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SUBSURFACE HYDROTHERMAL ALTERATION IN THE KAMOJANG GEOTHERMAL FIELD, WEST JAVA, INDONESIA

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ABSTRACT

The presently vapor-dominated Kamojang geothermal field is located in West Java (Indonesia). The field lies in high terrain, 1500 m above sea level, and is hosted by volcanic rocks. Samples from seven wells were kindly made available for this study, namely from KMJ-7, KMJ-10, KMJ-11, KMJ-12, KMJ-53, KMJ-59, and CHR-1 drilled to depths ranging from 536 – 1804 m. The reservoir is hosted by interbedded pyroclastic and lavas of andesite composition with some basaltic andesites and lacustrine tuffs.

The field is now vapor-dominated but the hydrothermal minerals show that the rock-altering fluid were dominantly liquid. There are 2 hydrothermal mineral assemblages present, namely those produced by "acid" and "neutral " pH fluids. The "acid" mineral assemblage which occupies shallow levels (down to 100 – 300 m) consists of kaolin, smectite, alunite, quartz, cristobalite, and pyrite. The altering fluid was of acid sulphate type formed due to the oxidation of H_2S. The "neutral pH" mineral assemblage occupies deeper levels and comprises varying proportion of quartz, adularia, albite, epidote, titanite, wairakite, laumontite, calcite, siderite, hematite, pyrite, anhydrite, smectite, chlorite, illite, and interlayered clays. The altering fluid was liquid of near neutral pH, and chloride-sulphate type.

In general, the present-day measured downwell temperatures are lower than those indicated by the alteration mineralogy (i.e. epidote, wairakite, laumontite, and clays) by about 10-50 ^oC and fluid inclusion homogenisation temperatures (by about 60 ^oC). This suggests cooling, although some of the measured downwell temperatures may be too low. Permeability has decreased due to mineral deposition, but tectonic activity has helped prolong it by reopening vertically permeable features.

Hydrothermal mineral parageneses and vein cross-cutting relationships in the deeper levels (below the "acid" assemblage zone), for example vein filled with quartz only and quartz+wairakite-calcite-anhydrite cut by vein of quartz-pyrite, suggest that although this field has undergone at least three hydrothermal episodes, the composition of the altering fluid was always of near neutral pH.

INTRODUCTION

The Kamojang geothermal field is located in West Java Province, Indonesia, about 35 km south of Bandung at an altitude of 1500 m.

This field has been the subject of geoscientific investigation since those made by the Dutch in 1920. Five shallow wells (18.5-130 m) were drilled by them between 1926 and 1928. Deeper exploration was begun in 1973 under the bilateral aid programme between the Goverments of Indonesia and New Zealand.

The Kamojang geothermal field is the first operational geothermal field in Indonesia. It has been producing electricity since 1983. The estimated field area is about 21 km^2, with a potential of about 300 MWe (Sudarman, *et al*, 1995). Steam development is being carried out by PERTAMINA (State Oil and Gas Enterprise) and the power generated by PLN (State Electricity Corporation). Currently the field produces 140 MWe. By the end of 1996, 70 wells had been drilled. The total steam output of 112 tonnes/hour needed to produce 140 MWe is taken from 24 production wells, with 4 make-up and 3 reinjection wells.

This paper descibes the hydrothermal alteration of the field based on the petrology and chemical compositions of the cores and cutting samples recovered from wells KMJ-7 (monitor well, 536 m), KMJ-10 (dry, 763 m), KMJ-11 (production well, 1029 m), KMJ-12 (production well, 1500 m), KMJ-53 (exploration/production well, 1300 m measured depth), KMJ-59 (exploration/production well 1298 m measured depth), and CHR-1 (exploration/production well, 1804 m). The samples for this research were kindly provided by PERTAMINA.

REGIONAL GEOLOGY AND THERMAL MANIFESTATIONS

The Kamojang geothermal field lies in the 15 km long and 4.5 km-wide Rakutak-Guntur volcanic chain. Robert *et al* (1983) suggest that the volcanoes in this chain erupted sequentially from the WSW to ENE, thus Gunung Rakutak is the oldest and G. Guntur is the youngest. The Kamojang area consists of 7 lithological units, i.e.,: from the oldest to the youngest these are the products of G. Cibatuipis (hornblende andesite lava). G. Pangkalan (labradorite lava and tuff), G. Gandapura (pyroxene andesite lava and tuff), G. Kancing (pyroclastic deposits and basaltic andesite lava), G. Masigit and G. Gajah (both are basaltic lavas), G. Guntur (pyroxene andesite lava). A volcano-sedimentary deposit which consists of colluvial, alluvial deposits, and volcanic debris occupies Danau Pangkalan area (Tim Pokja Kamojang, 1995).

The surface manifestations in the Kamojang area consist of hot pools, fumaroles, mud pots and hot springs lying in the so called Kawah Kamojang thermal area. According to Healy and Mahon (1982), most of the hot surface water contains high concentration of sulphate (1000-2000 ppm) but very low concentrations of chloride (< 5 ppm). The isotopic evidence suggests that the water is local meteoric water which has been heated by steam containing hydrogen sulphide, which oxidises to sulphuric acid to give water of a low pH and high sulphate concentration. Two warm springs (T= 38 & 49 ^{o}C) of neutral pH waters were reported by Healy and Mahon (1982) to occur 2 km south of the main activity.

SUBSURFACE GEOLOGY

Based on the petrologic descriptions of the available cores and cutting and combining them with the descriptions made by other workers (Wood, 1975; Browne, 1977; Healy, 1977; Purba, 1994) of samples which are no longer now available, the major lithologies in the studied wells are andesite ash, andesite lava, andesite breccia, and andesite tuff.

Six of the studied wells (KMJ-7 to KMJ-59) are located in the Danau Pangkalan depression, and one (CHR-1) is located outside the depression. The two areas are separated by two major structures, namely the Pangkalan rim and the Ciharus fault. All these wells were located inside the low resistivity boundary of < 10 Ohm-m, and the subsurface sequences are similar from well to well.

HYDROTHERMAL ALTERATION

The primary minerals present in the Kamojang subsurface rock samples are mainly feldspar (andesine-labradorite), pyroxene (hypersthene and augite), and olivine (forsterite). In general, the primary minerals in the andesite lavas are less altered than those in the pyroclastic rocks.

The hydrothermal minerals are:
Silica is present as cristobalite and quartz.
Albite is rare, and occurs as replacement of primary plagoclase.
Adularia is also rare, and occurs as vein and vug filling.
Epidote is rare; it occurs in veins and as vug filling.
Titanite is commonly replaces plagioclase. It is honey-coloured and anhedral.
Wairakite occurs as vein filling mineral. It usually shows the characteristic cross-hatch twinning, but some crystals do not do so.
Laumontite occurs as both replacement for plagioclase and as vug filling.
Calcite is abundant in all the studied wells. It occurs as both replacement and vein or vug filling.
Siderite is abundant in well KMJ-7, where it occurs both as a replacement and vug filling.
Iron oxides are hematite and titano-hematite. They occur as replacement and vug filling.
Pyrite occurs as vug and vein filling mineral, and is also disseminated in the matrix.
Sulphates present in Kamojang are anhydrite, gypsum, jarosite, and alunite.
Clays were mostly identified by X-ray diffraction (XRD) and scanning electron microscopy (SEM) with energy dispersive X-ray (EDX) spectra. They are kaolin, smectite, chlorite, illite, and interlayered clays.

The distribution of the hydrothermal minerals in the studied wells together with the lithologic units and measured downwell temperature profiles is summarised in Figure 1.

FLUID INCLUSION GEOTHERMOMETRY

Fluid inclusion homogenisation temperatures in conjunction with borehole temperatures, were used to deduce the thermal history of the Kamojang reservoir. Fluid inclusions' last ice melting temperatures were used to infer the composition of the reservoir fluid at the time of trapping. Two samples from well CHR-1 (1725 m) and four samples from well KMJ-12 (995 m) were suitable to measure. The inclusions measured occur in anhydrite crystals. The fluids in all samples were predominantly two phases (liquid plus vapor), with the vapor to liquid ratios ranging from 0.2 to 0.4. There were also single phase inclusions (all-liquid or all-vapor).

The homogenisation temperatures (Th) are plotted as a function of depth (Figs. 2A & B). These figures also show the boiling point versus depth curves, and the downhole temperature profiles.

For well KMJ-12 (995 m) the Ths are mostly fall within the range of 240-245 ^{o}C, which are about 30 ^{o}C higher than the present well temperature (190 ^{o}C) at this depth. This suggests either that these mode represent a previous thermal condition or else the well had not thermally stabilised. The Ths mode for well CHR-1 (1725 m) is within the range of 245-250 ^{o}C, i.e., about 60 ^{o}C above the downhole temperature measured after 15-16 days heating (185 ^{o}C). This also suggests that either the Th may record a previous thermal condition or the well had not stabilised thermally.

The ice melting temperatures (Tm) of the fluid inclusions from well KMJ-12 (995 m) fall into the range of –0.2 to –4 ^{o}C; these values correspond to apparent salinities of 0.35 to 6.43 wt% of NaCl (calculated using the formula of Potter *et al*, 1978). The Tms for well CHR-1 (1725 m) range from –0.2 to –0.9 ^{o}C, which corresponds to apparent salinities of 0.35 to 1.56 wt% NaCl. The inclusions are hosted by anhydrite, so the fluids must also be saturated with respect of $CaSO_4$.

RESERVOIR CHARACTERISATION

Hydrothermal Mineral Assemblages
and the Altering Fluid

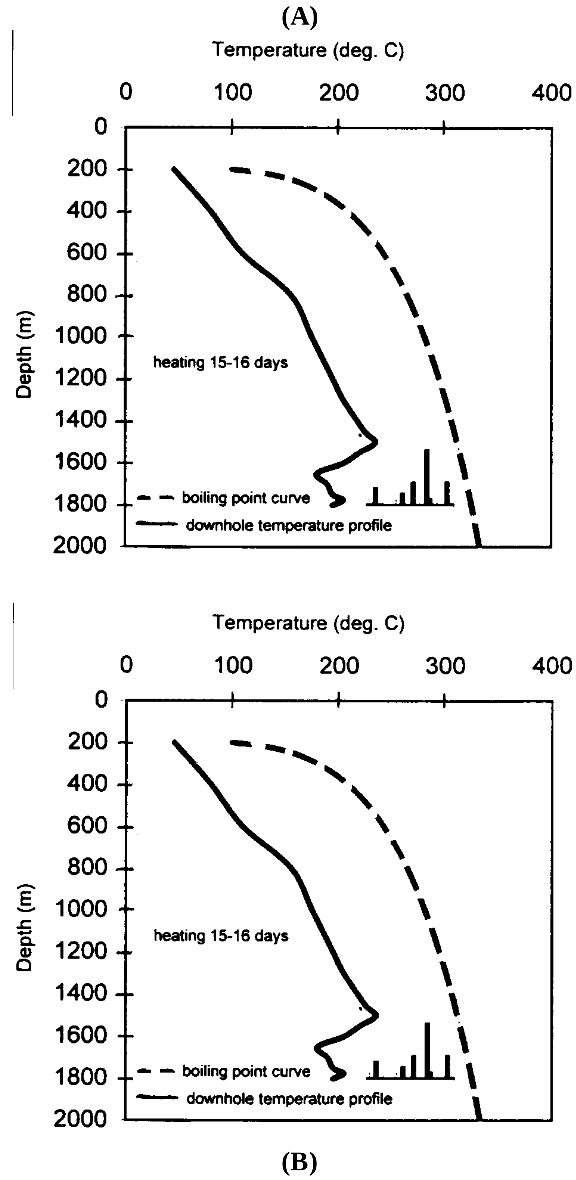

Figure 2. Plots of hydrostatic boiling point versus depth curve, borehole temperature profile, and histogram of fluid inclusions' Th from 995 m in well KMJ-12 (A) and from 1725 m in well CHR-1 (B).

There are 2 hydrothermal mineral assemblages present at Kamojang, i.e., "acid" and "neutral" assemblages, which occur in shallower and deeper levels, respectively. The "acid" assemblage occupies the shallower part of the system (down to about 100 – 300 m), and is characterised by the presence of kaolin with or without smectite, alunite, quartz, cristobalite, and pyrite. The deeper "neutral" assemblage comprises quartz, adularia, albite, epidote, titanite, wairakite, laumontite, calcite,

Depth (m)

siderite, hematite, titano-hematite, pyrite, anhydrite, smectite, chlorite, illite, and interlayered clays. Both assemblages indicate that the altering fluid was *liquid*. These assemblages are similar to those in Philippine geothermal systems (Reyes, 1990), which are also hosted by volcanic rocks and located in high terrain.

Hydrothermal Mineral Parageneses and Vein Cross-cutting Relationship

Replacement minerals and veins with several minerals, as well as cross-cutting veins are very common in the Kamojang field. They help reveal the changes that have taken place in the reservoir. Representative mineral paragenetic sequences are presented in Fig 3.

An early episode is characterised by simple quartz veining, a middle episode by many stages of mineralisation with more diverse mineralogy, including quartz, calcite, siderite, hematite, chlorite, illite, wairakite, epidote, and pyrite. Anhydrite, which formed due to the presence of acid sulfate-rich water, marks the last stage of the middle episode. The latest episode was characterised by deposition of quartz and pyrite.

Hydrothermal Alteration and Reservoir Hydrology

The shallowest occurrence of calcite seems to coincide with the deepest occurrence of kaolin and alunite. Kaolin and alunite form from the steam-heated water, and calcite will not survive in acid conditions. Therefore, the deepest occurrence of kaolin and alunite should mark the base of the more acidic condensate layer, and the shallowest occurrence of calcite may indicate the top of neutral sodium sulphate bicarbonate water. The depth of this boundary (at the time of the observed mineral assemblage formed) varies from well to well. In wells KMJ-7 and KMJ-10 it possibly occurs at around 100 m. In well CHR-1, it may be located at about 220 m. In wells KMJ-11, 12, 53, and 59 it is likely to occur at around 300 m depth.

The top of the present-day main steam zone in the studied wells is located at 880 m depth in well KMJ-11, and 880 m in well KMJ-12, at 679 m and 544 m vertical depths in wells KMJ-53 and KMJ-59, respectively, and at 1703 m in well CHR-1 (Tim Pokja Kamojang, 1995).

In the studied wells anhydrite occurs irregularly from 200 m down to a maximum depth of 1800 m. It forms due to the presence of sulfate-rich water which percolated down to these depths, became neutralised by reacting with host rocks and was conductively heated. Alunite, which is found down to 650 m by XRD on cuttings in well KMJ-59, may also result from the penetration of sulphate-rich water into this depth since it is stable at 200 ^{o}C (e.g. Reyes, 1990). However this interpretation for Kamojang suffers from uncertainty that the cuttings may be derived from shallower depths.

Comparison of Borehole and Mineral Deduced Temperatures

A comparison of borehole and calc-silicate mineral formation inferred temperatures in the Kamojang field is summarised in Table 1.

In many active geothermal fields clay minerals can be used as thermo-indicators because their structure and chemical composition are sensitive to thermal changes (e.g. Browne, 1978; Reyes, 1990; Iziquerdo, *et al*, 1995). At Kamojang, there are some clay zonations apparent in the studied wells. Interlayered clays do occur, but do not show progressive sequences, and this is probably due to conduit-flow type controlled by fracture permeability (Harvey & Browne, 1991) rather than pervasive fluid-rock interactions.

The shallowest part (down to about 300 m depth) of wells CHR-1, KMJ-12, KMJ-7, and KMJ-53 is dominated by kaolin, and smectite, which are stable at ambient temperature to about 80 ^{o}C. The intermediate depths are dominated by chlorite, or chlorite plus smectite (sometimes with illite), or chlorite plus interlayered clays. In wells KMJ-10 chlorite is stable at < 100 – 150 ^{o}C, but chlorite, illite, and smectite with interlayered clays are present together at < 75 – 100 ^{o}C. In other wells, chlorite with other clay species stable at varied measured temperatures. The deeper parts of well CHR-1, KMJ-53, and KMJ-59 are dominated by chlorite and illite, the temperatures ranging from 200 – 230 ^{o}C. Illite is usually stable above 220 ^{o}C (Browne, 1995). Illite and chlorite occur at 1725 m in well CHR-1 where the measured temperature is about 185 ^{o}C, but the fluid inclusion Ths ranging from 230 – 257 ^{o}C. These may also suggest cooling at this depth, or alternatively the well was not thermally stable when the temperatures were measured.

Permeability

The presence of pores, vugs and veins filled with secondary minerals in the reservoir rocks suggests a decrease in permeability. Some fractures in the main part of reservoir (e.g. in well KMJ-12, 650 m) are

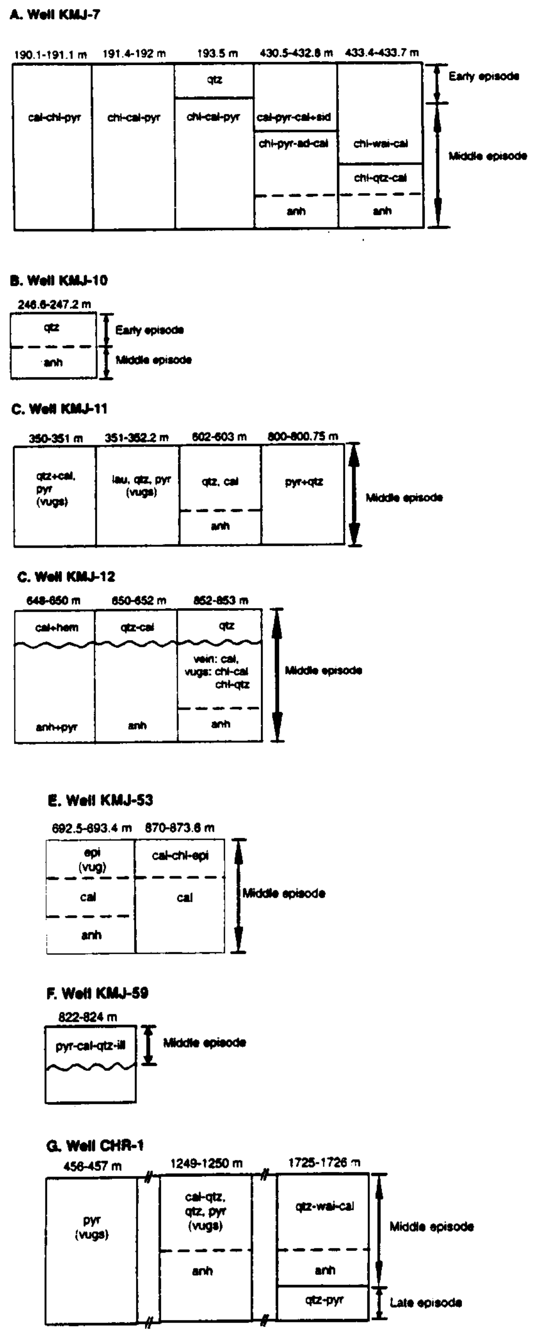

Fig.3. Representative hydrothermal mineral paragenetic sequences in the studied wells. Horizontal lines represent fracturing, dashed lines refilling, wavy line deformation. Qtz=quartz, cal=calcite, chl=chlorite, py=pyrite, ad=adularia, wai=wairakite, epi=epidote, lau=laumontite, hem=hematite, anh=anhydrite.

partly sealed with hydrothermal minerals. On the other hand, some cores with sheared textures and secondary minerals with deformed cleavages (e.g. in wells KMJ-7, 433 m, KMJ-12, 650 m. CHR-1, 1725 m) indicate a deformation event (probably due to faulting) after their deposition, which may have created new permeabilities. Some connected vesicles are present in some cores. These, together with intergranular pores, provide the present-day permeability in the reservoir rock.

The following hydrothermal minerals in cavities are higher-permeability indicators at Kamojang: quartz (e.g. 400 m/KMJ-7, 600 m/KMJ-10, 900 m/KMJ-11, 900 m/KMJ-12, 1725 m/CHR-1), calcite (e.g. 400 m/KMJ-7, 600-650 m/KMJ-10, 1725 m/CHR-1) and anhydrite (e.g. 400 m/KMJ-7, 600 m/KMJ-10, 900 m/KMJ-11, 900 m/KMJ-12, 1725 m/CHR-1).

Table 1. Comparison of borehole and calc-silicate mineral formation temperatures in the Kamojang field.

Mineral	Usual formation T (^oC)	Borehole T (^oC), depth and well no.
Wairakite	210-320	**220** (433m/KMJ-7) **180** (550m-603m / KMJ-11)[1] **210** (705-751.5 m/ KMJ-12, unstable)[2] **180-200** (1000 m, **1086** m/KMJ-12)[2] **240** (710m/KMJ-53)[3] **150-160** (1725m/ CHR-1)
Laumontite	120-210	**140** (96m/KMJ-7)[2] **110** (351m / KMJ-11)
Epidote	≥ 250	**245** (692.5m, 711m, 902m/KMJ-53) **175** (1191m / CHR-1)[4] **175-210** (600-**951**m/KMJ-12, unstable)[1,2]

Note:
1=Healy (1977), 2=Browne (1977), 3=Purba (1994), 4=Budiardjo (1990, in GENZL & TE, 1991).

CONCLUSIONS

The present-day vapor dominated fluid at Kamojang evolved from the previous hot water system, as it is indicated by its mineralogy and fluid inclusions. The "acid" mineral assemblage which occupies the shallow part of the system (from near surface down to about 300 m) indicates that the altering fluid here was dominantly of acid sulfate type. The alunite most likely formed from the oxidation of H_2S rather than magmatically derived SO_2. The neutral mineral assemblage occuring below the acid assemblage suggests that the altering liquid here was near neutral pH water.

The hydrothermal mineral parageneses and cross-cutting relationships evident in veins suggest that, although there were several mineralising episodes, the fluid compositions in deep levels (below the "acid" mineral zone) were the same, i.e., of near neutral pH chloride water. The sulfate-rich water, possibly derived from steam condensate, seems to have come after the deposition of the "neutral pH" assemblage.

In general, temperatures indicated by other calc-silicates and clays at Kamojang are higher than the stabilised downhole temperatures. This suggest cooling, although underestimation of the present-day temperatures is also possible. No detailed information about thermal changes could be obtained from the mineral parageneses because temperature indicating minerals are not always present in the cross-cutting veins. However, assuming that the measured temperatures in well CHR-1 represent the present-day thermal condition, then fluid inclusions hosted by anhydrite may record cooling in this part of reservoir by about 60 ^{o}C since the anhydrite deposited. At Kamojang clay minerals do not serve as good temperature indicators.

Permeability has decreased due to mineral deposition but tectonic activity has helped maintained it by reopening vertically permeable features. The hydrothermal minerals characterising high-permeability zones are quartz, calcite, and anhydrite occuring in veins.

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