51 | > 250 | 255 | 12 | (match) |
| OK2:1066.8 | 260 | - | - | - | - | 0.69 | > 250 | 239 | -21 | (too low) |
| OK2:1136.9 | 266 | Calcite | 2 16 | 269 - 270 (269.3) 278 - 289 (282.5) | -3 -17 | 0.47 | > 250 | 258 | +8 | -11 (match) -25 (match) |
| OK4:214.3 | 199 | - | - | - | - | 0.70 | 210 - 250 | 238 | -39 | (match) |
| OK4:273.1 | 215 | - | - | - | - | 0.53 | 210 - 250 | 253 | -38 | (little high) |
| OK4:306.3 | 222 | - | - | - | - | 0.71 | 210 - 250 | 237 | -15 | (match) |
| OK4:411.8 | 235 | - | - | - | - | 0.31 | > 250 | 273 | -38 | (match) |
| OK4:580.3 | 232 | Quartz | 11 | 239 - 250 (245.5) | -14 | - | > 250 | - | - | - |
| OK4:884.8 | 218 | Quartz | 16 | 274 - 293 (280.8) | -62 | - | > 250 | - | - | - |
| OK4:1188.7 | 201 | Quartz | 7 23 | 231 - 236 (232.2) 298 - 311 (305.7) | -31 -105 | - | > 250 | - | - | - |
| OK4:1341.1 | 194 | Quartz | 3 9 | 227 - 228 (227.7) 302 - 312 (306.9) | -34 -113 | - | > 250 | - | - | - |
| OK6:883.6 | 257 | - | - | - | - | 1.20 | 160 - 210 | 194 | -63 | (match) |
| OK6:946.4 | 259 | - | - | - | - | 0.73 | 210 - 250 | 235 | -24 | (match) |
| OK6:975.4 | 259 | Quartz | 6 | 215 - 217 (215.9) | -42 | 0.85 | 210 - 250 | 225 | -34 | 9 (match) |
| OK6:1062.8 | 260 | - | - | - | - | 0.73 | 210 - 250 | 235 | 25 | (match) |
| OK6:1113.4 | 261 | Quartz | 11 7 | 210 - 219 (215.2) 248 - 254 (251.6) | 40 +3 | 0.56 | 210 - 250 | 250 | 11 | +35 (match) -2 (match) |
| OK6:1141.8 | 262 | Quartz | 12 | 257 - 267 (263.3) | -9 | - | 210 - 250 | - | - | - |
| OK6:1159.8 | 263 | - | - | - | - | 0.45 | 210 - 250 | 260 | +3 | (little high) |
| OK6:1219.2 | n.m. | Quartz | 22 4 | 262 - 269 (266.2) 291 - 292 (291.6) | - | - | > 250 | - | - | - |

The presence of illite, wairakite, epidote and almandine in OK-1 reveal temperatures in the past exceeded present conditions in this part of the field by as much as 100°C.

Drillhole OK-2 taps the main upflow at Orakei Korako, and recombined analyses of its liquid and condensed steam+gas best represent present reservoir conditions and show their equilibrium with illite, quartz and pyrite.

Thermal conditions near OK-4 are now <235°C, which is inconsistent with the presence of epidote and other high-temperature secondary minerals. An increase in P_{CO_2} may be sufficient to move a fluid in equilibrium with albite-adularia at

250°C, towards the adularia-illite stability field at cooler temperatures. The distribution of illite in OK-4 may be due to either cooling, as a result of deep boiling and waning of thermal activity in the southern part of the system, or to a decrease in pH caused by an increase in P_{CO_2} .

Measured temperatures in the upper part of OK-6 are consistent with the present thermal regime, based on the occurrence of cristobalite, mordenite and smectite, although some discrepancies could result from unreliability of the downhole measurements. The presence of illite and epidote (below 1180m drilled depth) concur with the maximum temperature (257°C) in this drillhole.

Fluid Inclusions Geothermometry

The homogenization (T_h) and final ice melting (T_m) temperatures were determined on inclusions from 26 drillcores (Table 2). Most inclusions formed along healed fractures and are classified as secondary; no daughter minerals or other phases were seen.

The majority of fluid inclusions in the OK-1 samples homogenize into the liquid phase, with T_h values that are close to the appropriate T_{bore} , although some have values similar to the boiling temperature at their sample depth. Vapor inclusions in OK-1:1126.8m were too small (<2 microns) to measure.

Minimum T_h values for the OK-2 inclusions are similar to T_{bore} , and reveal subsurface temperatures have

changed little in this area since the fluids were trapped. The fluid inclusions are liquid-rich and have uniform liquid/vapor ratios; none show evidence of boiling.

Fluid inclusions in OK-4 have T_h values that follow the BPD curve, but differ from the present downwell temperature profile. Many T_h values are close to the maximum temperature measured in the well (235°C) and are higher than the present temperatures at the sample depths; The T_h values for OK-4:1341.1m exceed T_{bore} by as much as 120°C. Vapor inclusions and inclusions with variable liquid-vapor ratios from OK-4:580.3m indicate boiling once occurred at that depth.

Fluid inclusion data of samples from below 975m (drilled depth) in OK-6, are bimodal; one mode matches measured temperatures, but the other is 50°C lower.

The Illite Geothermometer

Petrography: The subsurface alteration at Orakei Korako can be characterized by dividing its mineral assemblage into zones based on the distribution of key thermally sensitive clay minerals; smectite, interlayered illite-smectite and illite. The inferred lower stability temperature of illite in New Zealand systems is >220°C (Simmons et al., 1992). Within deep reservoir rocks at Orakei Korako, illite is incipient, occurring as an alteration product of andesine and overprinting adularia. Less commonly it replaces ferromagnesian minerals and fills vesicles and fractures, occurring as clusters of subparallel hexagonal platelets (Figures. 4a, b).

Illite compositions: The Si contents and Fe/(Fe+Mg) ratios of illites at Orakei Korako vary (Bignall, 1994) but no consistent trend was recognized. This contrast with Lonker et al. (1990) who report that the Si contents and interlayer vacancies in illites at Broadlands-Ohaaki increase, but their Fe/(Fe+Mg) ratios decrease, closer to fluid flow zones. Hunziker et al. (1986) and Ma et al. (1992) showed that the K-content of illite could increase with crystallinity, although this is not evident at Orakei Korako.

Illite Crystallinity: The Kubler Index (KI; Kubler 1968) was used to quantify the progress of hydrothermal alteration, and is defined as the half height-peak width (expressed in °Δ2θ values) of the (001) air-dried illite reflection. Values of KI decrease with increasing crystallinity. The inter-laboratory standards of Warr and Rice (1993) were used to test sample preparation methods and measurement precision (Table 3). In this study, samples were analyzed with 40kV/20mA CuKa-radiation, whereas Warr and Rice (1993) used 40kV/30mA CuKa-radiation. Although the IC (°Δ2θ) values obtained are lower than those of Warr and Rice (1993), due to the different machine generator currents used, there is a consistent difference between the two measurement sets. This means that the IC values can confidently be taken as a measure of clay crystallinity.

Illite in Orakei Korako drillcores: The KI values of illite from Orakei Korako drillcores increase with depth (Figure 5), and some also show a weak correlation with the higher measured downhole temperatures (Figure 6). A decrease in illite (001) crystallinity,

with increasing temperature, in clays from OK1 is an obvious exception and the apparently anomalous OK-4/-6 results also require consideration. There are no major differences between the KI of the air-dried and glycolated samples, nor between the <0.2µm and 0.2-2µm fractions.

There is no direct relationship between T_{bore} and the IC of illites from OK-1 and OK-4, since present temperatures are now cooler than when the illites formed. Similarly, IC data from OK-6 cannot be correlated with T_{bore} since multiple well inflows occur.

An empirical relationship between measured downhole temperature and the Kubler Index, calibrated between 180 and 300°C, is proposed. This is based primarily on data from OK-2, where thermal conditions have clearly remained static since the present secondary mineral assemblage formed. This new relationship is:

$$T_{\text{bore}} (\text{°C}) = 300 - 88.4 \times K \text{ where } K \text{ is the Kubler Index } (\text{°}\Delta 2\theta) \text{ of the } (001) \text{ illite peak.}$$

This empirical relationship was applied to IC data of illites in cores from other drillholes at Orakei Korako (Table 2), to deduce subsurface (T_{IC}) conditions. The T_{IC} values for OK-1 match the fluid inclusion data, and the occurrence of tempera-

Table 3. Illite crystallinity (IC, 10Å peak) values for SW standards of Warr and Rice (1993; W&R), using 40kV/30mA CuKa-radiation; and University of Auckland (UA) samples, using 40kV/20mA CuKa-radiation machine operating conditions.

| Sample | Laboratory | Illite; dry 10Å | | Illite; glycolated 10Å | |
|--------|----------------|-----------------|-----------|------------------------|-----------|
| | | ICdry | d-spacing | ICglycol | d-spacing |
| SW-1 | UA (<0.2µm) | 0.38 | 10.041 | 0.33 | 10.007 |
| | UA (0.2 – 2µm) | 0.40 | 10.041 | 0.37 | 10.007 |
| | W&R | 0.63 | 10.146 | 0.57 | 10.103 |
| SW-2 | UA (thin) | 0.32 | 10.041 | 0.29 | 9.995 |
| | UA (thick) | 0.36 | 10.041 | 0.29 | 9.995 |
| | W&R | 0.47 | 10.101 | 0.44 | 10.072 |
| SW-4 | UA (thin) | 0.28 | 10.018 | 0.28 | 10.018 |
| | UA (thick) | 0.31 | 10.018 | 0.36 | 10.018 |
| | W&R | 0.38 | 10.081 | 0.38 | 10.071 |
| SW-6 | UA (thin) | 0.17 | 10.030 | 0.18 | 10.007 |
| | UA (thick) | 0.16 | 10.030 | 0.18 | 10.007 |
| | W&R | 0.25 | 10.082 | 0.25 | 10.080 |

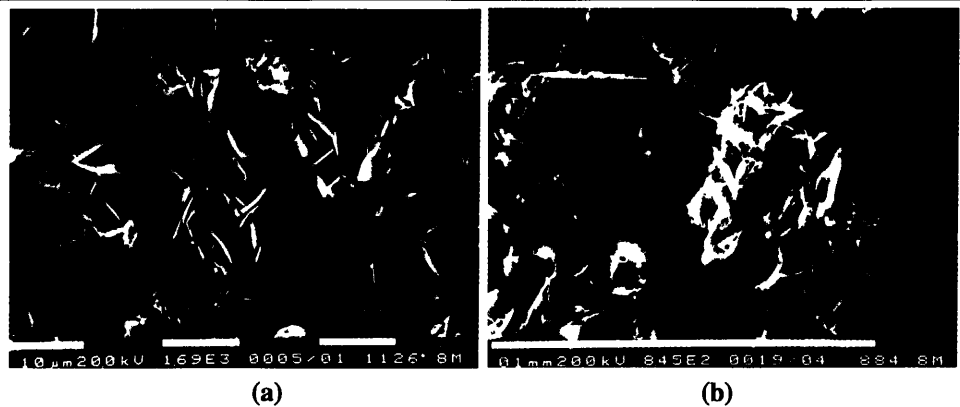


Figure 4. SEM electromicrographs of (a) hexagonal platelets of illite in the groundmass of tuff at OK-1:1126.8; and (b) illite replacing primary plagioclase in OK-4:884.8m.

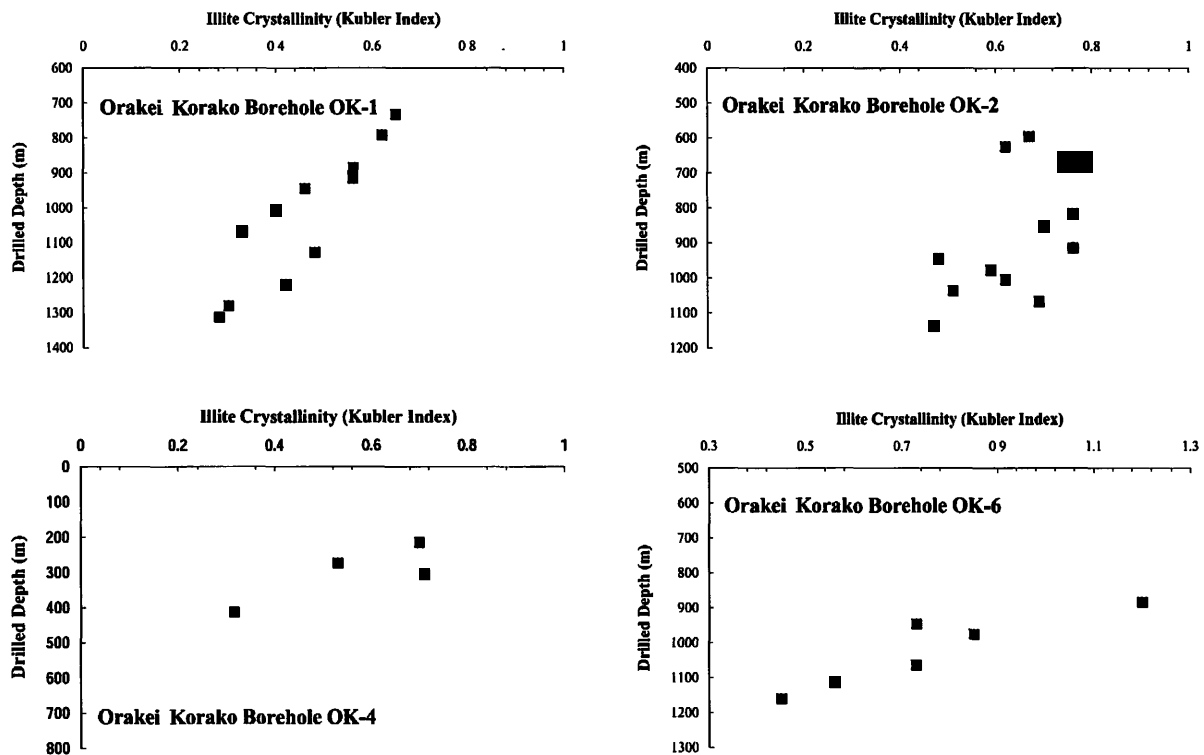


Figure 5. Crystallinity (Kubler Indices, $^{\circ}\Delta 2\theta$) of air-dried illite (001) reflections plotted against drilled depth of core samples from Orakeikorako Drillholes OK-1, -2, -4 and -6.

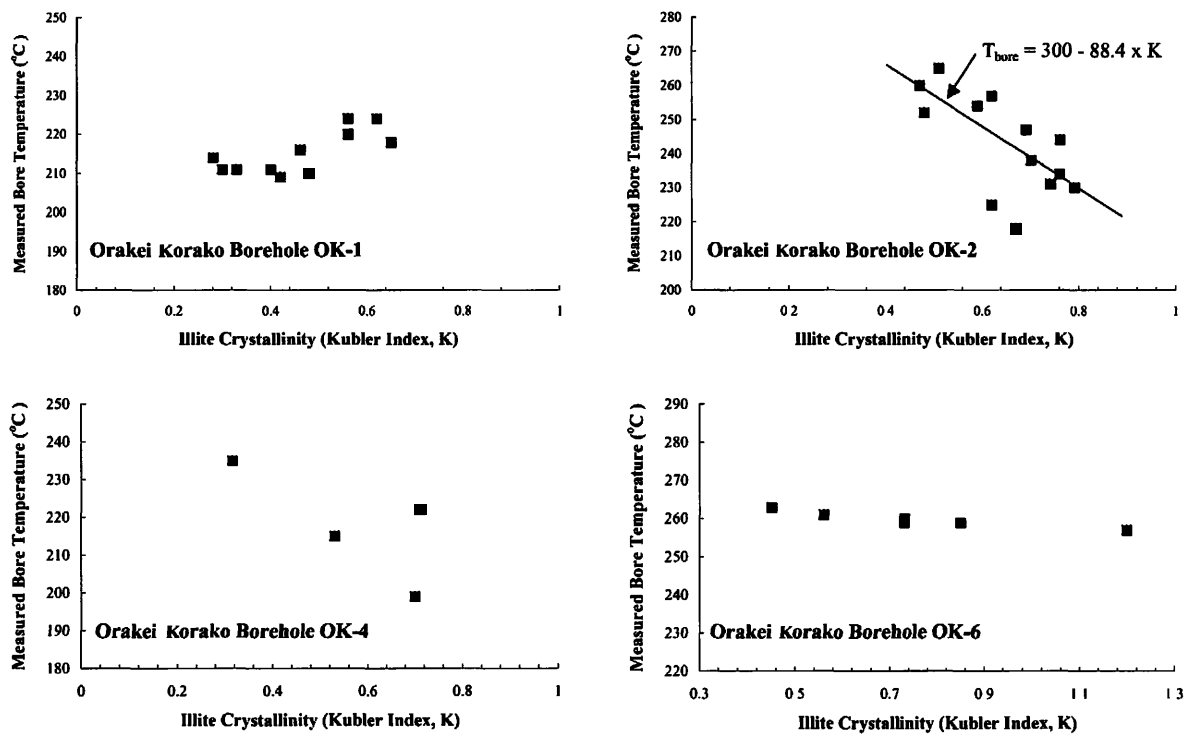


Figure 6. Crystallinity (Kubler Indices, $^{\circ}\Delta 2\theta$) of air-dried illite (001) reflections plotted against measured bore temperature (T_{bore}) in Orakeikorako Drillholes OK-1, -2, -4 and -6.

ture dependent secondary minerals. T_{IC} values of $>260^{\circ}\text{C}$ are indicated at depths where epidote occurs, although present temperatures are no more than 214°C . Fluid inclusion and mineral inferred temperatures match the T_{IC} data, indicating that the OK-4 area is cooler now than it was in the past. The OK-6 area may be heating up, since T_{IC} values of illite in its cores indicate temperatures that are lower than T_{bore} , although towards the bottom of the well the T_{bore} and T_{IC} converge to $\sim 260^{\circ}\text{C}$.

To test the usefulness of the new illite crystallinity (T_{IC}) geothermometer, it was applied to samples from two wells at Te Kopia (Figure 1), where measured bore temperatures reach 240°C in TK-1 and 222°C in TK-2. These are inconsistent with fluid inclusion homogenization temperatures (Bignall, 1994) and the presence of illite, prehnite, wairakite, epidote and other temperature indicating minerals. The T_{IC} temperatures are greater than the downwell temperatures but close to the maximum temperatures indicated by fluid inclusion and mineral geothermometry. This agreement shows that the reservoir at Te Kopia has cooled and supports the use of the $T_{(IC)}$ geothermometer to deduce maximum temperatures. Further evaluation of this geothermometer will be made using samples from exploratory wells in the Hachimantai geothermal area, northern Honshu (Hara *et al.*, in prep).

Discussion

Petrographic observations and fluid inclusion data, combined with the chemistry of deep fluids, shows that a pronounced change in fluid-mineral equilibrium conditions has occurred at Orakei Korako. This is indicated by illite overprinting an earlier albite-actinolite-quartz assemblage, although full equilibration between the illite and the altering fluid has not yet been reached (Bignall, 1994).

Comparisons of the fluid inclusion and the measured downhole temperatures are an important way to deduce the thermal evolution of a geothermal system. Well measurements, however, do not always represent conditions in the deep system since there may be multiple well-feed zones and mixing and dilution of fluids may occur. Further, suitable fluid inclusions may not be found. Temperature is clearly the most important factor controlling illite crystallinity and, therefore, the crystallinity of mixed layer illite/smectite and illite is a potential indicator of temperatures in hydrothermal systems.

Kubler Indices record an increase in illite crystallinity with depth at Orakei Korako, but they do not everywhere show a clear correlation with present measured drillhole temperatures. Thermal changes in the Orakei Korako geothermal system are inferred from the empirical relationship between the measured downhole temperatures and the Kubler Indices. This is based upon the IC of illites in samples recovered from a part of the system that is independently recognized as being thermally stable (OK-2 area), which indicate the OK-1 and OK-4 areas have cooled, whilst the OK-6 area is now hotter than at some time in the past (Bignall, 1994).

Illite crystallinity is a useful indicator of subsurface thermal conditions and can be readily determined by x-ray diffraction

techniques. Combined with fluid inclusion data and other mineral and solute geothermometry, it can aid in better siting exploratory and/or production wells. Illite crystallinity can provide valuable temperature information about a newly drilled well or zones too cool (i.e. $<250^{\circ}\text{C}$) or gassy for epidote or wairakite to form.

The T_{IC} data provides information about the maximum temperatures that have prevailed in a hydrothermal system, since illite does not usually retrograde. In thermally stable parts of an active geothermal system it may indicate present temperatures, and would be particularly useful where there is a paucity of fluid inclusion data or temperature dependent secondary minerals.

Acknowledgments

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