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Updating the Complexity of Tompaso Geothermal Conceptual Model, Indonesia

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ABSTRACT

The Tompaso geothermal field, located in North Sulawesi, Indonesia, presents a highly complex geothermal system influenced by various geological factors revealed by the recent data. This study updates the conceptual model of the Tompaso field based on new data from the latest drilling campaign and integrates findings on permeability control, hydrology, heat source, and reservoir structure. These updates comply with the general geological setting of Tompaso which is influenced by the Tondano Caldera, formed during explosive rhyolitic and dacitic eruptions, and composed of multiple volcanic formations including pre-, syn-, and post-caldera units.

Hydrological features include two major upflow zones, cold water downflows and cold aquifer layers that feed into the system, complicating the temperature distribution across the field. The reservoir's heat source and upflow are believed to be associated with two volcanic zones which are the Rindengan-Sempu complex and possibly near the Umeh-Wowok complex. The economic outflow zone is driven by the permeability in the Tompaso reservoir which is controlled by formation permeability including matrix and fracture, with different zones contributing to the overall flow dynamics. The deeper high-permeable zones are associated with high-intensity fracture zones which are laterally distributed by a formation with similar mechanical properties and more prone to be fractured, while the shallower pores or microfractures-supported in formation permeability dominate in volcanic pyroclastic rocks which consist of ignimbrite and volcanic breccia. The outflow from these two upflow are mixed on the northeastern part of the field, manifesting the thermal fluid on the surface. The reservoir is capped by a thin altered-tuff layer, protecting it from an overlying cold aquifer that is controlled by basaltic lava-dominated formation. Results from the latest semi-exploration and make-up wells and surveys are also presented and integrated to present an overall conceptual model of the field.

1. INTRODUCTION

Tompaso geothermal field is located in Minahasa district, about 60 km south of Manado, the capital of the province. The altitude of the field ranges from 700 – 900 meters above sea level and the morphology consists of flat terrain surrounded by volcanic high and caldera rim. It is close to Tondano Lake as the product of the volcanic eruption of an old Tondano Volcano. The field is part of the Lahendong working area which is owned and operated by PT. Pertamina Geothermal Energy (PGE). It supplies 40 MW (2 x 20 MW) from Unit 5 and 6 Lahendong Power Plants to the power grid. Tompaso field is believed to have a different reservoir from Lahendong field separated by the Lengkoan mountain range, supported by geoscientific evidence.

The references that discuss the Tompaso field conceptual model are few, but some publications have initiated the interpretation of its geothermal system and implications by using limited subsurface data. Utami et al. (2020) and Sidqi & Utami (2018) explain the geology and the geothermal system in the Minahasa district. Sardiyanto et al. (2015) focused on the permeability control analysis in the Tompaso field based on the surface and subsurface image log data. Lesmana et al. (2019) proposed the compartment possibilities within the Tompaso reservoir by using numerical simulation analysis. Meanwhile, the geological information of the Tompaso field has been updated by Ikhwan et al. (2021) which revised and complimented the detailed satellite image analysis published by (Lécuyer et al., 1997). It proposed a structural model in the eastern end of North Sulawesi that controlled the occurrence of 20x10 km² Tondano caldera.

The Tompaso field is going to add more generation capacity by looking at the opportunities outside the existing production area, therefore three new semi-exploration wells were drilled during 2022 – 2024. These wells result in the updated knowledge of Tompaso reservoir significantly and reveal its complexity regarding almost all aspects of its geothermal system including the permeability control, aquifer, hydrology, heat source and reservoir boundary. By using these new findings, this paper will discuss the updated Tompaso reservoir understanding that is represented by the wells data, which, unfortunately, is not as simple as published by previous studies.

2. GEOLOGY

2.1 Regional Geology

Katili (1991) described the Sulawesi formed due to the northward Australian plate movement and the New Guinea movements anticlockwise movement in Neogene. The northern arm is composed of late Paleogene to Neogene subduction-related volcanic arc rocks resulting from the west-dipping subduction of the Molucca Sea Plate and the south-dipping subduction Sulawesi Sea Plate (Satyana et al., 2011). The K-shaped island of Sulawesi comprises northern arms of tertiary sediments and volcanic-arc rocks, eastern arms of Cretaceous and Neogene accretionary-wedge materials (Hamilton, 1979) southern and western arms with Cretaceous accretionary-wedge rocks. Subduction complexes dominate the east and southeast arms (Figure 1.A).

The eastern end of North Sulawesi is a complex subduction area. Tectonic setting and volcanism in this area are controlled by two subductions with different orientations: the W-E trending North Sulawesi subduction in the north and the N-S trending Sangihe subduction in the east. The latter is a part of the double subduction system and the Halmahera subduction in the Mollucas Sea suture (Hall & Wilson, 2000). The North Sulawesi subduction controls the North Sulawesi arms shape, while the Sangihe subduction triggers the volcanism arc along the eastern end of North Sulawesi. The North Sulawesi area is divided into three compartments: 1) the NE-SW trending compartments (Minahasa compartments), 2) the central E-W trending segment (Gorontalo compartments) and, 3) the N-S trending compartment or Neck (Siahaan et al., 2005). The Minahasa compartment is part of Sangihe Ridge which created an inner volcanic arc.

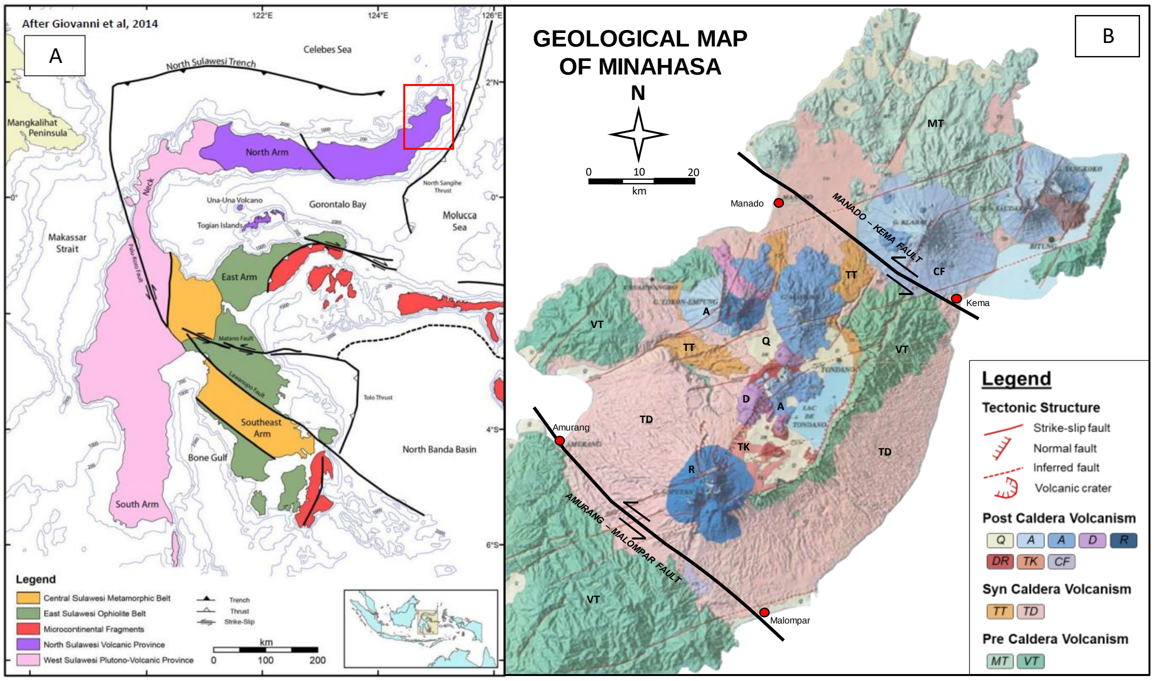

Figure 1: A) The major tectonic settings with four arms distribution of Sulawesi (Szentpéteri et al., 2015, after Pezzati (2014)). The red box is the Minahasa district. The index shows the Indonesia map. B) A geological map of the Minahasa district by Lecuyer et al. (1998) shows the distribution of pre, syn, and post-Tondano caldera products and domination of ENE-WSW structures control and form the caldera collapse oriented to NE-SW. This map combined with the two major strike-slip faults bound the Minahasa district in the northeast and southwest (Effendi and Bawono, 1997).

The Minahasa district is dominated by Quaternary and Recent volcanic products, which lie over the Tertiary volcanic product (Figure 1B). The most prominent volcanic structure feature is the Tondano caldera exposed in the eastern part of the Minahasa district. The Tondano erupted during Pliocene – Pleistocene yields a 20x10 km² caldera and spreads volcanic product extensively. The Tondano caldera produced two eruption episodes with remarkable volcanic products (Lecuyer et al., 1997). The Domato tuff (TD) was the first eruption product that deposited extensively beyond the caldera. This thick ignimbrite deposit is interpreted as erupted in the Pliocene as it lies on the upper Miocene volcanic deposit. The second eruption product, the Terras tuff (TT), is characterized by the dacitic ignimbrite in the north and north-west valley and inside the caldera. Several volcanic episodes occur due to the caldera collapsing block, either inside the caldera or through the caldera rim, such as the Lahendong volcanic complex erupting in the centre, the Rindengan – Sempu volcanic complex in the south, and the Mahawu volcanic complex in the north of caldera (Siahaan et al., 2005). These NE-trending volcanoes series extend to the Sangihe arc and the southern Philippines as the post-Tondano volcanism.

Geologic structures in the Minahasa area are mainly controlled by two major strike-slip faults that cut the North Arm of Sulawesi in two places, between Amurang - Malompar in the south and Manado - Kema in the north (Effendi & Bawono, 1997). Based on the shape of the western coastline of Minahasa, especially in the Manado area, we interpret that the faults moved laterally in the same directions, as the left lateral strike-slip fault. Yet, further analysis is needed to confirm this sense of movement hypothesis.

2.2 Stratigraphy

The stratigraphy of the Tompaso reservoir is merely derived from the drillhole data including cutting, coring and geophysics logs data which also has been detailed by Ikhwan et al. (2021), therefore it more focusing on the subsurface formation distribution. The deepest drilling reached elevation ±-1900 mRSL, penetrated by most wells on pads R1 & R2 and also the latest semi-exploration wells 54, 55 & 56. The Tompaso drilling campaign reveals that the stratigraphy between wells is mostly correlatable, which represents the pyroclastic-basin fill deposits in the caldera depression forming (Figure 2B). This subsurface stratigraphy can also be aligned with the regional Tondano formation proposed by Lecuyer (1997), including the Pre-Tondano, Syn-Tondano and Post-Tondano deposits.

2.2.1 Pre-Tondano Formation

The Pre-Tondano Formation has been identified in rock sequences penetrated by most of western wells in Tompaso, particularly within the lower sections of their trajectories. Wells situated in the R1 & R2 on the eastern part do not encounter this unit to the end of their trajectories. This was caused by these pads that were situated just right on the Tondono depression filled with a thick tuff layer which was also confirmed by gravity data. The Pre-Tondano formation consists of the domination of andesitic breccia with intercalations and layers of tuff, lapilli tuff, andesite lava, and volcanic breccia. The volcanic rocks within this unit are derived from volcanic activity predating the formation of the Tondano Caldera, occurring during the Late Pliocene to Plio-Pleistocene epochs (2.63 – 0.832 Ma). These rocks exhibit subsurface alteration, primarily propylitic, characterized by the presence of epidote and chlorite, along with calcite in some cases. Additionally, veins filled with prehnite and sericite minerals are observed. The alteration intensity in this unit varies from moderate to high (30 – 80%).

The Pre-Tondano formation also characterised by the high fracture intensity which up to 3 fractures per meter makes this formation is highly permeable, as identified from the borehole image log and spinner data in the 26, 27, 54, 55, and 56 wells. The occurrence of fractures might be controlled by the domination of brittle formations such as andesite lava, breccia and welded volcaniclastic. The fractures are well-oriented relatively to NE to NNE which is relatively parallel with the maximum horizontal stress in the Tompaso so they are mostly critically-stressed (Ikhwan et al., 2021). It is interpreted that the mechanical properties of this formation make it prone to being fractured and the propagation of the fractures is only well-developed in this formation. The base of this formation is remains unknown.

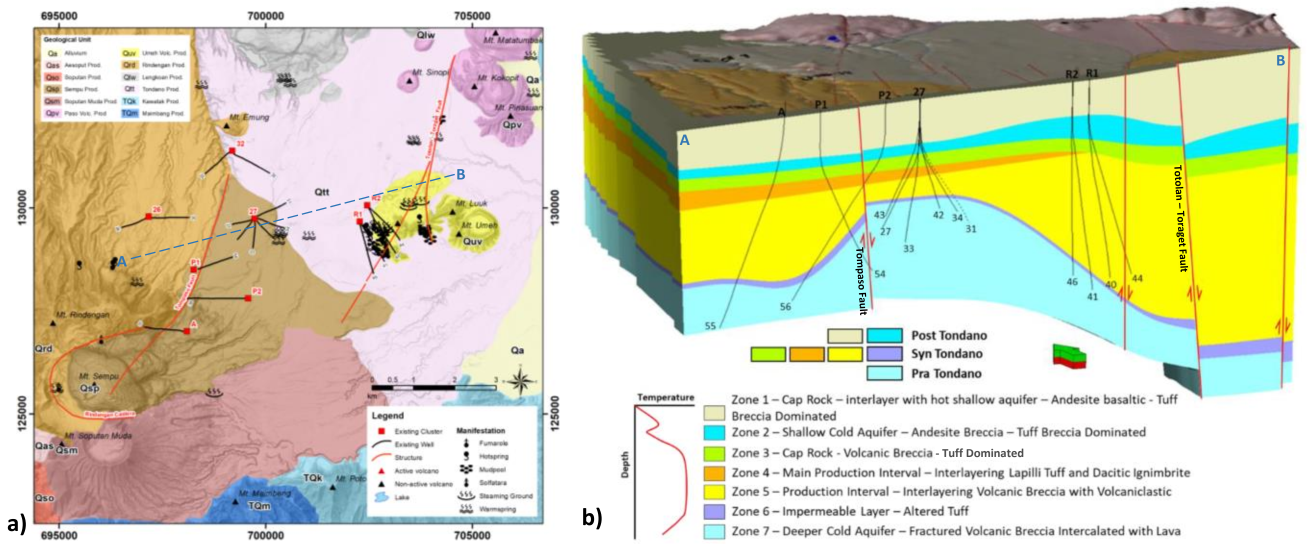

Figure 2: A) The geological map of the Tompaso field. Only two prominent tectonic structures can be delineated confidently on the map which are the Tompaso and Totolan-Toraget faults which strike relatively NNE. The Rindengan Caldera is a volcanic structure located in the southwest. B) The conceptual geological model of the Tompaso field is used in the static model. The zones/formation represent the distribution of dominant lithology in the reservoir and also their role in the temperature distribution and reservoir hydrology. Some of the wells are projected and some faults only exist to image the conceptual geology.

2.2.2 Syn-Tondano Formation

The Syn-Tondano formation is strongly dominated by pyroclastic deposits including tuff, lapilli tuff, volcanic breccia and ignimbrite and can be called the Tondano Tuff. However, a consistent andesite layer was also recorded in wells called The Tondano Andesite. The Tondano Tuff has been identified in all wells drilled in the Tompaso, with varying thicknesses encountered across different wells. In the eastern wells, this unit is found to be quite thick, extending to the final depths of the well trajectories. It is believed to be contemporaneous with the Tondano Andesite, dating back to the Plio-Pleistocene, during the period of volcanic activity that formed the Tondano Caldera forming. This unit is the result of rhyolitic to dacitic explosive eruptions, producing pyroclastic deposits that filled the Tondano depression. The Tondano Tuff consists of a sequence of thick tuff breccia and pumice breccia in the R1 & R2 pads. In western pads, this unit is found to be relatively thinner than in the eastern pads which indicates a downward distribution that makes the thickness of this formation thicker toward the east. The alteration minerals found in this unit include clay minerals, chlorite, epidote, some wairakite, and sericite, with the primary alteration being transitional to propylitic. The intensity of alteration ranges from moderate to high (40–85%).

2.2.3 Post-Tondano Formation

The Rindengan Volcanic Unit has been identified through drilling in wells located in the eastern part of the Tompaso field. This unit represents the products of post-caldera volcanic episodes that overlay the Syn-Tondano Formation. The thickness of the Post-Tondano Formation increases towards the Mt. Rindengan complex in the southwest part of the Tompaso field. The rocks within this unit are predominantly composed of andesitic breccia and andesitic lava. Some of the subsurface products of this unit are also found at the surface around the Pinabetengan area. The andesitic breccia is dark grey to reddish, with fragments primarily consisting of andesitic lithics and some tuff, and a groundmass composed of volcanic glass, tuff, and mineral fragments such as plagioclase and pyroxene. Alteration minerals include reddish-brown iron oxide and clay minerals, with iron oxide minerals being particularly abundant in andesitic fragments. The alteration intensity is moderate (20–40%) that dominated by argillic alteration minerals.

2.3 Structural Geology

The Tompaso features geological structures, including faults and volcanic-tectonic depressions, evident as fault scarps, stream deflections, and crater rims. There are only two prominent surface geological structures in the Tompaso due to the massive covering of the post-caldera volcanic deposits and surface erosion which are the northeast-southwest Tompaso Fault and Totolan-Toraget Fault with their associated lineaments (Figure 2A). The Tompaso Fault is relatively located in the west and the Totolan-Toraget Fault in the east. These faults have strong surface evidence both from imagery and surface outcrop and are proved by the gravity model. They are normal faults, dipping relatively to the southeast, and control the geometry of the reservoir. These faults are penetrated by wells and recorded in the image logs data and also control the occurrence of surface thermal manifestation that makes the confidence level of these faults' existence high.

The subsurface structure framework of Tompaso has been initiated by Sardiyanto et al. (2015) and detailed by Ikhwan et al. (2021) although some subsurface structures are added by using the recent drilling campaign data. The high-intensity fracture zone with moderate aperture is distributed along the Pre-Tondano formation. The fractures are consistently oriented relatively to the northeast-southwest. Similar orientation structures such as permeable fault core and large-aperture fractures set also intersect by the latest drilling activity and act as the main contributing feedzone to the well's output. Well 55 & 56 intersect the permeable fault core of the Tompaso Fault which is confirmed by the drilling parameter, image log and production logging data while the Totolan-Toraget Fault is encountered by the wells on the R1 & R2 pads.

3. GEOPHYSICS

3.1 Magnetotelluric

The horizontal map section of the 3D resistivity model at -500 mASL elevation (Figure 3A) describes the presence of a conductive zone < 10 ohms.meter at shallow cross-section, interpreted as clay cap (smectite dominated layer) dominantly distributed in the central area and extends southwest toward Rindengan – Sempu volcanic complex. In the southwestern area around the crater of Mt. Sempu, observed that in this zone the cap rock is not well developed. This gap cap rock zone is interpreted as an area where cold water downflow enters the reservoir, whereas this interpretation is supported by pressure and temperature measurements in wells. Pad 27 also indicates a zone where the cap rock is not well developed. Well's data indicates that at shallow depths this pad is composed of highly permeable basaltic lava lithology which causes a relatively higher resistivity response in this area. This basaltic lava layer originates from the younger volcanic product in the north of caldera (Kawangkoan-Mount Emung) which flows relatively to the south-southeast. This interpretation is derived based on the borehole geology data of pad 32 which also encounters the permeable basaltic lava formation that cause a high-resistivity response at the shallower depth, however, not well-developed in the other pads. This permeable basaltic lava is drawn the cold shallow aquifer thus the smectite alteration is not well developed, resulting in a low-conductive area. An extensive high-resistivity area also exists on the northern and southern of the Tompaso. It is interpreted that the caprock is not well developed in this area as the caprock forming might be strongly controlled by the distribution of the younger Rindengan-Sempu volcanic deposit.

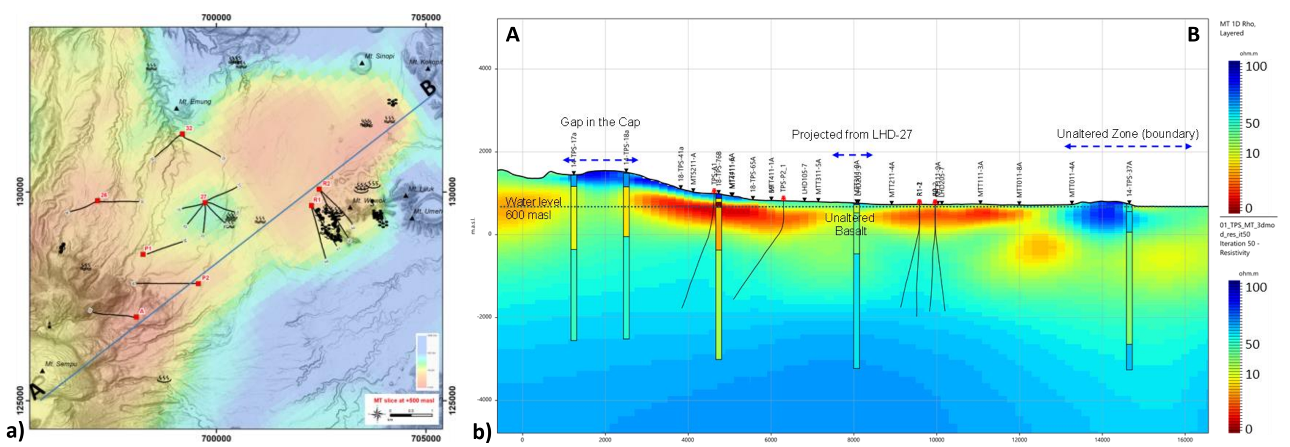

Figure 3: A) Horizontal cross section of Tompaso 3D model at 400 masl. B) Tompaso 1D & 3D MT model NW-SE cross-section. Some of the wells are projected.

Comparison between 1D and 3D MT resistivity inversion models is illustrated by the SW-NE vertical section (Figure 3B). The clay cap zone has an average thickness of around 1000 m. The bottom boundary of the conductive clay cap in this system is associated with a 180°C temperature contour, which acts as a smectite zone boundary. Beneath the transition zone is an updoming sub-resistive zone, interpreted as the propylitic zone acting as the geothermal reservoir. Underneath Mt. Sempu, a cap rock gap is interpreted as a zone where cold downflow enters the reservoir. In the central part, around cluster LHD-27, another cap rock gap is observed, which consists of basaltic lava lithology. In the northeastern area, there is a resistive zone identified as an unaltered zone, marking the northeastern boundary of the reservoir. Near Mt. Sempu, high conductivity values are observed in the cap rock, interpreted as a highly altered zone associated with the upflow zone around Mt. Sempu. However, in the Umeh upflow area, there is no identified high conductivity zone in the cap rock.

3.2 Gravity

Tompaso's residual gravity anomaly map (Figure 4A) was constructed through reduction with the average rock density value of 2.67 g/cm3. The gravity anomaly in Tompaso ranges from -15 to 20 mGal presented in red – yellow – a blue colour scale. The reds indicate high gravity anomalies, whereas the blues indicate low gravity anomalies. A contrasting low anomaly trending NNE – SSW could be seen from the gravity anomaly distribution map. This anomaly is inferred as a part of a tectonic depression zone, with two adjacent structures acting as its boundaries. Surrounding the depression zone, contrasting positive anomaly zones could be found (Totolan), which are thought to be consistent with intrusive rocks.

2D density model (Figure 4B) shows that the young volcanic lava in the west near pad 26 has a higher density contrast (250 kg/m3) that decreases towards pad 27 (0-50kg/m3) in which the sudden density value change between the two clusters are probably caused by fault zones. At the centre of the cross-section, a very low-density feature (<-250 kg/m3) was confirmed by well data from pad R1 and R2 as the thick Tondano Tuff layer in this area. The result of this inversion has been validated by petrophysical measurements of core samples from wells in pad 26, 27 and R2 clusters, which shows a trend of decreasing density value to the east.

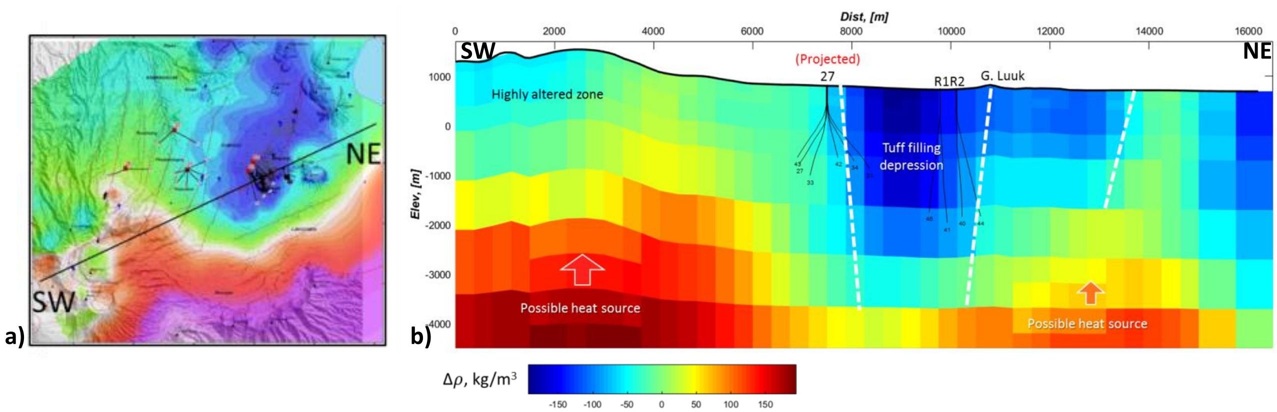

Figure 4: A) Residual gravity anomaly map using 2.67 gr/cm3 density value. B) 2D gravity model of Tompaso

4. GEOCHEMISTRY

The Tompaso field exhibits diverse geochemical manifestations associated with its volcanic and hydrothermal system. This field remarked by distinct manifestation clusters (refer to the geological map in Figure 2A): Mt. Rindengan cluster on the west, characterized by acid-sulfate waters and fumaroles; Kawangkoan–Mt. Emung cluster on the north, hosting neutral hot springs; Tempang–Mt. Umeh cluster on the east, featuring neutral chloride waters and fumaroles; and Mt. Pinasuan–Tondano cluster on the northeast, dominated by bicarbonate waters. The fluid geochemistry reveals complex mixing between meteoric water, vapor core, and surface water, as confirmed by isotopic analyses and ternary diagrams.

Geothermometer studies highlight reservoir temperatures ranging from 170°C to 314°C. Chloride waters dominate the productive wells, with Na/K and silica geothermometers indicating high thermal equilibrium in certain zones, while others show evidence of mixing with cooler aquifers. Gas geochemistry further supports vapor core contributions in specific areas, with fumaroles near Mt. Rindengan and Tempang displaying elevated gas signatures. Stable isotope analysis places most fluids near the meteoric water line, suggesting significant recharge contributions, although deviations indicate high-temperature water-rock interactions and steam-heating processes.

Geochemical modelling identifies two distinct parent fluids: one associated with pad 27, with higher chloride content and moderate temperatures (253°C), and another from pad R2, with lower chloride content but higher temperatures (275°C). These findings reveal the coexistence of two hydrological systems governed by geological controls, including fault structures and different heat source influences.

The chloride vs. boron diagram in Figure 5A shows the similarity in the ratio of conservative elements between manifestation fluids and well fluids in Tompaso, indicating that these fluids originate from the same reservoir. Mixing model graphs were used to determine parent fluids which indicated the closest to the upflow. Two different parent fluids in Tompaso also influence the presence of two distinct hydrologies. First, parent fluid from 27 has a higher chloride concentration and enthalpy based on Na-K-Ca geothermometry as much as 253°C. There is a mixing between the parent fluid and steam-heated water, which can be observed in 34, 43, 42, and 31, as indicated by lower chloride content and enthalpy. Well 55 is located closer to the Sempu upflow, still originating from the parent fluid pad 27, but they exhibit lower chloride and enthalpy values due to the influence of the deep cold-water aquifer. Well 54 has the same enthalpy value as 55 but with lower chloride content, indicating a higher contribution from the deeper cold aquifer compared to 55. Second, parent fluid from 46 has lower chloride but higher reservoir temperature based on Na-K-Ca geothermometry as much as 275°C which is influenced by the Umeh upflow.

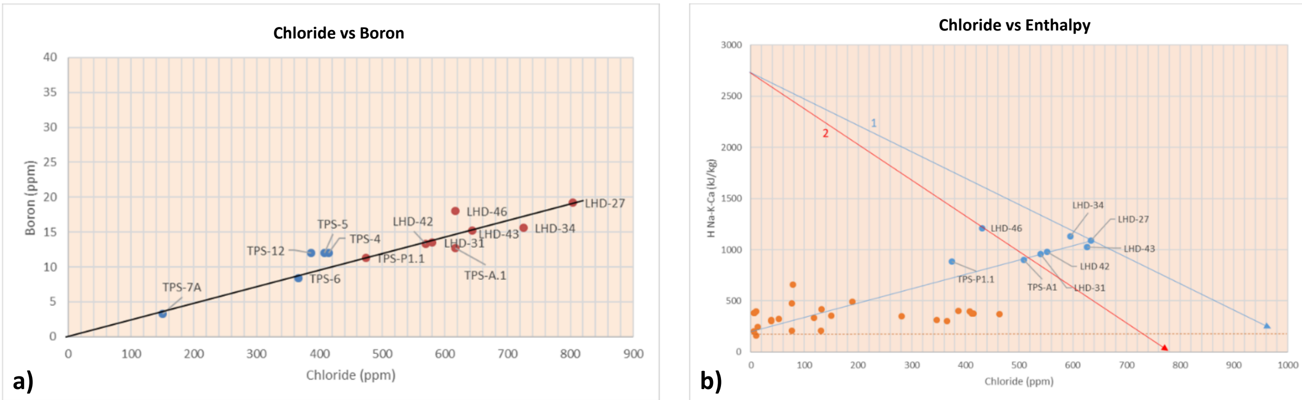

Figure 5: A) Ratio chloride and boron element from manifestation and well liquid samples. B) Chloride - enthalpy diagram

5. PERMEABILITY

Well data from the Tompaso demonstrates that permeability control is governed by fault, matrix and fracture permeability. The Tompaso features an interlayer of permeable and impermeable layers extending from the surface to the lower part of the reservoir. A comprehensive permeability analysis was conducted within the production interval of the 54 well, which includes an extensive dataset comprising cuttings, sidewall cores, resistivity, density, sonic, gamma-ray, borehole image logs, pressure-temperature (PT) tests, and production logging tests. 54 is the only well with such a complete dataset, and due to the consistent geological layering and uniform temperature profiles observed across the field, it can be used to represent rock properties for all other wells in Tompaso. However, permeable layers that overlie the caprock are only determined by limited data such as cutting and drilling parameters. The permeability type in this study also refer to the term by Ikhwan et al. (2024).

The analysis from the included data indicates that the permeability within the layer or formation in the production interval can be divided into two sections corresponding to zones in the geological model, despite the other permeable layers above the caprock. The upper permeable section consists of Zone 4 and Zone 5 (Figure 2B), which are interpreted to be controlled dominantly by matrix or microfractures. This interpretation is derived from both qualitative and quantitative analyses. The cuttings and core samples from these zones exhibit significant alteration, with secondary alteration minerals predominantly forming as direct deposits that fill the pores between grains or minerals. This is consistent with the lithology of these zones, which is dominated by porous pyroclastics and ignimbrites. Dynamic and static measurements of these lithologies indicate that matrix porosity and permeability are relatively high, reaching up to 50% and 30 millidarcies (mD), respectively. Borehole image log data also show that fractures are less intense, and large aperture fractures are absent in this interval, suggesting that fracture permeability is likely negligible and that matrix or microfractures-supported formation porosity might be the dominant control on permeability. This interval is the primary contributor to the production well's output with temperatures over 260°C. This case is also indicated by the study in Los Humeros Volcanic Complex (Cavazos-Alvarez et al., 2020).

The lower permeable section is located in Zone 7, which consists of high-intensity fractured volcanic breccia interlayered with lava, originating from Pre-Caldera volcanic activity. Petrophysical analysis from both static and dynamic measurements indicates that this zone exhibits relatively low matrix porosity and permeability magnitudes. However, the fracture density in this zone is very high, up to 3 fractures per meter, leading to an intensely fractured zone. Geomechanical studies reveal that most of these fractures are critically stressed (Ikhwan et al, 2021), resulting in high fracture permeability. This is corroborated by fracture properties analysis from sonic logs. Consequently, the permeability magnitude in this zone, controlled by fractures, is significantly higher compared to the upper permeable section, which is controlled by intra-pores porosity.

Drilling data further supports this, as all total loss zones in the wells are encountered within this section, characterizing it as a high permeability zone. However, this lower permeable section contains a colder temperature aquifer, which impacts the well's enthalpy in Tompaso. The upper permeable section and the lower permeable section are separated by an impermeable layer, Zone 6, consisting of altered-tuff formation. This barrier prevents the mixing of hot reservoir fluids from the upper section with the colder fluids from Zone 7.

The fault core permeability is encountered by the 55 and 56 wells. These fault strike relatively to NNE-SSW and are interpreted as the part of Tompaso fault zone. This type of permeability exhibits the highest permeability magnitude among all of the wells in the Tompaso field therefore the production capacity of these wells is the largest. This also indicates that the permeability control of the existing production wells with the latest semi-exploration wells is different. However, the thermodynamics within the fault core permeability is different due to the influence of layers with different temperatures. Therefore, the well-targeting strategy on this fault have to consider the intersection depth between fault and well.

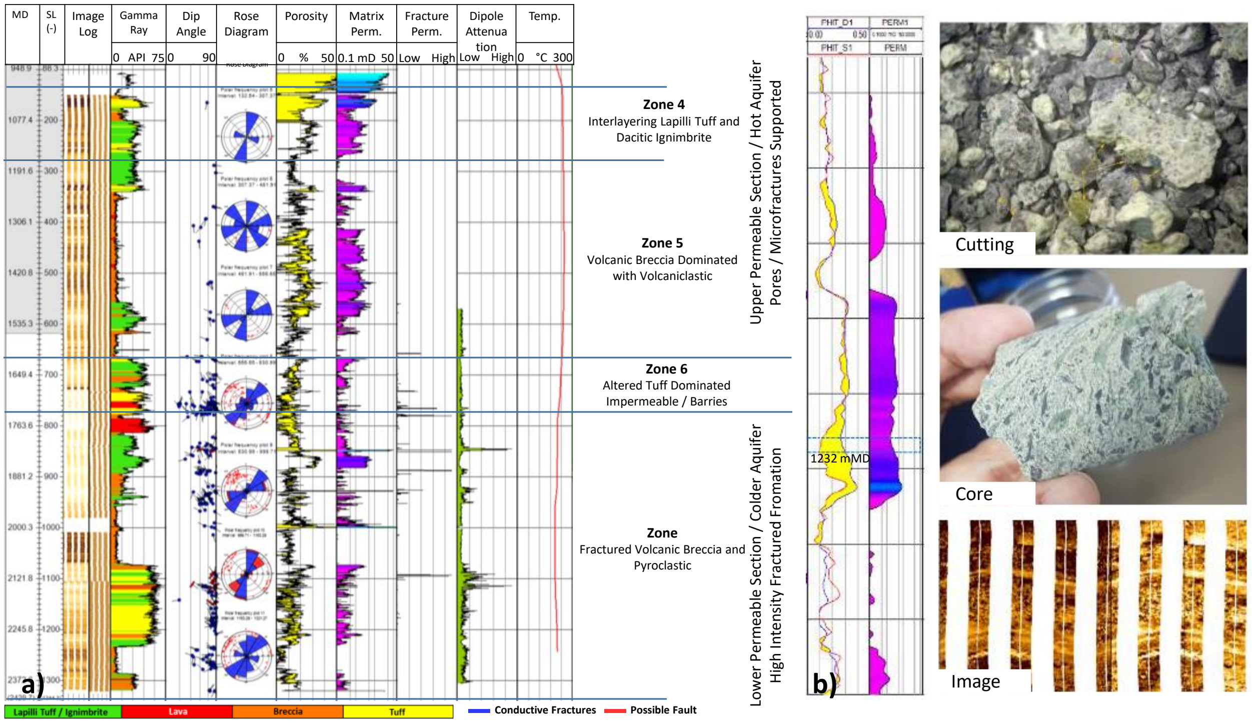

Figure 6: A) A typical logging measurement in the Tompaso well. Dynamic matrix porosity and permeability and fracture permeability are measured by using the sonic and density log with refer to static core sample measurement. B) An example of integrated petrophysics measurement at 1232 mMD shows porous and permeable ignimbrite.

6. TOMPASO CONCEPTUAL MODEL

3.1 Heat Source

The area presumed as the Tompaso geothermal system's heat source was identified from several geoscience parameters. Based on the volcanism's age, Tompaso's heat source is thought to have originated from the cooling pluton/magma beneath Mt. Rindengan – Sempu complex. Age-wise, the volcanic activities in this complex occurred approximately 0.5 – 0.1 Ma. Hydrothermal activities could also be observed through the presence of several active manifestations in the forms of solfataras, fumarole and acid sulphate water. Geochemical indicators from wells and manifestation fluid geochemistry (NCG, mixing model, chloride content) also confirm that the upflow zone is located below Mt. Rindengan – Sempu complex.

The presence of another heat source besides the one underneath Mt. Rindengan–Sempu was indicated after the discovery of high-temperature measurements from wells in pad R1 and R2 (maximum temperature up to 320ºC). The heat source near these pads might be related to the monogenetic volcanic activities of Mt. Umeh – Wowok which also shows a high-density body anomaly, although have a smaller dimension compared to the density anomaly under Mt. Rindengan – Sempu.

3.2 Upflow

Two estimated upflow zones in the Tompaso prospect, Sempu upflow in the southwest area and Umeh upflow near the pad of R1 and R2, based on the pressure & temperature data. The Sempu upflow interpreted as a focused upflow controlled by the Tompaso Fault and its associated fault zone that extent somewhere in the south of pad A and P2, therefore, it is might not directly be correlated with the activity of the Rindengan-Sempu volcanic complex. This concept was proved by drilling in well 55 which is directed relatively toward the Rindengan caldera rim. Although these wells targeted the Sempu volcanic dome, it had not found the interpreted southeast upflow core with a consistent convective isothermal temperature gradient. However, it indicates the presence of the adjacent up-flow zone as an occurrence of the steam zone with temperatures up to 280°C at the shallower production interval with benign fluid geochemistry. The Umeh - Tempang upflow shows the highest temperature zone in Tompaso, which is controlled by the Totolan-Toraget Fault and its associated fault zone in the southern extension of the pad R1 and R2 near Umeh Volcano. This is proved by the measured temperature in all wells on these pads which are up to 320°C. This upflow zone is also interpreted as a narrow-focused flow controlled.

3.3 Outflow

Pad 27 as the main production wells in the Tompaso field are drawn the economic outflow zone associated with the Sempu upflow. The Tompaso fault, as the control of this upflow, drives the hydrothermal fluid northeast and waning as the interaction between the permeable porous fault and formation. The permeability of this formation is controlled by pores or microfractures and hosts the main production interval. This formation consists of pyroclastic and dacitic ignimbrite which indicates good matrix porosity and permeability (up to 30 mD) from static and dynamic petrophysical analysis. The outflow from Umeh interpreted flows toward relatively the north through the extension of the Totolan-Toraget fault to the fumarole of Totolan manifestation. This outflow might be dominantly controlled by the vertical permeability of the Totolan-Toraget permeable fault-core. These two outflows are interpreted to be mixed somewhere in the north area of the Tompaso area.

3.4 Cold Downflow

The Tompaso field is likely to have many cold water surrounding the reservoir both spatially and vertically as shown by the resistivity and well's temperature data. Spatially, the interpreted cold water existence is interpreted by using resistivity which has been discussed above. These cold water zones are believed as the source of the cold aquifer layers through depth in the Tompaso geothermal field, feeding the cold layer above and below the reservoir zone. It is captured by the temperature data of wells as the reversal temperature profiles at the shallow and deep elevations. The shallow cold aquifer (Zone 2) seems controlled by near Sempu cold water downflow, and flows relatively towards east-northeast, following the hydrothermal fluid hydrology. However, the thin impermeable caprock (Zone 3) underlying this shallow cold aquifer prevents the mixture between the cold aquifer with reservoir fluid. The lower cold aquifer (Zone 7) seems to have originated from the southern cold downflow and flows relatively towards N-NW through the fractured formation in depth. This case scenario leads to a crossflow hydrology within the Tompaso's reservoir. Moreover, the microgravity data also support that this cold water downflow could act as the natural recharge area of Tompaso.

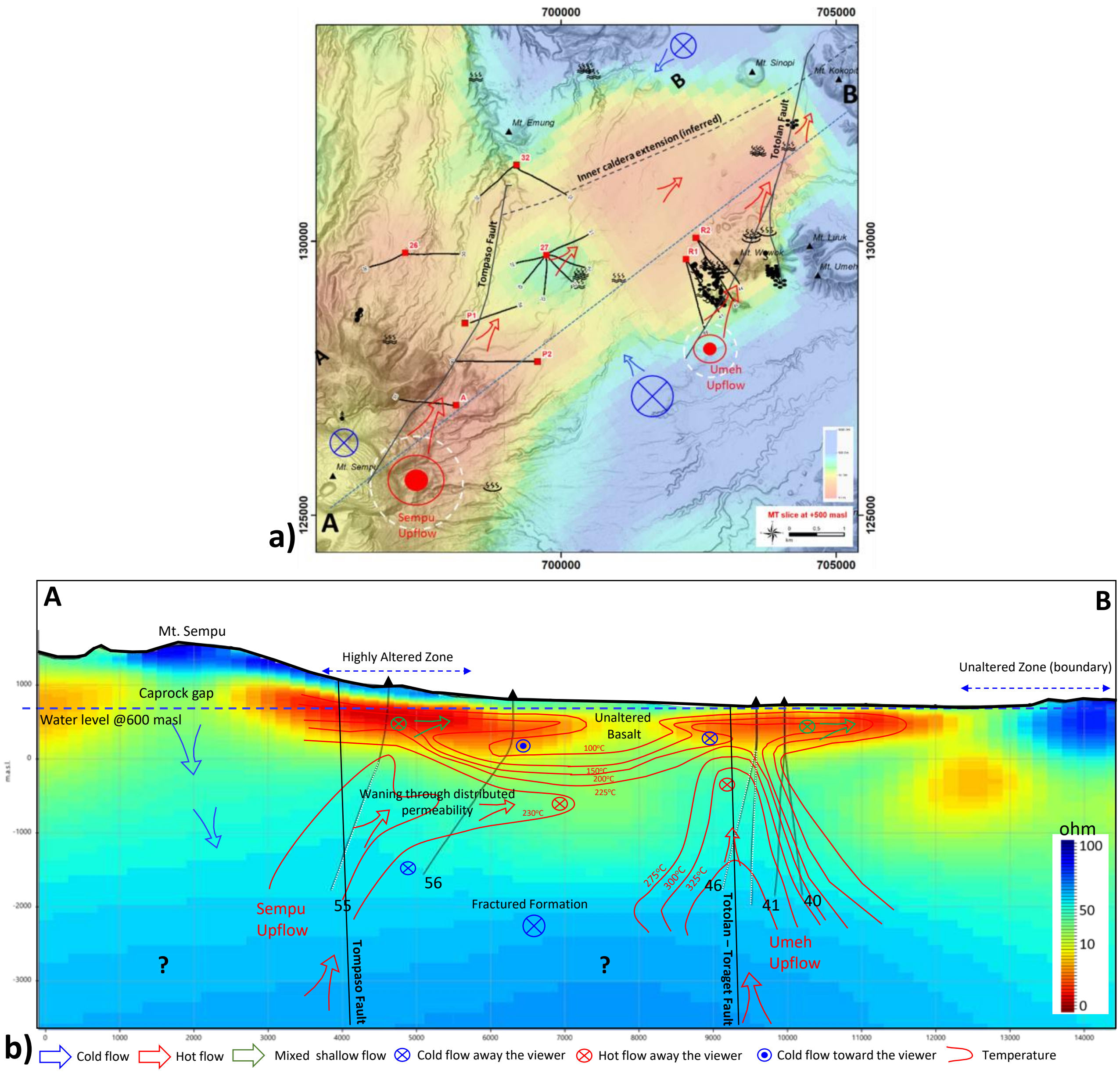

Figure 7: The conceptual model of the Tompaso field in map view (A) and vertical section (B). The model shows the dynamic hydrology of within the reservoir including the direction of the cold and hot flow. Some of the wells are projected.

3.5 Caprock

The caprock of Tompaso can be divided into three layers. The upper caprock consists of a tuff breccia-dominated layer which also interlayer with a hot shallow aquifer (Zone 1). The middle caprock is the main caprock and separates the shallow cold aquifer and the reservoir zone, consisting of volcanic breccia and tuff-dominated rock (Zone 3). The lower caprock is between the reservoir and the lower cold aquifer, consisting of an altered tuff (Zone 6). The cap rock of the Tompaso indicates the strong influence of the Post-Tondano formation. This interpretation is based on the geometry of the young Sempu-Rindengan lava deposit on the surface that matches the geometry of the low-resistive layer as seen on the resistivity map slices at 400 mASL. Despite they are only thin layers, the integrity of these cap rock layers is surprisingly able to keep the reservoir from mixing with the cold aquifer overlying and underlying. Therefore, a further study to identify the rock properties of these cap rocks is needed.

3.6 Reservoir unit

Based on rock alteration analysis conducted on core and cutting samples, the Syn-Tondano and Pre-Tondano volcanic units act as reservoir units. The reservoir rocks in the Syn-Tondano group are dominated by altered tuff breccia and pyroclastic rocks, while the reservoir rocks in the Pre-Tondano group consist of fractured andesite, basaltic andesite, and andesitic breccia with interlayers of andesite lava, pumice andesitic breccia, and tuff breccia. The reservoir in the Syn-Tondano group, dominated by altered tuff breccia, generally has permeability controlled by matrix permeability. This is the main production interval in Tompaso which has productive feedzones with high-temperature fluid (> 250°C). These feedzones are laterally distributed among Tompaso wells, generally from 80 to 200 mASL. The image log data indicates these feedzones are less correlated with fractures as only a few conductive fractures were picked with no high-intensity fractures or large aperture fault/fracture. The lithology in this main zone is dominated by pyroclastic, including tuff, lapilli tuff, ignimbrite, welded ignimbrite and volcanic breccia. Petrophysics analysis from wells indicates that this unit has a high porosity of up to 50% and permeability of up to 30 mD, making it a medium to distribute the permeability laterally.

In contrast, the Pre-Tondano group is dominated by more brittle lithology such as volcanic breccia and lava, which makes they are more prone to be fractured. The image log data shows the significant increase of factures density in this unit which makes it more permeable than the Syn-Tondano formation. However, this fractured formation contains colder water, which also could be derived from marginal water from the southern downflo area, proved by the temperature deflection among the production wells. Thus, the next targeting strategy of the Tompaso should be to avoid this formation as it could decrease the well's production.

3.7 Reservoir Fluid

Tompaso reservoir fluid shows benign fluid characteristics with a pH range of 8-9. This is proved by the results of the drilling of all the production wells shows that the Tompaso field reservoir fluid is still benign, approaching the upflow area in the about section. Almost all water fluid data reflects the same system and does not form compartments or differences in fluid characteristics. The results of the cation geothermometer from the Tompaso wells produced a lower temperature estimate than the PT data which shows the occurrence of reservoir fluid dilution by the cool aquifer, and this was also shown in the 54 well which had a lower TDS than the cluster 27 and 55 wells corresponds to the conceptual model.

The existence of hot and colder fluids within the same reservoir continuum has raised the potential of fluid mixing in natural state conditions. Fortunately, the thin cap layers above and within the reservoir are capable enough to minimize the contact between these fluids. However, the permeable fault that has good lateral and vertical permeability within the fault plane, might act as the conduit where the fluid mixing could happen. The fault intersect and drain the flow from the permeable layers as it has bigger pressure loss due to the greater fault permeability. This is indicates the heterogeneity of the thermodynamics within the fault which also proved by the well temperature data. The fluid mixing could also happen inside the well if the well intersects both the main reservoir zone and the cold aquifer.

3.8 Reservoir Boundary

The boundaries and controls of the Tompaso geothermal reservoir are interpreted to be influenced by several geological factors. The Tompaso Fault, which controls the Sempu upflow, providing significant vertical permeability and horizontal permeability along the strike, is believed to limit horizontal permeability and transmissivity on the reservoir's western side. This hypothesis is supported by drilling results, which show relatively low permeability in 26 and at the tip of 55 wells. Additionally, a high resistivity zone in the western area is thought to contain cold water downflow, further supporting the existence of a western boundary for the reservoir.

On the northern side, the reservoir appears to be bounded by an interpreted extension of the ENE-WSW inner rim of the Tondano caldera. This interpretation is corroborated by drilling results from pad 32 on the northern side of this interpreted structure, which also indicate low permeability. Extensive cold water downflow, inferred from magnetotelluric data, is believed to bind the eastern and southern parts of the prospect, which are controlled by permeable formations on the surface, providing a conduit for the cold water.

7. CONCLUSION

The updated conceptual model of the Tompaso geothermal field highlights the intricate interplay between geological, hydrological, and geochemical, reflecting the field's complexity. Key findings from the study underscore the significant role of structural controls, particularly the Tompaso and Totolan-Toraget faults, in dictating fluid flow and permeability within the reservoir. These faults act as primary conduits for the upflow zones, with evidence of fracture permeability enhancing the geothermal system's productivity. The geophysical data, particularly the magnetotelluric and gravity analyses, have further refined the understanding of caprock integrity and the delineation of cold downflow and colder aquifer zones, which significantly influence the thermal and hydrological regimes.

Geochemical analyses reveal a dual hydrological system, with distinct parent fluids contributing to the reservoir's thermal dynamics. The coexistence of chloride-dominated and bicarbonate-rich fluids emphasizes the presence of vapor core area and meteoric water influence.

The integration of well data, including fracture analysis and reservoir properties, provides a robust framework for reservoir characterization. The identification of high-permeability zones controlled by distributed fractures and matrix porosity offers insights into targeting strategies for future drilling campaigns. However, the presence of colder aquifers in the lower reservoir sections necessitates strategic well placement to mitigate enthalpy losses.

Overall, the findings present a significant advancement in understanding the Tompaso geothermal system's complexity. Future work should focus on quantifying the impact of identified geological features on reservoir performance. Additionally, continued integration of multidisciplinary data is critical to refining the model and informing sustainable field development.

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