

## Discovery of New Geothermal Manifestations as Indicators of the Upflow Zone in the Lumut Balai Geothermal Field, Indonesia

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### ABSTRACT

Recent field investigations in the Lumut Balai geothermal field, South Sumatra, Indonesia, have identified previously unrecognized geothermal surface manifestations in the southern part of the producing area, within the Tanjung Tiga prospect. These manifestations comprise fumaroles, hot springs, mud pools, and hydrothermally altered grounds, expanding the known extent of surface expressions associated with the system. This study evaluates the geochemical characteristics of the newly identified manifestations to assess their connection to the main geothermal reservoir and to delineate the geothermal upflow zone. Water and gas samples were analyzed for major ion chemistry, and gas composition, complemented by in situ measurements of temperature and pH, following established geothermal geochemical approaches (Giggenbach, 1988; Nicholson, 1993). Results indicate that fumaroles in the Tanjung Tiga prospect area contain higher non-condensable gas (NCG) concentrations than those observed in the currently developed sector, suggesting elevated subsurface temperatures and closer proximity to the upflow zone. Geothermometric calculations, including aqueous and gas geothermometers, estimate reservoir temperatures of approximately 275–300 °C beneath the Tanjung Tiga prospect, consistent with high-temperature upflow conditions (D'Amore and Truesdell, 1985). These integrated geochemical findings refined the conceptual model of the Lumut Balai geothermal system and provide a robust basis for upflow zone delineation and future exploration targeting in the southern sector of the field.

### 1. INTRODUCTION

The upflow zone of a geothermal system represents the primary pathway for high-temperature fluids ascending from the deep reservoir. This zone is typically associated with elevated subsurface temperatures, high enthalpy fluids, and enhanced permeability controlled by major faults or fracture systems. Surface manifestations located near upflow zones often exhibit higher temperatures and elevated concentrations of non-condensable gases compared to manifestations associated with outflow or peripheral areas. However, in developed geothermal fields, the location of surface manifestations does not always coincide with the main production area, and upflow zones may remain poorly constrained.

The Lumut Balai geothermal field, located in South Sumatra, Indonesia, is one of the country's most actively developed volcanic-hosted geothermal systems. The first commercial unit (Lumut Balai Unit 1) began operation in 2019, and more recently, the additional 55 MW Lumut Balai Unit 2 geothermal power plant has completed commissioning and is now fully operational since June 2025.

Studies of the Lumut Balai system have primarily focused on manifestations and reservoir characteristics in the central and northeastern sectors of the field, where fluid discharge is generally interpreted as outflow or marginal expressions of the system. However, ongoing field investigations have identified new geothermal surface manifestations in the southern sector particularly in the Tanjung Tiga prospects which exhibit distinct thermal and geochemical signatures. These newly discovered features suggest a more complex fluid circulation pattern than previously recognized and raise important questions regarding the location and nature of the geothermal upflow zone.

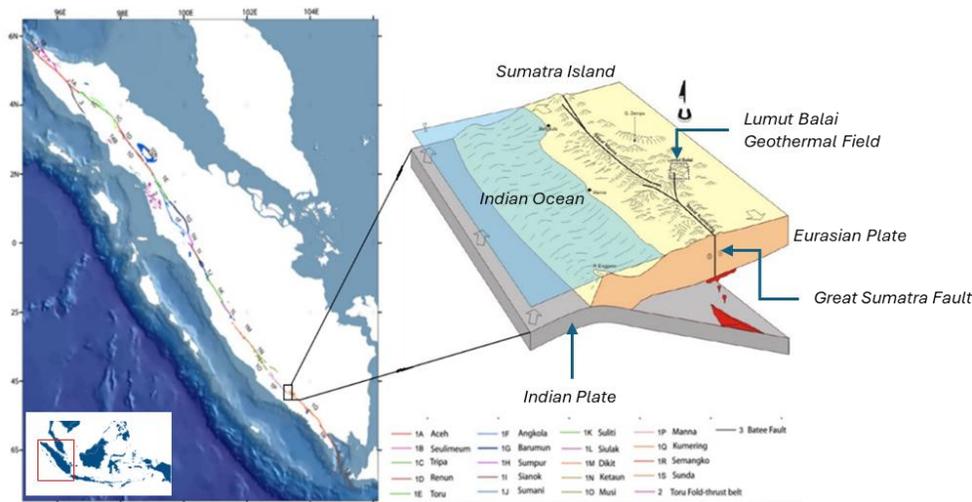
This paper presents field observations and geochemical data from the newly identified surface manifestations in the Lumut Balai geothermal field. It evaluates the relationships between these manifestations, production well fluids, and subsurface reservoir characteristics to delineate the upflow zone of the system. Understanding the spatial and geochemical context of these manifestations is vital not only for improving the conceptual model of the Lumut Balai geothermal system but also for informing ongoing exploration and development strategies, including potential expansion associated with future power plant units.

### 2. GEOLOGICAL AND STRUCTURAL SETTING

#### 2.1 Regional Geological Setting

The Lumut Balai geothermal field is situated in South Sumatra, Indonesia, within the Sunda volcanic arc, a tectonically active region where the Indo-Australian Plate subducts beneath the Eurasian Plate. Quaternary volcanism associated with this arc produces elevated geothermal gradients and widespread geothermal potential along Sumatra. Fault systems, particularly the Sumatra Fault System (SFS), exert a fundamental control on regional deformation, volcanic activity, and fluid migration pathways in the crust (Nurseto et al., 2021).

A recent structural study in Southern Sumatra highlights that intrusive volcanic bodies and fault structures parallel to the SFS are key controls on geothermal potential by influencing permeability and heat distribution (Prasetyo et al., 2025)



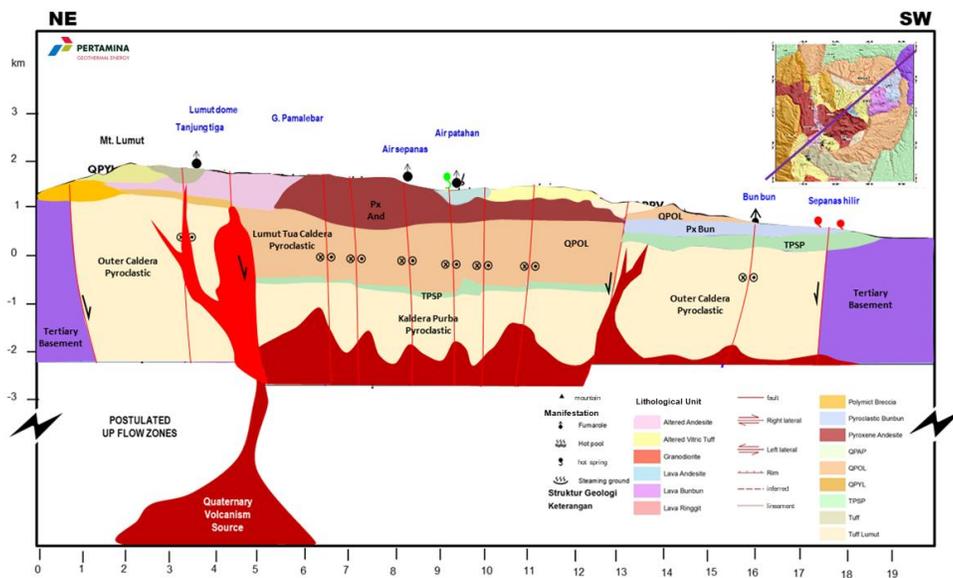
**Figure 1: Regional tectonic setting of Lumut Balai Geothermal Field in Sumatra Island, Indonesia (modified from Sieh, K. and D. Natawidjaja, 2000). Lumut Balai is situated approximately 60 km east of Komering Segment of the Great Sumatra Fault (Nurseto et al., 2021; Pratama et al., 2021)**

### 2.2 Lumut Balai Geological Setting

The Lumut Balai geothermal system is hosted within the Lumut Balai volcanic complex, which includes a caldera structure approximately 9 km in diameter. The geothermal field is situated within and adjacent to this caldera and is classified as a volcanic-hosted, high-enthalpy geothermal system (Pratama et al., 2021). Geological evolution of the area reflects multiple volcanic and structural events that have influenced reservoir development and fluid pathways.

Based on surface mapping, drilling data, and three-dimensional geological modeling, the stratigraphy of the Lumut Balai field has been subdivided into five principal units: the Tertiary Basement, Pre-Old Lumut, Pre-Caldera, Caldera, and Post-Caldera units (Pratama et al., 2021). These units are composed predominantly of andesitic to basaltic-andesitic lava flows, volcanic breccias, tuffs, and tuff breccias, with minor sedimentary intercalations. These lithologies collectively function as reservoir rocks and caprock units within the geothermal system.

Hydrothermal alteration is pervasive and displays systematic vertical and lateral zonation. Surface exposures are characterized mainly by argillic alteration, while deeper zones intersected by wells show propylitic to epidote-bearing assemblages, indicating high-temperature fluid-rock interaction and upward fluid circulation from depth (Nurseto et al., 2021; Pratama et al., 2021)



**Figure 2: Geological section of Lumut Balai Geothermal Field (PGE, 2025)**

### 2.3 Structural Geology and Permeability Control

Structural features play a fundamental role in controlling permeability and geothermal fluid flow within the Lumut Balai geothermal field. Major fault systems in the area are interpreted as splays and subsidiary structures of the GSFS, with dominant orientations of NE–SW and N–S, consistent with the regional tectonic stress regime (Pratama et al., 2021). Key structures include the Air Ringkih and Air Udangan faults (NE–SW trending), as well as faults associated with the Lumut Balai caldera margin and the Air Gemuha Besar fault (N–S trending), which are interpreted to act as primary conduits for ascending geothermal fluids.

The importance of structural control on geothermal potential at Lumut Balai is further supported by a recent study integrating Analytic Hierarchy Process (AHP) into a Play Fairway Analysis (PFA) framework (Nusantara et al., 2023). In that study, eighteen geological, geochemical, and geophysical parameters were evaluated to construct a geothermal favorability model. Structural attributes, such as fault density, fault orientation, and fault intersection zones, were identified as key criteria contributing to high favorability areas, highlighting the dominant role of fault-controlled permeability in the system (Nusantara et al., 2023).

Field observations from the present study show that newly identified geothermal manifestations in the Tanjung Tiga prospect, including fumaroles, hot springs, mud pool, and hydrothermally altered zones, are spatially associated with these structurally controlled corridors. The coincidence between manifestation distribution, mapped fault zones, and areas of high favorability identified by the PFA model supports the interpretation that the southern sector of the Lumut Balai field represents an active upflow zone rather than a distal outflow area (Pratama et al., 2021; Nusantara et al., 2023).

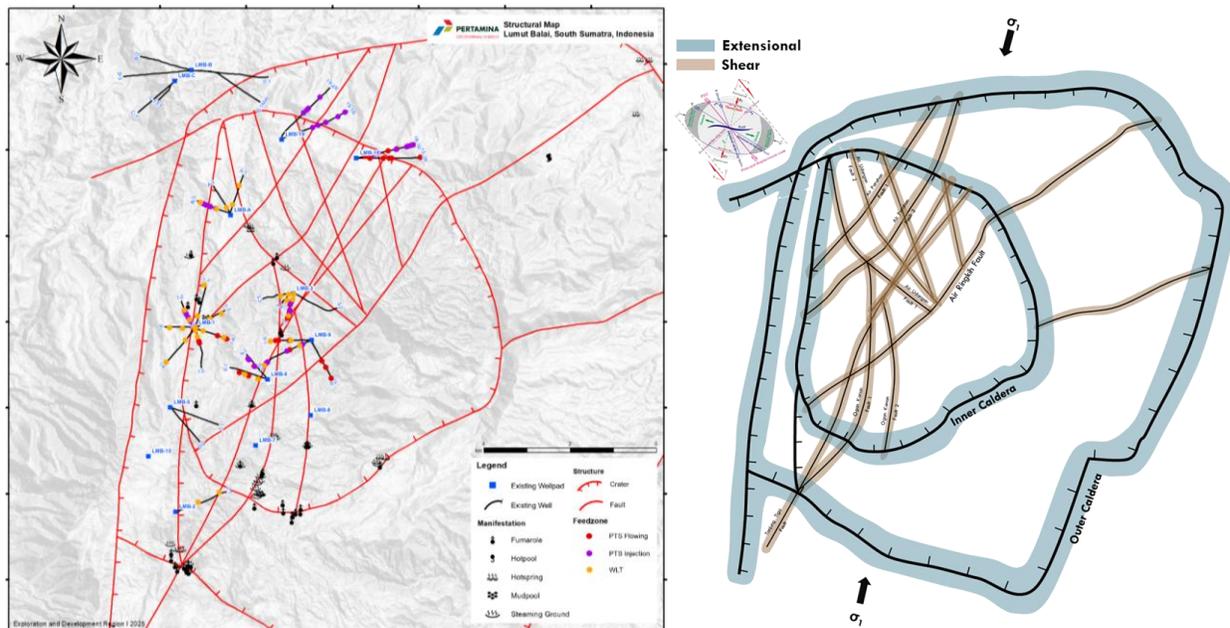


Figure 3: Geological structure of Lumut Balai geothermal field (PGE, 2025)

## 3. LUMUT BALAI GEOTHERMAL MANIFESTATIONS

### 3.1 Overview of Lumut Balai Geothermal Manifestations

The Lumut Balai geothermal field exhibits a variety of surface geothermal manifestations, including hot springs, fumaroles, mud pools, steaming grounds, and hydrothermally altered zones. These manifestations are unevenly distributed across the field and reflect different expressions of geothermal fluid discharge related to subsurface temperature, permeability, and fluid pathways. Previous studies have documented manifestations mainly around the central and northern parts of the field, which are generally interpreted as outflow or marginal expressions of the geothermal system (Pratama et al., 2021; Nurseto et al., 2021).

### 3.2 Previously Known Manifestations at Lumut Balai

Previously identified geothermal manifestations in the Lumut Balai field are dominated by warm to moderately hot springs and low-temperature fumaroles located near the existing production area. Measured surface temperatures of these manifestations generally range from moderate to high values, with pH values varying from acidic to near-neutral conditions. These manifestations are commonly associated with hydrothermally altered volcanic rocks and diffuse steaming grounds, indicating lateral fluid flow and near-surface boiling processes.

Geochemical characteristics reported in earlier studies suggest that these manifestations are influenced by steam-heated waters and mixed geothermal fluids, consistent with an outflow or peripheral zone of the geothermal system (Nurseto et al., 2021; Pratama et al., 2021). The distribution of manifestation on Lumut Balai geothermal field shown on the map (Figure 4).

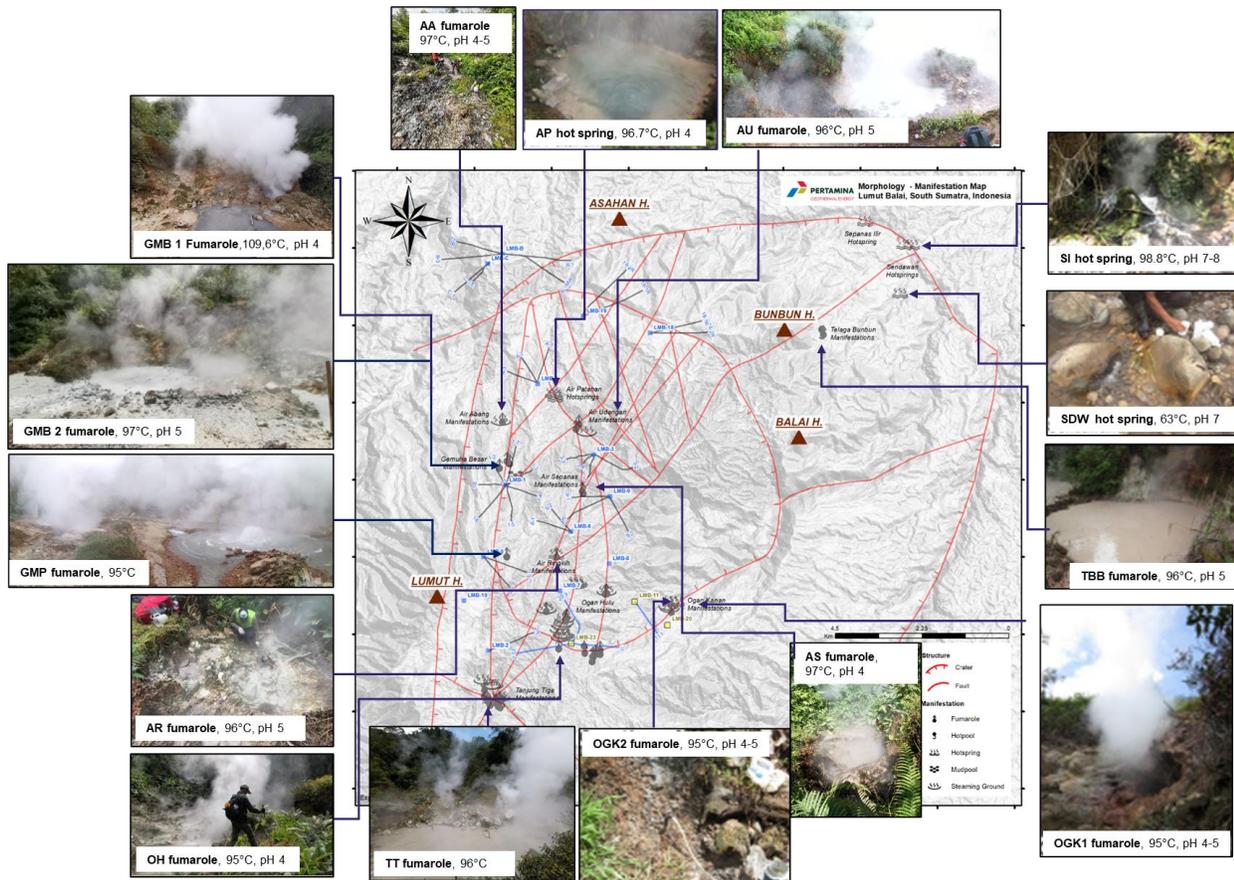


Figure 4: Location and distribution of Lumut Balai geothermal manifestation (PGE, 2025)

### 3.3 Newly Identified Manifestations in the Tanjung Tiga Prospect

Recent field investigations have identified several new geothermal manifestations in the southern sector of the Lumut Balai field, within the Tanjung Tiga prospect area. These newly discovered features include high-temperature fumaroles, active steaming grounds, mud pools, and zones of intense hydrothermal alteration. The location of the newly discovered manifestation can be seen on Figure 5. Compared to previously known manifestations, the new fumaroles exhibit higher surface temperatures and stronger gas discharge.

Field measurements indicate that fumarole temperatures in the Tanjung Tiga area are higher than those observed around the current production zone, with several vents showing vigorous steam emission. Mud pools and altered grounds are commonly associated with these fumaroles and display characteristic clay-rich alteration, suggesting sustained interaction with ascending geothermal fluids.

The newly identified manifestations are spatially clustered and aligned along prominent structural trends identified in geological mapping. Their distribution coincides with mapped fault corridors and areas of enhanced fracture density, indicating a strong structural control on fluid ascent. In addition, the relative proximity of these manifestations to structurally complex zones distinguish them from the more dispersed manifestations observed in the central production area.

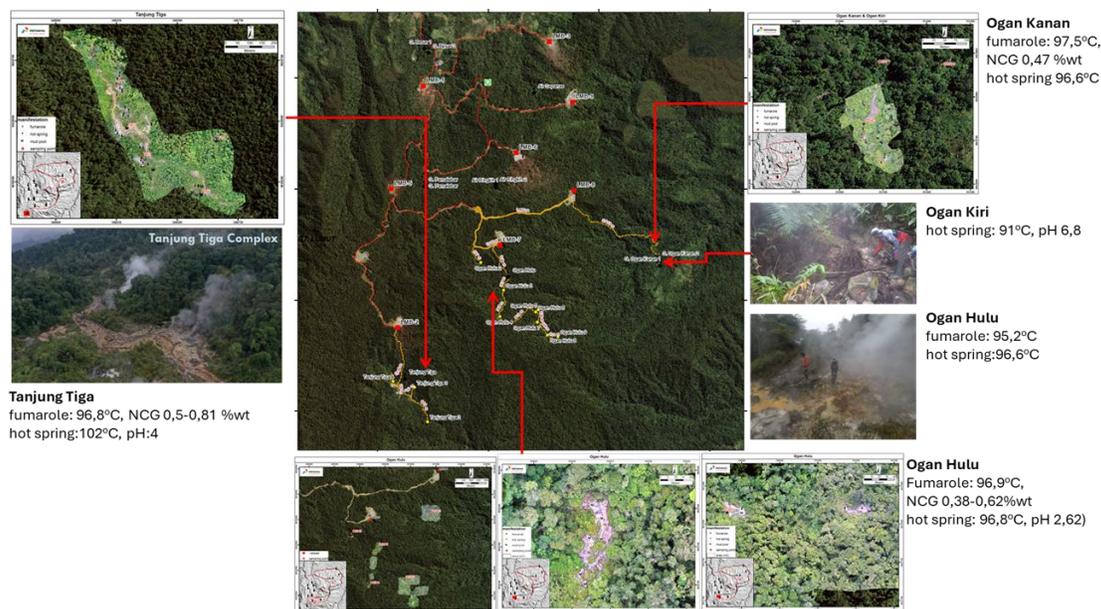
The Tanjung Tiga prospect comprises several clusters of geothermal manifestations, including fumaroles, hot springs, hot pools, mud pools, and widespread hydrothermally altered rocks distributed across the area. These manifestations exhibit higher surface temperatures and stronger thermal discharge compared to those observed in the existing production area. In the Tanjung Tiga manifestation complex, fumaroles reach a maximum temperature of 96.8 °C, with measured steam pressures and velocities of up to 12.87 mbar and 30.37 m/s, respectively. Hot springs within this complex reach temperatures as high as 102 °C and exhibit acidic conditions (pH ≈ 4). Heat loss calculations for the Tanjung Tiga complex indicate a total thermal output of approximately 25.61 MW, reflecting significant subsurface heat discharge.

The Ogan Hulu manifestation area is characterized by fumaroles, hot springs, mud pools, and extensive hydrothermally altered rocks. This area represents the most thermally active zone within the southern sector, with calculated heat loss reaching approximately 84.1 MW. The highest fumarole temperature recorded is 96.9 °C, accompanied by steam pressures of 11.24 mbar and steam velocities up to 45.7 m/s. Hot pools within the Ogan Hulu complex exhibit temperatures up to 96.8 °C, and the area is particularly prone to the occurrence of active mud pools, indicating intense near-surface hydrothermal activity.

The Ogan Hulu Baru area consists of hot pools, mud pools, fumaroles, and altered rocks. Although spatially more limited, this manifestation cluster still displays elevated thermal characteristics. Heat loss estimates yield a value of approximately 2.75 MW. Maximum fumarole temperatures reach 95.2 °C, with associated steam pressures and velocities of 2.01 mbar and 19.87 m/s, respectively. Hot pools in this area reach temperatures of up to 96.6 °C.

The Ogan Kanan area hosts localized fumaroles and hot springs with comparatively lower thermal output. Heat loss calculations indicate a value of approximately 0.022 MW. Despite the lower heat loss, fumarole temperatures remain high, reaching up to 97.5 °C, with steam pressures of 11.56 mbar and velocities of 37.54 m/s. Hot pools in this area record temperatures up to 96.9 °C. In contrast, the Ogan Kiri area is dominated by hot and warm springs, with maximum recorded temperatures of approximately 91 °C, representing a lower-temperature manifestation relative to other clusters within the Tanjung Tiga prospect.

Overall, the distribution, thermal intensity, and heat loss characteristics of the Tanjung Tiga, Ogan Hulu, Ogan Hulu Baru, Ogan Kanan, and Ogan Kiri manifestation clusters highlight significant variability in surface geothermal expression. The concentration of high-temperature fumaroles, high steam flux, and substantial heat loss in the Tanjung Tiga and Ogan Hulu areas distinguishes them from peripheral manifestations and provides important observational constraints for subsequent geochemical and structural interpretations.



**Figure 5: Location and distribution of newly identified Lumut Balai geothermal manifestation on Tanjung Tiga prospect**

## 4. GEOCHEMICAL CHARACTERISTICS

### 4.1 Sampling and Analytical Overview

Geochemical sampling was conducted on selected geothermal manifestations across the Lumut Balai geothermal field, with emphasis on newly identified manifestations in the Tanjung Tiga prospect area and comparison sites within the existing production zone. Collected samples include geothermal waters from hot springs, fumarole condensates, and free gases from fumarolic vents.

In-situ measurements of temperature and pH were conducted at each sampling location. Water samples were analyzed for major ions, while gas samples were analyzed for major gas components and non-condensable gases (NCG). Stable isotope analyses ( $\delta^{18}\text{O}$  and  $\delta\text{D}$ ) were performed to evaluate fluid origin and mixing processes.

### 4.2 Water Geochemistry

The chemical characteristics of geothermal fluids in the Lumut Balai field are first evaluated based on pH, as fluid acidity plays an important role in surface facility design, particularly for wellhead equipment and pipeline materials in production systems. Measured pH values of fluids from production wells in the Lumut Balai field range from 6.4 to 7.3, indicating predominantly neutral fluid conditions.

The classification of geothermal waters and the interpretation of fluid equilibrium states follow the conceptual framework proposed by Giggenbach (1988), where chloride waters represent mature reservoir fluids, while sulfate and bicarbonate waters reflect near-surface steam heating and meteoric water mixing.

The type of geothermal waters using the  $\text{Cl-SO}_4\text{-HCO}_3$  trilinear diagram (Figure 6, left) reveals distinct water types across the field. The hot spring manifestations Sepanas Ilir (SI) and Sendawan (SDW) are classified as chloride waters, with measured pH values ranging from 7.12 to 7.81. These waters are interpreted as mature geothermal fluids representative of reservoir conditions. Chloride concentrations in these manifestations reach approximately 4260 ppm and 1900 ppm, respectively. Both SI and SDW are located in the northeastern part of the Lumut Balai field, extending from the Lumut Tua caldera to the Sepanas Ilir rim, and are spatially associated with the main production zone.

Several manifestations, including OGH2, GMB3, MP-K, AP2, AP3, and TBB, are classified as sulphate waters, which are commonly interpreted as steam-heated waters formed by condensation of acidic gases near the surface. In contrast, bicarbonate-type waters are represented by manifestations SH, OGKr1, and OGKr2, reflecting peripheral or mixed geothermal waters influenced by interaction with shallow groundwater. Manifestations representing the Tanjung Tiga prospect exhibit both sulphate water and bicarbonate water characteristics. Sulphate waters in this prospect are represented by OGH2, while bicarbonate waters are represented by OGKr1 and OGKr2. The presence of these water types indicates variable degrees of steam heating and fluid mixing within the southern sector of the Lumut Balai geothermal field.

Fluid equilibrium conditions for both geothermal manifestations and production wells were evaluated using the Na–K–Mg ternary diagram (Figure 6, right). Fluids from the production wells plot within the fully equilibrated field, indicating chemical equilibrium with the geothermal reservoir and minimal influence from shallow groundwater mixing. This interpretation is supported by very low magnesium concentrations ( $Mg < 0.4$  ppm), which are characteristic of deep, high-temperature reservoir fluids.

In contrast, fluids from manifestations SI and SDW, which are classified as chloride waters, plot within the partially equilibrated field on the Na–K–Mg diagram. These waters exhibit higher magnesium concentrations of approximately 1.67 ppm and 0.91 ppm, respectively, indicating a mixing process between reservoir fluids and shallow meteoric waters.

Manifestations representing the Lumut Balai existing production area (AP2, AP3, MP-K, SH, AA, GMB3, and TBB) as well as those associated with the Tanjung Tiga prospect area (OGH2, OGKr1, and OGKr2) plot within the immature water field on the Na–K–Mg diagram. This distribution indicates that fluids discharging at the surface in these areas are still significantly influenced by meteoric water input and have not reached full chemical equilibrium with the deep geothermal reservoir.

Evaluation of the Cl/B ratio diagram (Figure 7) indicates that geothermal fluids from both surface manifestations and production wells originate from a common geothermal reservoir. The clustering of manifestation and well fluid data along a consistent Cl/B trend suggests a shared deep fluid source, despite differences in surface modification processes such as mixing, boiling, or steam heating. This geochemical relationship provides further evidence of hydraulic connectivity between the deep reservoir and surface expressions across the Lumut Balai geothermal field.

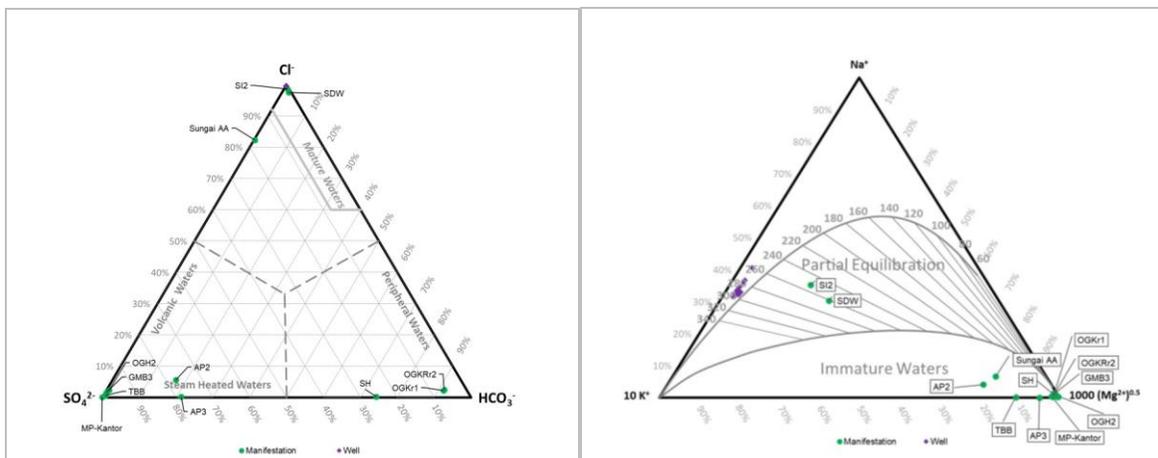


Figure 6: Cl–SO<sub>4</sub>–HCO<sub>3</sub> trilinear diagram and Na–K–Mg trilinear diagram of Lumut Balai

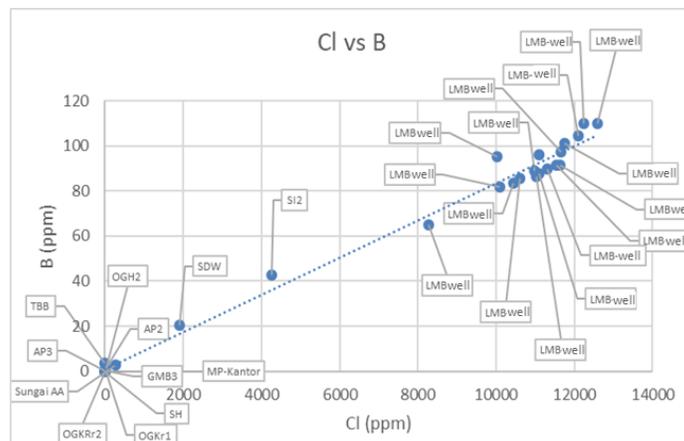


Figure 7: Cl vs B diagram of Lumut Balai

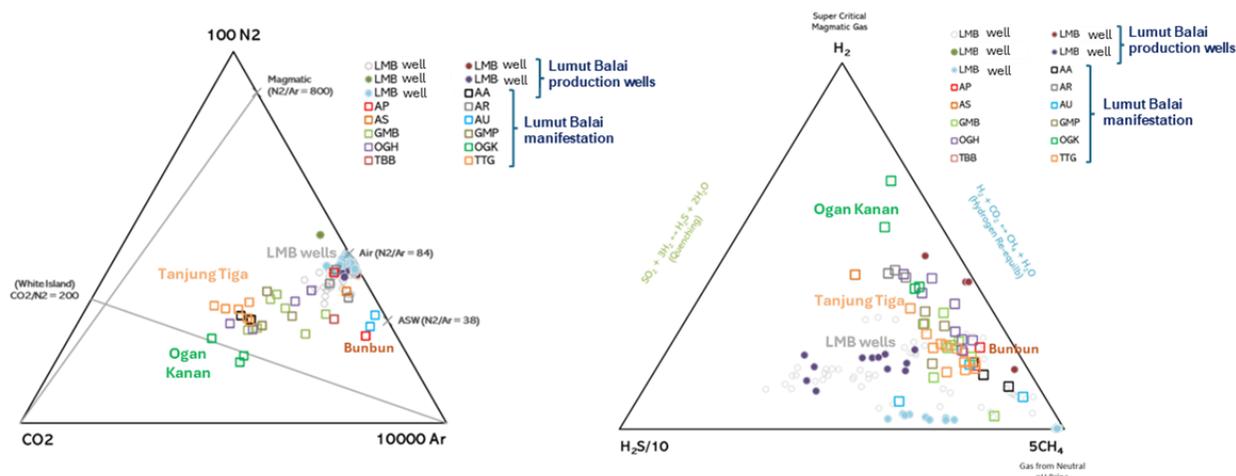
### 4.3 Gas Geochemistry

Gas geochemical characteristics of the Lumut Balai geothermal system were evaluated using  $N_2$ – $CO_2$ –Ar and  $H_2$ – $H_2S$ – $CH_4$  trilinear diagrams (Figure 8). The dataset includes gas samples from fumaroles as well as production well data contributing to Lumut Balai Geothermal Power Plant Units 1 and 2, collected during the production period.

The interpretation of gas origins, magmatic contributions, and hydrogen re-equilibration processes is consistent with gas geochemical models developed by Giggenbach (1996), which relate  $CO_2$ -rich gas compositions and elevated NCG contents to deep geothermal upflow conditions.

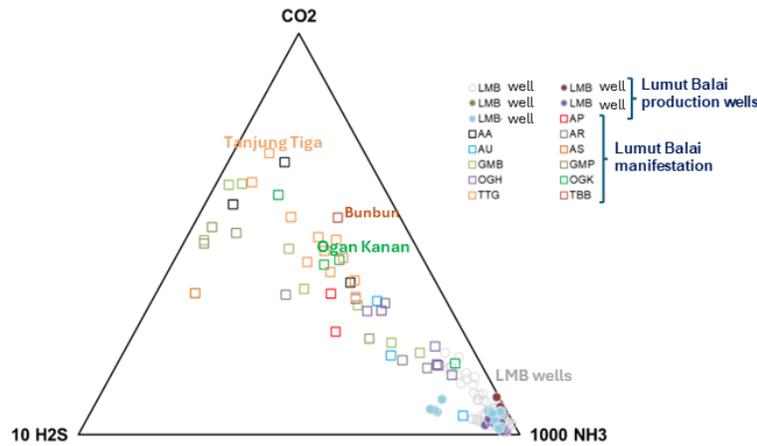
The  $N_2$ – $CO_2$ –Ar trilinear diagram shows that most fumarolic gases and production well gases cluster toward the  $CO_2$ -rich end member, reflecting a dominant geothermal origin. Fumaroles located in the Ogan Kanan manifestation complex, particularly OGK, plot along the White Island line with a  $CO_2/N_2$  ratio of approximately 200, indicating a measurable contribution of magmatic volatiles to the discharged gases. However, results from the  $H_2$ – $H_2S$ – $CH_4$  trilinear diagram (Figure 8, right) indicate that gas samples from OGK have undergone neutralization through hydrogen re-equilibration, shifting toward gas compositions associated with neutral-pH brine-derived fluids. This suggests that although magmatic gases contribute to the system, subsequent interaction with reservoir fluids has modified the original gas signature.

Fumaroles in the Ogan Hulu and Tanjung Tiga areas display gas compositions indicative of an upflow zone, with measured non-condensable gas (NCG) contents ranging from 0.47 to 0.77 wt%. Fumaroles AS, AR, AU-2, AU-1, and AP-1 plot close to the air-saturated water (ASW) point, suggesting limited atmospheric contamination and a strong connection to ascending geothermal fluids. In contrast, fumaroles TBB, AA, GMB-2, GMB-1, and OGH exhibit displacement away from the ASW point. This shift indicates that the discharged gases are influenced by heated meteoric waters that have interacted with a reservoir heat source and subsequently experienced hydrogen re-equilibration during ascent. Gas compositions from production wells in the Lumut Balai field plot close to the air point on the trilinear diagrams (Figure 8), reflecting equilibrium conditions within the geothermal reservoir and consistent gas characteristics across the producing wells.



**Figure 8:**  $N_2$ – $CO_2$ –Ar and  $H_2$ – $H_2S$ – $CH_4$  trilinear diagrams showing gas geochemical characteristics of fumaroles and production wells in the Lumut Balai geothermal field

The  $CO_2$ – $H_2S$ – $NH_3$  gas relationships and their implications for upflow and boiling processes are interpreted following established geothermal gas models (Giggenbach, 1996; Nicholson, 1993). Further gas geochemistry evaluation using the  $CO_2$ – $H_2S$ – $NH_3$  trilinear diagram (Figure 9) shows that gases from Tanjung Tiga fumaroles plot closest to the  $CO_2$  apex when compared to other fumaroles in the Lumut Balai field. This gas composition reflects a strong contribution of deep-seated  $CO_2$  and indicates limited near-surface modification, which is characteristic of upflow conditions within a geothermal system. Carbon dioxide concentrations in fumarolic gases are generally higher than those measured in production wells at Lumut Balai. In contrast, gases from the production wells plot toward the  $NH_3$  apex, suggesting that the reservoir fluids have undergone boiling processes, during which  $NH_3$  becomes enriched in the vapor phase. This distinction between surface manifestations and production well gases highlights differences in phase separation and fluid evolution during ascent from the reservoir.



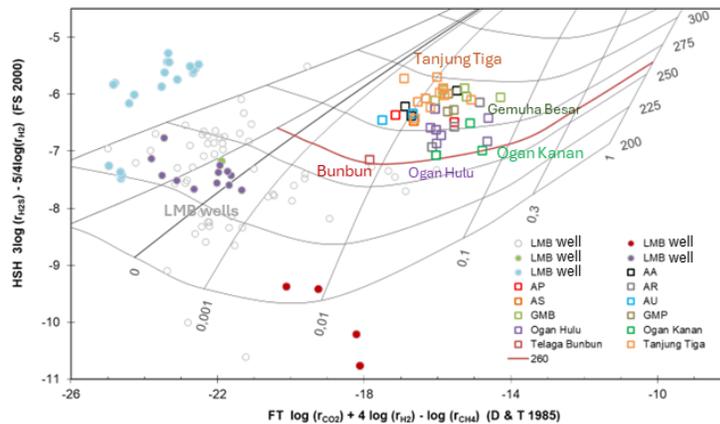
**Figure 9: CO<sub>2</sub>-H<sub>2</sub>S-NH<sub>3</sub> trilinear diagram showing gas compositions of fumaroles and production wells in the Lumut Balai geothermal field**

**4.4 Geothermometry**

Reservoir temperature estimates for the Lumut Balai geothermal system were derived using both water and gas geothermometers, applied to hot spring manifestations and production well fluids. Reservoir temperatures estimated from chloride hot springs in the Sendawan (SI) and Sendawan (SDW) areas, located in the northeastern sector of the field, were calculated using the Na-K-Ca geothermometer. The application of water and gas geothermometers and their interpretation follow established geothermal geochemistry principles (Giggenbach, 1988; Giggenbach and Goguel, 1989; Nicholson, 1993). These calculations yield reservoir temperatures of approximately 218 °C for SI and 221 °C for SDW. In comparison, geothermometric estimates based on fluid samples from production wells in the Lumut Balai field indicate higher reservoir temperatures, ranging from approximately 236 to 270 °C, reflecting conditions closer to the deep geothermal reservoir.

Gas geothermometry was further evaluated using the FT-HSH geothermometer, which is based on the equilibrium relationships among H<sub>2</sub>, H<sub>2</sub>S, and CO<sub>2</sub> in high-temperature geothermal systems. This geothermometer is particularly applicable to vapor-dominated and two-phase systems, where gas compositions are controlled by redox reactions buffered by mineral assemblages at depth. The FT-HSH geothermometer has been widely applied to estimate reservoir temperatures in volcanic-hosted geothermal systems and provides reliable temperature estimates when gas compositions reflect near-equilibrium conditions (D’Amore and Truesdell, 1985).

Based on the FT-HSH geothermometer (Figure 10), fumaroles from the Tanjung Tiga area indicate reservoir temperatures in the range of 275–300 °C, suggesting proximity to the geothermal upflow zone. Fumaroles from Ogan Hulu yield temperatures of 250–275 °C, whereas gases from the Ogan Kanan area indicate lower equilibrium temperatures of approximately 200 °C, consistent with lateral outflow or marginal system conditions.



**Figure 10: FT-HSH gas geothermometer (D’Amore and Truesdell, 1985) showing estimated reservoir temperatures for geothermal manifestations in the Lumut Balai field**

**5. DISCUSSION: IMPLICATIONS FOR UPFLOW ZONE OF LUMUT BALAI GEOTHERMAL FIELD**

The distribution and characteristics of geothermal manifestations in the Lumut Balai geothermal field provide important constraints on the location of active upflow zones. Newly identified manifestations in the southern sector, particularly within the Tanjung Tiga and Ogan Hulu areas, are spatially concentrated and aligned along major structural trends mapped in the field. These manifestations are characterized by high-temperature fumaroles, vigorous steam discharge, extensive hydrothermal alteration, and significant heat loss, indicating focused upward flow of geothermal fluids along permeable fault zones.

Compared to manifestations in the central production area, which are more diffuse and commonly associated with steam-heated or mixed waters, the southern manifestations exhibit features consistent with structurally controlled fluid ascent from depth. This structural association supports the interpretation that fault-controlled permeability plays a key role in channeling upflow fluids toward the surface in the Tanjung Tiga prospect.

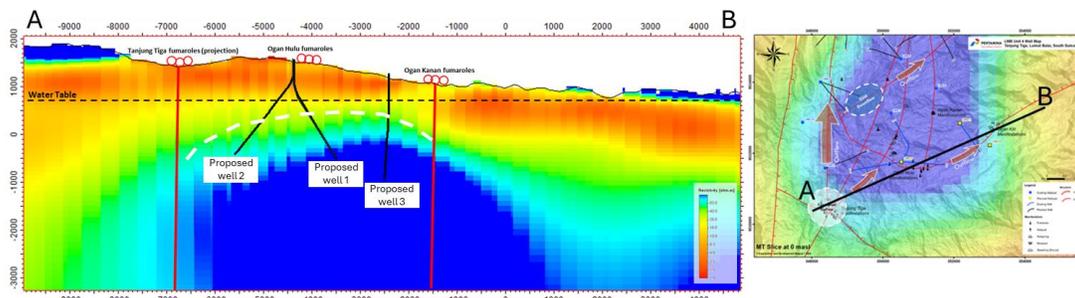
Gas geochemical data provides some of the most compelling evidence for delineating upflow zones. Fumaroles in the Tanjung Tiga and Ogan Hulu areas exhibit elevated non-condensable gas contents and gas compositions indicative of deep fluid ascent. Trilinear  $N_2$ – $CO_2$ – $Ar$  diagrams show a dominant  $CO_2$  component, with limited atmospheric influence, consistent with a geothermal origin. The presence of magmatic volatile input is indicated by fumaroles in the Ogan Kanan area, particularly OGK, which plots along the White Island line. However, hydrogen re-equilibration observed in  $H_2$ – $H_2S$ – $CH_4$  diagrams suggests that these gases have interacted with neutral-pH reservoir brines, modifying their original magmatic signature. Results from the  $CO_2$ – $H_2S$ – $NH_3$  diagram further distinguish the Tanjung Tiga fumaroles, which plot closest to the  $CO_2$  apex relative to other manifestations. This pattern reflects minimal boiling and near-surface modification, characteristic of proximal upflow conditions. In contrast, gases from production wells plot toward the  $NH_3$  apex, indicating boiling processes occurring within the reservoir and along wellbores.

Geothermometric results integrate well with geological, geochemical, and heat loss observations. Gas geothermometry indicates reservoir temperatures of 275–300 °C beneath the Tanjung Tiga area, the highest estimated temperatures in the field. Slightly lower temperatures are calculated for the Ogan Hulu area (250–275 °C), while significantly lower temperatures characterize the Ogan Kanan area (~200 °C). These temperature gradients suggest that the primary upflow zone is centered beneath Tanjung Tiga, with thermal outflow extending toward Ogan Hulu and peripheral cooling toward Ogan Kanan. The consistency between high geothermometric temperatures, elevated  $CO_2$ -rich gas compositions, and significant surface heat loss strongly supports the interpretation of Tanjung Tiga as a proximal upflow zone within the Lumut Balai geothermal system.

The concentration of high-temperature manifestations,  $CO_2$ -rich gases, elevated heat loss, and high geothermometric temperatures beneath the Tanjung Tiga area is consistent with conceptual models of geothermal upflow zones described by Nicholson (1993) and Giggenbach (1996)

## 6. IMPLICATIONS FOR EXPLORATION & DEVELOPMENT

The integrated interpretation of surface manifestations, water and gas geochemistry, heat loss, and geothermometry indicates that the Tanjung Tiga prospect represents a key upflow zone within the Lumut Balai geothermal field. This finding has important implications for ongoing exploration and development, particularly for Lumut Balai's new geothermal power plant, where targeting structurally controlled permeability zones in the southern sector may enhance resource utilization and field expansion (Figure 11).



**Figure 11: The conceptual model of Lumut Balai from integrated geology, geochemistry, and geophysics data (PGE, 2025) shows the upflow zone of Tanjung Tiga prospect area as a favorable area for the next Lumut Balai's exploration & development**

## 7. CONCLUSION

This study captures the discovery and characterization of new geothermal manifestations in the southern sector of the Lumut Balai geothermal field, with particular emphasis on the Tanjung Tiga prospect. Field observations reveal high-temperature fumaroles, extensive hydrothermal alteration, and significant surface heat loss, indicating focused upward discharge of geothermal fluids.

Gas geochemistry provides strong constraints on fluid origin and flow processes.  $CO_2$ -rich gas compositions, elevated non-condensable gas contents, and trilinear gas relationships indicate deep fluid ascent beneath the Tanjung Tiga and Ogan Hulu areas. The observed gas trends and hydrogen re-equilibration processes are consistent with conceptual models of gas–brine interaction and phase separation in high-temperature geothermal systems (Giggenbach, 1992).

The integrated interpretation of geological, geochemical, thermal, and geothermometric data delineates the Tanjung Tiga prospect as the primary upflow zone of the Lumut Balai geothermal system. These results are consistent with established geothermal system models (Giggenbach, 1988; Nicholson, 1993) and provide a robust scientific basis for ongoing exploration and development, particularly in support of the next Lumut Balai geothermal power plant.

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