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Conceptual Modelof Hydrothermal SystematKotamobagu Geothermal Field, North Sulawesi, Indonesia

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Abstract

A conceptual model that is proposed here is based on the interconnections of the geological and chemical characteristics of the hydrothermal system of Kotamobagu. Chemical analyses were performed on thirty water samples collected from hot spring, river, and shallow well on the southern and northern parts of Mt. Muayat at Kotamobagu geothermal field. The acidic water samples with pH of about 2, which come from a steaming ground and are discharging near the summit of Mt. Muayat, are identified to have a water chemistry of SO_4 type. Hot springs discharging at the lower elevation of Mt. Muayat, on the other hand, are determined to be of bicarbonate water type while acidic hot springs discharging at cliff on the slope of Mt. Muayat and at Makaroyen at 7 km NE of Mt. Muayat are Cl-SO_4 type. On the foot of Mt. Wuluramatus, at the west of Makaroyen are alkaline chloride water types and hot springs discharge at the west and south west of Mt. Muayat are hybrid type. Temperature of 130-160°C, 180-230°C and 210-320°C were also estimated using different geochemical geothermometers such as quartz geothermometer, Na-K-Ca-Mg and Na-K geothermometers, respectively.

1. INTRODUCTION

The Kotamobagu geothermal field is located in North Sulawesi Province, Indonesia, approximately 200 km southwest of Manado City, the capital of the province (Figure 1).

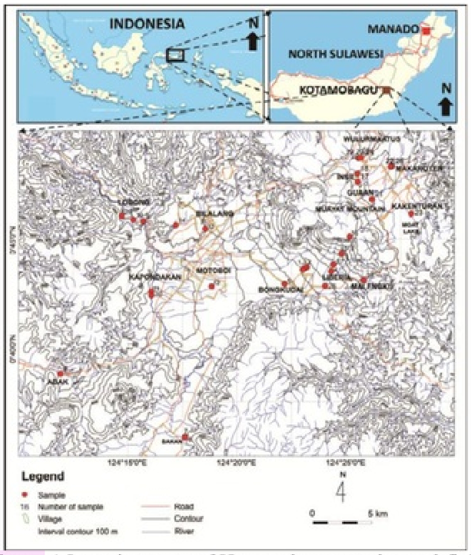

Figure 1 Location map of Kotamobagu geothermal field

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It has been proved that the field is one of the geothermal prospects in Indonesia(Hochstein and Sudarman,2008).Pertamina Geothermal Energy Co. (PT.PGE) conducted feasibility studies in Kotamobagu and concluded that the field has high potential for power generation. The results, however, have not been reported in details in public. Furthermore, a conceptual model of the field has not been developed yet. Thus, we have carried out geochemical survey in this area and tried to develop a conceptual model of hydrothermal system in Kotamobagu.

2. GEOLOGY

2.1. Geological Setting

A geological map of the Kotamobagu area is shown in Figure 2. The area is covered by Paleogene, Neogene and Quaternary rocks. The Paleogene sedimentary rocks consist of shale and sandstone with intercalated limestone and chert, and are overlain by the Neogene and Quaternary volcanic rocks. The Neogene volcanic rocks are the products of the Old volcanoes, and consist of breccia, tuff, andesitic lava, dacite and rhyolite from Mt. Simut and Mt. Lemibut located to the north of Mt. Muayat. The Quaternary volcanic rocks consist of Old and Young Ambangvolcanics. Tuff-pumice and andesitic breccia are the products of the Old Ambang Volcano. The Young Ambang volcanic rocks consist of andesitic lava and volcanic breccia, overlain asymmetrically by Mt. Muayat, Mt. Banga, and Mt. Ambang.

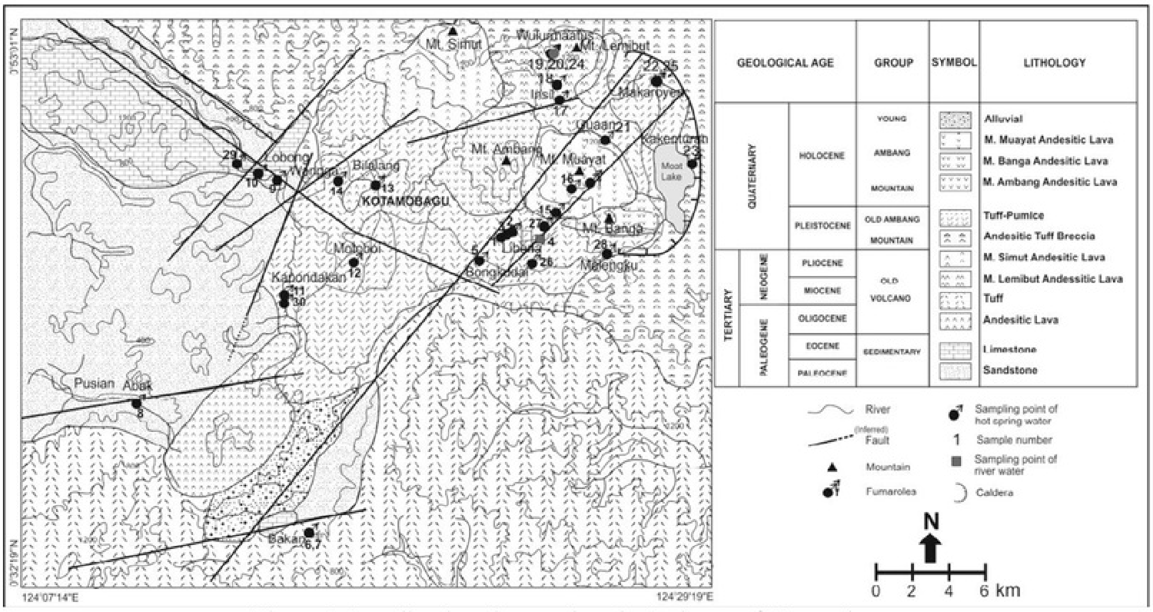

Figure 2 Sampling locations and geological map of Kotamobagu

2.2. Geological Structure

Faults in Kotamobagu have directions northwest to southeast, northeast to southwest and west to east as shown in Figure 2.

There are northwest to southeast, northeast to southwest and west to east trending faults in the Kotamobagu field as shown in Figure 2. Fumaroles at the top of Mt. Muayat (1385 m above sea level (a.s.l.)) located in the east of Kotamobagu have a high temperature of 102.7°C, and are associated with northeast to southwest trending faults (Pertamina Geothermal Energy Co., personal communication). A west to east fault system which crosses the sedimentary rocks controls the appearance of hot springs at Pusian and Bakan, located to the southwest and south, respectively, of Kotamobagu. A fault system with a northwest to southeast direction controls the presence of hot springs at Lobong in the west of Kotamobagu (Pertamina Geothermal Energy, personal communication). This fault system also controls the appearance of hot springs at Liberia and Bongkudai villages.

3. SAMPLING LOCATION

Water samples at thirty locations were collected from hot spring and shallow wells in the area of 20 km (NS) by 30 km (EW) of Kotamobagu. As shown in Figure 2, elevation of sampling site ranges from 144m up to 1,438 m.

Sample MUAH-16 was collected at a natural discharge at an elevation of 1,438 m near fumaroles on top of Mt. Muayat. The number of the sample ID corresponds to that in Figure 2. Three samples were collected from shallow wells; MAKH-25, LOBH-9 from the wells of 15 m and 20 m depth, MOTH-12 from that of 80 m. The river water samples were collected on the southern slope of Mt. Muayat at Liberia and Malengku village; LIBR-4, LIBR-26, LIBR-27, MALR-28 and one sample about 8 km tonorth of Mt. Muayat;WULR-24. Hot springs at Bakan (BAKH-6 and BAKH-7) and Abak (ABAH-8) are located in the south eastern end of Kotamobagu, about 20 km south east of Mt. Muayat. Samples at Liberia village (LIBH-1, LIBH-2, and LIBH-3) were collected in the paddy field. Three samples (MAKH-22, WULH-19 and WULH-20) were collected from natural discharges at northern side of Mt. Muayat. Sample KAKH-23 was collected from natural discharge near of the Moat Lake that located in the east of Mt. Muayat. Sample at Guaan village (GUAH-21) was collected at farm with elevation of 1064 m on the north-eastern slope of Mt. Muayat.Natural discharges on river floor were collected at Abak (ABAH-8), Lobong LOBH-29, Bongkudai (BONH-5) and Insil (INSH-17, INSH-18). Natural discharges on river bank were collected at Kapondakan (KAPH-11, KAPH-30). Natural discharge beside the river was collected at Wangga (WANH-14) and Lobong (LOBH-10).

4. SAMPLING METHOD AND ANALYSIS

All samples were collected in 250 ml polypropylene bottle after filtrating by 0.45 μm membrane filter. Water temperature, Electric conductivity (EC) and pH were measured on site by portable instruments. The anion (F, Cl, Br, NO_3, PO_4 and SO_4) and cation (Li, Na, NH_4, K, Mg, and Ca) were analyzed using ion chromatography system (Dionex ICS-90). Bicarbonate (HCO_3^-) was measured with the titration method at Kyushu university laboratory. Concentration of SiO_2 and Fe total were measured by spectrophotometer (Hitachi U 1800) using the molybdate yellow method and the 1,10-phenanthroline method, respectively.

5. RESULTS AND DISCUSSION

5.1. Water chemistry

Analyzed results of water chemistry are summarized in Table 1. Twenty one samples (ID: 1-16, 26-30) are located in the southern area of Mt. Muayat and nine samples (ID: 17-25) located in the northern area of Mt. Muayat.

The quality of the analysis was evaluated using the ion balance (IB) between anion and cation (Appelo and Postma, 2005):

$$IB(\%) = \frac{\sum Cations(meq./L) - \sum Anions(meq./L)}{\sum Cations(meq./L) + \sum Anions(meq./L)} \times 100$$

All analysis reported in this study have IB<12.5% except acidic samples.

5.2. Samples in The Southern Area of Mt. Muayat

Samples of LIBR-4, LIBR-26, LIBR-27, MUAH-15, and MUAH-16 show very acidic as low as pH about 2.These samples have high conductivity ranging from 2,860 to 5,670 μS/cm excepted for LIBR-26 and LIBR-27 which have conductivity values of 270 and 488 μS/cm, respectively. LOBH-29 is acidic with pH=3.4 and relatively low EC value of 148μS/cm. Other samples have pH of neutral about 6-7. Samples are divided into two groups with respect to EC: 12-698 μS/cm for (MALR-28, LIBH-1, LIBH-2, LIBH-3, BONH-5, BILH-13, WANH-14, LOBH-9, LOBH-29, and KAPH-30) and 1376-3210 μS/cm (BAKH-6, BAKH -7, ABAH-8, LOBH-10, KAPH-11,and MOTH-12).Temperature of hot spring waters shows relatively high, 70-94^{o} C, for BAKH-6, BAKH-7, ABAH-8, LOBH-10, KAPH-11 and KAPH-30. These hot springs discharge at the margin of Kotamobagu (Figure 2) whereas other hot springs in closer locations to Mt. Muayat where active fumaroles present and their temperature are relatively low at the range of 37-52^{o} C.

Ternary diagram is plotted for Cl-SO_4-HCO_3inFigure 3. From this figure, water quality can be divided into four categories:

1. SO_4 type of MUAH-16
2. Cl-SO_4 type of LIBR-4 and MUAH-15
3. HCO_3 type of LIBH-1, LIBH-2, LIBH-3, BONH-5, BILH-13, WANH-14
4. Hybrid type of BAKH-6 and 7, ABAH-8, LOBH-9 and 10, KAPH-11, MOTH-12.

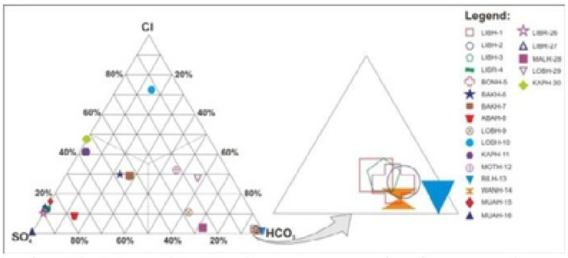

Figure 3 Ternary plot for Cl, $SO_4$and HCO_3 in water samples from southern area of Mt. Muayat.

The MUAH-16 sample was plotted in the SO_4 corner of the ternary diagram, indicating steam heated water. This sample was collected near fumaroles at the top of Mt. Muayat, where steam derived from boiling at depth containing H_2S reacts with oxygen rich surface water, and H_2S is oxidized to form SO_4 rich acidic water. At lower elevations on Mt. Muayat, there are natural discharges from the cliff surface where MUAH-15 was collected. This sample is of Cl-SO_4 type, suggesting volcanic water origin. Volcanic water is produced through the degassing of magma mainly consist of water vapor, CO_2, SO_2 and/or H_2S and HCl. The high temperature chloride water containing volcanic gases (CO_2 and H_2S) is mixing with cold meteoric water and is flowing up to the surface.
Sample LIBR-4 is river water and of acidic. The sample plots between MUAH-16 and MUAH-15 on the SO_4-Cl axis, implying that the acidic river water is a mixture of MUAH-16 and MUAH-15 waters.
Samples collected at lower elevations on the southern and southwestern slopes of Mt. Muayat are plotted in the HCO_3 corner and are identified as HCO_3 type waters. These bicarbonate type waters may occur near the surface in geothermal areas where steam carbon dioxide condenses in an aquifer. Under stagnant conditions, reactions with the rocks leads to a neutral pH, and the water discharges as hot springs such as in Liberia, Bongkudai, Bilalang and Wangga villages LIBH-1, LIBH-2, LIBH-3, BONH-5, BILH-13 and WANH-14.
The hybrid type of water, may be caused by mixing of different types of water (BAKH-6 and 7, KAPH-11, and 10, MOTH-12) or by interaction with surrounding rocks (ABAH-8 and LOBH-9). For example, the high Cl concentration at Lobong, LOBH-10, may be originated from deep geothermal waters flowing through a fault, leading to interaction with sedimentary rocks prior to discharging as a hot spring.

5.3. Samples in The Northern Area of Mt. Muayat

Samples of MAKH-22 and MAKH-25 show acidic as low as pH about 3 and have conductivities in the range from 160 to 302µS/cm. Other samples have pH of relatively neutral about 6-8. Sample of INSH-17 with low EC is 53 µS/cm and the others have in the range; 160-1061 µS/cm for INSH-18, WULH-19, WULH-20, GUAH-21, MAKH-22, KAKH-23, WULR-24 and MAKH-25. Temperature of hot spring waters shows in the range from 27 to 50^0 C for (MAKH-22, MAKH-25, INSH-17, INSH-18, WULH-19, WULH-20, GUAH-21, KAKH-23) and 26^0 C of a river (WULR-24).
Ternary diagram is plotted for Cl-SO_4-HCO_3 inFigure 4.

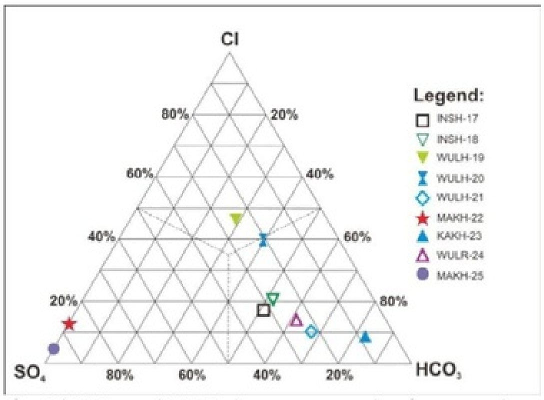

Figure4 Ternary plot for Cl, SO_4 and HCO_3 in water samples from northern area of Mt. Muayat.

From this figure, water quality can be divided into three categories:

1. Cl-SO_4 (MAKH-22 and MAKH-25)
2. HCO_3 (KAKH-23 and GUAH-21)
3. Cl (WULH-19 and WULH-20)

Samples plotted near the corner of SO_4 on the SO_4-Cl axis (MAKH-22 and MAKH-25) areof Cl-SO_4 type. This discharge may be directly delivered from lateral flow of deep Cl-SO_4 water.

Samples collected at lower elevations on the northern slope of Mt. Muayat are plotted near the corner of HCO_3 (KAKH-23 and GUAH-21) and are identified as of HCO_3 type.

SamplesWULH-19 and WULH-20 plotted near the bottom area of chloride and also plotted on the boundary between Cl and HCO_3 area are identified as alkali chloride waters. These samples have high concentration of Na, Cl and significant concentration of bicarbonate as shown inTable 3.1.Cl water in Wuluramatusmay flow directly to the surface and discharge from boiling at deep, high chloride springs, whose pH ranges from near neutral to alkaline. The alkali-chloride waters are derived from the outflow of the deep neutral chloride waters.

5.4. Water Geochemical Geothermometer

Hot spring waters were used for estimating the reservoir temperature. The Quartz, Na-K, Na-K-Ca and Na-K-Ca-Mg geothermometers were used for temperature calculations: Quartz maximum steam loss (Fournier, 1977), Na-K (Fournier 1979 and Truesdell 1976), Na-K-Ca (Fournier;Truesdell, 1973) and Na-K-Ca-Mg with Magnesium corrected (Fournier and Potter, 1979). Result of geothermometer calculation by quartz no steam loss show the temperature in a range from 88 to 190 °C, with the highest temperature value 190°Cfor the sample from the summit of Mt. Muayat (MUAH-16) as shown in Figure5.

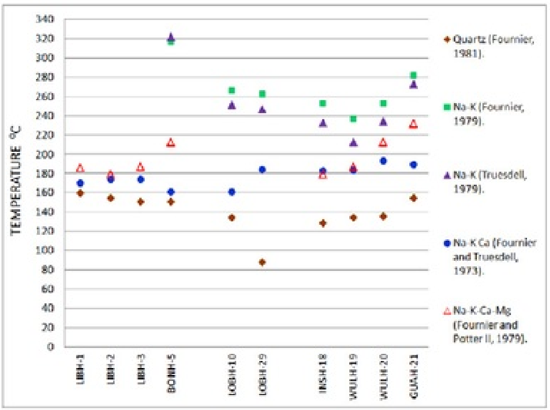

Figure5 Temperatures calculated by quartz geothermometers and Na-K-Cageothermometerwith magnesium correction.

Temperatures are calculated in a range 170-190°C using the Na-K-Cageothermometer. The temperatures are calculated in a range from 180 to 220°C for LIBH-1, LIBH-2, LIBH-3, and BONH-5 on the southern slope Mt Muayat; from 180 to 230°C for INSH-17, WULH-19, WULH-20, and GUAH-21 on the northern slope of Mt Muayat by the NA-K-Ca-Mg geothermometer.

The maximum temperatures are calculated by the Na-K geothermometer in a range from 230 to 250°C of INSH-17, WULH-19, WULH-20; 270-280°C for GUAH-21 on the northern slope of Mt. Muayat; 320°C for BONH-5 on the southern slope of Mt. Muayat. Temperature of LOBH-10 is calculated about 260°C.

Data except acidic waters are plotted on a Na-K-Mg triangular diagram (Giggenbach, 1988) in Figure 6.

The figure shows only one sample of KAPH-11 indicates temperatures by the Na-K and Mg-K geothermometeras 132 and 160^0 C, respectively.

Samples plotted in immature waters but not at the corner of $(Mg)^{1/2}$ are used to estimate temperatures using the Na-K geothermometer by linearly extrapolating for full equilibrium, which is 260°C.

5.5. Geothermal System

In the Kotamobagu area, the sedimentary formation has been reformed as a regressive process from the deep of Sulawesi marine to continent in Eocene-Miocene to Pleistocene. This geological setting proving the sedimentary formation in Lobong areais marine origin (Apandi and Bachri, 1997; Kavalieris et al., 1992).

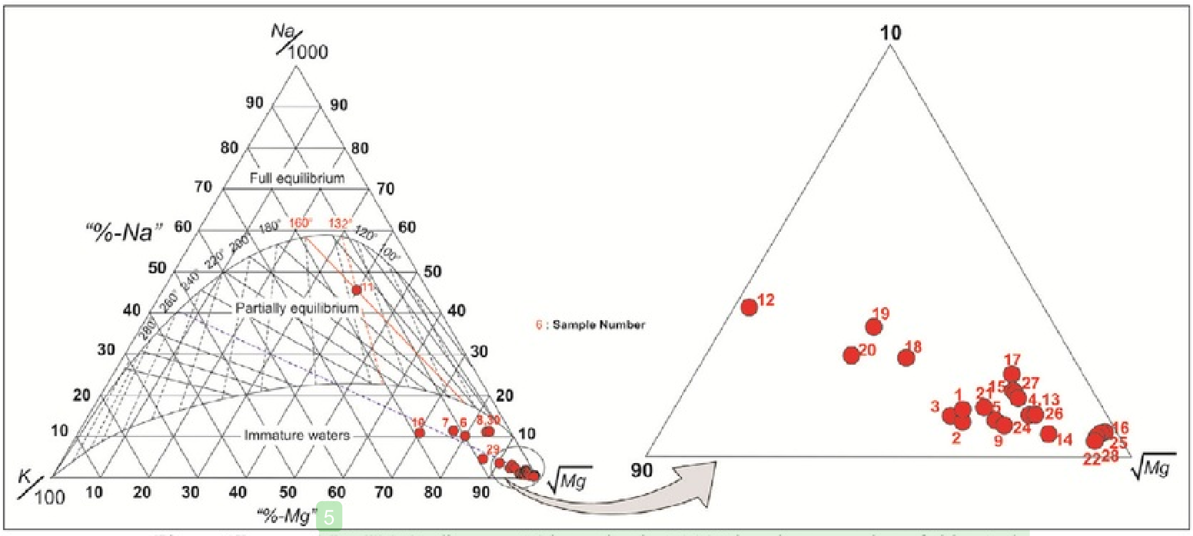

Figure6Ternary NA-K-Mg diagram (Giggenbach, 1988)showing samples of this study.

In order to assess the origin of Na-Cl component in waters, the contents of Li, Rb, Cs, B and Cl has been examined. The B, Cl and alkali metals are clear tracers of deep system (Chiodini et al, 1991). Marked high Cl and Li concentrations of LOBH-10, 700 mg/l and 2.26 mg/l, respectively compared to other hot spring waters in Kotamobagu indicates that this water is from a deep reservoir formed in a sedimentary formation. These high concentrations of Cl and Li together with geological setting and high estimated reservoir temperature of LOBH-10 imply that the source of geothermal waters in Lobong is from the deep reservoir formed in a sedimentary formation and not derived directly from that below Mt. Muayat. On the basis of the result above, the Kotamobagu geothermal field has two geothermal systems as follows:

1. Geothermal system formed below and related to Mt. Muayat.
2. Geothermal system formed in the sedimentary formation inLobong area.

5.6. Conceptual Model

On the basis of the results above, a conceptual model of a hydrothermal system in Kotamobagu was developed as shown in Figure 7.

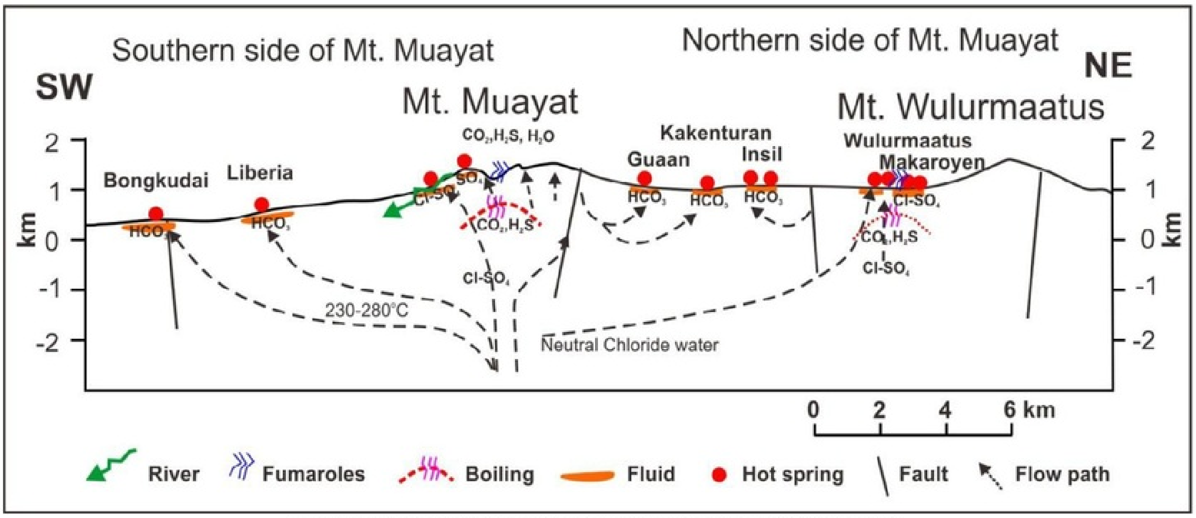

Figure 7 Conceptual model of Kotamobagu geothermal field.

High temperature geothermal fluidof Cl-SO_4 type flows upward below Mt. Muayat and Makaroyen area. This fluid eventually starts boiling at depth, releasing H_2S gas which forms steam heated waters by mixing with oxygen-rich surface water. The deep water from below Mt. Muayat also flows laterally to the south and discharges Cl-SO_4 type water. Neutral chloride waters flow laterally to the north of Mt. Muayatat the west of Makaroyen,reach the foot of Mt. Wulurmaatus and then discharge to the surface as Cl water. In the northern area of Mt. Muayat, Cl-SO_4 type water is also discharging in the Makaroyen area.

6. CONCLUSIONS

Geochemical studies in the Kotamobagu geothermal field are concluded as follows:

1. The water samples are characterized into five groups of SO_4, Cl-SO_4, HCO_3, hybrid and Cltypes.
2. Water geochemical geothermometer presents temperature of 88 to 190°C by the Quartz geothermometer, 180-230^{0}C by the Na-K-Ca-Mg and maximum temperature of 230-320^{0}C by the Na-K geothermometer in Mt. Muayat.
3. Hot spring water of LOBH-10 in Lobong area may be derived from geothermal system formed below sedimentary formation and not from Mt.Muayat.
4. A conceptual model of a hydrothermal system in Kotamobagu was developed.

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