Integrated Geoscience Data to Identify Heat Source Beneath Umeh Volcanic Complex in Tompaso Geothermal Field

Sigit Suryanto1,2, R.M. Tofan Sastranegara1, Antonius Rishang Untoro1, Nanda Najih H. Affif1, Ristio Effendi1, Imam B. Raharjo1 and Suryantini2
1Pertamina Geothermal Energy, Indonesia
2Geothermal Engineering Master’s Program, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung. Jl. Ganesha 10, Bandung 40132, Indonesia

Email: sigitsuryanto@pertamina.com
https://orcid.org/0000-0003-1981-3581

Abstract. Integrated geoscience data evaluation is needed to determine the location of the heat source in the Tompaso Geothermal Field. The location of the heat source in the Tompaso Geothermal Field should be known to update the conceptual model. The updated conceptual model can be used as a reference in development plans of Tompaso Geothermal Field. Therefore, through integrated geoscience data evaluation such as geological settings, remote sensing data, resistivity and gravity data, fluid chemistry data, and temperature measurements data from wells are expected to determine the presence of the heat sources, especially beneath Umeh Volcanic Complex (UVC) in the Tompaso Geothermal Field. Based on geological and remote sensing data, the location of heat sources of Tompaso Geothermal Field are predicted beneath Sempu Volcanic Complex (SVC) and Umeh Volcanic Complex (UVC). SVC is related to recent volcanic activity while UVC is related to “monogenetic” volcanism. The gravity data beneath SVC showed high gravity anomaly contrasts than its surrounding areas, while high gravity anomaly beneath UVC has lower contrast than SVC. However, chemical fluid analysis from thermal manifestations and temperature from the wells indicated the presence of heat source beneath UVC.

1. Introduction
The Tompaso Geothermal Field is located in Tompaso District, Minahasa Regency, North Sulawesi Province. It can be reached by a light vehicle from Manado, the capital city of North Sulawesi Province, about 60 km southern part of the city (Figure 1). The field is a part of the Lahendong Working Area, owned and operated by PT. Pertamina Geothermal Energy (PGE). Tompaso Geothermal Field has total installed capacity of 2x20 MW.

Tompaso Geothermal Field is situated in the northern arm of Sulawesi Island. The Northern arm of Sulawesi, especially at the Minahasa Compartmment, overlie the westward dipping subduction zone from Molucca sea plate [1] (Figure 2). These quaternary subduction form the Minahasa–Sangihe volcanic arc.
Figure 1. Location of the Tompaso Geothermal Field in North Sulawesi, Indonesia.

Figure 2. Tectonic map and illustration of converging plate in the Molucca Sea and Sorong sutures [1].
2. Geology

2.1. Stratigraphy

Volcanism at Tompaso Field began from Pre-Tondano episode to the recent active volcanism. Pre-Tondano volcanism episode started at Middle Miocene to Pliocene [2]. These volcanism episodes parallel with a transgressive event, which was created sedimentary deposits in the marine environment. The genesis of Tondano depression at Tondano Episode occurred on Pliocene to Pleistocene and proven by age dating caldera collapse deposit [2, 3] from 2.0 Ma (Domato tuff), 1.3 Ma (Teras tuff), 0.87 Ma (Tondano tuff) and 0.1 Ma (Kakas tuff). On the Tondano episode, younger volcano activity emerged at the bottom off Tondano Depression creating some volcanoes such as Rindengan Group, Wawona Lengkoan Group, Soputan Muda, Manimporok, Sempu, Umeh Volcanic Complex (UVC) consisting Mt. Umeh and Mt. Wowok, and Paso Volcanic Complex (PVC) consisting Mt. Pinasuan, Mt. Kokopit, Mt. Matatumbak, Mt. Sinopi and Mt. Semelenduk. Soputan volcanism is the youngest recent volcanic activity at Tompaso Field, which covers up the southwest boundary of Tondano Depression.

The Tompaso geological data were collected from several PGE internal reports of geological activities and also from other scientific publications related to the field [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13]. The Tompaso Field had experienced 3 volcanism episodes: Pre-Tondano episode, Tondano Episode, Post-Tondano Episode, and Active Volcanism Episode (recent) created a physical characteristic of The Tompaso Field.

Volcano-stratigraphy of Tompaso Field was built from morphological data using remote sensing data and from field data related to geoscience necessity. Tompaso Field could be divided into several volcanic products, which are Figure 3 and Figure 4.

- Lambeyan Group
- Tondano Group
- Rindengan Group
- Manimporok Group
- Umeh Volcanic Complex (UVC) Group
- Wawona – Lengkoan Group
- Soputan Muda Group
- Sempu Group
- Pinasuan Kokopit Matatumbak Group
- Sinopi Semelenduk Group
- Soputan Group
- Alluvium

UVC group was the main focus of this research. It is the volcanic complex of deformed and dissected paleo volcano on the bottom of Tondano Depression near the Tondano Lake. There is an isolated hill named Mt. Emung at Kanonang Area, which probably has the same age as UVC. UVC consists of tuff breccia with pumice fragment as a dominant component with glassy groundmass. Umeh center of the eruption has a circular feature that looks like a small crater with no thermal manifestation at the surface.
**Figure 3.** Geological map and geothermal manifestation distribution of Tompaso Field.

| Period       | Age (Ma) | Pre Tondano | Tondano | Post Tondano | Recent Vulcanism |
|--------------|----------|-------------|---------|--------------|-----------------|
| Recent       |          |             |         |              |                 |
| Holocene     | 0.1      |             |         |              |                 |
| Pleistocene  | 0.47     |             |         |              |                 |
| Pliocene     | 0.87     |             |         |              |                 |
| Middle Miocene | 2.19  |             |         |              |                 |

**Figure 4.** Volcano-stratigraphy of Tompaso Field and the volcanism history with age dating data from Gondwana (1988) in [2].
2.2. Geological structure

Geological structure of Tompaso Field had been studied by several researchers since [1] and periodically updated with upcoming data and interpretation that relevant to the development for further understanding [6, 10, 11, 12]. Some data used to build a structural geology map of Tompaso were remote sensing data, Digital Elevation Model (DEM), geothermal manifestation data, geological field survey data, subsurface data from the wellbore, geophysical interpretation from several methods, and other publication related to the field.

Tompaso Field has several distinctive geological structures such as fault lineament and depression related to volcano-tectonic activity near the volcano body. Spatial location and it is pattern identified from LIDAR and IFSAR image analysis, which gave clear and accurate texture as well as morphological patterns. Morphological signature related to the geological structure which had been identified at Tompaso Field were escarpment, river deflection, circular feature, lineament of the valley, and lineament of a volcano. The main direction of geological structure in Tompaso Field is ENE–WSW as Soputan pattern, NE–SW as Tompaso–Toraget–Totolan pattern, and minor NW–SW as Sonder pattern (Figure 5).

![Figure 5. Geological structure map of Tompaso Field Pertamina Geothermal Energy.](image)

Tectonically, Tompaso Field located inside Tondano Depression at compressional tectonic regime resulted from a shear model with the main horizontal compression of NE–SW. The Riedel shear model is consistent and applicable to describing geological structure in Tompaso. Dextral and sinistral movement could also be found in several segments in Tompaso Field with correspondent minor to major vertical movement. Strike-slip fault deformation could lead to the development of the damage zone, which is mainly located in 3 areas: tip damage zone, wall damage zone, and linking damage zone [14]. Damage zone lean-to found at the intersection of two main geological structures of the strike-slip movement, which called intersection damage [14]. Pull apart basin model also one of
consistent geological structure model at Tompaso Field to explain the step over of NE–SW Tompaso–
Toraget pattern and following basin structure that identified by gravity survey. Ranoan Fault,
Tompaso Fault, Semelenduk Fault, and Toraget–Totolan Fault have Tompaso–Toraget pattern (NE–
SW) and play as step over fault which related to the evolution of Tondano Depression [8].

Soputan Fault with ENE–WSW pattern follows through Soputan Volcano to eastward of Tondano
Lake across Tompaso Field. Soputan fault intersected some Tompaso-Toraget fault patterns at
Tonsewer Selatan (Tompaso Fault) and Toraget (Toraget Fault). The intersection area of those
different patterns, if subjected to the model of the damage zone, could be classified as an intersection
damage zone. Meanwhile, the intersection of Soputan Fault with Toraget Fault correlated with the
appearance of Toraget geothermal manifestation complex and the emplacement of Umeh Volcanic
Complex (UVC).

Umeh Volcanic Complex (UVC) consists of strongly dissected volcanic morphology of Mt. Umeh
and Mt. Wowok at relative flat to low wavy land of the bottom Tondano depression Figure 6. From
low land area UVC give morphology like “monogenetic” volcano but concerning to the MT
Resistivity data of spreading low resistivity tuff related deposit shown more than 1000-meter depth
and widely spread relatively to northward. Nowadays, we could not identify any sign of geothermal
manifestation such as fumarole and solfatara at the Mt. Umeh crater. On the contrary, we could find
reworked sediment in the form of weathered lapilli and tuff.

![Figure 6. Typical UVC (Mt. Umeh and Mt. Wowok) morphology view from north. Mt. Umeh show circular feature, possibly old eruption crater at the centre.](image)

UVC is located at the intersection of the major geological structure at the Minahasa Compartment
known as Soputan Fault (ENE–WSW) with one step over the segment of Tondano pull-apart basin
known as Toraget–Totolan fault. Some other monogenetic shaped volcano such as Paso Volcanic
Complex (Consist of Mt. Pinasuan, Mt. Kokopit, Mt. Matatumbak, Mt. Sinopi, and Mt. Semelenduk)
also located parallel to the Toraget–Totolan fault with direction relatively NE–SW. NE–SW trending
long valley could be seen in LIDAR cross-cut the UVC and PVC with the appearance of fumarole in
Totolan village as the result of Toraget–Totolan fault activity. Intersection damage zone of Soputan fault with Toraget–Totolan fault assumed to be the possible cause of heat source emplacement beneath UVC due to lower subsurface pressure at the damage zone to lead magma migration. It is still uncertain whether those identified heat source directly related to the genesis of UVC or PVC, but it is clear that the mechanism of how these volcano clusters emplaced (UVC and PVC) were the same.

3. Geophysics
Gravity is one of the geophysical methods that can be used to determine a heat sources location. Modeling of gravity data is needed to map the distribution of gravity values in a geothermal field both laterally and vertically. An anomaly of high gravity in the volcano complex is generally correlated with the existence of a fresh and highly dense rock body so that it can correlate with the existence of a heat source in a geothermal field. This interpretation will be supported by resistivity data from Magnetotelluric. The updoming pattern of the resistivity model is generally correlated with the influence of the heat source from the bottom.

![Figure 7](image-url)

**Figure 7.** Section of MT resistivity and gravity model of Tompaso show the distribution of UVC products. Heat source beneath UVC is closely related to high resistivity body with up doming pattern.

The result of gravity data modeling in Tompaso Field showed that there were high gravity anomalies in several locations: on Sempu Volcanic Complex (SVC) and Umeh Volcanic Complex (UVC). SVC high gravity anomaly complex revealed a very high contrast value compared to its surroundings. Although UVC also revealed contrast high gravity anomaly, its difference in gravity values was not too high for its surroundings (Figure 7). Hence it can be interpreted that the heat source on SVC was greater than on UVC. This interpretation was also supported by updoming patterns in resistivity model from Magnetotelluric and the existence of a very active Soputan Volcano, which is located close to SVC.
High gravity anomaly on UVC did not look too large, both vertically and horizontally. This was certainly related to the formation of UVC, which was only a small volcanic body in the form of a cone. The volcano complex appeared after the Tondano eruption phase. The presence of high gravity anomaly on UVC that indicated the existence of heat source was supported by geothermal manifestation data and wells temperature that will be discussed later.

4. Geochemistry
Based on the thermal feature mapping in Tompaso, according to [15], geothermal manifestations distribution in Tompaso could be divided into four different regions:

- Manifestations on Tempang–Tompaso–Mount Umeh (UVC) area was dominated by chloride hot springs, mud pools, acidic hot springs, and steaming ground.
- Manifestations on Acid Crater–Mount Riendengan (SVC) area was dominated by fumaroles, solfatara, and hot springs.
- Manifestations on Kawangkoan–Mount Emung area, was dominated by bicarbonate and sulfate hot springs.
- Manifestations that appear on the edge of Tondano Lake and Remboken Village were dominated by bicarbonate hot springs

The manifestation complex on UVC appeared around the damage zone, which correlated with the intersection of two main structures: Soputan Fault (ENE–WSW direction) and Toraget Fault (NE–SW direction). The manifestations on UVC consisted of chloride hot springs, mud pools, acidic hot springs, and steaming ground. The hot chloride spring temperatures reach 98°C (boiling), silica sinters appeared around the chloride hot springs. The hot chloride spring location was around the acidic hot spring, so it was likely that the location was the upflow of the Tompaso geothermal system.

**Figure 8.** Gas data of geothermal manifestations in Tompaso Field.
Viewed from the gas content (NCG), geothermal manifestations on UVC had higher NCG content compared to its vicinity. The high gas content in a manifestation was generally related to the degassing process of a rocking body (intrusion) that moved vertically so that it appeared on the surface, forming a manifestation that was rich in NCG. This data could indicate that there was an intrusion rock that might act as a heat source under UVC (Figure 8 and 9).

Figure 9. NCG distribution map in Tompaso Field.

Other geochemical data that supported the existence of heat source on UVC was deuterium and oxygen-18 isotope taken from the water and condensate manifestations from UVC. TPS-8 (UVC) sample was taken from fumarole or steam condensate revealed a more positive shifting of oxygen-18 to an andesitic line (Figure 10). Oxygen-18 shifting was the result of the interaction between geothermal activity and meteoric water coming from the surface. Isotopes data performed the ratio value between deuterium and oxygen-18 approached the andesitic line [16]. In other words, isotopes were derived from the volcanic activity below the surface so that they might be related to the presence of a heat source.
5. Wellbore data

Figure 10. The graph showing the ratio between O-18 and Deuterium in Tompaso Field.

Figure 11. Temperature and pressure data from several geothermal wells in Tompaso Field.
Based on pressure and temperature data from well LHD-B, a directional well that was directed just below the UVC showed higher temperature compared to production wells in LHD-A. Regarded SVC as the primary heat source was correlated with recent volcanic activity, UVC was farther than production wells in LHD-A but had a higher temperature even more than 300°C. (Figure 1). In normal hydrology, the location near the heat source will have a temperature greater than farther. This did not occur at LHD-B, which had a higher temperature than LHD-A so possibly due to the presence of an intrusion body at the bottom of UVC that acts as the heat source.

6. Interpretation
The complex manifestation of UVC appeared in the damage zone resulting from the intersection of Soputan Fault and Toraget–Totolan Fault. Manifestations in UVC appeared as fumaroles, boiling chloride springs, silica sinter, and acid sulfate manifestations with high NCG content that indicated the upflow of the geothermal system. The content of deuterium and oxygen-18 from the manifestations on UVC showed the shifting toward the andesitic zone so that it could be interpreted that the sampled fluids were influenced by geothermal parent fluid. The result of gravity data modeling showed the presence of high gravity anomaly under UVC and the result of resistivity data modeling showed updoming pattern in the same location with the gravity anomaly. LHD-B well, which directed below UVC had a higher temperature than LHD-A well that is located near the primary SVC heat source. Thus, it could be interpreted that there was a heat source under UVC (Figure 12).

This research needs to be further confirmed by well chemistry data from wells which directed below UVC. Currently, the data is not available, because the well cannot be tested for production due to social problems.

![Figure 12](image-url)  
*Figure 12. Location of heat source beneath UVC in Tompaso Geothermal Field*
7. Conclusion
The result of integrated geoscience data evaluation such as geological settings, remote sensing data, gravity and resistivity data, fluid chemistry data, and temperature measurement data from wells indicated the presence of heat source beneath UVC. The size of the heat source under UVC is smaller than the heat source under SVC in the Tompaso Geothermal Field.

References
[1] Hall R and Wilson M E J 2000 Neogene Sutures in Eastern Indonesia Journal of Asian Earth Sciences 18 781-808
[2] Utami P 2011 Hydrothermal Alteration and the Evolution of the Lahendong Geothermal System, North Sulawesi, Indonesia Unpublished PhD Thesis University of Auckland (Auckland New Zealand)
[3] Lecuyer F 1998 Relations entre le volcanisme actif et la tectonique actuelle dans la région de Tondano au nord de Sulawesi (Indonésie) Thèse Doct. Université Blaise Pascal Clermont-Ferrand
[4] Bachri S 1977 Geologi Lapangan Panasbumi Lahendong – Tompaso, Minahasa, Sulawesi Utara Direktorat Geologi
[5] Effendi A C and Bawono S S 1997 Geologic Map of the Manado Quadrangle, North Sulawesi, 1:250,000 scale (Geological Survey Indonesia Bandung)
[6] Ganda S and Sunaryo D 1982 Laporan Pendahuluan Geologi Daerah Minahasa, Sulawesi Utara Pertamina Internal Report
[7] Kushendratno, Pallister J S, Kristianto, Bina F R, McCausland W, Carn S, Haerani N, Griswold J and Keeler R 2012 Recent explosive eruptions and volcano hazards at Soputan volcano a basalt stratovolcano in North Sulawesi Indonesia Bull Volcano
[8] Lécuyer F, Bellier O, Gougoud A and Vincent P M 1997 Tectonique active du Nord-Est de Sulawesi (Indonésie) et contrôle structural de la caldeira de Tondano Comptes Rendus de l’Académie Des Sciences-Series II-Earth and Planetary Science 325(8) 607–613
[9] Pedjoprajitno S 2012 Morphostructure Control Towards the Development of Mahawu Volcanic Complex, North Sulawesi Indonesian Journal of Geology 7 39-54
[10] Sardiyanto and Nurseto S T 2013 Analisa Struktur Geologi Lapangan Tompaso Pertamina internal report
[11] Sardiyanto, Nurseto S T, Prasetyo I M, Thamrin M H and Kamah M Y 2015 Permeability Control on Tompaso Geothermal Field and Its Relationship to Regional Tectonic Setting Proc., World Geothermal Congress
[12] Siahaan E E, Soemarinda S, Fauzi A, Silitonga T, Azimudin T, and Raharjo I B 2005 Tectonism and volcanism study in the Minahasa compartment of the north arm of Sulawesi related to Lahendong geothermal field Indonesia Proc., of the World Geothermal Congress
[13] Utami P, Siahaan E E, Azimudin T, Suroto, Browne P R L and Simmons S F 2004 Overview of Lahendong Geothermal Field, North Sulawesi Indonesia Proc., of the 26th NZ Geothermal Workshop
[14] Peacock D, Nixon C, Rotevatn A, Sanderson D and Zuluaga L 2016 Glossary of fault and other fracture networks Journal of Structural Geology 92
[15] Handoko B T 2010 Resource Assessment of Tompaso Geothermal Field, Indonesia United National University Geothermal Training Program Reports 30 647-674
[16] Giggenbach W F 1992 Isotopic Shifts in Waters from Geothermal and Volcanic System Along Convergent Plate Boundaries and Their Origin Earth and Planetary Science Letters 113 495-510