Benefits of Surface Thermal Features Monitoring From Geochemical Observations at the Salak Geothermal Field

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ABSTRACT

Surface thermal manifestation monitoring at Salak field has been conducted regularly since 1994 when commercial production began. This surveillance program aims to monitor any environmental impact of field production and, potentially, reservoir processes from both the chemical and morphological changes in the thermal manifestations. Monitoring of thermal features is composed of two methodologies, namely, geotechnical and geochemical. This paper will focus on the analysis of changes in chemistry of the Salak thermal features: Cibeureum/Getih and Cipamatutan fumaroles and Sarimaya chloride spring.

The effects of the recent drilling campaign, reservoir boiling, migration of injection and invasion of marginal recharge (MR) have been identified using integrated analysis of fluid chemistries of both the thermal features and the produced reservoir. The increase in N_2 and Ar was utilized to identify the presence of drilling fluids in the underlying reservoir. The decreasing trend in non-condensable gases (NCG) could represent reservoir boiling process. The invasion of cooler marginal recharge could be identified by the presence of certain organic material (e.g., CH_4) and diluted chloride (Cl). This integrated study to understand the relationship between the reservoir processes and the changes in natural outflow of the Salak geothermal field is continuously conducted by regularly monitoring surface thermal features.

INTRODUCTION

The Awibengkok geothermal field, also known as Salak, is located 60 km south of Jakarta on the island of Java, Indonesia (Figure 1). The original exploration contract area, including the current proven field, lies in the highlands on the southwestern flank of the Gunung Salak volcano (2,211 m asl), for which the contract area was named. A proven reservoir area of 18 km^2 and an installed capacity of 377 MWe yields a power density of about 20 MWe/km^2 despite all injection being done infield (Stimac et al., 2008). The reservoir is the largest producer of geothermal power in Indonesia (Ibrahim et al., 2005; Stimac et al., op. cit.). Currently, there are 75 producers, 24 injectors, five monitoring and seven abandoned wells at the Awibengkok geothermal field.

Thermal features associated with Awibengkok define a classical distribution seen in many other commercially exploited liquid-dominated geothermal resources in a volcanic environment (Rohrs, 1986; Stimac et al., op. cit.). The most obvious thermal manifestations, fumaroles and hot springs, are directly related to the Awibengkok geothermal system. The surface thermal features at Awibengkok consist of a chloride spring, six bicarbonate springs and three fumaroles.

Fumaroles in Awibengkok field are observed at elevations >1200 m ASL. The Parabakti fumarole, located in the northwestern part of Well D-8 (Figure 2), has a gas composition that indicates proximity to a high-temperature geothermal source, whereas, both the Cibeureum and Cipamatutan fumarole complexes (Figure 2) have gas compositions more consistent with lower temperature geothermal outflows (Stimac et al., 2008).

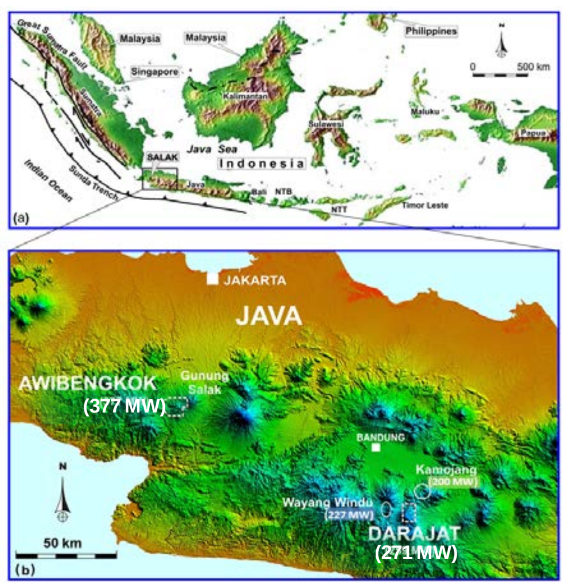

Figure 1: Location map that shows Salak contract area on the western part (Syaffitri and Molling, 2013).

The Sarimaya hot spring has the highest chloride concentration amongst springs and is located several kilometers to the north of the Salak geothermal reservoir at an elevation of 696 m ASL (Figure 2). This thermal feature is thought to originate from one of the main outflow paths of the Awibengkok geothermal system (Stimac et al, 2008).

Monitoring of surface thermal features has been performed regularly since 1994 when commercial production began. This surveillance program aims to monitor any environmental impact of field production and, potentially, reservoir processes through both the chemical and morphological changes in the thermal manifestations. The thermal feature monitoring consists of two schemes, namely, geotechnical and geochemical. This paper will focus on the analysis of changes in chemistry of the Cibeureum/Getih and Cipamatutan fumaroles and Sarimaya chloride spring.

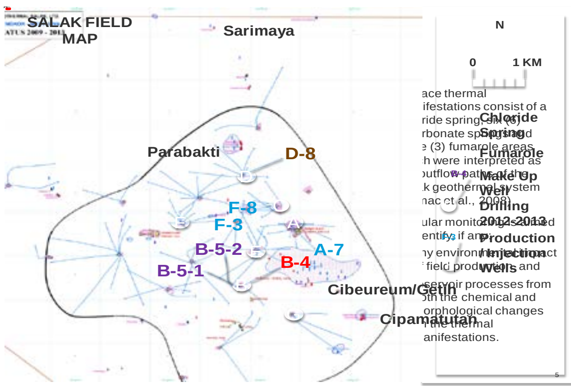

Figure 2: Map of Salak geothermal field.

METHODOLOGY

Geochemical monitoring of surface thermal features consists of collecting samples from the fumaroles and springs, laboratory analysis and data QA/QC before any interpretation is done (Figure 3). In the fumaroles, gas, steam condensate, and stable isotope (from the condensate) samples are collected. A challenge in sampling fumaroles is to ensure that the samplers are able to collect the steam discharges safely (i.e., area has low H_2S concentration, accessible pathway, etc.). Normally, fumaroles with high superheat and discharge rate are sampled as these characteristics suggest that there is direct connection with the underlying reservoir.

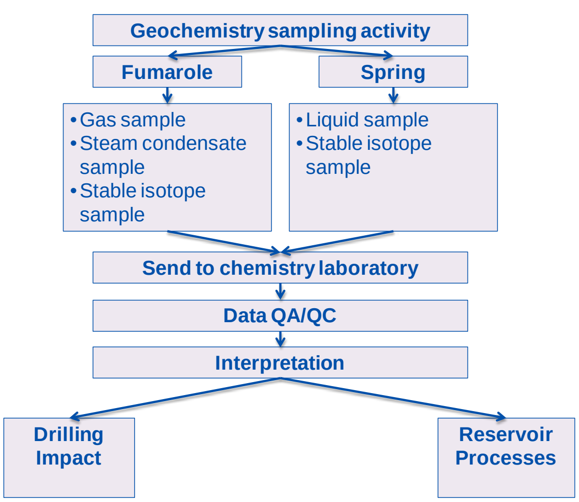

Figure 3: Workflow of surface thermal monitoring from geochemical observation.

Sampling hot springs is quite easy and liquid and stable isotopes samples are normally collected. Prior to collecting the sample, the sample bottle has to be flushed several times to wash and condition the bottle. For water sample quality and preservation, samples for cation and anion analyses are filtered and unacidified while sample for SiO_2 analysis is filtered and acidified. In the field, the pH of the samples is measured and recorded.

The field sampling activity is recorded for future reference. The laboratory data is subsequently uploaded into the database. Data QA/QC is conducted to ensure quality interpretation is done. The parameters used to check data quality from gas samples are % air contamination, estimated superheat, presence of certain gas species, etc. For data quality of liquid samples, the ion charge balance is used, i.e., the ion charge balance should be within 5%.

SALAK THERMAL FEATURES

Kawah Cibeureum/Getih Fumarole Complex: The Cibeureum fumarole complex hosts abundant mud pools and steam vents with varying intensity of activity. The thermal features are generally weak in the east, south and central portions of the fumarole complex, and vigorous in the west and northern portions. Several tranquil mud pools cover most of the area (around 800 m x 1,200 m) and have hampered access to Kawah Cibeureum. Due to the inaccessibility of Kawah Cibeureum, the Getih 2 fumarole was chosen as replacement since 2012 (Syaffitri et al., 2012). This thermal feature appears to be more active, has generally low H_2S levels and considered as a safer location to conduct geochemical sampling.

The Getih 2 fumarole is at an elevation of 1,241 m ASL (Figure 4) with about a 15 cm vent diameter and discharges along the steep wall of a nearby river. The Getih fumarole area is sparsely altered compared to the strongly altered ground around the Cibeureum Crater. The measured temperature of the Getih 2 fumarole is 101.7°C; at this elevation, saturation temperature is about 95.84°C hence there is 5.86°C of superheat at Getih 2. The estimated superheat at Getih 2 has almost doubled from 3°C in 2012 to about 6°C in 2013; the presence of superheat suggests that Getih 2 has direct connection with the underlying geothermal system. This increase in superheat at Getih 2 may be related to continued dry out of the steam cap in the eastern part of the Salak reservoir.

Figure 4: Photos showing the Getih 2 sampling site in 2013.

Kawah Cipamatutan Fumarole Complex: This fumarole area is approximately 250 m x 400 m in size. Geotechnical monitoring indicated that this area has suffered some minor landslides since the last visit in 2012. Furthermore, landslide or ground movement may potentially occur in the northeast and southwest portions of Kawah Cipamatutan based the location of the vigorous thermal features, steep topography and absence of vegetation. In 2013, some mud pools appeared drier than in 2012 although the monitoring team discovered relatively new fumaroles discharging from landslide fissures located south of the area. The extensive fumarolic activity has killed the vegetation and weakened the soil surface thus creating landslide hazards. Unfortunately, these new fumaroles could not be sampled because of safety issues. The 2013 sampling location is the same as that of 2012 (Figure 5).

The sampled fumarole at Kawah Cipamatutan, similar to the 2012 sampling location, is at an elevation of 1,268 m ASL. Measured temperature in the fumarole is 95.75^{o}C; the measured temperature is same as the saturation temperature hence there seems to be no superheat in 2013. Historically, superheat at Cipamatutan has decreased from 1.4°C in 2008 to saturated conditions in 2012-2013. This resaturation may be due to cooler liquid invasion into the geothermal system or near surface processes. It was raining during the 2013 sampling period and the vent may have gotten wet when sampled.

Figure 5: 2013 geotechnical monitoring has discovered several new fumaroles from landslide fissures located south of the Kawah Cipamatutan area.

Sarimaya Hot Spring

Sarimaya is the only high chloride spring in Salak field and located near rice fields. Unfortunately, the local residents have altered the thermal feature for their everyday use and irrigation purposes when visited in 2013. To collect good quality liquid sample from Sarimaya, the samplers need to dig and dam the water pool to separate the hot spring water from the cold water found at the corner of the pool.

Figure 6: Sarimaya hot chloride spring during 2011 - 2013.

The Sarimaya hot spring discharges at an elevation of 696 m ASL. The spring appears cloudy due to the colloidal silica or high Total Dissolved Solids (TDS). The measured discharge temperature has decreased from 61.2^{o}C in 2011 to 60.6^{o}C in 2013. Morphologically, the Sarimaya spring does not exhibit significant natural physical changes (Figure 6).

USES OF SURFACE THERMAL FEATURE MONITORING DATA

The geochemical sampling aims to investigate the relationship, if any, between the surface thermal features and the Salak reservoir. In some instances, operational changes (e.g., change in injection management) may also be manifested in the thermal features.

Impact of Make-up Well Drilling

The closest newly drilled wells (i.e., Wells B-4, B-5-1 and B-5-2) from Getih and Cipamatutan were drilled in October 2012 (Figure 2). Drilling of these wells has impacted nearby steam cap wells in east Salak (Julinawati and Syaffitri, 2012). The aerated mud used in drilling these wells appears to have slightly increased the total NCG and significantly increased N_2 and Ar at most of the wells at Pads A and E (Figure 2). Furthermore, Simatupang and Syaffitri (2013) postulated that the latest newly drilled well at east Salak, Well D-8, has the most impact to nearby steam cap wells at Pads C and D.

The working hypothesis during the 2013 surface thermal manifestation monitoring was that the make-up well drilling during 2012-2013 may have potentially affected the chemistry (and intensity) of the thermal manifestations. However, analysis of the chemistry of the thermal features indicates that there were no significant changes in NCG, N_2 and Ar concentrations at both the Getih and Cipamatutan fumaroles. The following hypotheses are proposed to explain this phenomenon:

- the surface thermal sampling was conducted way later than when the closest newly drilled wells (Wells B-4, B-5-1 and B-5-2) were drilled (Figures 7 and 8) and
- drilling did not impact both fumaroles because these thermal features are too far from Well D-8 (unfortunately, Parabakti, the closest fumarole to Well D-8, was not sampled because of its low intensity of activity and discharge pressure).

Based on interpretation of the 2013 thermal feature chemistry, the 2012-2013 Salak Drilling Campaign did not clearly impact the surface thermal manifestations. Consequently, it is recommended to consider sampling the surface thermal manifestations at the same time during or right after the drilling activity is completed

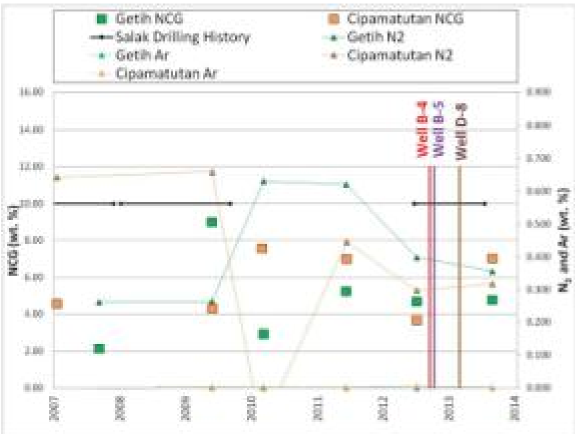

Figure 7: Chart showing N_2 and Ar concentrations at Getih and Cipamatutan fumaroles. Note the almost stable concentrations during the 2012 and 2013 monitoring vis-à-vis 2012-2013 Salak Drilling Campaign.

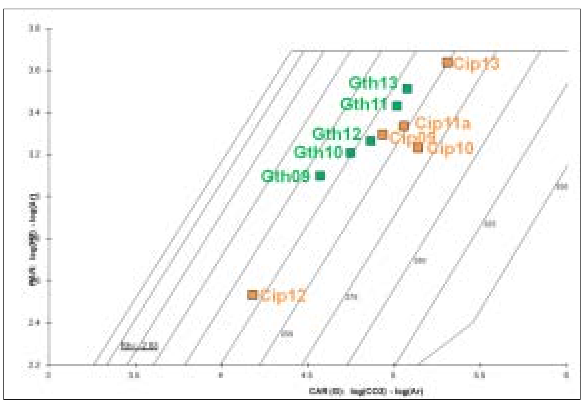

Figure 8: HAr-CAr Gas Grid showing the 2011 and 2013 samples from both the Getih and Cipamatutan fumaroles. Both Getih (Gth13) and Cipamatutan (Cpm13) samples shifted towards the Ar-loss direction (upper right portion of the chart) suggesting the absence of air. If drilling (which uses aerated mud) is impacting the thermal features, there should be a gain in Ar.

Reservoir Processes

Both the Getih (east central) and Cipamatutan (southeast edge) fumaroles showed "step-increases" in NCG content after 2009 (Figure 9). After the respective NCG "step-increase", a slow decline in NCG is observed in both fumaroles. In the case of Cipamatutan, the NCG step-increase was in 2010. The exact timing of the step-increase in NCG in Getih fumarole is believed to be in 2011. Based on review of the data (e.g., very high NCG content 9 wt% perhaps caused by drilling), it is believed that the Getih NCG value in 2009 is anomalous so that the NCG step-increase is most likely in 2011. The significant drop of NCG in the Cipamatutan fumarole in 2012 is considered anomalous and a result of non-ideal sampling conditions. The significant increase in N_2 and Ar in the Cip12 sample (Figure 12) confirms the anomalous conditions of sampling in 2012 at the Cipamatutan fumarole. With these caveats, the 2010 and 2011 NCG step-increases at the Cipamatutan and Getih fumaroles, respectively, are caused by condensation of steam either in the reservoir or above the clay-cap. Condensation is the preferred process of NCG increase because the nearest all steam producers have less than 2.5 wt% NCG in the steam, whereas, Cipamatutan and Getih fumaroles steam have approximately 7 and 5 wt%. The rapid rise in NCG content in 2010 at Cipamatutan and 2011 at Getih possibly represents a faster arrival of MR caused by increased rates of pressure decline in the Eastern area (Libert et al., 2014). The reduced injection at Well G contributes to this accelerated pressure decline.

The relative increase of CO_2 in the Getih samples on the HAr-CAr (Figure 8), CH_4-CO_2-H_2S (Figure 10) and N_2-CO_2-Ar (Figure 11) of samples after 2010 represents correlates with an increase in NCG. Hence, CO_2 coincides with a relative loss of the more volatile NCG species (CH_4, N_2, Ar). Condensation and increased relative CO_2 are both consistent with the production of NCG from a peripheral liquid condensing steam in one location with subsequent boiling of the HCO_3 enriched liquid further towards the middle of the superheated reservoir. Figure 10 and 12 shows that sample of Well A-7 in 2013 has similar chemistry with Gth13. Molling et al. (2007) concluded that downhole sample (DHS) data showed there is MR inflow at 4,240' The MR fluid at Well A-7 is composed of dilute chloride (~300 ppm) with high bicarbonate, magnesium and ammonium concentrations. This chemical composition is consistent with the HCO_3-enriched fluid coming from outside of the reservoir and originating from shallow depths. The MR coming into the reservoir beneath Getih is probably similar to the MR entering the shallow part of Well A-7.

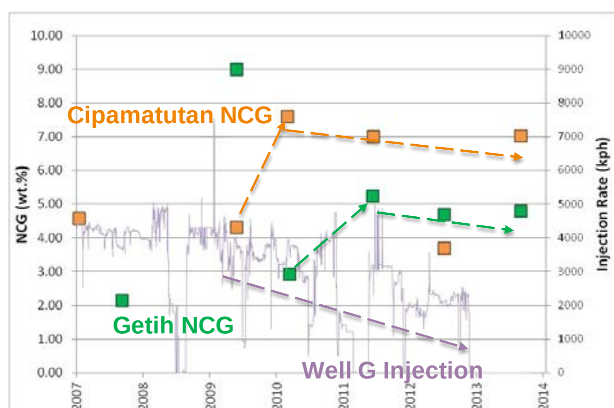

Figure 9: Historical of injection rates of Well G and NCG concentration from the Salak fumaroles.

The Cipamatutan Fumarole shows a slight increase in CH_4 and significant increase in NH_3 from 2010 to 2013. Both species increases are consistent with the arrival of more organic material in the peripheral liquid (MR) as time progresses. This hypothesis is considered as possible as the edge Cipamatutan fumarole first sees condensation in 2010 and then the more central Getih fumarole experiences the NCG increase (condensation) later in 2011.

The small drop in NCG in both the condensed steam of the Cipamatutan fumarole (2010-2013) and Getih fumarole (2011-2013) could reflect the additional steam from low NCG injectate as the injection at Well G was lowered and finally stopped by 2013. The later stabilization in NCG content at Getih is probably related to the continuous boiling of the remaining injected brine from Well G (Julinawati and Molling, 2010, Ibid. 2011; Syaffitri et al., 2012).

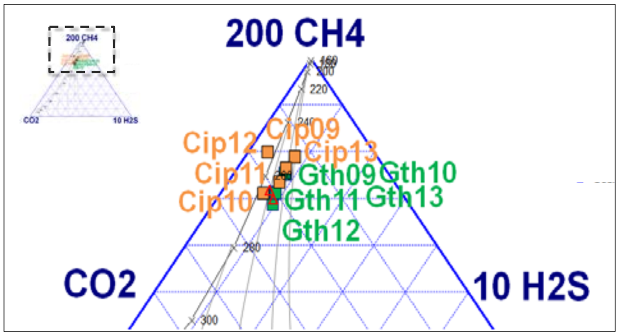

Figure 10: CH_4-CO_2-H_2S ternary chart of the 2012-2013 Salak fumarole samples and selected nearby wells.

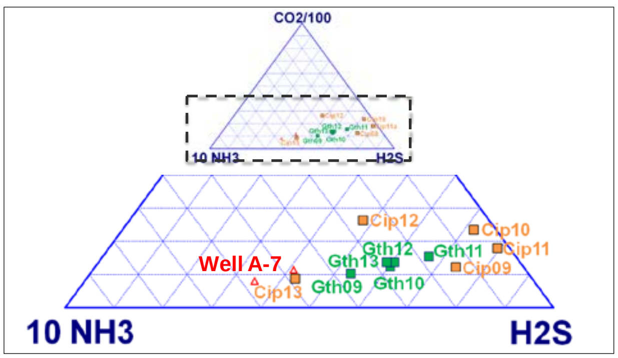

Figure 11: CO_2-NH_3-H_2S ternary chart of the 2012-2013 Salak fumarole samples and selected nearby wells.

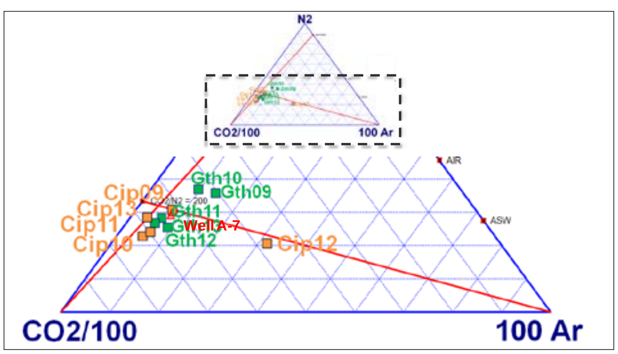

Figure 12: N_2-CO_2-Ar ternary chart of the 2012-2013 Salak fumarole samples and selected nearby wells.

Sarimaya's historical chloride shows a declining trend since 1995 from ~3200 ppm to ~900 ppm in 2013. The chloride concentration in the Salak reservoir (represented by Well F-3 and F-8) has been increasing rapidly due to infield injection from 1995 to 2003 and then stabilized between 8000-8200 ppmw chloride until 2011 and then a slight increase in 2012-2013. Therefore, Sarimaya has been diluting and the Salak brine has been increasing since start-up in 1994. Salak brine increasing is related to injection breakthrough. Injection breakthrough was observed since then and based on chloride matching, majority of the Well F wells were estimated to have produced 30 to 50% injectate although during the early years, no signs of thermal deterioration were observed (Acuña et al., 2008, Sunio and Molling, op. cit.). The diluting of chloride in Sarimaya represents groundwater that has been diluting Sarimaya since 1995. This phenomenon is easily explained as the liquid level in Salak has lowered with extraction and the reservoir pressure has decreased thereby decreasing the drive amount of Salak outflow to Sarimaya. In fact, the Salak reservoir brine liquid level is estimated to have been below Sarimaya, as early as 2010 (Baroek et al, 2010).

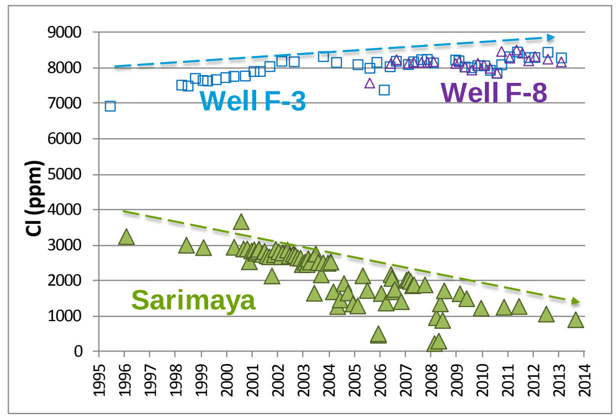

Figure 13: Historical chloride (Cl) content of Sarimaya compared with Wells F-3 and F-8 which represents the Salak reservoir.

CONCLUSIONS

- There was no clear correlation between drilling activities and the chemistry of the thermal manifestations. This is possibly due to:
  - Either surface thermal sampling was conducted too late (~11 months) after the drilling activity completed, or
  - Getih and Cipamatutan are located too far away (4 km) from the latest drilling activity
- Step-increases in NCG content at the Cipamatutan fumarole in 2010 and Getih fumarole in 2011, respectively, are caused by condensation of steam either in the reservoir or above the clay-cap.
- After 2010, the small drop in NCG in both the condensed steam of the Cipamatutan and Getih fumaroles could reflect the additional steam from low NCG injectate as nearby injection was lowered and finally stopped.
- Condensation and slight increase of CO_2 are both consistent with the production of NCG from a peripheral liquid condensing steam in one location with subsequent boiling of the HCO_3-enriched peripheral liquid.
- Arrival of MR id further suggested by the coeval increase of CH_4 and NH_3 at the southeast edge of the Salak reservoir.
- Liquid level in Salak reservoir brine is too low to be supplying Sarimaya. Hence, groundwater continues to dilute the Sarimaya hot spring.

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