# STYLES OF HYDROTHERMAL ALTERATION IN THE DARAJAT GEOTHERMAL FIELD, WEST JAVA, INDONESIA : A PROGRESS REPORT

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SUMMARY-Hydrothermal minerals in the Darajat geothermal field occur in two main styles: replacement and in veins. The former is a product of reactions between thermal fluids and primary minerals present in the reservoir rocks, comprising andesite lavas and pyroclastics. Although the minerals formed in both styles are the same, e.g. wairakite, prehnite, epidote, calcite, their significance differs and show that changes in hydrology have occurred in at least part of the Darajat reservoir. The textural relations within the vein minerals, for example, record local progressive cooling.

## 1. INTRODUCTION

Hydrothermal minerals occurring in the matrix of rocks in geothermal systems reveal past and present interactions between circulating fluids and the host rocks. By contrast, vein minerals record processes that have occurred, such as boiling and mixing, that affect fluids in the systems.

This paper describes the styles of alteration and the distribution of the hydrothermal minerals in part of the Darajat geothermal field and discusses their significance to its hydrology.

## 2. SETTING AND GEOLOGY

The Darajat geothermal field is located in West Java, Indonesia, about 150 km southeast of Jakarta. There are several other geothermal fields nearby, e.g. Kamojang, and these all lie within 30 km of Quaternary volcanic centers, including the historically active Papandayan and Guntur volcanoes. The Darajat field itself is situated within the Kendang stratovolcanic complex on the northern flank of Papandayan and lies at elevations of 1600-2200 m above sea level in an eruptive center of the Kendang Complex.

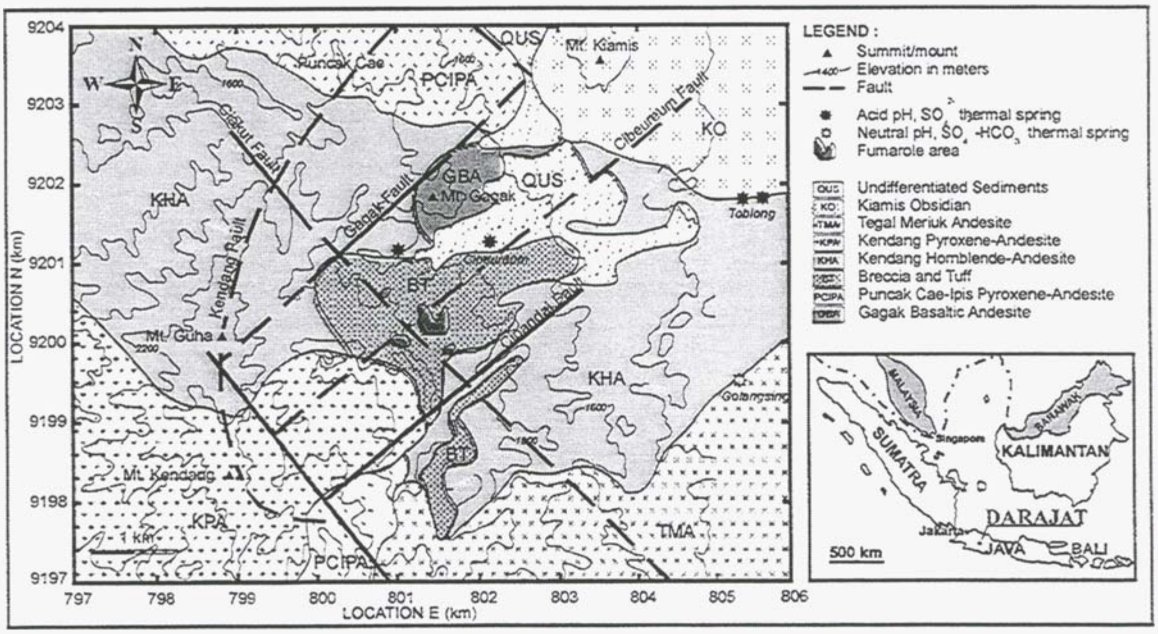


Figure 1. Geology and surface manifestations of the Darajat geothermal field. Location grid is universal transverse mercator (UTM) of zone 48 (in km). Geology map is fkom Healy (1975) and surface manifestation map is taken fkom Amoseas Indonesia Inc. (1987) report.

The field is one of the world few known dry-steam geothermal resources. At present, it has an output of 125 MWe. During the early exploration of the field, Healy (1975) revealed that the Darajat system and its surrounds are covered by Quaternary volcanic rocks (Figure 1). These are dominated by andesitic lavas derived from Mt. Kendang, which comprise pyroxene and hornblende rich, Puncak Cae-Ipis and Tegal Meriuk types. Around Mt. Gagak, the volcanic rocks have slightly different compositions and are basaltic. Pyroclastic breccias and tuffs are present in the main fumarole area. According to Alzwar et. al. (1992), all these rocks are Pleistocene. These rocks are overlain in the northeast by the youngest unit, an obsidian flow from Mt. Kiamis. This is dacitic and a product from a parasitic cone in the Kendang caldera; it is younger than 50,000 years (Amoseas Indonesia Inc., 1987). However, several phreatic eruptions succeeded the Kiamis obsidian producing tuffs and breccias.

An andesite complex is the deepest unit drilled. It consists of andesite lavas and microdiorites and is more than 800 m thick. Geothermal Energy of New Zealand Ltd. (1996) suggested that the complex is dome shaped with an axis trending approximately N-S. This andesite complex is the host rock of the Darajat reservoir (e.g. Amoseas Indonesia Inc., 1989). Several cores from well DRJ-1 represent the unaltered host rocks. They are subalkaline, Ca-rich andesites. Plagioclase is dominant: 3040% of the phenocrysts and 20-40% of the groundmass. The phenocrysts are mainly labradorite-bytownite but some are as sodic as andesine and the groundmass is mostly labradorite. Pyroxene is present as phenocrysts: up to 5% augite and up to 10% hypersthene (enstatite), and up to 3% groundmass. Other primary minerals include titanomagnetite and apatite.

## 3. SURFACE MANIFESTATIONS

Surface thermal manifestations, mainly generated by ascending steam, occur near the junction between the Gagak and Cipandai faults at elevations of 1800-2000 m and consist of steaming ground, steam heated acid boiling pools and fumaroles with temperatures of 50-90°C (Amoseas Indonesia Inc., 1987). No neutral pH chloride water discharges at Darajat, but several thermal water outflows occur east of the fumarole area at elevations of 1200-1600 m. They are the Cibeureum, Toblong and Golangsing hot springs. The first two are acid $SO_4$ waters at 50-60°C, while the Golangsing spring has a pH of ~6 and comprises $SO_4$-$HCO_3$ water below 30°C.

## 4. EXTENT OF RESERVOIR

The Darajat reservoir is considered steam-dominated having a temperature of about 240°C and a pressure of 35 bar. The present reservoir lies, in large part, beneath the main fumarolic area. It has an asymmetric dome-like shape trending NNW-SSE with an axis approximately parallel to the Kendang fault. The thermal system may extend for some distance to the north and west. A condensate zone probably overlies the steam reservoir (e.g. Amoseas Indonesia Inc., 1987).

The reservoir contains mainly steam but with ~2% non-condensable gases, consisting of ~94 wt.% $CO_2$, 3 wt.% $H_2S$ and 3 wt.% other gases. During the early stages of the well flow tests as much as 2 wt.% liquid water discharged from several wells. Tests indicate that the reservoir contains about 33% water (Amoseas Indonesia Inc., 1989). This is a dilute, near neutral pH, Na-$SO_4$-$HCO_3$-Cl water with less than 2200 ppm total dissolved solids (Amoseas Indonesia Inc., 1989).

Table 1. Common hydrothermal alteration products of primary minerals in Darajat andesite

| | Primary constituent | Intensity of alteration | Common hydrothermal alteration product | Occurrence |
|---|---|---|---|---|
| Groundmass | Volcanic glass | 0-100% | Cristobalite, tridymite, opal-CT, quartz | - |
| | | | Calcite | - |
| | | | Smectite, chlorite, illite | - |
| | Microcrystalline plagioclase | 0-60% | Calcite | - |
| | | | Smectite, chlorite, illite | - |
| Phenocrysts | Plagioclase | 0-100% | Quartz | Cracks |
| | | | Laumontite, pumpellyite, prehnite, epidote | Core, cavity, cracks |
| | | | Calcite, anhydrite | Cracks, cavity |
| | | | Adularia | Cracks |
| | | | Smectite, chlorite, illite | Cracks |
| | Augite | 0-100% | Quartz | Cracks, cavity |
| | | | Prehnite, epidote | Core, surface |
| | | | Calcite, anhydrite | Cracks, cavity |
| | | | Smectite, chlorite, illite | Cracks |
| | | | Opaque minerals | Surface |
| | Hypersthene | 0-100% | Smectite, chlorite, illite | Cracks |
| | | | Opaque minerals | Surface |

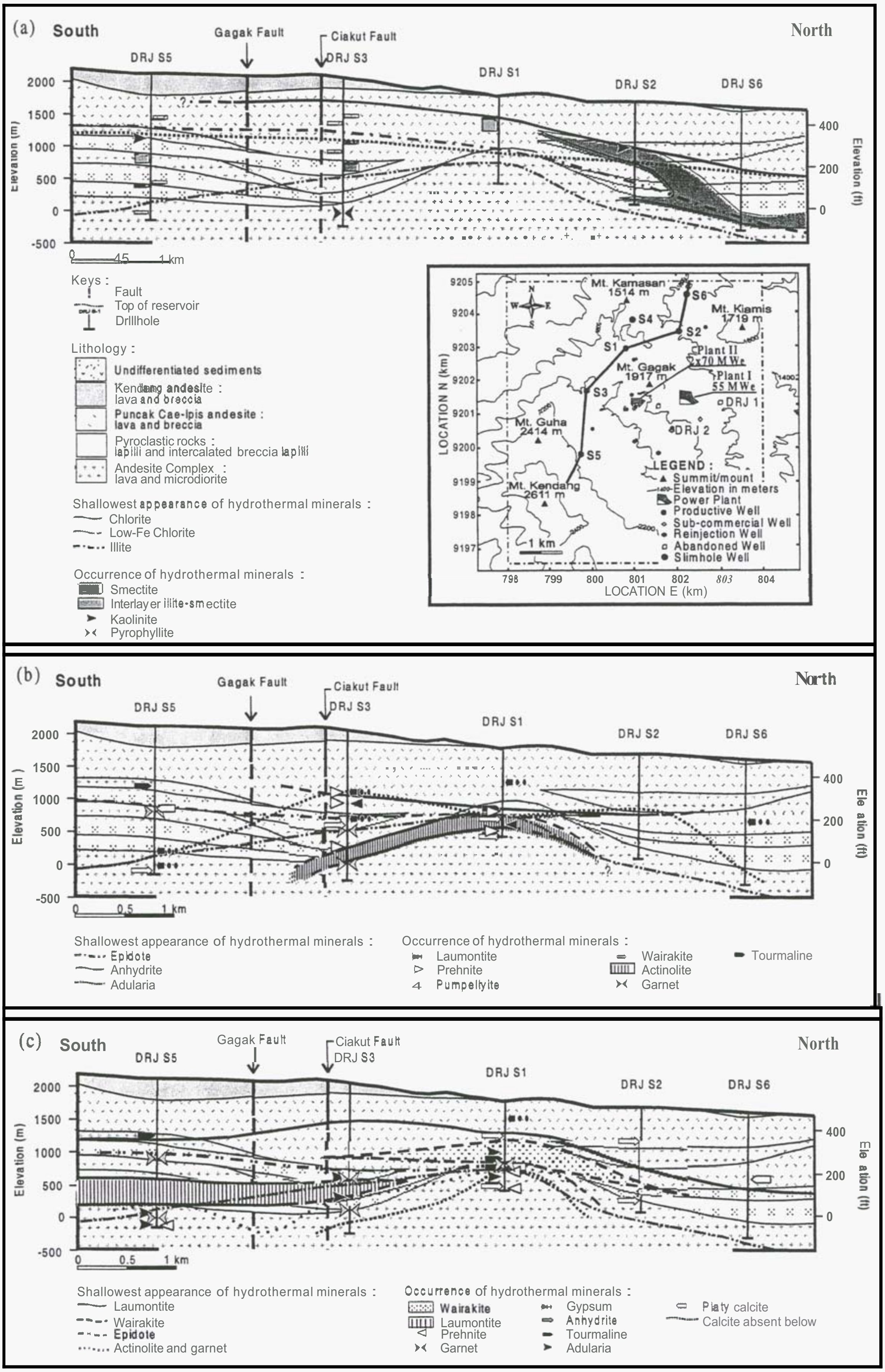


**Figure 2. South-north cross-sections,** from DRJ **S5, S3, S1, S2 to** *S6,* **showing distribution** of **hydrothermal minerals present in the** matrix of rocks, **including (a) clay minerals and (b) non-clay minerals, and** *(c)* **hydrothermal minerals present in veins. Location** of **drillholes is given in the inset.**

## 5. DISTRIBUTION OF HYDROTHERMAL MINERALS

The common style of alteration of the primary minerals in Darajat is shown in Table 1 and the occurrence and distribution of the hydrothermal minerals is shown in Figure 2, in south to north cross sections.

Andesite lavas and intrusive rocks mostly have intensities of hydrothermal alteration ranging from low to moderate. The alteration of the groundmass is usually more intense than that of the phenocrysts. Pyroclastic rocks are more intensely altered; tuff is completely altered, even at shallow depths. The intensity of alteration of andesite lava varies, even on a millimeter scale and proximity to fractures and veins. Veins range from less than 0.5 mm to 20 mm wide. They mostly dip 80" to almost vertical with respect to the core axis. Older veins are almost horizontal, but some dip 30-60°. Fractures mostly dip at 80-90".

### 5.1. Clay minerals

Clay minerals present include smectite, chlorite, illite and phases with interlayers. Smectite mostly replaces the groundmass. It is present throughout the northern area, but in well DRJ S3 and S5 it appears to be local (Figure 2a). Smectite is absent in well DRJ S1, however, interlayered illite-smectite is present from 1200 to 1500 m. Here, the amount of illite ranges from 40 to 70%. Interlayered clay is also present locally in wells DRJ S3 and S5 and most contains 80% illite. Discrete illite forms very small flakes replacing plagioclase first along cracks. The shallowest Occurrence of illite is at 1000-1300 m in the south but it is deeper in the north. Illite is mostly associated with chlorite.

Chlorite is the most common clay at Darajat. It replaces almost all primary minerals, including plagioclase and quartz, despite their contrasting compositions. The shallowest occurrence of chlorite is at –1800 m, but it is deeper to the north. Chlorite in DRJ S1 is mostly Fe-rich, whereas that in DRJ S2 and S6 contains little Fe. Generally, low-Fe chlorite is present below –1200 m at the south and 700 m at the north.

Kaolinite is present locally in wells DRJ S2 and S5 (Figure 2a) and halloysite is present at shallow depths in well DRJ-2. Both indicate that a low temperature acid fluid has interacted with the rocks. Hot acid fluid was also present in well DRJ S3, as indicated by the presence of pyrophyllite at elevations of –100 m below sea level. This pyrophyllite seems to be Fe-rich.

### 5.2. Non-clay minerals

The most common hydrothermal minerals are *quartz,* calcite and anhydrite. *Quartz* replaces primary plagioclase and pyroxene phenocrysts along cracks and from the crystal surfaces inward. It also replaces the groundmass, mostly glass. *Quartz* is also commonly present in veins and vugs. Calcite is present mostly at shallow depths and its abundance decreases with depth. It replaces plagioclase, pyroxene and the groundmass. Calcite is more dominant in phenocrysts than in the groundmass and it is also more abundant in lavas than in tuffs. Calcite is also very common in veins and cavities. Platy calcite, indicating boiling, is present at –700 m in well DRJ S1 and 600 m in DRJ S6. Anhydrite replaces plagioclase and pyroxene along cracks and fiom crystal surfaces inward. It is also present as cavity filling. Anhydrite is first present at ~1000 m (Figure 2b).

Calc-silicate minerals provide the beauty of the hydrothermal alteration at Darajat. Laumontite and wairakite are common and mostly present in veins. Laumontite is first present at –1500 m in well DRJ S1, but occurs deeper in DRJ S5 and S6 (Figure 2c). Laumontite also replaces plagioclase at several depths in wells DRJ S1, S3 and S6. In DRJ S5, laumontite is present as a replacement mineral at sea level and occurs in veins at 1200 and 200-600 m. Wairakite is present mostly in veins at 800–1200 m in DRJ S1. It also replaces plagioclase at –600 m in DRJ S1 and S3 and –100 m below sea level in DRJ S5.

Prehnite and pumpellyite replace plagioclase and pyroxene along cracks and occur in cavities. They are mostly associated with chlorite and epidote. They are present at ~1000 m in DRJ S3 and –600 m in DRJ S1. Most prehnite is present in veins. It is dominant in well DRJ S1, fiom 500 to 900 m, and also occurs at –100 m in DRJ S5, where it has deposited on the surface of epidote.

Epidote replaces plagioclase and pyroxene at the crystal surfaces and has deposited in cavities. In intensely altered rocks, epidote is also disseminated in the groundmass, clustering with chlorite and titanite. Epidote also commonly occurs in veins in association with chlorite and wairakite. Epidote is first present at 700-900 m, but it is absent in wells DRJ S2 and S6. The amount of epidote generally increases with depth, especially where actinolite coexists. Actinolite is disseminated in the groundmass, replaces plagioclase from the crystal surface inward, fills veins and cavities and is associated with chlorite, epidote and opaque minerals. Replacement actinolite is present only in DRJ S1 and S3 but it fills veins in core from DRJ S5 at –250 m.

Garnet is rare but it occurs in an epidote-rich zone, i.e. at ~500 in well DRJ S3 and ~800 m in DRJ S5. It is present in veins at 600-800 m in wells DRJ S1, S3 and S5. In the last two wells, garnet also occurs at 0-100 m. Garnet is present at the margin of the veins, associated with epidote and actinolite. Prehnite and wairakite usually deposited after epidote. The sequence of deposition in veins indicates that wairakite deposited after epidote and actinolite and prehnite deposited after wairakite. However, all calc-silicates were then overprinted by calcite and anhydrite. Below -100 m in well DRJ S3 and 700 m in DRJ S1, calcite is absent, but calc-silicates are still dominant (Figure 2c).

Other minerals present include tourmaline, secondary feldspars, alunite and diaspore. Tourmaline occurs at ~1200 m in well DRJ S5 and 500-800 m in DRJ S1. It forms radiating clusters and replaces plagioclase, but most occurs in cavities and vugs associated with calcite and anhydrite. Secondary feldspars include albite and adularia that replace plagioclase along cracks. Adularia has a broad dome shaped distribution (Figure 2b). It is likely overprinted by chlorite, illite and, sometimes, calcite along cracks. Adularia is also rarely present in veins. Alunite occurs at shallow depths, i.e. 43 m depth in well DRJ-2, replacing plagioclase. Diaspore is present in association with pyrophyllite at ~100 m in well DRJ S3. Alunite and diaspore indicate where acid fluids have interacted with rocks. Opaque minerals and iron oxides are common. Pyrite is common and the oxidation products are usually reddish brown, clay size minerals. They mostly occur within glass but also affect smectite and chlorite.

Table 2. Composition of representative deep

| Well | DRJ-1 | | DRJ-2 | DRJ-5 | | DRJ S1 | |
|---|---|---|---|---|---|---|---|
| Depth (m) | 475 | 668 | 625 | 1830 | 2470 | - | |
| Sample taken | 1985 | 1985 | 1988 | 1988 | 1988 | 1998 | 1998 |
| Sample | DH | DH | DH | DH | DH | DH | SP |
| pH (25°C) | 6.95 | 7.13 | 7.47 | 7.25 | 7.93 | 3.50 | 5.00 |
| $a(Na^+)$ | 4.57 | 6.36 | 3.97 | 1.67 | 0.69 | 1.64 | 0.50 |
| $a(K^+)$ | 0.14 | 0.12 | 0.07 | 0.05 | 0.02 | 0.46 | 0.08 |
| $a(Ca^{2+})$ | 0.05 | 0.06 | 0.03 | 0.08 | 0.05 | 1.65 | 0.44 |
| $a(Mg^{2+})$ | 0.03 | 0.02 | 0.00 | 0.00 | 0.00 | 0.70 | 0.01 |

## 6. FLUID - MINERAL REACTIONS

Hydrothermal minerals form as a result of interactions between thermal fluids and rocks or due to processes affecting the circulating fluids. One significant control on the formation of hydrothermal minerals is the initial compositions of these circulating fluids, since this determines which minerals will deposit, dissolve or be replaced. The fluids will be affected by several processes, so their compositions will change temporally and spatially and so react later in slightly different ways.

Table 2 lists the compositions of seven downhole waters. These compositions are plotted on logarithmic activity ratio diagrams in Figure 3 to show the stability of the hydrothermal minerals (Figure 3). The fluid discharging from well DRJ S1 is the only representative deep fluid in Darajat. The other fluids do not plot on the diagrams, likely because those from DRJ-1, 2 and 5 might have been influenced by condensation, as these wells lie outside the reservoir.

Figure 3 shows that the deep fluid in Darajat is in equilibrium with illite and chlorite. This is consistent with the abundance of chlorite, in association with illite, as a replacement mineral. Steam separation, due to boiling, can bring the fluid into equilibrium with K-feldspar and epidote. This residual liquid then interacts with the rocks and produces adularia and epidote. Temperature controls the zonation of epidote ± actinolite to wairakite ± prehnite ± pumpellyite to laumontite. This sequence is also present in veins; e.g. garnet, in association with actinolite and epidote, occurs at the margins, whereas prehnite is present in the middle of the veins. This indicates cooling from above 300 to ~200°C (Bird et. al., 1984).

Diagrams involving $a_{Ca}$ show that when the concentration of dissolved $CO_2$ is low, calcite and calc-silicates may coexist, but when $CO_2$ is high, calc-silicates will not be present, whereas calcite will be dominant. The amount of $CO_2$ dissolved in the Darajat fluids ranges from 0.1 to 0.5% (Kingston Morisson Ltd., 1996), enough to form calcite in the matrix. Due to boiling, $CO_2$ loss promotes deposition of calcite, which commonly overprints calc-silicate minerals in veins. Anhydrite is usually associated with calcite. The occurrence of anhydrite near epidote may result from descending $HCO_3$-$SO_4$ water produced within the condensate zone overlying the reservoir (Moore et. al., 2000).

## 7. CONCLUSIONS

The Darajat geothermal field is now dry-steam dominated but the occurrence of minerals such as epidote, zeolites and prehnite, indicates that the field was, or may still be, two phase. Fluids above 300°C once existed deep in the system. Steam derived from boiling may ascend continuously and rapidly through fractures and discharge at the surface. On the other hand, liquid will rise more slowly. It interacts with surrounding rocks and replaces them but it can also precipitate minerals in veins depending on the processes that occur.

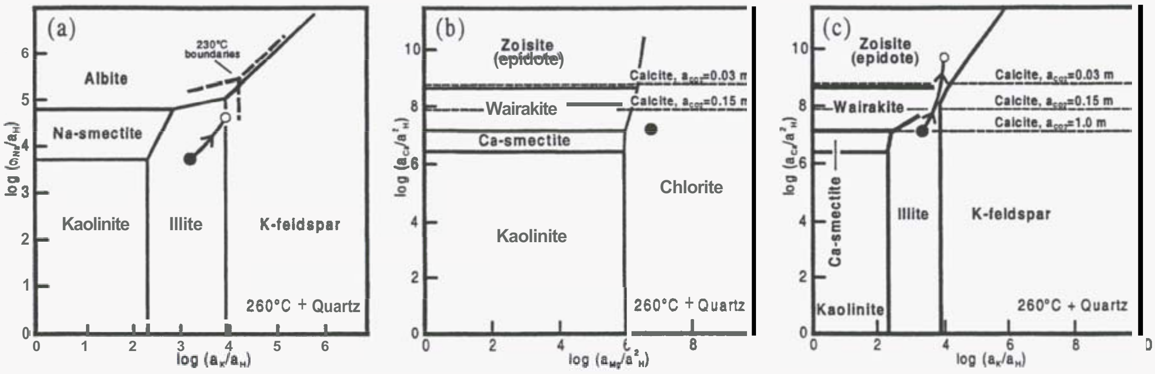


Figure 3. Plot of the Darajat deep fluid in activity diagrams of : (a) log ($a_K/a_H$) vs. log ($a_{Na}/a_H$), (b) log ($a_{Mg}/a^2_H$) vs. log ($a_{Ca}/a^2_H$) and (c) log ($a_K/a_H$) vs. log ($a_{Ca}/a^2_H$) at 260°C. The deep fluid plotted is from well DRJ S1: ● represents downhole sample and ○ is separated water; the shift is due to steam separation.

However, further study is still needed to understand the paleohydrology of the Darajat geothermal field. This includes mineral chemistry and fluid inclusion geothermometry.

## 8. ACKNOWLEDGEMENTS

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