A Lithostatically Pressurized Clay Cap of the Vapor-dominated Reservoir
Deduced from Hydrothermal Alterations of Borehole Cuttings in the
Mataloko Geothermal Field, Flores Island, Eastern Indonesia

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Abstract

X-ray powder examination on the alteration of the drill hole cuttings revealed a mineralogical zoning of kaolinite -α-cristobalite (I) - zeolite (II) - and kaolinite (III) - zones toward the bottom of the well MT-1 in the Mataloko geothermal field, central Flores, eastern Indonesia. Zone II is further subdivided into the upper heulandite (Iia) - middle laumontite (IIb) - and lower wairakite (Iic) - subzones in descending order. A temperature profile in the crystallization process deduced from the phase equilibria of zeolite minerals and the kaolinite crystallinity index dramatically increases toward the deeper part exceeding the hydrostatic boiling-point curve of pure water and reaching 236°C at a depth of around 180 m. This depth is ascribed to the maximum enthalpy point on the two-phase region of water, dividing the deeper vapor-dominated reservoir and shallower vapor condensation zone. The vapor condensation zone generally is 360 m thick, but in the Mataloko area it was only half as thick, owing to lithostatic pressure. Abundant clay and zeolite minerals in Zone II might have formed an extremely impermeable zone, and the continuing excess heat supply might have generated a lithostatically-pressurized clay cap. The lithostatic pressure has since been released.

Keywords: Flores, Mataloko, hydrothermal alteration, kaolinite crystallinity index, wairakite, vapor-dominated reservoir, vapor condensation zone, lithostatic pressure, clay cap

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1. Introduction

Indonesia is an archipelago composed of about 17,000 islands, extending over 5,100 km east to west, and as such, a comprehensive electrical transmission network is not realistic, particularly in remote island areas. However, most of the islands are volcanic and have the potential for natural-, local- and green-power geothermal resources. The Indonesian government supports the construction of small-scale geothermal power stations in these islands through the Rural Electrification Program (Dwipa, 2002). To contribute to accelerating the Rural Electrification Program, the Directorate General of Geology and Mineral Resources of Indonesia (DGGMR), the New Energy and Industrial Technology Development Organization (NEDO) and the Geological Survey of Japan (GSJ), AIST, have conducted a five-year bilateral international cooperation program named the "Research Cooperation Project on the Exploration of Small-Scale Geothermal Resources in the Eastern Part of Indonesia" from FY1997 to FY2001 (Muraoka et al., 1998). The Mataloko geothermal field, in central Flores Island, eastern Indonesia (Fig. 1), was selected as a model field. The results of this project were comprehensively described in 31 papers in a special issue (Geological Survey of Japan, 2002). This project was completed successfully with the flow-test steam production of 15 tons per hour from the NEDO well MT-2 at the depth of 162.35 m, later deepened by DGGMR to 182.02 m (Sueyoshi et al., 2002; Sitorus et al., 2002).

However, because of the limited instrumentation in the remote island, the earlier two wells MTL-1 drilled by DGGMR and MT-1 drilled by NEDO encountered an unexpected blow out of steam at the depths of 103.23 m and 207.26 m, respectively, and the pressure-temperature logging data of the three wells were insufficient to characterize the reservoir condition. Therefore, the supplementary characterization of the Mataloko geothermal reservoir would be attained through the use of available cutting samples and other methods. The well MT-1 is the deepest among the three wells and the most adequate for the mineralogical analyses. The mineral constituents of the cutting samples from the well MT-1 were examined by the X-ray powder diffraction method in GSJ’s laboratories as a part of the invitation program during February 2001 by the first author (A. N.) with subsequent works by the second author (M. T.). This paper describes the results of X-ray analyses on cutting samples from the well MT-1 and tries to characterize the Mataloko geothermal reservoir from the mineralogical viewpoint.

2. Geological Setting and the Well MT-1

Flores Island is one of the main islands of Nusa Tenggara Timur (East) Province extending from...
latitude 8°12' to 8°58' S and from longitude 119°47' to 123°01' E (Fig. 1). The Mataloko geothermal field is situated southeast of Bajawa City in central Flores Island. Flores Island forms part of the Lesser Sunda-Banda arc where the Australia Continental Plate is apparently underplating the Banda Ocean Plate. The inner Lesser Sunda arc is composed of relatively immature volcanic islands and the oldest exposed rock unit is the Miocene volcanic and sedimentary strata deposited under the marine environment. The surroundings of Bajawa City, central Flores Island, are entirely covered by the Pliocene and Quaternary volcanic rocks (Fig. 2). The Miocene sediments and volcanic rocks are only exposed in the northern coastal areas (Muraoka et al., 2002a). Many late Quaternary volcanoes are recognized in the vicinity of Bajawa City. Inerie volcano lies near the southwestern coast and forms a typical stratovolcano. Inie Lika volcano lies north of Bajawa City and phreato-magmatic eruption occurred during January 11-19, 2001, after 95 years of quiescence (Muraoka et al., 2002b); its southern flank is shown in Fig. 2. Bobo volcano lies south of Bajawa City. Inie Lika and Bobo volcanoes are typical composite volcanoes and form parts of the Bajawa Cinder Cone Complex that is composed of about 60 numbers of cinder cones trending in the NNW–SSE direction. The major part is linearly aligned along Inie Lika and Bobo volcanoes but another branch is also found from Bajawa to Mataloko.

In the area covered by Fig. 2, the Miocene Nangapanda Formation is only drawn on the cross section. The oldest exposed unit is the Pliocene Maumbawa Basalt in the eastern area. This is overlain by the Welas Tuff, 2.5 Ma in the K-Ar age, that is altered to chlorite-bearing green tuff probably due to the ash-flow deposition in a marine environment and is only exposed in two narrow valleys. Pliocene basins were bounded by the Bajawa-Mataloko ridge: to the north the Aesesa Formation deposited in a lacustrine environment and to the south the Waebela Basalt, pillow lava and hyaloclastite, deposited in a marine environment. The Quaternary volcanic sequences are classified into the Sasa Andesite, Aimere Scoria Flow Deposits, Siutoro Andesite, lahar deposits, Mataloko Andesite, Bobo Andesite, Inie Lika Andesite, Inerie Basalt and alluvium in ascending order. The Sasa Andesite forms cinder cone volcanoes similar to those of the Bajawa Cinder Cone Complex, but is distinguished by the reverse magnetization, older than 0.73 Ma. The Aimere Scoria Flow Deposits are primary products from the Bajawa rift zone that might have initially formed an NNW–SSE elongated volcano (Muraoka et al., 2002b, 2002c). The Siutoro Andesite forms Siutoro volcano near the southern coastal area. After these units appeared, apical extension with rifting activity might have caused a collapse of Nage caldera, probably a Kilauea-type, and an asymmetrical collapse of eastern flanks of the elongated volcano in the Bajawa rift zone. Most of the lahar deposits might have occurred in this stage. The Mataloko Andesite, Bobo Andesite and Inie Lika Andesite form the Bajawa Cinder Cone Complex and their distribution delineates the extent of the Bajawa rift zone. The Inerie Basalt forms Inerie volcano near the southwestern coastal area. Most of volcanic rocks consist of tholeiitic rock series in this area, as typical of the immature volcanic arc. However, the Bajawa rift zone volcanic rocks such as the Aimere Scoria Flow Deposits and Bajawa Cinder Cone Complex are composed of calc-alkaline rock series and are quite homogeneous (Muraoka et al., 2002c). Most of geothermal manifestations seem to be associated with the Bajawa Cinder Cone Complex (Muraoka et al., 2002a, 2002c).

There are nine hydrothermally altered areas around Bajawa and their descriptions are given in Akasako et al. (2002) and Tagomori et al. (2002). The localities of main six altered areas are shown in Fig. 2. One of them, the Mataloko geothermal field is composed mainly of soft whitish clay originating from the Mataloko Andesite and its alteration zone has a general trend of ENE–WSW direction along the Wae Luja River that is 1.0 km long and 0.3 km wide, as shown in Fig. 3. The altered area has a mineralogical zoning...
Fig. 2 Generalized geological map of the southern Bajawa geothermal field (modified from Muraoka et al., 2002a).
made up of, smectite-, kaolinite- and alunite-zones toward the center (Nasution et al., 1999). There are active steaming grounds with fumaroles, mud pools and many hot springs along the floor of the Wae Luja River within the center of the alteration zone where silicification and pyritization are also pervasive (Nasution et al., 1999). Takahashi et al. (2002a, 2002b) studied geochemistry of the hot spring waters in the Bajawa geothermal field and clarified that the chemical nature of the hot spring water is of the sulfate type in the Mataloko area.

3. Samples and Analytical Procedures

Cutting samples for X-ray analyses were chosen from seventeen depths from the well MT-1. Their depths and brief lithology are summarized in Table 1. Samples of 15–25 g were automatically powdered by an agate motor. The orientation samples to check for clay minerals were prepared by the following method.
The bulk powder (5-10 g) was scattered into pure water in a 2-liter beaker, and after 12-16 hours, the supernatant solution of 350-450 ml was recovered by siphon. The non-treated clay fractions were collected by a centrifugal separator (2,000 rpm, 20 min.) from a half portion of the supernatant solution and then dried on a slide glass. The residual supernatant solution was acidified by 6N-HCl solution and heated up at 95°C for 30 minutes. The HCl-treated fractions were collected and dried by the same procedure. The clay fractions on glass plates were less than 2 μm in their sizes.

To the samples showing weak peaks near 10 degree (2θ) on the X-ray chart, the original bulk samples were acidified again by 10% HCl solution for the identification of laumontite. Such bulk samples were also heated up at 400°C for 16 hours for the discrimination of heulandite group mineral by the Alietti test (Alietti, 1972). Zeolite particles (100-250 mesh) sieved from the original bulk powder were concentrated by using a magnetic separator and heavy liquid solution (ρ=2.25 g/cm³).

The X-ray parameters, using CuKα1 graphite-monocrilized radiation (Rigaku Rotorflex Ru-200 V), were set at 40 kV and 100 mA with a step-scanning rate of 4 degree/minute and with a slit system of 1°-1°-0.3 mm-0.3 mm for all the samples including orientation samples.

4. Outlines of Mineral Occurrence

Twenty-seven kinds of minerals were identified in all the samples studied. They are quartz, α-cristobalite, k-feldspar, smectite, sericite, chlorite, kaolinite, heulandite, epistilbite, laumontite, yugawaralite, wairakite, anhydrite, alunite, natroalunite, jarosite, woodhouseite, gibbsite, pyrite and calcite as secondary minerals and relic plagioclase and pyroxene including minor hematite and magnetite as primary minerals. Furthermore mixed-layer clay minerals of smectite and kaolinite, and of sericite and smectite were found at a several depths. Relative abundances of each mineral are listed in Table 1. Representative X-ray charts are shown in Fig. 4. Stratigraphic distributions of main minerals are as follows:

a. Silica minerals: Quartz is recognized in all the samples. The sharp peak near 22° (2θ) on the X-ray charts showing the d-spacing of 4.05-4.04 Å is identified as α-cristobalite. This mineral occurs at the depths shallower than 121 m. At a depth from the surface to 61 m, α-cristobalite is abundant compared to its content

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Table 1  Mineral constituents and mineral zoning in the cutting samples of the well MT-1, the Mataloko geothermal field, central Flores.

<table>
<thead>
<tr>
<th>No</th>
<th>Depth (m)</th>
<th>Lithology</th>
<th>Zoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-10</td>
<td>Tuff breccia</td>
<td>Zone-I</td>
</tr>
<tr>
<td>2</td>
<td>10-46</td>
<td>Andesite*</td>
<td>Zone-II</td>
</tr>
<tr>
<td>3</td>
<td>46-49</td>
<td>Andesite*</td>
<td>Zone-III</td>
</tr>
<tr>
<td>4</td>
<td>49-58</td>
<td>Andesite*</td>
<td>Zone-Gb</td>
</tr>
<tr>
<td>5</td>
<td>59-61</td>
<td>Andesite*</td>
<td>Zone-Sc</td>
</tr>
<tr>
<td>6</td>
<td>61-100</td>
<td>Andesite*</td>
<td>Zone-Ib</td>
</tr>
<tr>
<td>7</td>
<td>100-106</td>
<td>Andesite</td>
<td>Zone-Ia</td>
</tr>
<tr>
<td>8</td>
<td>106-121</td>
<td>Andesite</td>
<td>Zone-Ic</td>
</tr>
<tr>
<td>9</td>
<td>121-167</td>
<td>Andesite*</td>
<td>Zone-Ia</td>
</tr>
<tr>
<td>10</td>
<td>127-164</td>
<td>Tuff breccia</td>
<td>Zone-III</td>
</tr>
<tr>
<td>11</td>
<td>142-180</td>
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<td>Zone-Ia</td>
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<td>12</td>
<td>160-183</td>
<td>Tuff</td>
<td>Zone-Ia</td>
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<tr>
<td>13</td>
<td>163-166</td>
<td>Tuff breccia</td>
<td>Zone-Ia</td>
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<td>Tuff</td>
<td>Zone-Ia</td>
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<tr>
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<td>172-184</td>
<td>Tuff</td>
<td>Zone-Ia</td>
</tr>
<tr>
<td>16</td>
<td>184-190</td>
<td>Tuff</td>
<td>Zone-Ia</td>
</tr>
<tr>
<td>17</td>
<td>190-207</td>
<td>Tuff</td>
<td>Zone-Ia</td>
</tr>
</tbody>
</table>

+++, very abundant; +++, fairly abundant; +, subordinate and -, existent.
*, includes tuffaceous fragments and **, includes andesitic lava fragments.

Qz, quartz; Or, α-cristobalite; Pl, plagioclase; Kf, K-feldspar; Sm, smectite; Sr, sericite; Ch, chlorite; Ka, kaolinite; S/K, smectite/kaolinite mixed-layer clay mineral; S/S, smectite/sericite mixed-layer clay mineral; Hu, heulandite; Es, epistilbite; Yu, yugawaralite; Li, laumontite; Wa, wairakite; Ah, anhydrite; Al, alunite; Na, natroalunite; Jr, jarosite; Wd, woodhouseite; Gb, gibbsite; Ru, rutile; Py, pyrite; Hm, hematite; Mg, magnetite; Cc, calcite and Px, pyroxene.

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Fig. 4a X-ray diffraction patterns of representative samples. Ori, non-oriented sample; EG, oriented sample with addition of ethylene glycol; 6N-HCl, oriented sample treated by 6N-HCl; 10% HCl, bulk sample treated by 10% HCl; 400°C, bulk sample heated up at 400°C for 16 hours. Numbers in the circle corresponds to those in Table 1. Mineral symbols are also the same as those in Table 1.

in samples from the deeper horizons and commonly coexists with smectite, kaolinite and minor pyrite, rarely accompanying sericite and natroalunite. The mineral has been transformed into quartz by the rising temperature below the level.

b. Clay minerals: Just like quartz, smectite is also found in all the samples. Minor sericite is ascertained at a depth from 10 to 49 m. Kaolinite occurs in two horizons, the first horizon at a depth from the surface to 61 m (together with α-cristobalite) and the second horizon at a depth below 172 m. The kaolinite
in the lower horizon shows sharp X-ray diffraction peaks compared to kaolinite from the upper horizons and commonly coexists with pyrite, smectite, minor anhydrite, rare natroalunite and jarosite. The mixed-layer clay minerals of smectite and kaolinite that show weak asymmetrical broad peaks at the angle less than 12 degree (2θ), are distinguished from the original 7 Å-kaolinite diffraction through ethylene glycol treatment and are not negligible in the upper horizon. Minor chlorite is found at the level of 142-160 m and 163-172 m with some amounts of zeolite minerals.

c. Zeolite minerals: Ca-zeolites such as heulandite, epistilbite, laumontite, yugawaralite and wairakite are found below the depth of 61 m but their individual contents are usually low except for wairakite at two depths (Table 1). Among them, heulandite occurs in the shallower horizon (61-100 m) with smectite and α-crystobalite. Wairakite distinguishable from tetragonal and orthorhombic analcime by the strong intensity of (200) reflection occurs in the deeper level and is a common component between 127 and 172 m depths, occasionally coexisting with epistilbite, laumontite, yugawaralite and chlorite.
5. Mineral Zoning

Quartz, smectite and pyrite commonly occur in the drill core cuttings. Albitization of plagioclase was not checked by microscopic observation, and therefore, they are omitted from the critical minerals. The above-mentioned mineral assemblages enable the recognition of the hydrothermal mineral zoning: the kaolinite-\(\alpha\)-cristobalite (I)-, zeolite (II)- and kaolinite (III)- zones are defined at the depth intervals of 0-61 m, 61-172 m and 172-207 m, respectively.

In the upper kaolinite-\(\alpha\)-cristobalite - zone (Zone-I), natroalunite and pyrite are often observed. The hot waters on the ground surface are predominantly of sulfate composition (Takahashi et al. 2002a), so that the mineralization in this zone could be related to the acidic solutions originating from the oxidation of \(H_2S\) gas near the surface. The andesitic composition of the source material and the absence of an amorphous phase indicate that crystallization might have been caused mainly by dissolving glassy materials and iron silicates into acidic solutions, releasing vapor.

To consider the mineralogical zoning below the depth of 61 m, the following aspect is of critical importance. If the zeolite minerals are neglected due to their low abundances and the zoning scheme is defined based exclusively on the abundant clay minerals, a very different zoning scheme might possibly be drawn below the depth of 61 m. However, as mentioned below, it is impossible to neglect the zeolite crystallization in terms of thermal history of the Mataloko geothermal system.

Heulandite occurs at the depth of 61-100 m with chlorite but without other zeolite minerals, and does not appear at other levels. The only coexisting clay mineral is smectite in this horizon. As mentioned above, wairakite occurs commonly at the depth from 127 to 172 m. Primary pyroxene and plagioclase are still preserved at the first appearance of the zeolite mineral at a depth of 61 m, but they tend to disappear below the depth or decrease toward the deeper level. This is partly ascribed to the fact that wairakite tends to completely replaces plagioclase below the depth of 127 m. Laumontite is often found below the 100 m depth and a critical mineral at the depth from 100 m to 127 m. In this horizon, epistilbite occasionally coexists with laumontite. Consequently, the zeolite zone is divided into three parts: the heulandite (IIa)-, laumontite (IIb)- and wairakite (IIC) - subzones toward the deeper horizon. The dehydration of zeolite minerals toward the deeper level is one of the basic characteristics in the alteration process of Zone-II.

The lower kaolinite-zone (Zone-III) is more dominant in pyrite compared with one from the upper zones and also characterized by a variety of sulfate minerals such as anhydrite, alunite, natroalunite, jarosite and woodhouseite. These minerals might have crystallized from acidic solution similar to those in Zone-I.

6. Analytical Result

Temperature logging was not carried out in the well MT-1, and therefore other kinds of geothermometers are useful to evaluate the Mataloko geothermal reservoir. In the field of hydrothermal alteration mineralogy, the temperature profile can be estimated by the analysis of zeolite mineral assemblages by referring to experimental data and by the measurement of clay mineral crystallinity. Using these techniques, an attempt is made here to estimate the temperature profile.

6-(1) Estimation by experimental phase reaction data of zeolite

Pressure-temperature stability relationships of zeolite minerals under experimental hydrothermal conditions were provided by Cho et al. (1987) for heulandite-laumontite, by Zeng and Liou (1982) for yugawaralite-wairakite and by Liou (1971) for laumontite-wairakite. Zeng and Liou (1982) thermodynamically determined the phase diagram for the laumontite-yugawaralite reaction. Epistilbite is
found in the studied cuttings but no phase equilibrium data have yet been published on the mineral. On the applying the phase stability relationship to the field geology, Liou (1971) emphasized that the equilibrium curve shifts toward low temperature by increasing the NaCl-concentration in the solution and by decreasing of the ratio of $P_{\text{fluid}}/P_{\text{total}}$ in the hydrothermal system. Furthermore, Seki et al. (1983) drew attention to the fact that increasing of the CO$_2$ concentration in the fluid decreases the equilibrium temperature.

Takahashi et al. (2002a, 2002b) made clear that the NaCl-content of the surface hot spring solution is remarkably low. As carbonate mineral is only found in the 142-160m levels, two factors are neglected from the consideration. As the data on the partial water pressure in the Mataloko hydrothermal system are not given, the condition of $P_{\text{fluid}} = P_{\text{total}}$ was assumed as a first approximation. Yugawaralite is recognized together with laumontite and wairakite at the two horizons of 127-142 m and 163-166 m. According to Zeng and Liou (1982), the invariant point indicating the three minerals' stable association is located at about 234°C and 550 bar, but the bottom pressure of the well MT-1 was only 50 bar even in the higher lithostatic case, so it would be impossible for the assemblage of laumontite, yugawaralite and wairakite to exist under the equilibrium condition in the Mataloko geothermal system, leaving the invariant reaction out of consideration. The hydrothermal experiments undertaken by these workers were carried out at the pressure higher than 500 bar. The reaction temperatures near the surface were calculated by extrapolation. The obtained univariant reaction temperature are 112°C at 100 m (Hu/Lm), 135°C at 142 m (Lm/Yu) and 225°C at 166 m (Yu/Wa), respectively, which are plotted in Fig. 5.

There are two methods to calculate kaolinite crystallinity. In this study, the crystallinity index was defined as the measurement of the peak width at a half height of the basal reflection plane (001). The validity of this method was proven by Eckhart and von Gaertner (1962). They obtained good relationships between decreasing of the peak width (increasing of crystallinity) and increasing of coal rank, and they concluded that the crystallinity depends on paleogeothermal temperature. Furthermore, Eckhart (1965) showed that the kaolinite crystallinity increases with coal rank below 200°C, and at a temperature higher than this, the crystallinity reaches an invariable constant. On the other hand, Stadler (1971) denied the relationships between kaolinite crystallinity and coal rank. An attempt is made here to use the kaolinite crystallinity as a supplementary temperature indicator for confirming those obtained from zeolite minerals in the zeolitic alteration (Zone-II) and lower acidic alteration (Zone-III).

As the studied sample sometimes contains the mixed-layer clay mineral of smectite and kaolinite, the
HCl-treated orientation samples were used for this measurement. The measured values are plotted in Fig 6. Each depth of the sample (D) is given as a middle horizon of each depth interval of cuttings in this figure. The peak width in the upper kaolinite-\(\alpha\)-cristobalite zone gradually decreases as the depth increases, showing an invariable value in Zone-III as the limit. Generally speaking, it is very difficult to discriminate between dickite and well-crystallized kaolinite on the bulk powder X-ray chart. Judging from the weaker intensity of the basal reflection at 3.5 Å compared to one at 7 Å on the orientation sample chart, the kaolinite mineral in Zone-III is identified as kaolinite rather than dickite. Consequently, according to Eckhart (1965), the kaolinite in the lower Zone-III should have suffered by the heating of the temperature above 200°C. The 200°C temperature is assumed in Zone-II, although there is no kaolinite occurrence in this zone.

Four kinds of regression curves: the linear, second order polynomial, logarithmic and exponential functions were assumed for determining the relationship between the depth (D in m) and peak width (W in 2θ degree). The best approximation was obtained by the second order polynomial function with a formula of

\[
W = - 0.00002D^2 - 0.0063D + 0.6633
\]

where R-value is 0.977. The depth with a temperature of 200°C was estimated to be about 160 m from this regression formula, corresponding to Subzone-Iic. Thus, no contradiction is found between the zeolite reaction temperature and kaolinite crystallinity index, which support the Eckhart's theory, suggesting that the fluid pressure was approximately consistent with the total pressure of the geothermal system at the last stage of zeolitic mineralization process.

![Fig. 6](image)

7. Discussion

7-(1) Thermal history of the Mataloko geothermal system

The thermal history of the Mataloko geothermal system is discussed based on the mineralogical evidence. Based on the mineral assemblages in the well MT-1, a single cycle of thermal evolution of the geothermal system in the given depth range of the well can basically be defined. The cycle evolved from the formation of the upper acidic alteration zone at an earlier stage and subsequently followed by the lower zeolite mineralization at a later stage. One exception to the single cycle is kaolinite mineralization in Zone-III and it will be discussed below.

As described above, the abundant quartz-smectite assemblage commonly occurs below the kaolinite -
α-cristobalite zone, and the voluminous occurrence of smectite over the wide depth range indicates that the alteration process was pervasive. Smectite commonly expands to 16-17 Å by the addition of ethylene-glycol and shifts to 12-16 Å by 6N-HCl treatments, but does not show the 10 Å reflection on the ethylene-glycol treatment sample chart, with the only exceptions are those taken from the depth of 160-163 m. Thus, most of smectite is not specified as the mixed-layer clay mineral of smectite and sericite, and the HCl treatment-diffraction made clear the aluminous nature of the smectite that should be identified as montmorillonite.

Thick montmorillonite zones are usually developed below the kaolinite or alunite-kaolinite zone near the surface, as observed in other geothermal fields: Wairakei, New Zealand (Steiner, 1977), The Geysers, U. S. A. (White et al., 1988) and Otake, Japan (Hayashi, 1973). The Otake area exhibits a typical example where the alunite-, kaolinite-, montmorillonite- and zeolite-zones are distributed in a descending order. Hayashi (1973) interpreted that the montmorillonite-zone with a thickness of 200-400 m has been formed under the weaker acidic environment with higher Al₂O₃-concentration of wall rocks (15.3-16.4%). In The Geysers geothermal field, the montmorillonite-zone begins in the middle horizon of the kaolinite-zone, descending through the mixed-layer illite-montmorillonite-zone in the well Y-12 core, under strong sulfuric condition (White et al., 1988). Therefore, it is accepted that the montmorillonite below Zone-I in the well MT-1 has crystallized under acidic condition, and the assemblage of relic natrolite-alunite without relic pyroxene in Subzone-IIa strongly suggests the montmorillonite origin.

During the earlier crystallization stage, the geothermal reservoir would have been open to the ground surface through the network channels and the kaolinite - α-cristobalite zone would be well developed, making a tight clay cap by supplying heat and gas from the deeper part and recharging groundwater from the surface. Then at the later stage, the liquid condensate below the growing clay cap might have been gradually neutralized or weakly alkalified due to the pyrite and sulfate mineralization and heulandite crystallization replacing plagioclase. During the zeolitization process, the hydrothermal reservoir would have been closed to the surface particularly due to the development of the thick clay cap resulting in temperature rising up rapidly. Laumontite, yugawaralite and wairakite successively occurred in the zone by the phase reactions (progressively replacing each lower-temperature zeolite phase) and the reservoir system would have gradually been changed from the hot-water type to the vapor-dominated one (White et al., 1971). At the latest stage of the zeolitization, the temperature at the well bottom depth might have reached near or over 200°C. Wairakite might have crystallized from the condensed alkaline solution and would have replaced the relic plagioclase (Wirshing and Holler, 1989). After the wairakite crystallization, the temperature near the well bottom depth would have exceeded the hydrostatic boiling-point curve of pure water (Fig. 5). This indicates that the system would have become dry and hydrothermal alterations would basically become extinct except for minor interaction between the rocks and interstitial liquid condensates.

To explain the presence of kaolinite in Zone-III, it is believed that this mineral recrystallized with many of the sulfate minerals from the acidic solution by the oxidation of H₂S gas forming in the areas near the surface or along fractures open to the surface. If there was no kaolinite in Zone-III, then Zone-III may be interpreted as a deeper extension of Subzone-IIc. In fact, laumontite and wairakite appears, and yugawaralite and epistilbite disappears in Zone-III. This equilibrium regime is consistent with that of the later stage of the cycle in the given depth. Thus, kaolinite and the accompanying sulfate minerals should be explained by another formation condition. There are two possibilities, that is, kaolinite and the accompanying sulfate minerals could have been formed in the stage earlier or later than the single alteration cycle mentioned above. Stratigraphically speaking, the earlier stage case could be attributed to the near-surface condition like the top
of the Aimere Scoria Flow Deposits before the Mataloko Andesite appeared, while the later stage case could be attributed to very young fractures opening to the surface after the Mataloko Andesite appeared. However, it will be difficult to explain the latter case because laumontite and wairakite, being less acid-proof zeolites (Sakurai and Hayashi, 1952), were well preserved in the acidic conditions existing near the fracture. Therefore, kaolinite and the accompanying sulfate minerals in Zone-III are rather ascribed to the stage earlier than the major single alteration cycle mentioned above. In other words, kaolinite and the accompanying sulfate minerals in Zone-III may be relic alteration minerals, but the kaolinite crystallinity might have been re-equilibrated in the later single alteration cycle as seen in the crystallinity index curve (Fig. 6). Although still open to further investigations, it is most likely that kaolinite and the accompanying sulfate minerals in Zone-III could have been originated near the old ground surface at the top of the Aimere Scoria Flow Deposits before the Mataloko Andesite had overlain it (see cross sections in Fig. 2).

From this mineralogical examination, clear thermal histories down to the depth of the well bottom could be postulated. The shallower occurrence of wairakite in Zone-II may suggest a lithostatically-controlled high temperature regime at the last zeolitization stage that led the shallower development of the vapor-dominated reservoir in the Mataloko area.

A scheme of heat conduction at the last zeolitic alteration stage of the major single alteration cycle is postulated here. Brauckmann and Fuchtbauer (1983) showed the distribution of the kaolinite crystallinity index with an exponential increase in the sediments near basaltic sill intrusion. Figure 5, a plot showing the temperature profile of the zeolite phase reaction, also indicates an exponential distribution of temperature with the formula

\[ T = 40.1 e^{0.0097D} \]

where \( T \) is the temperature in °C, \( D \) is the depth in m and the obtained R-value is 0.901. The curve obtained resembles its exponential pattern, suggesting that the heat conduction of Zone-II was derived from the impermeability of the thick clay cap and the high heat supplied from the deeper horizons.

7-(2) A lithostatically pressurized clay cap of the Mataloko vapor-dominated reservoir

The thermal regime of the Mataloko geothermal system is evaluated here by comparing its data with other available data. Figure 7 summarizes all the available data, not only from the well MT-1 but also from MT-2. Only kaolinite and the accompanying sulfate minerals in Zone-III are considered as relic minerals on their origins but kaolinite might have also been re-equilibrated in the major single alteration cycle. All the mineralogical data such as the zeolite phase relationship and the kaolinite crystallinity index consistently indicate a "hypothetical temperature curve at the crystallization stage" as given in Fig. 7. This hypothetical curve clearly exceeds the hydrostatic boiling-point curve of pure water in Subzone-IIc and Zone-III, the maximum of which is close to the lithostatic boiling-point curve at a rock density of 1.8 g/cm³. Sueyoshi et al. (2002) showed the temperature logging data from the well MT-2 (Fig. 7), but it is unfortunately confined to the shallower depth and is of short standing time. Sawaki and Muraoka (2002) reported a several homogenization temperature data of fluid inclusions in quartz and calcite from the wells MT-1 and MT-2 (Fig. 7). They also found that the homogenization temperature of the fluid inclusions exceeds the hydrostatic boiling-point curve of pure water. Their data are consistent with the hypothetical temperature curve and confirm the reliability of the present study. Fluid inclusion data are empirically known to show nearly a modern hydrothermal temperature regime, and therefore, the hypothetical curve may represent a very recent temperature regime in the Mataloko geothermal system. To explain such the high temperature conditions, Sawaki and Muraoka (2002) speculated that surface units of 100 m thickness were eroded off after the
Fig. 7 Summary of the temperature regimes in the Mataloko geothermal system. Temperature logging data of the well MT-2 are given by Sueyoshi et al. (2002). Lateral bars indicate homogenization temperatures of fluid inclusions by Sawaki and Muraoka (2002). Cal, calcite; Qtz, quartz; Hu, heulandite; Lm, laumontite; Yu, yugawaralite; Wa, wairakite; Ka, kaolinite crystallinity index; closed circle, temperatures estimated from zeolite univariant reactions; open circle, a temperature estimated from kaolinite crystallinity index.

Formation of the fluid inclusions as a 100 m upward boiling-point curve (Fig. 7). However, based on the present study, it is noted that the high temperature gradient intervals of the hypothetical temperature curve coincided well with the zones of prevalent clay minerals, possibly having formed an almost impermeable clay cap. This might have played the role of the lithostatically pressurized cap that has bounded a lower vapor-dominated reservoir and upper vapor condensation zone. The hypothetical curve, in fact, reaches 236°C at a depth around 180 m which is ascribed to the maximum enthalpy point on the two-phase region of water, because the pressure of the lithostatic boiling-point curve at a rock density of 1.8 g/cm³ reaches 31.8 kg/cm² (32.4 bar) at the depth of around 180 m, that is, the known pressure of the maximum enthalpy point (White et al., 1971).
The mineralogical temperature profile thus indicates that the Mataloko reservoir had, at least once, experienced a vapor-dominated reservoir up to a very shallow depth. The vapor condensation zone above the vapor-dominated reservoir generally has a thickness of 360 m (White et al., 1971, 1988), but it has only a half of that in the Mataloko area at the time of crystallization. Abundant clay and zeolite minerals in Zone-II might have formed an extremely impermeable zone and the continuing excess heat supply might have generated a lithostatically pressurized clay cap for the rock density of 1.8 g/cm$^3$.

The hypothetical temperature curve may represent a very recent temperature regime in the Mataloko geothermal system, as supported by the fluid inclusion data. Nevertheless, Sitorus et al. (2002) reported that the maximum temperature and pressure of the well MT-2, 35 m north of the well MT-1, was 192.30°C and 13.86 bar at a depth of 175 m. These pressure-temperature conditions are far less than those of the vapor-dominated system (White et al., 1971). Although they were not measured in the same well, it is most likely that the lithostatically pressurized clay cap of the well MT-1 has very recently been liberated by the break of the WNW-ESE trending Wae Luja fault (Tagomori et al., 2002; Akasako et al., 2002) and the present temperature regime in the Mataloko geothermal system may have somewhat declined to the "hypothetical temperature curve at the present stage" as shown in Fig. 7. This possibility is strongly supported by Muraoka et al. (2002a) that many conjugate sets of the WNW-ESE and ENE-WSW strike-slip type faults are detected near the Bajawa rift zone on the satellite image and their origin may be ascribed to the recent dike filling beneath the Bajawa rift zone because their local E-W contraction stress field is incompatible with the regional N-S contraction stress regime. Based on this idea, the fault break and the resulting pressure drop are considered to have occurred after most of the Bajawa Cinder Cone Complex (dike fillers) appeared and before most of surface alterations took place. Because the former is dated to be 160-72 ka and the latter is dated to be 33-0 ka by the thermoluminescence method by Takashima et al. (2002), the fault break and the resulting pressure drop might be estimated to have occurred during 72-33 ka.

Normally, such a recent temperature decline should also have been recorded in the mineral equilibria and fluid inclusions, but this has not actually been recorded. This could be explained by the vapor-dominated nature itself that Subzone-IIc and Zone-III have already been filled with dry steam at the time of the fault break and the water-rock interaction was limited. This also suggests that the thickness of the vapor condensation zone was instantaneously raised to 360 m by the fault break but the vapor-dominated reservoir could still be preserved beneath the thickened vapor condensation zone as observed in the single-phase dry steam discharge during the flow test of the well MT-2 (Matsuda et al., 2002).

**Summary and Conclusions**

As only three shallow wells were drilled in the Mataloko geothermal field, characterization of the reservoir is still open to further investigations. In determining the primary characteristics of the system, hydrothermal minerals of cutting samples from the well MT-1 were analyzed by means of the X-ray powder diffraction method and the following results were obtained.

1. Hydrothermal alteration mineral assemblage is divided into kaolinite - α-cristobalite (I) -, zeolite (II) - and kaolinite (III) - zones in descending order, where Zone II is subdivided into the heulandite (IIa) -, laumontite (IIIb) - and wairakite (IIc) - subzones in descending order.

2. The temperature profile deduced from the phase equilibria of zeolite minerals and kaolinite crystallinity index dramatically increases toward the deeper part exceeding the hydrostatic boiling-point curve of pure water and reaching 236°C at a depth of around 180 m. This depth is ascribed to the maximum
enthalpy point on the two-phase region of water, separating the deeper vapor-dominated reservoir and the shallower vapor condensation zone.

(3) The vapor condensation zone generally has a thickness of 360 m, but it was only about half as thick in the Mataloko area at the time of crystallization. Abundant clay and zeolite minerals in Zone-II might have formed an extremely impermeable zone and the continuing excess heat supply might have generated a lithostatically pressurized clay cap at a rock density of 1.8 g/cm³.

(4) These results are consistent with the fluid inclusion study (Sawaki and Muraoka, 2002) and the dry steam nature during the flow test of the well MT-2 (Matsuda et al., 2002). The present temperature-pressure regime shows that the lithostatic pressure control might have ceased (Sitorus et al., 2002), probably due to the fault break during 72–33 ka, but the vapor-dominated reservoir might still be preserved beneath the thickened vapor condensation zone.

(5) The relatively recent record of the lithostatically pressurized clay cap of the vapor-dominated reservoir in the Mataloko geothermal field has a promising potential for the economical development of geothermal power plants there.

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