Bulletin of the Geological Survery of Japan, vol. 53 (2/3), p. 375-387, 2002

Conceptual models for geothermal systems in the Wolo Bobo, Nage and Mataloko fields, Bajawa area, central Flores, Indonesia

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Hideo AKASAKO, Koji MATSUDA, Koichi TAGOMORI, Takehiro KOSEKI, Hiroshi TAKAHASHI and Sjafra DWIPA (2002) Conceptual models for geothermal systems in the Wolo Bobo, Nage and Mataloko fields, Bajawa area, central Flores, Indonesia. *Bull. Geol. Surv. Japan,* vol. 53 (2/3), p. 375-387, 10 figs.

Abstract: This study was carried out on the Research Cooperation Project on the Exploration of Small-scale Geothermal Resources in the Eastern Part of Indonesia. The main purpose of this project is to construct a geothermal expert modeling system for Indonesia. For this purpose, the Bajawa area in the central Flores was selected as a model field. Through regional geology and geochemistry surveys in the earlier stage, the Wolo Bobo, Nage and Mataloko fields are regarded to have a high potential for geothermal development in the Bajawa area. In the following stage, explorations were focused on these three fields.

In the Wolo Bobo field, the fractured zone extending northward through the altered ground of Wolo Bobo, represented by the arrangement of many volcanic cones, controls the volcanism. Magmatic fluids flow up along this fractured zone around the altered surface and the original temperature of these fluids is at least 525 ℃. There are intensive acid reservoirs of SO_4 type hot water (170 ℃ to 180 ℃) at about 300 m under the ground, resulted from the mixing of these fluids with underground water. Hot spring waters with relatively high Cl concentration, discharge about 2.5 km south of the altered surface, are derived from one of these reservoirs. The steam and gas from the reservoir altered the surface.

In the Nage field, magmatic fluids flow up along the fault trending southwestward along the Wae Bana River. These fluids result in an intensive acid hot water of SO_4 type (about 150 ℃) at about 200 m under the surface, through the mixing with underground water. This hot water is diluted by underground water and flows out along the Wae Bana River.

In the Mataloko field, recharged meteoric water from the volcanic cones, surrounding the altered surface of Mataloko, changes to hot water at a deep level by the heat and gases from the magma and through water-rock interaction. Although this hot water is still not detected, the hot water flows up to the level of 400 m or 500 m deep, the lower limit of the argillized impermeable layer, along the fractured zones extending southward on the western and eastern sides of the altered surface. The fractured zone accompanied by the Wae Luja Fault extending northwestward also controls the flow pattern of the hot water. The temperature of this geothermal reservoir is estimated to be 270 ℃ to 306 ℃. Steam and gas derived from this reservoir flow up along the fractured zone of the Wae Luja Fault. They bring about a steam-dominated reservoir with a temperature of 192 ℃ to 230 ℃ in the upper part of the impermeable layer. The mixing of the steam and gas with shallow groundwater brings about an acid hot water of SO_4 type near the surface along the Wae Luja River.

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Keywords: geothermal system, conceptual model, Mataloko, Flores Island, Eastern Indonesia

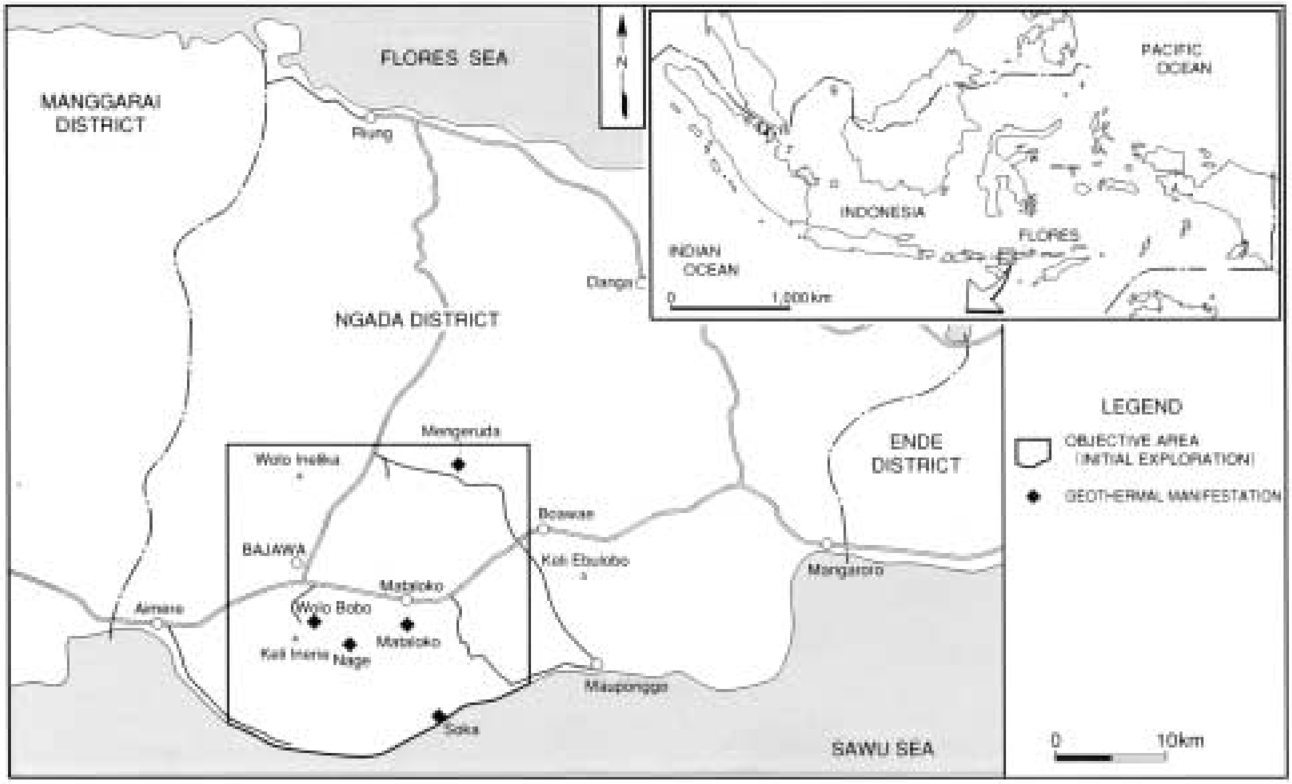

Fig. 1 Location map of the Bajawa area.

1. Introduction

The Research Cooperation Project on the Exploration of Small-scale Geothermal Resources in the Eastern Part of Indonesia was signed in 1998 by two Japanese organizations and an Indonesian organization, the New Energy and Industrial Technology Development Organization (NEDO, Japan), Geological Survey of Japan (GSJ) and Directorate General Geology and Mineral Resources (DGGMR, Indonesia). The main objective of this international cooperation project is to construct the "Geothermal Expert Modeling System for Indonesia" (iGEMS). The project started in early 1998 in the Nusa Tenggara area, eastern Indonesia, as a model field. After the analysis of the existing data and site reconnaissance, the Bajawa area of about 400 km^2, south central part of Flores Island, was chosen for an initial exploration area for this project (see Fig. 1). Various explorations have been carried out in and around this area (Nasution *et al.,* 1999; Matsuda *et al.,* 2000; Muraoka *et al.,* 2000; Takahashi *et al.,* 2000; Takashima *et al.,* 2000; Yasukawa *et al.,* 2000).

The Wolo Bobo, Nage and Mataloko geothermal fields in this area are expected to have a high potential for geothermal development, based on geological and geochemical data. A detailed exploration area of about 70 km^2 was selected for the next exploration stage, containing these three geothermal fields, in 1999. Geological, geochemical, soil air (mercury), gravity and resistivity (MT/CSMT) surveys were carried out in this detailed exploration area in FY 1999 - 2000. Most surveys focused on the Mataloko field, because a direct contribution of magmatic fluids to the geothermal systems in the Wolo Bobo and Nage fields is estimated from the chemistry of hot spring water. On the other hand, a direct contribution of magmatic fluid is not detected and neutral hot water reservoir is expected in the Mataloko field. In this fiscal year, the Volcanological Survey of Indonesia (VSI, one of the institutes belonging to DGGMR) drilled a shallow well, MTL-1, in the Mataloko field. The drilling of this well was unfortunately stopped at the 103.23 m depth, because of a steam blowout while drilling. The measured temperature of discharge steam is 115 ℃ at the wellhead. As further drilling works were judged to be impossible, this well was filled with cement.

Accounting for the topographic and access road conditions together with these survey data, exploratory wells of MT-1 and MT-2 were drilled near the site of well MTL-1 in FY 2000 - 2001. The drilling of well MT-1 was also stopped at 207.26 m deep because of a steam blowout while drilling. The measured temperature of discharge steam is 150 ℃ at the wellhead. As further drilling works were judged to be impossible, this well was filled with cement. When well MT-2 was drilled to a 162.35 m depth, steam was also blown out but the steam discharge was fortunately controllable. From the discharge test with the Russel-James method, the largest steam flow rate was calculated to be 4.58 kg/s at a wellhead pressure of 0.37 MPaG, assuming a saturation state at the end of the discharge pipe. In this paper, conceptual models for the geothermal systems of the three fields will be represented based on these exploration data. These models will contribute to confirm the utility of the constructed iGEMS.

2. Geology

Takahashi *et al.* (2000) classify the volcanic rocks, covering the Wolo Bobo, Nage and Mataloko geothermal fields, into five units: the Old Volcanics, the Bajawa Caldera Volcanics, the Cone Volcanics (older), the Cone Volcanics (younger) and the Inerie Volcanics in ascending order, as shown in Fig. 2. They state that the Green Tuff of the Neogene distributes under these volcanic rocks as a basement rock. Tagomori *et al.* (2002) point out that there is a high Bouguer anomaly in and around the Nage field as shown in Fig. 3. From this figure, they consider that there are intrusive rocks with a high density at a deep level.

Takahashi *et al.* (2000) report that the K-Ar ages of the Cone Volcanics (older) from Wolo Sasa (volcanic cone on the northern side of the altered surface of Mataloko) and Cone Volcanics (younger) from Wolo Manulalu (volcanic cone on the southeastern side of the altered surface of Wolo Bobo) are 0.506±0.030 Ma and less than 0.15 Ma, respectively. The alteration zone name of "Wolo Bobo", in Fig. 2, is given by the name of volcanic cone situated about 1 km north of the altered surface, because it is more famous than the other volcanic cones near the altered surface.

Takahashi *et al.* (2000) estimate four lineaments from the arrangement of the volcanic cones as shown in Fig. 2. The extent of two lineaments among them, extend north through Wolo Bobo and northwest between Wolo Bobo and Mataloko, is considerably long. These two lineaments are considered to be main structure controlling the volcanism in the Bajawa area (Muraoka *et al.*, 2000).

3. Geothermal system in the Wolo Bobo field

3.1 Geochemistry of geothermal manifestation and altered surface

There are fumaroles with a temperature of about 95 ℃ in the altered surface of the Wolo Bobo (see Fig. 4). The altered surface extends southeast for about 200 m and its width is about 100 m. The alteration is characterized by intensive silicification of

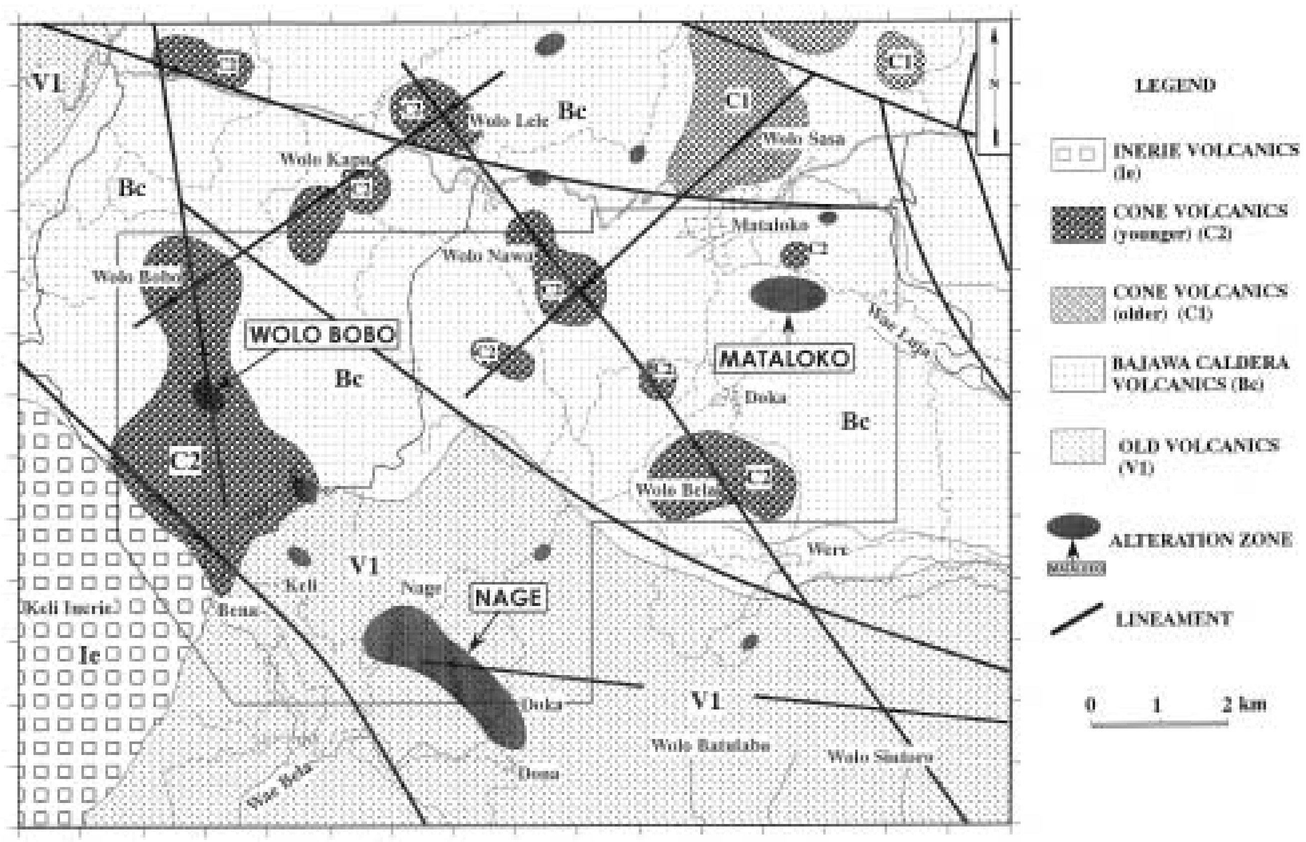

Fig. 2 Geological map of the Wolo Bobo, Nage and Mataloko geothermal fields (after Takahashi *et al.*, 2000).

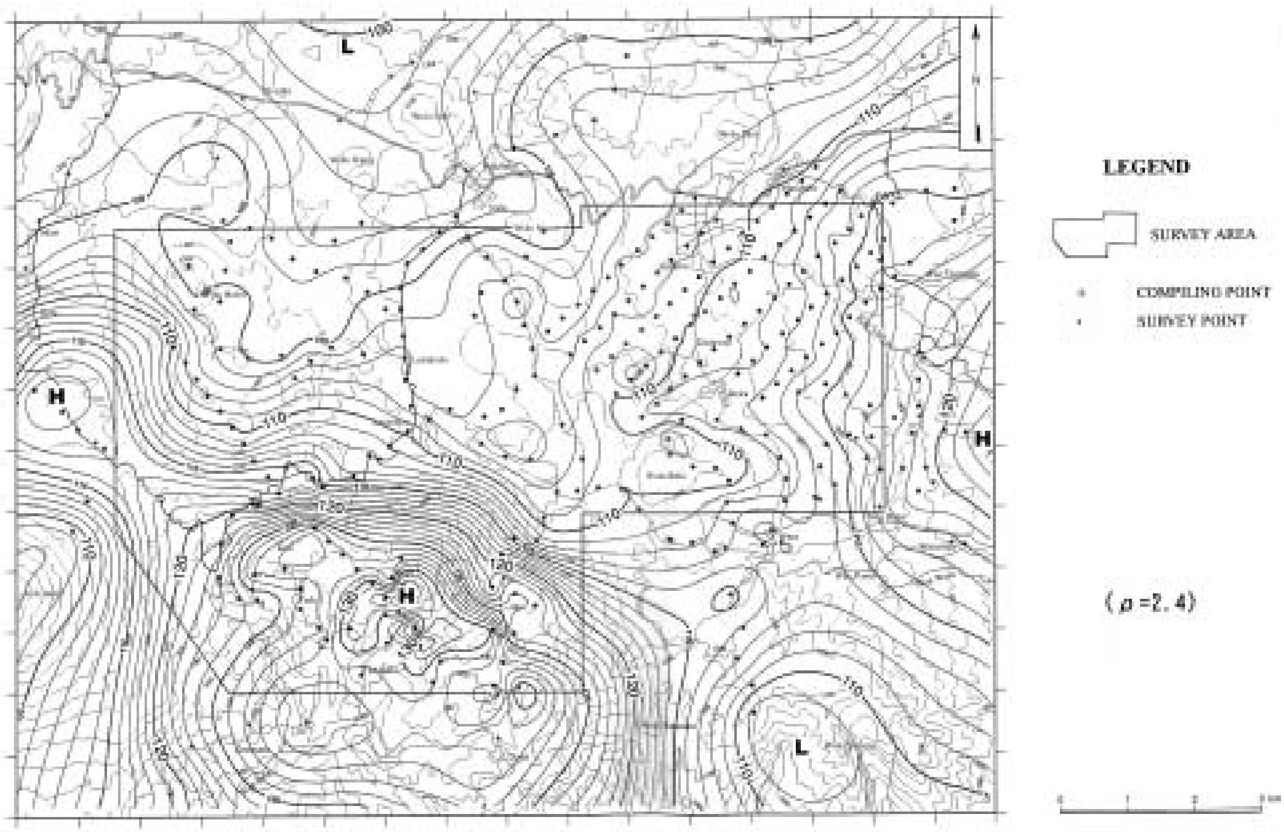

Fig. 3 Bouguer anomaly map of the Wolo Bobo, Nage and Mataloko geothermal fields (ρ=2.4; after Tagomori *et al.*, 2002).

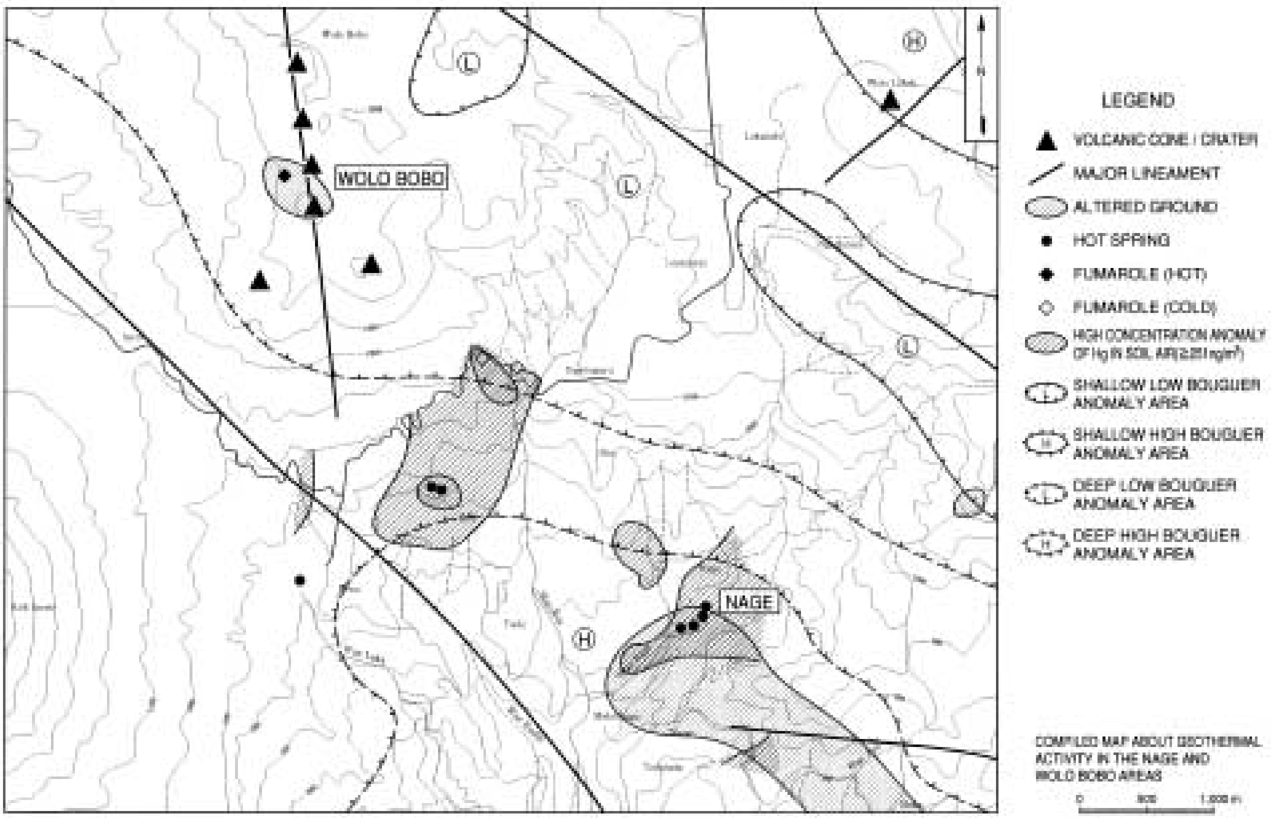

Fig. 4 Geothermal manifestation and altered surface in the Wolo Bobo and Nage geothermal fields. The geological data, Hg concentration data in the soil air and gravity data are based on Takahashi *et al.* (2000), West Japan Engineering Consultants, Inc. and Mitsubishi Materials Natural Resources Development Corp. (2000) and Tagomori *et al.* (2002), respectively.

the Cone Volcanics (younger) and occurrence of sublimated sulphur. Identified secondary minerals in the samples from this altered surface are quartz, α-cristobalite, tridymite, alunite, gypsum, kaolinite, pyrite, siderite, anatase and sulphur. Hydrothermal alteration under an acid condition is indicated by most of these minerals.

Matsuda *et al.* (2002) report the gas composition of the fumarolic gas as follows: CO_2 of 93.3 vol%, H_2S of 5.68 vol% and residual gas of 1.02 vol% (main component is N_2 of 98.1 vol%). This indicates that the fumarolic gas is derived mainly from a reservoir of hot water. However, SO_2 gas of 50 ppm was detected by the Kitagawa precision gas detector in the fumarolic gas. Moreover, Cl of 0.90 mg/l is detected in the condensate of the fumarolic gas (Matsuda *et al.*, 2002). Therefore, it is considered that there is contribution of magmatic gas to the fumarolic gas.

Matsuda *et al.* (2002) report that δD and $\delta^{18}O$ values of the steam water are -47 ‰ and -7.4 ‰, respectively. Judging from these values, the main origin of the steam water is meteoric water as shown in Fig. 5.

From these data, acid gas with a high temperature emitted from magma comes up near the surface and there is an acid reservoir of SO_4 type hot water that resulted from mixing of the magmatic gas with underground water. Applying a $\delta^{13}C(CO_2\text{-}CH_4)$ geothermometer (D'Amore and Panichi, 1987), a temperature of 525 ℃ is estimated. This is considered to be a temperature condition near the magma. On the other hand, a temperature of 290 ℃ is estimated by CO_2-Ar geothermometer (Giggenbach, 1992) and that of 170 ℃ to 180 ℃ is estimated by CO_2-H_2S-H_2-CH_4 geothermometer (D'Amore and Panichi, 1980) and H_2-Ar geothermometer (Giggenbach, 1980). The former is regarded to be a condition on the way where the fluid flows up from the magma. The latter will be at the reservoir of acid hot water resulted from the magmatic fluid.

Acid to neutral hot water of SO_4 type discharge at the foot of a steep cliff in Tude, a distance of about 2.5 km south-southeast from the fumaroles (Matsuda *et al.*, 2000). There is altered surface characterized silicification and argillization of the Old Volcanics around the hot springs. Judging from the $\delta D(H_2O)$ and $\delta^{18}O(H_2O)$ values, the origin of hot water is mainly meteoric water. On the other hand, neutral hot water has a considerably high Cl concentration (110 mg/l) and temperature (71.4 ℃). Its SO_4/Cl ratio of about 8.7 is close to acid crater lake water in the Keli Mutu Volcano, central Flores Island (Pasternack and Varekamp,

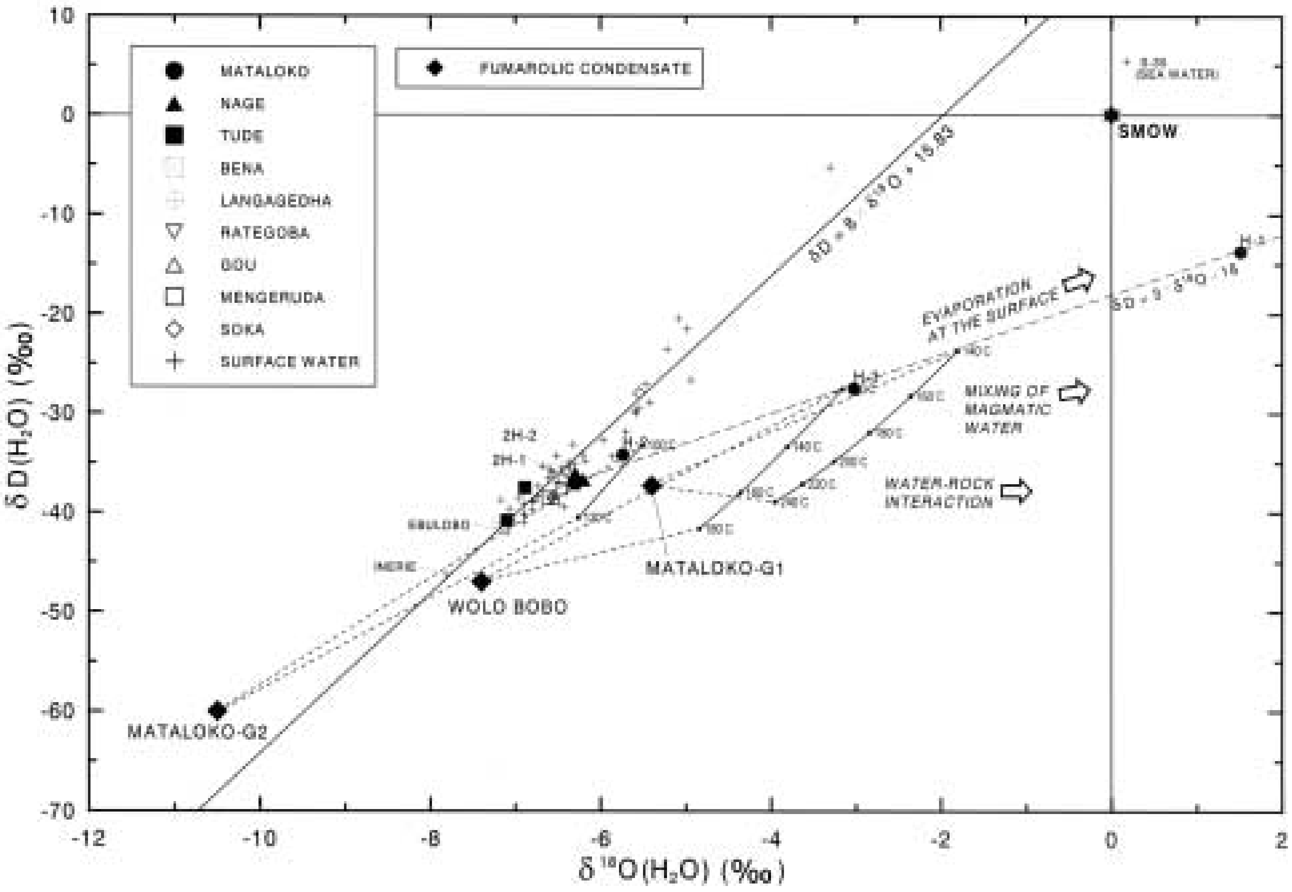

Fig. 5 The δD-$\delta^{18}O$ diagram of hot spring water, surface water and fumarolic condensate. All data are based on Matsuda *et al.* (2002).

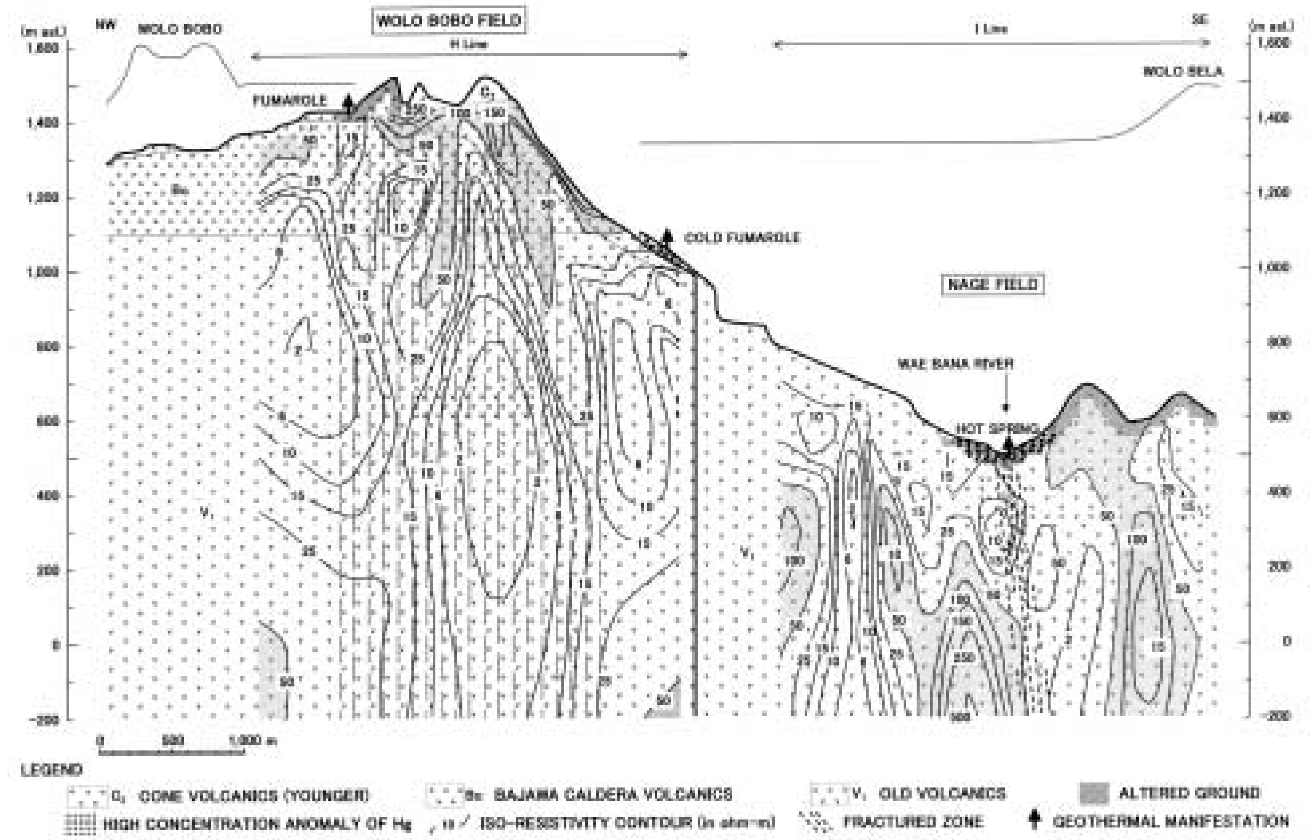

Fig. 6 Cross sections along the resistivity measurement lines in the Wolo Bobo and Nage fields. The resistivity data are based on Tagomori *et al.* (2002).

1994). Considering its relatively large values of $\delta^{34}S(SO_4$, 11.1 ‰) and $\delta^{13}C(HCO_3$, -9.1 ‰) together with the other data, a contribution of a magmatic fluid is estimated. Acid hot water has resulted from the dilution of neutral hot water and oxidation of H_2S gas flowing up from a deeper part.

There are cold fumaroles and altered surface a distance of about 2 km southeast of the Wolo Bobo fumaroles. The alteration is characterized by silicification and the occurrence of sublimated sulphur is sometimes recognized. There is the smell of H_2S gas from the cold fumaroles.

3.2 Geological structure

According to Takahashi *et al.* (2000), there is a fault estimated from the north trending lineament, given by the arrangement of the volcanic cones through the altered surface. This fault is the main structure controlling the volcanism in this field, as mentioned before. The geothermal manifestation, indicating a contribution of magmatic fluid, and altered surface distribute around this fault. It is considered that magmatic fluid flows up along the fractured zone accompanied with this fault around the altered surface. According to Tagomori *et al.* (2002), a conductive part is detected at around 300 m deep under the altered surface, by the CSMT/MT survey (see Fig. 6). It is considered that this conductive part corresponds to the reservoir of acid hot water that resulted from the magmatic fluid and underground water.

3.3 Conceptual geothermal model

In the Wolo Bobo field, the volcanism occurred along the fault trending north and gave the arrangement of many volcanic cones in this trend. The temperature around the residual magma is estimated to be at least 525 ℃. Magmatic fluid flows up along the fractured zone accompanied by this fault around the altered surface and cools gradually (see Fig. 7). Its temperature decreases to about 290 ℃ as it flows up. The fluid flows into underground water. This mixture results in an intensive acid hot water (170 ℃ to 180 ℃) of SO_4 type with relatively high Cl concentration at about 300 m deep. The steam and gas derived from this hot water, containing a certain amount of magmatic gas, come up to the surface and result in the Wolo Bobo alteration zone. As this acid hot water flows south, it changes to a neutral pH hot water through water-rock interaction and dilution by underground water. This hot water flows out around the altered surface for a distance of about 2.5 km. The hot water changes again to an acid type by the

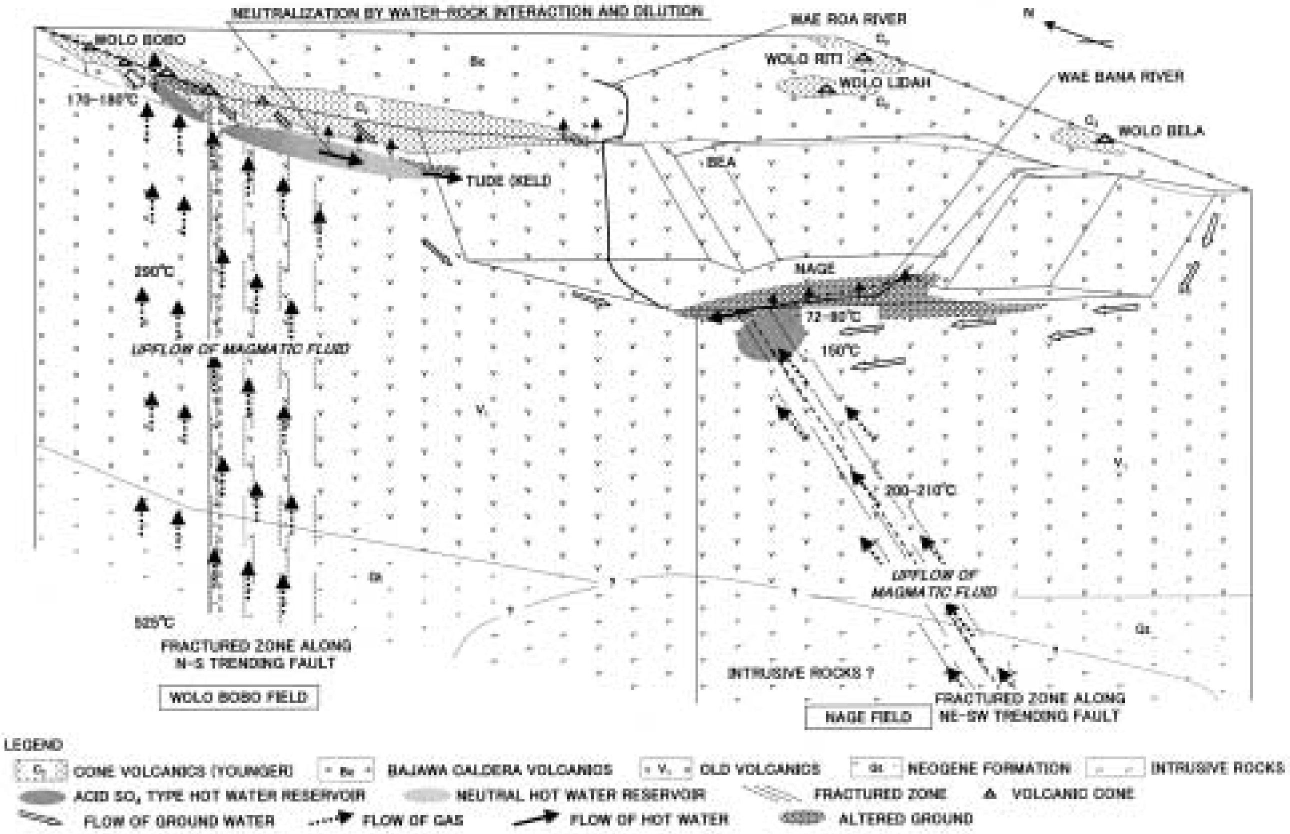

Fig. 7 Modified geothermal model around the Wolo Bobo and Nage fields.

oxidation of H_2S gas around the surface.

4. Geothermal system in the Nage field

4.1 Geochemistry of geothermal manifestation and altered surface

There are hot springs (72 ℃ to 80 ℃) along the Wae Bana River with about a 500 m spacing (see Fig. 4). A high Hg concentration anomaly in the soil air is detected along the river extending to the northeast (West Japan Engineering Consultants, Inc. and Mitsubishi Materials Natural Resources Development Corp., 2000). The hot springs are surrounded by altered surface. The limits of the altered surface are not clear because plants cover the ground. Takahashi *et al.* (2000) reports that the following zonation of the alteration is recognized from the center (around the hot springs) to the marginal part of altered surface; silicification zone characterized by the occurrence of quartz and pyrophyllite, silicification-argillization zone consisting of quartz, α-cristobalite, kaolinite and alunite, argillization zone consisting of smectite and pyrite. The occurrence of these secondary minerals suggests that the hydrothermal alteration resulted from acid hot water and temperature at the center was higher than 100 ℃. However, there is no geothermal manifestation giving such a temperature condition. It is considered that this temperature condition is the past.

The hot spring water samples are all acid and classified into the SO_4 type (Matsuda *et al.*, 2000). Their Cl concentration and F concentration are considerably high (399 to 461 mg/l and 6.02 to 7.53 mg/l, respectively), very different from those of typical steam heated acid hot water. Moreover, their SO_4/Cl ratio of about 1 and F/Cl ratio of about 0.015 are very close to acid crater lake water in the Keli Mutu volcano (Pasternack and Varekamp, 1994). The value of $\delta^{34}S(SO_4)$ of the hot water samples is relatively large at 9.9 to 11.1 ‰, and they increase with the increase of SO_4 concentration. These features indicate the contribution of a high temperature magmatic fluid into the geothermal system. Applying the computer code "SOLVEQ" by Reed and Spycher (1984), the chemical equilibrium temperature of quartz and anhydrite is about 150 ℃ and 200 ℃ to 210 ℃, respectively (Matsuda *et al.*, 2000). It is considered that these equilibrium temperatures indicate that the reservoir heated by the magmatic fluid or fluid on its way upward.

The hot springs show gas bubbling and gypsum deposition is recognized on the marginal part of hot water pool. Chemical composition and isotopic data of the bubbling gas indicate it contains air that is dissolved in water (Matsuda *et al.,* 2002).

4.2 Geological structure

The Nage geothermal field is a basin covered by the Old Volcanics surrounded by a steep cliff. A fault trending northeast is estimated along the Wae Bana River from distribution of hot springs and high Hg concentration anomaly in the soil air (West Japan Engineering Consultants, Inc. and Mitsubishi Materials Natural Resources Development Corp., 2000), as shown in Fig. 4. However, the extent of the altered surface is seemingly independent of this fault. The result is from alteration that is caused by present and past hydrothermal activity, as mentioned before. Tagomori *et al.* (2002) report that a conductive part is detected at around a 200 m depth under the altered surface around the Wae Bana River by the CSMT/MT survey (see Fig. 6). It is considered that this conductive part corresponds to the reservoir of the acid hot water that resulted from the magmatic fluid and underground water.

4.3 Conceptual geothermal model

In the Nage field, magmatic fluids flow up along the fault trending southwest along the Wae Bana River (see Fig. 7). A high density body is estimated at a deep level by the gravity survey (Tagomori *et al.,* 2002). There is a possibility that the magmatic fluid comes from this intrusive body. The temperature of the fluids flowing upward is estimated to be about 290 ℃. These fluids flow into the underground water. The fluids make the underground water an intensive acid hot water (about 150 ℃) of SO_4 type with relatively high Cl and F concentrations at about a 200 m depth. This acid hot water is diluted by underground water and flows out with bubbling gas along the Wae Bana River. The hydrothermal alteration around the geothermal manifestation was resulted from this hot water. However, it is regarded that the most intensive alteration had occurred in the past because the temperature estimated from the occurrence of secondary minerals on the surface is considerably higher than the present condition.

5. Geothermal system in the Mataloko field

5.1 Geochemistry of geothermal manifestation and altered surface

There are fumaroles and hot springs on about a

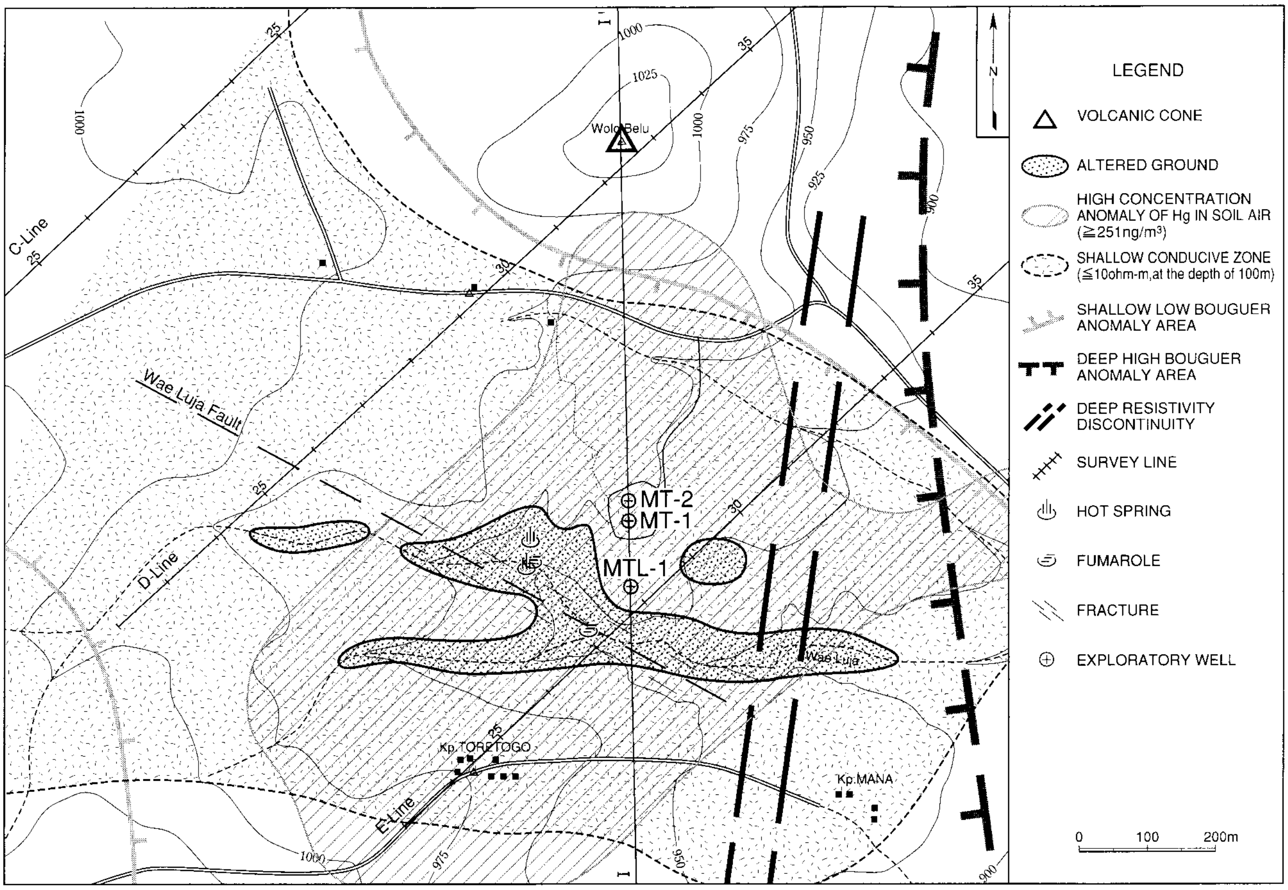

Fig. 8 Geothermal manifestation and altered surface in the Mataloko geothermal field. The geological data are based on Takahashi *et al.* (2000). The concentration data of Hg in the soil air, resistivity data and gravity data are based on Tagomori *et al.* (2000).

1 km spacing along the Wae Luja River (see Fig. 8). The hot springs show gas bubbling and are surrounded by altered surface. The alteration is characterized by argillization and silicification. Takahashi *et al.* (2000) report that the following secondary minerals are identified in the samples from the altered surface; quartz, α-cristobalite, kaolinite, alunite, smectite, jarosite, pyrite and sulphur. The occurrence of these secondary minerals indicates that the hydrothermal alteration resulted mainly from acid hot water.

Sueyoshi *et al.* (2002) report that most cutting samples from the wells of MT-1 and MT-2 are argillized rocks, though there are some rather fresh rocks. According to them, the alteration in the shallow parts of these wells (shallower than 50 m and 70 m for MT-1 and MT-2, respectively) is characterized by the occurrence of kaolinite indicating an acid condition. On the other hand, the alterations in the deeper parts are characterized by the occurrence of montmorillonite and chlorite/montmorillonite interstratified mineral. Moreover, wairakite is identified at depths of 142 m, 160 m, 181 m, and 202 m in MT-1 and at a depth of 150 m in MT-2. It is deduced that the activity of acid hot water is limited only near the surface.

The hot spring water (about 89 ℃) is acid and classified into the SO_4 type (Matsuda *et al.,* 2000). The hot water samples give extremely low Cl and F concentration (1.5 to 18.0 mg/l and 0.13 to 0.27 mg/l, respectively). Their $\delta^{34}S(SO_4)$ values are small at -1.6 to -2.5 ‰ and rather constant, independent of their SO_4 concentration. This indicates that acid hot water was mainly resulted from the oxidation of H_2S gas around the surface. The hot water samples give larger values of $\delta D(H_2O)$ and $\delta^{18}O(H_2O)$ than the cold surface water in the Bajawa area (see Fig. 5). The slope of this shift from the meteoric water line in Fig. 5 ($\Delta\delta D/\Delta\delta^{18}O$ value of about 3) indicates that steam loss occurs at 70 to 90 ℃ (Ellis and Mahon, 1977). This temperature condition is close to the measured water temperature at the discharge or outflow point.

Matsuda *et al.* (2002) report the chemical composition and isotopic data of the fumarolic gas in this field. Applying a $\delta D(H_2\text{-}CH_4)$ geothermometer (D'Amore and Panichi, 1987), a temperature of 120 ℃ to 130 ℃ is estimated. This temperature is regarded as being in the reservoir of steam heated acid water. The temperature condition of around 300 ℃ given by most of the other geothermometers is considered to be in a deeper part than the level of the reservoir.

Matsuda *et al.* (2002) discuss the geochemistry of the discharge fluid from the exploration well of MT-2. According to their interpretation, there is a steam-dominated reservoir with a temperature of 192 ℃ to 230 ℃ under the shallow acid aquifer of SO_4 type hot water. The discharge fluids from wells MTL-1, MT-1 and MT-2 are regarded to come from this steam-dominated reservoir. They also deduce that there is a deep, rather extensive water-dominated reservoir with a temperature of 270 ℃ to 306 ℃.

5.2 Geological structure

This field is covered by the Bajawa Caldera Volcanics. Three wells (MTL-1, MT-1 and MT-2) drilled in this field are very shallow. They are still in the Bajawa Caldera Volcanics and have not reached the Old Volcanics under the Bajawa Caldera Volcanics (Sueyoshi *et al.,* 2002).

The Wae Luja Fault extending south-southeast is estimated along the Wae Luja River in the Mataloko field (Takahashi *et al.,* 2000). The hot springs, fumaroles and altered surfaces are distributed along this fault. The shallow conductive zone (near the surface to 400 m or 500 m deep; Tagomori *et al.,* 2002) and high Hg concentration anomaly in the soil air (Tagomori *et al.,* 2000) also extend along this fault (see Fig. 8). The shallow conductive zone is regarded to be an argillized impermeable layer (cap rock) from the data of wells MT-1 and MT-2. On the other hand, no geological structure corresponding to the Wae Luja Fault is detected at a deeper level, though three faults trending north are estimated around the altered surface from the resistivity data (Tagomori *et al.,* 2002), as shown in Fig. 9. From these factors, it is considered that the Wae Luja Fault controls the geothermal activity near the surface and the estimated three faults (MF1, MF2 and MF3) control the geothermal activity at a deep level. A fault trending north is also estimated between MF1 and MF2 from the gravity data (Tagomori *et al.,* 2002). This fault is regarded to correspond to MF1 or MF2.

5.3 Conceptual geothermal model

In the Mataloko field, recharged meteoric water from the surrounding volcanic cones changes to hot water at a deep level by the heat and gases from the magma and through water-rock interaction. Although this hot water is still not detected, the hot water flows up along the faults of MF1 and MF2 trending north (see Fig. 10). Above the intersections of these faults with the Wae Luja Fault, the hot water also flows up along the Wae Luja Fault to the depth level of 400 m or 500 m, the lower limit of the argillized impermeable layer. The temperature of the geothermal reservoir along the Wae Luja Fault and MF2 is estimated to be 270 ℃ to 306 ℃ and a sealing zone is estimated at the top of this reservoir. The steam and gas derived from this reservoir flow up along the fractured zone of

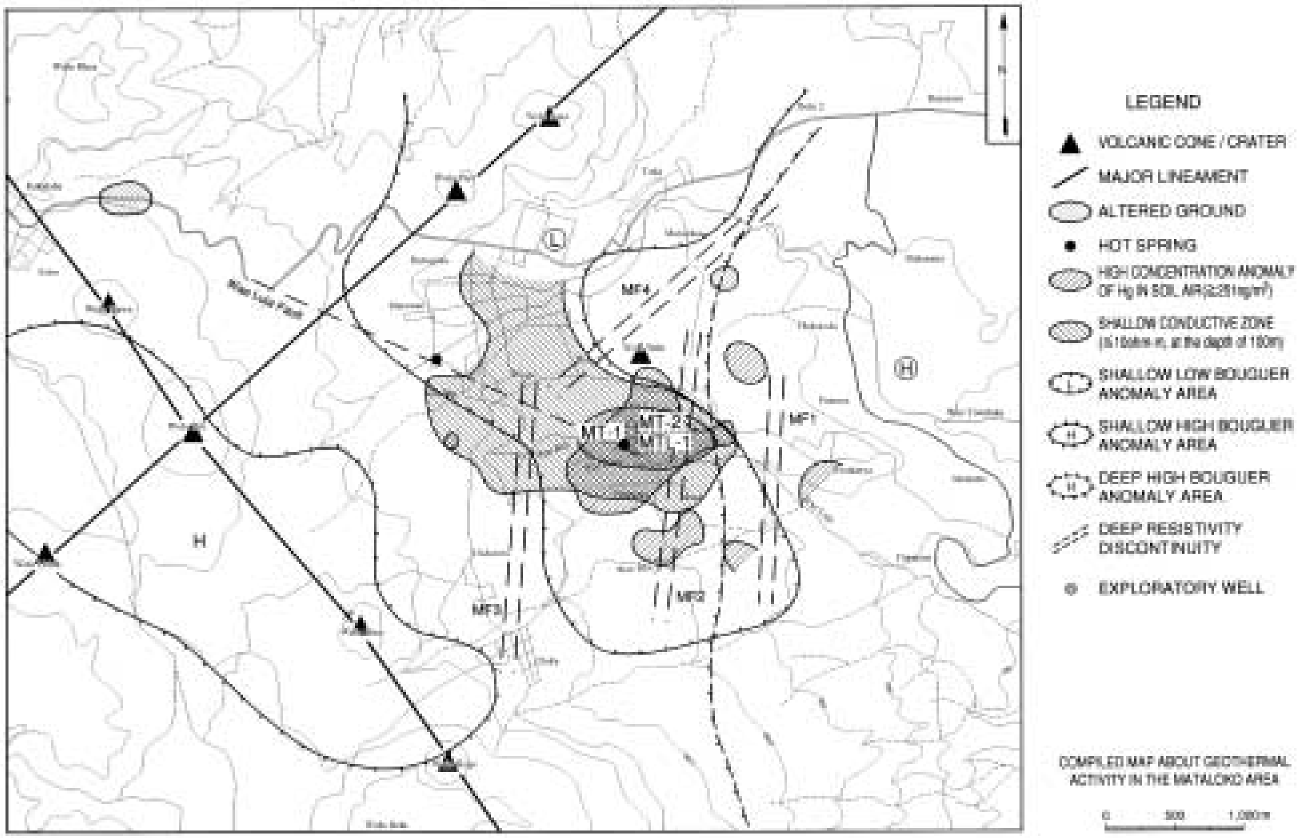

Fig. 9 Compiled map about geological structure in the Mataloko area. The geological data are based on Takahashi *et al.* (2000). The concentration data of Hg in soil air, resistivity data and gravity data are based on Tagomori *et al.* (2000) and Tagomori *et al.* (2002).

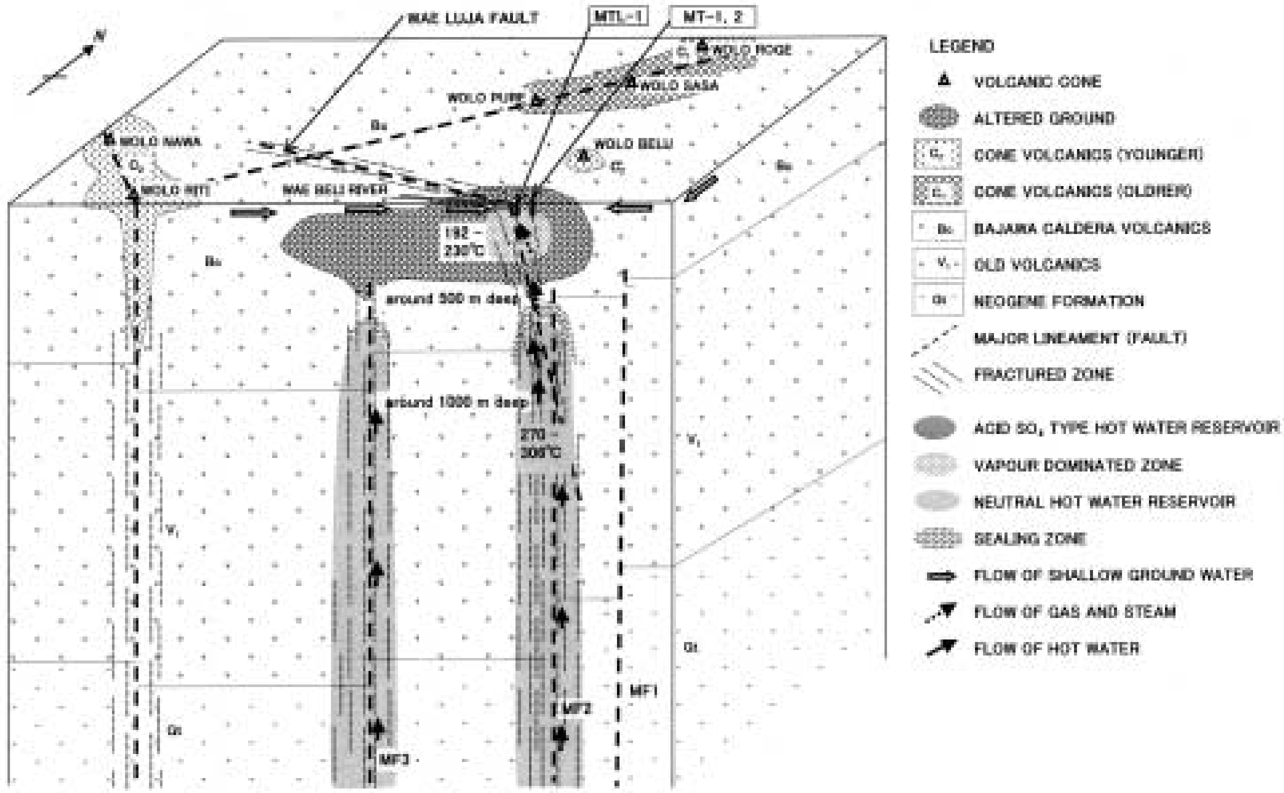

Fig. 10 Modified geothermal model around the Mataloko field.

the Wae Luja Fault and result in a steam-dominated reservoir with a temperature of 192 ℃ to 230 ℃ in the upper part of the impermeable layer. The three exploration wells stopped drilling in this steam-dominated reservoir. The mixing of the steam and gas with shallow groundwater occurs near the surface along the Wae Luja River. This brings about an acid hot water of SO_4 type around the surface. On the other hand, the steam and gas derived from the reservoir along MF3 do not flow up through the impermeable layer because there was no geothermal manifestation or high Hg concentration anomaly is recognized around MF3.

6. Summary

From the geothermal explorations in the Wolo Bobo, Nage and Mataloko fields, the following conceptual models are estimated. In the Wolo Bobo field, the fractured zone extending northward through the altered surface of Wolo Bobo controls the volcanism. Magmatic fluids flow up along this fractured zone and the original temperature of these fluids are at least 525 ℃. The mixing of these fluids with underground water results an intensive acid hot water (170 ℃ to 180 ℃) of SO_4 type at a depth of about 300 m. In the Nage field, magmatic fluids flow up along the fault trending southwest along the Wae Bana River. These fluids result in an intensive acid hot water (about 150 ℃) of SO_4 type at a depth of about 200 m, through the mixing with underground water. Intensive acid hot water is not available for geothermal development. For the geothermal systems in the Wolo Bobo and Nage fields, contributions of magmatic fluids are regarded. Therefore, it is very important to know the area where the intensive acid hot water resulted from the magmatic fluids distribution for the future geothermal exploration on these fields.

In the Mataloko field, recharged meteoric water from the surrounding volcanic cones changes to hot water at a deep level by the heat and gases from the magma and through water-rock interaction. There is an argillized impermeable layer from the surface to the depth level of 400 m or 500 m. The hot water flows up to the lower limit of the impermeable layer, along the fractured zones extending south, on the western and eastern sides of the altered surface. The fractured zone accompanied by the Wae Luja Fault extending northwest also controls the flow pattern of the hot water. The temperature of this geothermal reservoir is estimated to be 270 ℃ to 306 ℃. Steam and gas derived from this reservoir flow up along the fractured zone of the Wae Luja Fault. They result in a steam-dominated reservoir with a temperature of 192 ℃ to 230 ℃ in the upper part of the impermeable layer. The mixing of the steam and gas with shallow ground water brings about acid hot water of SO_4 type near the surface along the Wae Luja River.

All exploration wells drilled in the Mataloko field do not reach the reservoir of deep hot water. They are still in the steam cap above the reservoir. For stable electric power generation in the future, it is desired to know the quality of the reservoir in the future exploration.

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Received October 26, 2001
Accepted February 21, 2002

インドネシア共和国フローレス島中部バジャワ地域の
ウォロボボ，ナゲ，マタロコ地熱地帯における地熱系に関する概念モデル

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要　旨

インドネシア共和国で遠隔離島小規模地熱の探査に関する研究協力が実施された．このプロジェクトの主要な目的はインドネシア版地熱資源総合解析システムを構築することにある．この目的のため，フローレス島中部のバジャワ地域がモデルフィールドとして選定された．初期における広域の地質調査と地化学調査により，バジャワ地域内ではウォロボボ，ナゲ，マタロコ地熱地帯の地熱ポテンシャルが高いと推定された．このため，探査の重点はこれら 3 地熱地帯におかれた．

ウォロボボ地熱地帯では，ウォロボボ変質帯をとおる火口丘群の配列により示される南北方向の断裂帯が火山活動を規制している．変質帯付近のこの断裂帯を高温のマグマ起源ガスや蒸気が上昇しており，供給源付近は 525 ℃ 程度の温度と推定される．このガス・蒸気が地下水に吹き込み，地下 300 m 付近に強酸性 SO_4 型熱水 (170〜180 ℃) が分布していると推定される．変質帯の南方約 2.5 km 付近に湧出する Cl 濃度の比較的高い温泉水の起源はこのような熱水層の 1 つと推定される．また，変質帯は主としてこの熱水層から派生したガスや蒸気によって形成されたと考えられる．

ナゲ地熱地帯では，ワエバナ川沿いの北東・南西方向の断層に沿って高温のマグマ起源ガスや蒸気が上昇している．このガス・蒸気が地下水に吹き込み，地下 200 m 付近に強酸性 SO_4 型熱水 (約 150 ℃) が分布していると推定される．この熱水が地下水による希釈を受けてワエバナ川沿いに湧出している．

マタロコ地熱地帯では，マタロコ変質帯周辺の火口丘群から地下へ浸透した天水を起源とする深部熱水がマグマからの熱やガス，岩石との相互反応によって形成されている．この熱水はまだ確認されていないが，マタロコ変質帯の東西両側に推定される南北方向の断裂帯に沿って地下 400 m ないし 500 m 付近の粘土化した難透水層の下端付近まで上昇している．また，北西－南東方向のワエルジャ断層沿いの断裂帯も熱水の流動を規制していると考えられる．この貯留層は 270〜306 ℃ の温度と推定される．この貯留層から派生した蒸気・ガスはワエルジャ断層沿いの断裂帯に沿って上昇している．これらの蒸気・ガスによって難透水層上部に 192〜230 ℃ の蒸気卓越層が形成されている．また，この蒸気・ガスが浅層地下水に吹き込んで生成された酸性 SO_4 型熱水がワエルジャ川沿いの地表付近に分布している．