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Waesano, Indonesia: Integrated Exploration Results and Resource Assessment

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1. ABSTRACT

The Waesano Geothermal Project is located on Flores Island, Indonesia. Surface exploration has been completed, including geological mapping, geochemical sampling, and geophysical surveys including MT and gravity. A conceptual model of the reservoir has been constructed that features a high-temperature (>240°C) volcanic-hosted geothermal reservoir, at least partly neutral saline, but with an acid-magmatic centre. The resource is developed in Paleogene to Neogene sedimentary and volcanic rocks at a depth of >1000-1300 mVD and is estimated to be capable of generating at least 30 MW. The next step of the project is an exploration drilling campaign.

2. INTRODUCTION

The Waesano Geothermal Project is an exploration project of PT Sarana Multi Infrastruktur (SMI), an Indonesian State-Owned Enterprise under the Ministry of Finance. Waesano has been assigned to SMI by the Ministry of Energy. Jacobs has been engaged by SMI to provide technical support for the exploration activities and is preparing for exploration drilling in 2020 with financial support from the New Zealand government's Ministry of Finance and Trade (MFAT) and the World Bank. The project is located on Flores Island in East Nusa Tenggara Province (Figure 1). The regional capital is Labuan Bajo with port and airport facilities.

Surface geoscience exploration has been completed including geological mapping, geochemical sampling and geophysical surveys (MT and gravity). A high-temperature resource of at least 30 MW has been estimated. The next phase of exploration in 2020 will include a drilling campaign consisting of drilling and testing of three slim wells and one standard size well.

Figure 1. Location of the Waesano Geothermal Project on the island of Flores in East Nusa Tenggara Province, Indonesia.

3. GEOSCIENTIFIC DATA AND CONCEPTUAL MODEL

3.1. Data Sources

Various early surface geoscientific studies were carried out by Indonesian government agencies. A regional geothermal study was made by Johnstone (2005). More recently, Badan Geologi has carried out more systematic surveys compiled in a series of unpublished reports which summarise earlier work and subsequent surveys by Badan Geology. The most recent work by Badan Geologi comprised an in-fill and extension MT survey conducted in 2016. Additional geochemical sampling, analysis and a review of earlier work was similarly carried out by Jacobs (2016). The MT data collected by Badan Geologi has been reprocessed under MFAT funding in 2017 and the modelling of this reprocessed data has been used to guide an update to the concept model of the field undertaken by Jacobs in 2017.

3.2. Results of Surface Exploration

3.2.1. Regional Tectonic Setting

Flores is situated near the western margin of the Cenozoic to Recent Banda andesitic volcanic arc that comprises the Lesser Sunda Islands of eastern Indonesia (Figure 2). Unlike the Sunda arc, where dense oceanic crust of the Australian Plate subducts below buoyant Sundaland continental crust, the Banda arc is a zone of complex collisional tectonics involving the N-S convergence of buoyant crust of the Australian plate that is under plating immature crust of the SE Sundaland and Timor Plates. The collisional tectonics between buoyant continental crust of the Australian Plate and Sundaland/Timor resulted in the Miocene-recent compressional reversal (thrust faulting) of the Flores back arc basin that was thought to be initially rifted during the Paleocene.

The principal maximum horizontal stress (σ1) is expected to be oriented N to NNW in the intra-arc region of western Flores, in a dominantly strike-slip regime. This is supported by earthquake focal mechanism data presented in the World Stress Map (Heidbach et al., 2016) and regional-scale NE-striking sinistral faults (Figure 2). A NNW-oriented σ1 is also consistent with the alignment of monogenetic volcanic features and recent fissures in the Bajawa Rift, 100 km to the east of Waesano (Muraoka et al., 2005).

The en-echelon orientation of the volcanic edifices of the Banda arc is characteristic of arcs formed above oblique subduction systems (other examples include the Aleutian and Kuril arcs). However, the orientation of volcanoes in the Banda arc relative to the plate collision angle cannot be explained by the convergence angle alone (which is current oriented NNE) and a counter-clockwise rotation of the arc block is proposed to satisfy this observation (Muraoka et al., 2005).

A Wadati-Benioff seismic zone continues from the Sunda to the Banda arc. Different authors place the boundary between them in different places with the latter progressively rotated around on itself due to the collision with continental Australia. Apart from the Wetar-Alar gap in the volcanism, the continuation of arc-style volcanism possibly reflects down going Oceanic Australian plate material that was subducted preceding the continental collision with the Australian continental crust. Since there is continuity in the Wadati Benioff zone from the Sunda arc to Waesano in the western part of Flores, it is justifiable to consider the region around Waesano to be a part of the Sunda arc (albeit, adjacent to its eastern boundary with the Banda arc). Rock types range from arc tholeiites to potassic calc-alkaline with andesite as the predominate lithology.

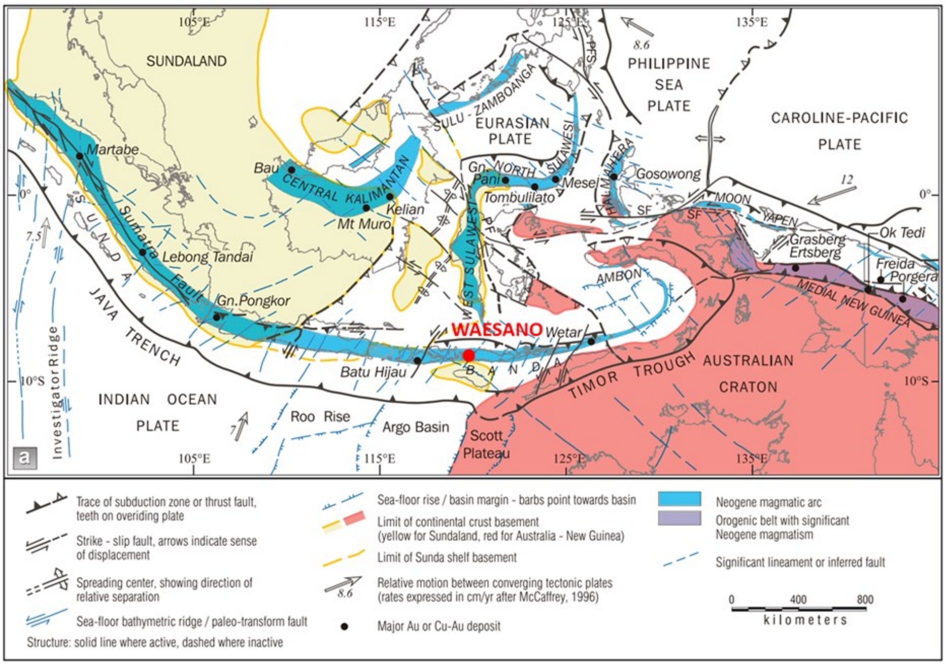

Figure 2. Tectonic map of Indonesia and surrounding areas (Garwin et al., 2005).

3.2.2. Local Geology and Hydrothermal Alteration

The topography of the Waesano prospect area is shown in Figure 4. Poco Dedeng (1195 masl), in the SE, is a Quaternary andesitic stratovolcano that lies above older Quaternary andesites. No historic eruptions have been documented here and there has been limited radiometric dating – the youngest known date for its volcanic products is 0.2 Ma.

The depression that hosts Lake Sanonggoang (660 masl) appears to be a set of maars or a caldera collapse. The lake has a maximum depth of 90m. Bedding on the lake shore, including relict silica terraces, dip consistently toward the lake. The lake craters and Poco Dedeng volcano are situated along a NW trend, suggesting an extensional or dextral-extensional feature.

There are numerous pyroclastic and extrusive (i.e., lava) units that surround the lake that may be associated with its formation. Paleogene to Neogene sediments outcrop to 15 km to the NE of the Waesano springs and are expected to be present underneath the Neogene to Quaternary volcanics at a depth of <1 km (Figure 3).

Data from the drilled Ulumbu geothermal field, about 50 km east of Waesano may be indicative of the subsurface geology at Waesano. Wells at Ulumbu intersected Cenozoic sediments at approximately -200 mrsl (a vertical depth of ~800 m). These sediments, which extend to -1300mrsl are reported to be (roughly) half composed of hard limestones and half of volcaniclastic and calcareous sandstones, mudstones and siltstones. Basaltic lavas also occur intercalated with the sediments in the deepest units. The permeability in these units is characterized to be "moderate" to "low-moderate". The best permeability encountered within the Ulumbu wells is in a 200 m-thick volcanic unit directly overlying the sediments.

From limited petrology, the hydrothermal alteration exposed at the surface at Waesano appears to be predominantly comprised of an advanced argillic assemblage of natroalunite, halloysite, cristobalite, and orpiment. The absence of higher temperature minerals (e.g., epidote) suggests that there hasn't been a significant amount of erosion since the commencement of geothermal activity in the area.

Two shallow wells (WW-1 and WW-2) drilled to 250 m in the northern part of the Waesano prospect area (Figure 4) intersected altered volcanic tuffs, tuff breccias, and andesite extrusives. The observed low-temperature argillic assemblages encountered are consistent with the mineralogy commonly associated with "clay caps" that form above geothermal systems. The reservoir is expected to be hosted primarily in Paleogene-Neogene limestones and siliciclastic and calcareous sediments. Neogene to recent volcanics that reside over the top of these basement sediments are expected to be <1 km thick and host the clay cap to the geothermal system, but if thick enough may also host permeable reservoir beneath the clay cap.

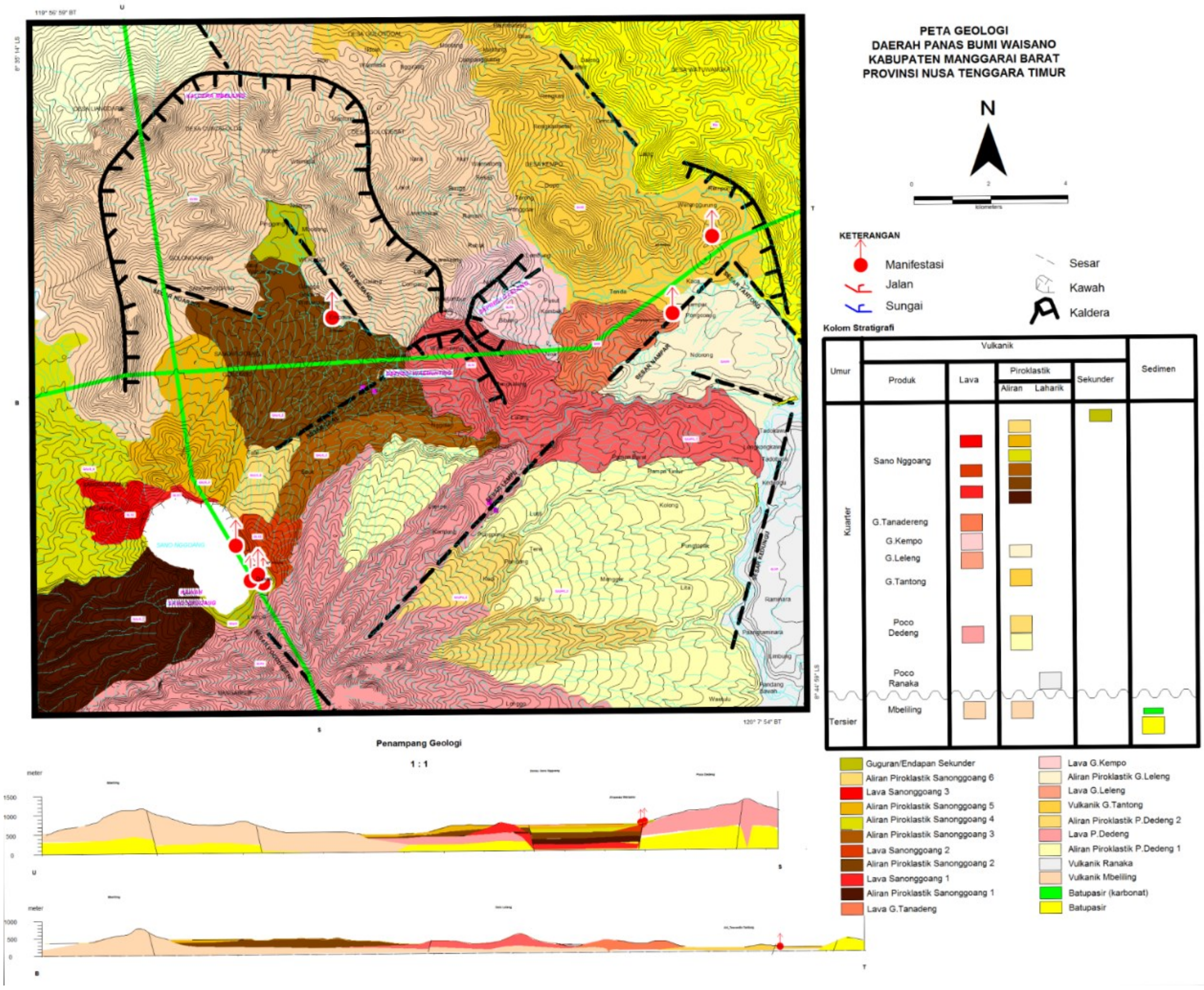

Figure 3. Geological map of Waesano and the surrounding region (Badan Geologi, 2016).

3.2.3. Geochemistry and Surface Manifestations

Surface thermal activity at Waesano includes hot springs (97°C maximum) on the SE shore of Lake Sanonggoang, some strongly effervescent with some sulphur deposition. The individual spring flowrates are low but the maximum temperature is close to boiling (97°C). There is a pervasive smell of H_2S. There are also numerous gas seeps from the lake bed close to SE shore. The hot springs are about 800 m SSE of relict sinter terraces (confirmed as opal-A and quartz by XRD; Panda Geoscience, 2016). The terraces are tilted towards the lake which suggests they formed after the last eruption, or caldera collapse, but then subsided with consolidation of eruptive material. The presence of opal-A in these sinters suggests that their age is likely <10,000 years old (Herdianita et al., 2000). The silica terraces are important because they show that boiling chloride water once reached the surface here. Such deposits generally only develop from upflow of high temperature (>230°C), near neutral pH reservoir waters, either from shallow depth or with rapid upflow - to produce silica supersaturated water at the surface. This reservoir may still exist (sealed off) and together with the current activity provides some width to the possible neutral liquid resource at depth. The only activity around the silica terraces is some gas bubbling and slightly tepid water. There are no discrete steam vents at Waesano, but there is relict altered ground just to the north of the main thermal area.

Outlying thermal activity includes Bubok, 6 km to the north (320 mrsl), a 32°C, low-chloride, effervescent spring and Nampar Mancing, 13 km NE of Waesano (140 mrsl), where 3000 ppm Cl, warm (<40°C) water seeps from a large travertine apron. The relationship of these springs to Waesano is uncertain.

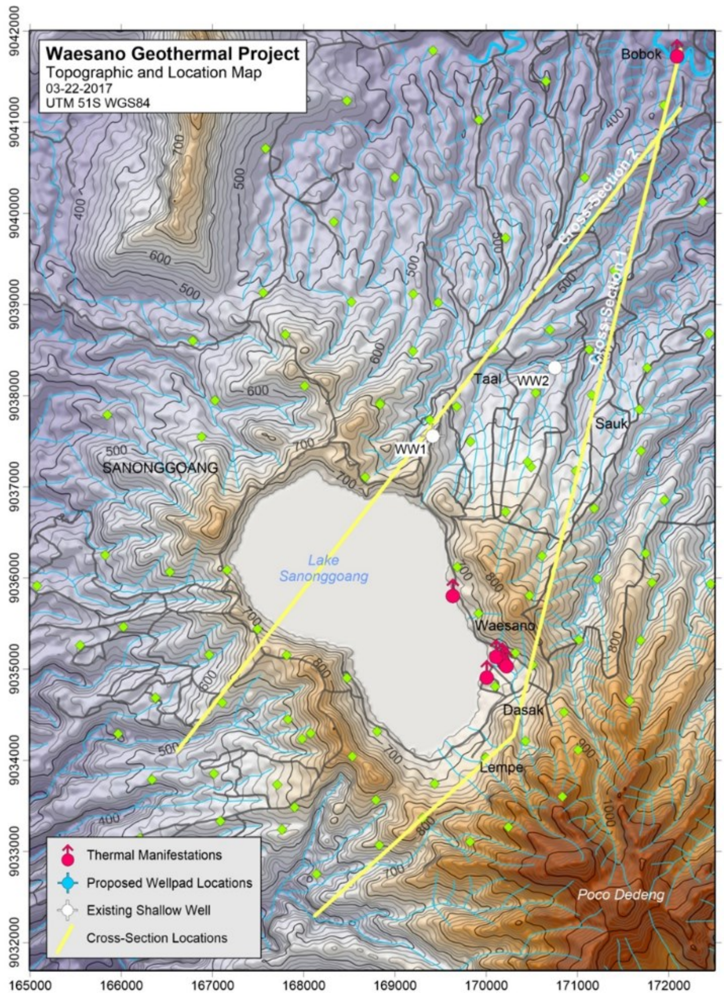

Figure 4. Topographic map of the Waesano geothermal field, showing springs, existing wells and MT stations.

An analysis of the hottest spring at Waesano (WS-02, 97°C) is presented in Table 1 together with geothermal waters from other fields that may represent analogues. The WS-02 water is a near-neutral pH, sodium chloride brine with 20,000 ppm chloride. The salinity is high compared to mature geothermal systems associated with arc volcanism. Its presence at high elevations introduces an element of uncertainty to the interpretation of the chemistry, especially considering that the liquid level at Ulumbu (which occurs ~50 km to the east) occurs ~600 m deeper, at around 0 masl.

Solute geothermometry based on Na, K, Ca give indicated source temperatures of 240-250°C. Gas bubbles vigorously through the spring water and samples collected in 2016 show gas in typical proportions for high temperature fluid with CO_2/H_2S of about 30 and hydrogen-based geothermometers giving temperatures of >250°C. Overall, the water and gas chemistry indicate that the water has equilibrated in a neutral pH reservoir at high temperature. The relatively high Mg and low SiO_2 likely reflect the low flow rate of the springs, providing time for some re-equilibration of these constituents. WS-02 has a large $\delta^{18}O$ isotopic shift of about +10‰ to the right of the meteoric water line, characteristic of high-temperature systems.

In the vicinity of WS-02 there are numerous other small springs and seeps which are diluted and cooler than WS-02. These springs have much higher sulphate levels and lower pH's, most likely produced from bacterial oxidation of the dissolved H_2S (producing distinctive white filamental sulphur).

Included in Table 1 are analyses of waters from several fields that are recharged by seawater. The Waesano spring chemistry shares some aspects of thermally altered seawater including the high salinity and high calcium but the isotopic composition and high boron content do not support a simple seawater source. A more likely analogue is the saline water from St Lucia which shares most of the features of the Waesano water including the high salinity and high concentration of boron. The St Lucia water is from a shallow aquifer of condensate formed above an acid-magmatic vapour zone containing gaseous HCl, SO_2 and B.

The chemistry of the lake (Table 1) is produced at least partly by the springs flowing into it, but it has twice as much boron (relative to chloride). High boron concentrations are characteristic of magmatic vapour plumes. The lake has an acidic pH of about 2.6, at least partly due to lake shore acid springs and bacterial oxidation of H_2S in lake-bed gas seeps. Thermal surveys of the lake bed did not discover any submerged hot springs. The outlet to the lake is on the eastern shore.

In summary, the chemistry of the hot springs at Waesano points to the existence of a neutral pH, very saline reservoir at depth, with a temperature of >240°C. However, the high elevation of the chloride springs and the similarity to analogous systems suggest there is a magmatic vapour zone beneath Waesano. The implication of this is that corrosive conditions may exist alongside or beneath the neutral liquid reservoir.

Table 1. Chemistry of Waesano hot springs in comparison to other saline thermal and nonthermal waters.

Location	Description	Temp	pH	Na	K	Ca	Mg	Cl	SO_4	$tHCO_3$	B	SiO_2	Cl/B	Cl/SO_4	Na/K
		°C						ppm							
Waesano (WS-02)		97	6.4	9,111	1357	2285	24.0	19,921	29	153	621	119	9.8	1861	11.4
St Lucia	condensate, acid magmatic	~200	5.1	5,900	290	11,600	100	37,000	1,195		3500	212	3	84	34.6
Svartsengi	thermally altered seawater	240	5.4	6,382	989	1066	1.29	13,506	32	578	7	425	597	1136	11.0
Wayang Windu	mature magmatic	265	6.0	7,330	1640	677	0.65	14,090	16	5	477	642	9	2386	7.6
Fresh Seawater		**cold**	**8.0**	**10,561**	**380**	**400**	**1272**	**18,980**	**2,649**	**142**	**5**	**~3**	**1258**	**19**	**47.3**
Waesano Lake Water		27	2.6	215	19	77	9.0	421	351	<20	29	91	4.4	3	18.8

3.2.4. MT Resistivity

An MT survey was initially conducted by Badan Geologi in 2015. Upon review, it was evident that there was considerable noise in the data at low frequencies and that standard processing for this data was resulting in the inversion models having a significant quantity of artefacts that complicated the interpretation of the conductor geometry. The MT data was therefore reprocessed by CCG in February 2017 and the resulting dataset was improved significantly; specifically, the reprocessing corrected some anomalously thick and deep conductive bodies throughout the survey area. Inversion models created from the reprocessed data exhibit a resistivity pattern that is consistent with that found associated with high temperature geothermal systems in volcanic settings around the world.

Interpolations of 1D Occams inversion models (using the TE TM invariant) were creating using WinGLink and Leapfrog Geo 3D modelling software, and cross-sections of this model are provided in Figure 5. The resistivity signature which is characterized by an expansive conductive layer (<10 ohm-m), commonly 500 to 1000 m thick, displays some layering (predominantly north of the lake) and thins to the north. This conductor is underlain by a more resistive (20 to 200 ohm-m) unit throughout most of the survey area. A low resistivity layer also extends a few hundred meters from the top of the conductor to the surface. This stacked resistivity pattern of thin resistor-conductor-thick resistor is characteristic to many high temperature volcanic geothermal systems and commonly represents the downward transition from unaltered near surface rocks (resistive) to argillically altered volcanic rocks that comprise the clay cap to the geothermal system (conductive) and finally to propyllitically altered rocks of the geothermal reservoir (resistive).

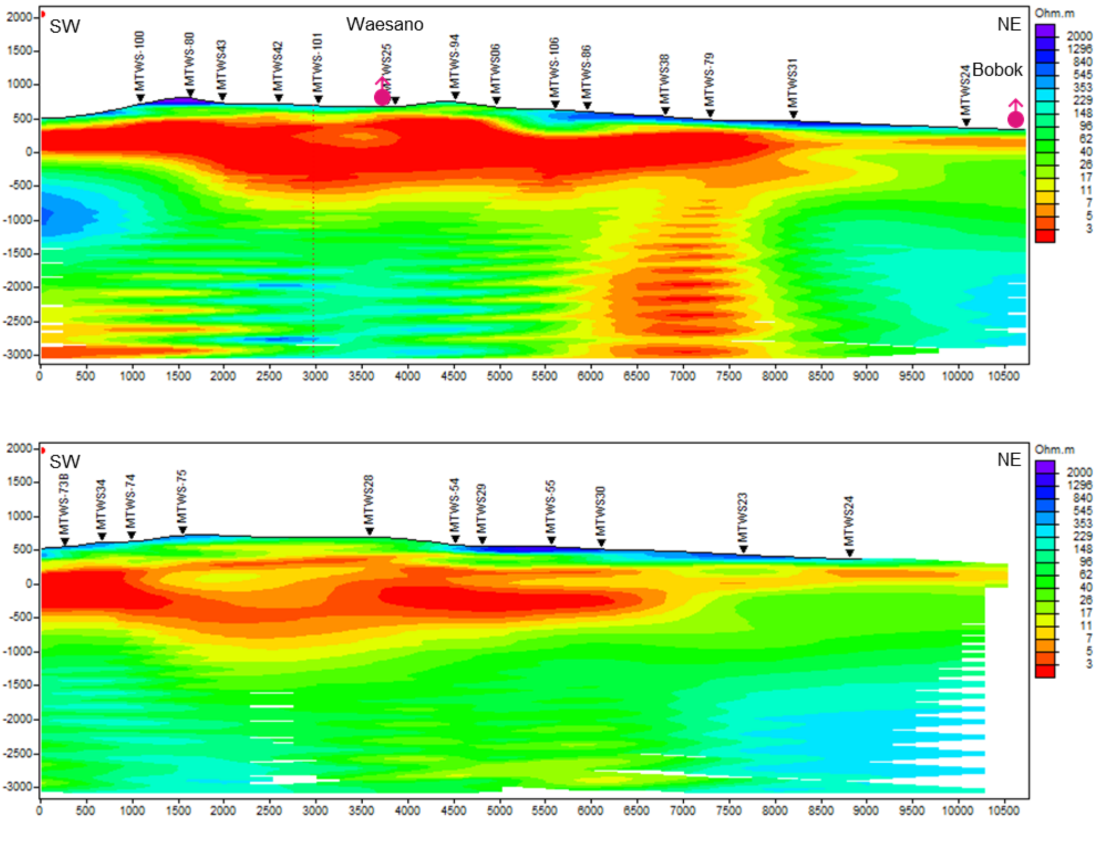

Figure 5. Stitched Occam 1D models (TE TM invariant) along Cross-Section 1 (top) and Cross-Section 2 (bottom). Dotted line (top) is location of kink in section profile.

In the proposed drilling areas, the base of the clay cap (represented by the lower <10 ohm-m iso-surface) appears to extend to depths of 1100 to 1300 mVD. The relatively deep nature of this conductor is consistent with the resistivity signature of the neighbouring Ulumbu geothermal field, where traverses of DC vertical electric soundings imaged a low resistivity layer extending to depths of 1100 m or more in large areas of the field (KRTA, 1989). Note that there is some uncertainty regarding the validity of the presented penetration depths of the survey for Ulumbu, as the maximum electrode spacing was AB/2 = 2000 m, and depth penetrations of AB/4 or greater are likely optimistic.

The thinning of the conductor to the north in the Waesano area is coincident with the gas-rich spring at Bobok and may represent a trend of weakening alteration intensity along a N-directed outflow path. The layered nature of the conductor to the north of Lake Sanonggoang may indicate that this is a lower temperature region of the geothermal system (conductors are generally more cohesive when they are formed above prominent high temperature upflow zones). The 1D inversion models display a few deep conductors in various parts of the field that are of unknown origin. These are likely to represent modelling artefacts, but may be the signature of electrically conductive sediments in the basement units.

In summary, the modelled resistivity data for Waesano displays a conductor geometry that is consistent with it being the signature of a hydrothermal clay cap formed above an active geothermal system. The base of the conductor, which is commonly used as a proxy for the transition from the clay cap to the reservoir in geothermal systems, occurs at a depth of 1100 to 1300 m VD throughout a large part of the survey area.

3.2.5. Gravity

The original data was reprocessed for this assessment using a terrain model to 200 km. The total Bouguer anomaly was calculated from the observed gravity after applying terrain, free air, Bouguer and latitude corrections. Bouguer anomaly maps were created using the assumption of a rock density of both 2.6 g/cm^3 and 2.2 g/cm^3 (Figure 6), and 2D forward models were created in WinGLink to assist with the interpretation of the results.

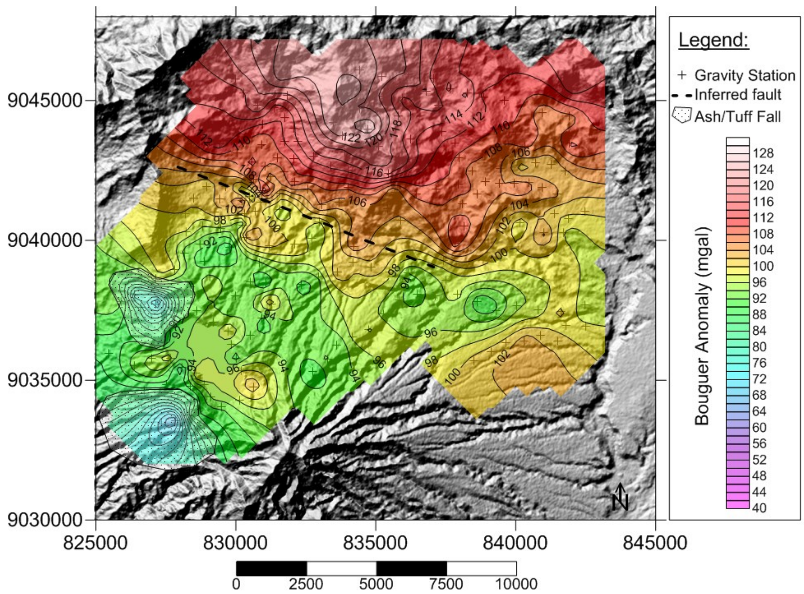

Figure 6. Interpretation of Bouguer anomaly in the Waesano area assuming ρ=2.2 g/cm^3.

The Bouguer anomaly trend provides an insight to the density and extent of rock bodies in the area. In both models, the gravity anomaly is relatively high (above 100 and 110 mgal using densities of 2.6 g/cm^3 and 2.2 g/cm^3 respectively) in the ranges to the north of Waesano, which suggests that higher density material is found in this area. This is consistent with the geologic maps of the region, which suggest that this area is dominated by Paleogene-Neogene sediments and volcanics (units that are likely to have a higher bulk density than the Quaternary volcanics). The anomaly decreases to the south, with a particularly strong anomaly gradient (~10 mgal·km-1) about 5 km to the north east of the lake. This trend suggests that the basement rocks may be down-faulted to the SSW along an ESE-striking extensional structure, with lower density rock overlying the downthrown block. A large regional fault of similar orientation and kinematics (the Cancar Fault) occurs 100 km to the east of Waesano in the region surrounding the Ulumbu geothermal field.

The Bouguer anomaly map for Waesano also highlights zones of low density (50-70 mgal) directly to the southwest and northwest of Lake Sanonggoang. These can be associated with low density infill from Quaternary pyroclastic flows and tuffs from Sanonggoang. Given their circular nature, it is conceivable that these features represent buried craters, perhaps formed by phreatomagmatic eruptions.

In summary, gravity data for the prospect area displays circular low-density anomalies around Lake Sanonggoang that may represent infilled craters, which were perhaps originally formed by phreatomagmatic eruptions.

3.3. Integrated Conceptual Resource Model

An integrated interpretation of the above geoscientific information has been conducted to develop a preliminary conceptual understanding of the Waesano geothermal resource. The key components of this conceptual model are detailed and representative cross-sections are provided in Figure 7 and Figure 8. A discussion of the implication of the conceptual model for understanding specific project risks is provided at the end of this section.

Reservoir Temperatures

There are multiple lines of evidence that indicate the presence of a >240°C resource at Waesano, including cation geothermometry, gas geothermometry, the large oxygen isotope shift in fluid samples, high Cl and B contents and the large flat-lying low resistivity body (dominantly <5 ohm-m) that has been imaged by the MT data.

Reservoir Chemistry

The preferred model is that the geothermal reservoir feeding the springs is a mature, meteorically-derived water that is mixed with a condensed and neutralized magmatic vapour plume. In this scenario the reservoir fluid is expected to be near-neutral pH and high salinity (>15,000 ppm Cl), but has adjacent zones of acidic condensate and magmatic vapour at a yet to be determined location. The carbonate sedimentary sequences that are expected in the subsurface likely play an important role in neutralizing this acidic fluid. There is still some uncertainty regarding the relationship between the near-neutral pH brine that appears in the hottest springs at the Waesano thermal area and the acidic lake waters in Lake Sanonggoang.

Host Rocks & Permeability

The deep reservoir at Waesano is probably hosted in Paleogene to Neogene sedimentary units lying below ~300-1000 m of volcanics (dominantly andesitic). The sediments are expected to be primarily carbonates, volcaniclastic and calcareous sandstones and lesser intercalated basalt extrusives. Argillically-altered volcanic rocks (encountered in shallow wells WW1 and WW2) and volcaniclastic sandstones are likely to constitute the cap rock to the system.

It is expected that permeability in the system will be controlled mainly by secondary features (such as faults and fracturing) and that stratigraphic permeability will play a minor role. Interlayered mudstone and siltstone units will likely represent local zones of low permeability. The disconformity between the Paleogene-Neogene sediments and overlying volcanics may represent a relatively shallow permeable zone, as is the case at Ulumbu. Additionally, there may be favourable zones of high fracture density related to NNW oriented extensional structures, or that there is an anisotropic NNW-oriented grain of fracture permeability in the reservoir.

Depth to Reservoir

The depth to the reservoir at Waesano can be approximated by the depth to the base of the <10 ohm-m conductor, at 1000 to 1300 mVD over a large extent of the prospect area. The low resistivity body in the upper one km of the system likely represents a low permeability cap rock to the system, however, isolated zones of permeability may be present here as well.

Resource Area

There is a well-defined maximum northern boundary to the Waesano system, as defined by the disappearance of the shallow cohesive conductor 3-4 km NW of the lake. The western, southern, and eastern extents of the system are more unclear as the conductor extends to the limits of the MT survey area in these directions. Considering the areal extent of the shallow conductor and the nature of the thermal manifestations, the best that can be concluded is that the system has an area of between 1 and 20 km^2. This parameter will remain ambiguous until the results of the drilling campaign are obtained.

Heat Source

The chemistry of the Waesano thermal manifestations and Lake Sanonggoang and the surrounding young volcanic features in the Waesano prospect area all suggest the presence of a magmatic heat source beneath Waesano. There are some lines of evidence (namely the acid lake chemistry) to suggest that the magmatic heat source is currently situated below Lake Sanonggoang.

System Evolution

It is likely that the shallow (and potentially deep) hydrology of the system has been episodic, related to the eruptions (at least two) that have formed the lake. evolved overtime, affecting the discharge rates at Waesano as deduced by the presence of relict sinter terraces and widespread advanced argillic alteration (as reported by Badan Geologi). These fluctuations over time may be the result of hydrologic changes in the reservoir, but they may also be the result of pathway sealing processes occurring closer to the surface (i.e., they are not necessarily the signature of a drastic change in the deep reservoir over time).

4. CONCLUSIONS

Surface exploration of the Waesano Geothermal Project has been completed, including geological mapping, geochemical sampling, and geophysical surveys including MT and gravity. The next step of the project is an exploration drilling campaign. A conceptual model of the reservoir has been constructed that features a high-temperature (>240°C) volcanic-hosted geothermal reservoir, at least partly neutral saline, but with an acid-magmatic centre. The resource is developed in Paleogene to Neogene sedimentary and volcanic rocks at a depth of >1000-1300 mVD. Resource assessment estimates indicate a generating capacity of at least 30 MW.

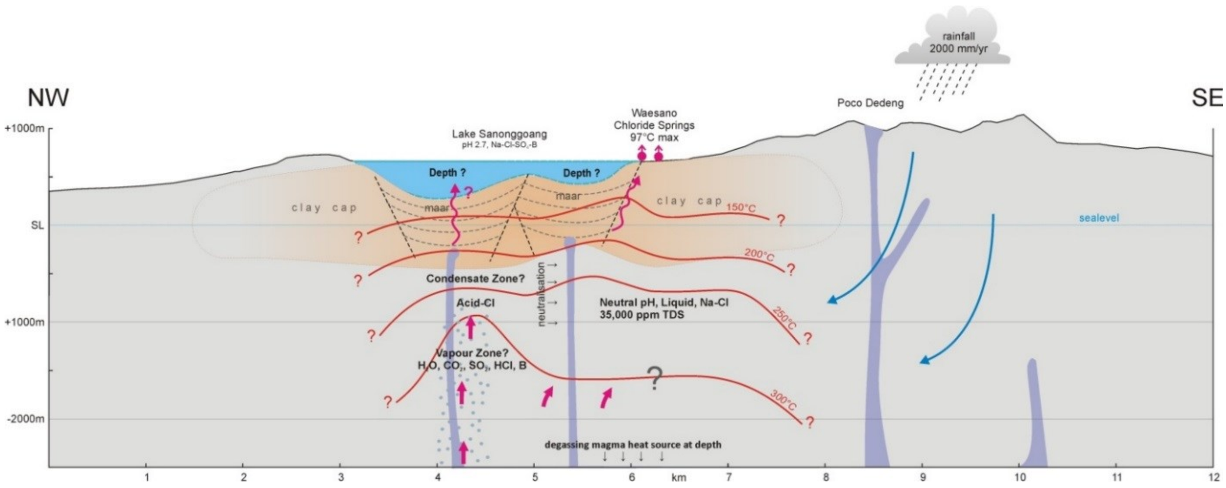

Figure 7. NW-SE conceptual model of the Waesano geothermal system.

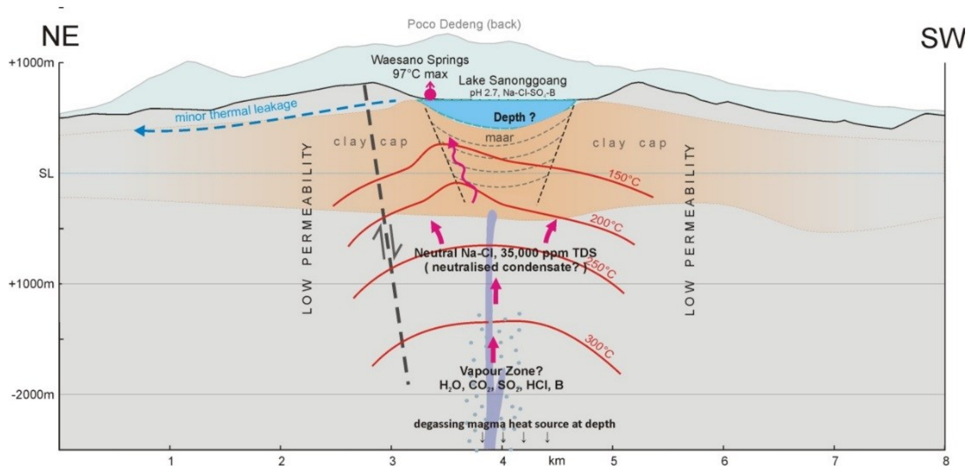

Figure 8. NE-SW conceptual model of the Waesano geothermal system.

5. ACKNOWLEDGEMENTS

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