Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Remote Sensing Volcanostratigraphy as a Tool to Support Delineation of Geothermal System Boundary Associated with High Terrain – Composite Volcanic

Suryantini[1,2] and Hendro Wibowo[1]

[1]Prodi Teknik Geologi FITB – ITB
[2]Prodi Teknik Panas Bumi FTTM – ITB
Jl. Ganesha 10 Bandung 40132

suryantini@gl.itb.ac.id

Keywords: Volcanostratigraphy, high terrain, composite volcanic

ABSTRACT

In a high terrain volcanic associated hydrothermal system, lithology boundaries of a volcanic rock unit are difficult to map and interpret. Field mapping in volcanic area is difficult because some lithology looks similar and thus lithology boundary of a volcanic rock unit might be misinterpreted. On the other hand, in a high terrain volcanic associated hydrothermal system this boundary might control the occurrence of thermal springs manifestation that may indicate the boundary of this system. This geothermal system boundary is important for predicting delineation of possible clay cap at depth that often correlates with top of reservoir extent. It also aid in designing geophysical and soil geochemistry survey. Thus, predicting the lithology boundary at the early stage of geothermal exploration is crucial. Mapping of volcanic lithology can be supported by interpretation of remote sensing data. In this paper we use ASTER DEM data to create digital elevation model. This data will be used to construct volcanostratigraphy units by delineation of ridges and rivers that will point to central of eruption or edifice. One edifice will form one volcanostratigraphy unit. The unit boundary subsequently is overlain and intersected with the occurrence of any thermal manifestation such as occurrence and chemistry of thermal springs and cold springs that were contaminated by thermal fluid. By understanding the hydrology of the area (hence high terrain volcanic geothermal system) and the assumption that the thermal anomaly coming from the young and active geothermal system, then area associated with geothermal system can be interpreted and geothermal system boundary can be delineated. The method has been applied in Patuha, Wayang Windu, and Karaha-Talaga Bodas geothermal field. It proves that geothermal system boundary is crucial in designing further exploration program such as geophysical survey and interpreting the extend of reservoir that may effect the calculation of resource. It can be concluded that this method is a potential tool to determine the boundary of geothermal system in particular in high terrain – composite volcanic hydrothermal system. However, applicability of this method in other volcanic type other than high terrain composite volcanoes still need to be studied.

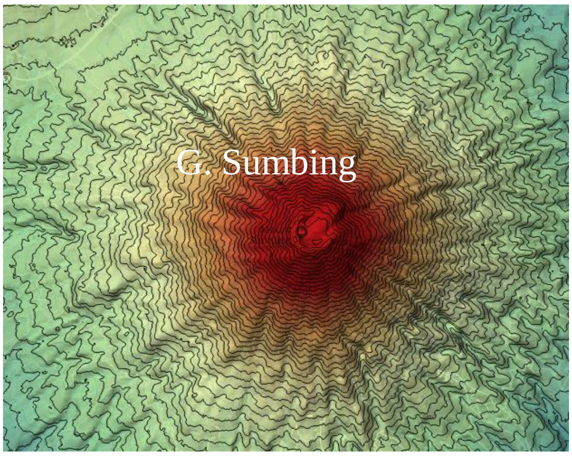
1. INTRODUCTION

A composite volcanoes (including compound volcanoes) is relatively large, long-lived constructional volcanic edifice, comprising lava and volcaniclastic products erupted from one or more vents, and their recycled equivalents. The term ‘‘composite’’ is more emphasized on volcanic cones that have a composite growth history, punctuated by one or more episodes of sector collapse, whereas the term ‘‘compound’’ is more to denote edifices comprising multiple cones, resulting from limited vent migration over time within a restricted area (Davidson J and De Silva S., 2000). This type of volcanoes mostly found in a convergent plate margin associated with high terrain andesitic volcanoes.

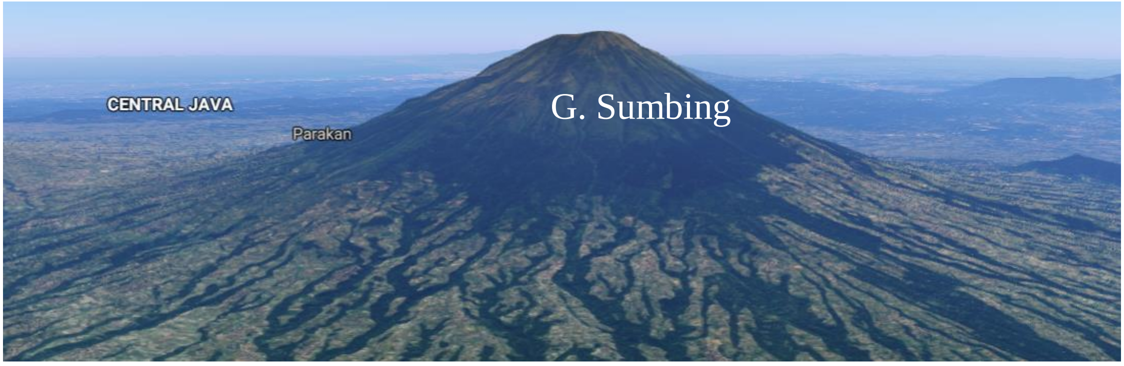
The landscape of composite volcanoes (Figure 1a-e from ASTER DEM and Google Earth) can vary with age, which is related to eruption history, and the level of erosion including sector collapse. It can form (Figure 1a) a “classic” cone shape; (Figure 1b) a compound volcano; (Figure 1c) a compound volcano with numerous Holocene vents (the youngest being the symmetrical cone with a single active vent), (Figure 1d) twin volcanoes or (Figure 1e) associated with caldera. The variation of this landscape reflects an increasing tendency for vent location to migrate over time. Although they are cluster of composite edifices.

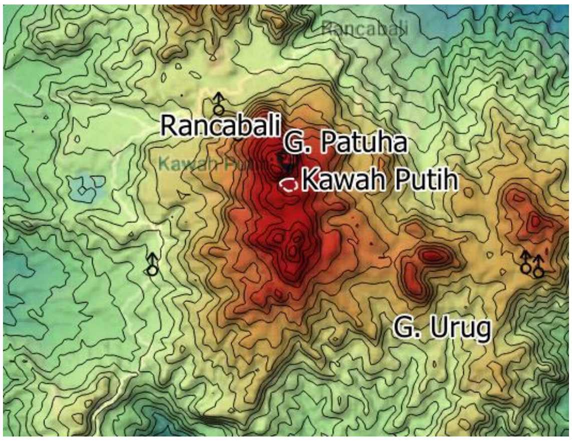
Geothermal system(s) may associate with only one or more volcanic edifice of a composite cone. The younger edifices tend to contribute higher heat than the older one. But it is not always true that the youngest edifice host the most potential geothermal resources. This is because the edifices that are too young are usually related to the activity of young magmas that are still very active in emitting acidic and corrosive magmatic gases which can affect the production of geothermal energy. Hydrothermal systems that are associated with young magmas less than 50,000 years old are generally low resources (Wohletz and Heikein, 1993). A hydrothermal systems associated with composite cone as the heat source may be related to the nearby older volcanoes or to the overlying composite cones. But the occurrence of surface manifestation including argillic and acid alteration, silica sinter deposits, hot springs, fumaroles, mudpots and/or geysers will become the crucial clue to interpret the association of hydrothermal system with its potent heat source that is volcanoes or edifice of composite cone.

Surface manifestations such as hot springs are geothermal fluids, which flow through permeability or conduit which can be controlled by lithology contact, or structural geology such as fault and fracture. This fluid emerges to the surface as hotsprings as various type of water such as chloride water, bicarbonate water, sulphate water or mixing of these fluids. In high terrain composite cone, the occurrence of hot springs is controlled by hydraulic gradient where slope of topography and dip of lithology play an important role in distributing and spreading the hot or warm springs. Meanwhile lithology dip and slope of topography in young volcanic is strongly associate with the deposition of lava and pyroclastic on the flank of a composite volcano. Thus, by delineating the lava and pyroclastic, one can infer the source of edifice that erupting this product, where this edifice may be the young magmatic or volcanoe that become the heat source of the geothermal system and so does the heat that have been carried by the fluid flow and emerge as hot or warm springs on the surface. Therefore it can be concluded that by integrating the mapping of lithology, the hydrology and thermal springs, one can interpreted the main source of geothermal system and also the boundary of a geothermal system.

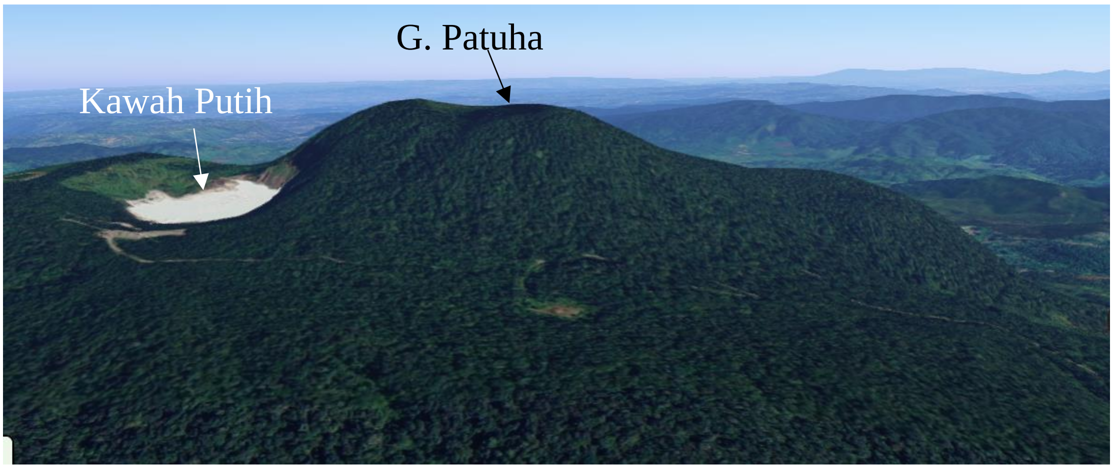


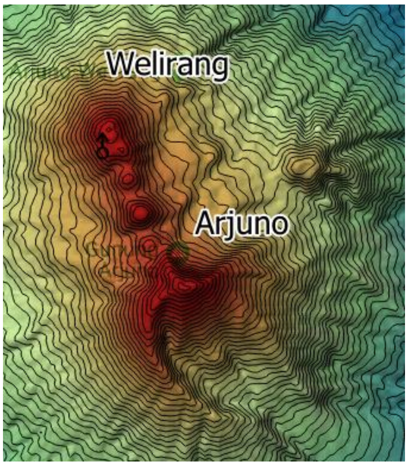
a) Landscape of classic cone shape



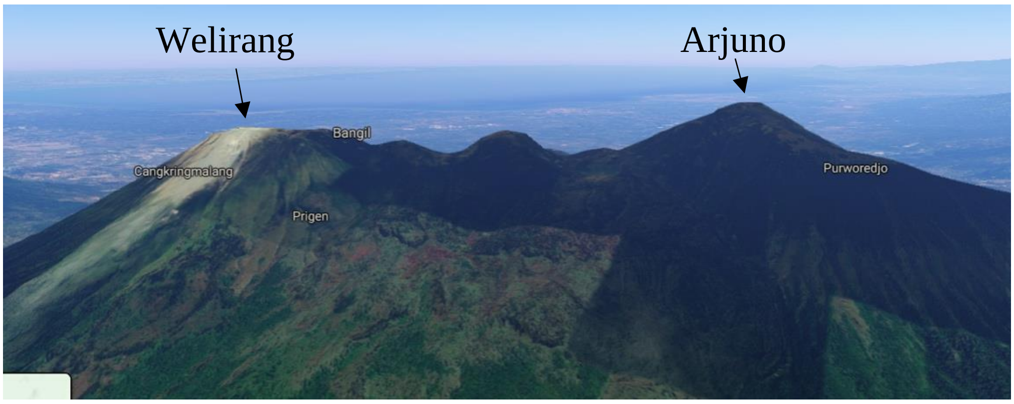


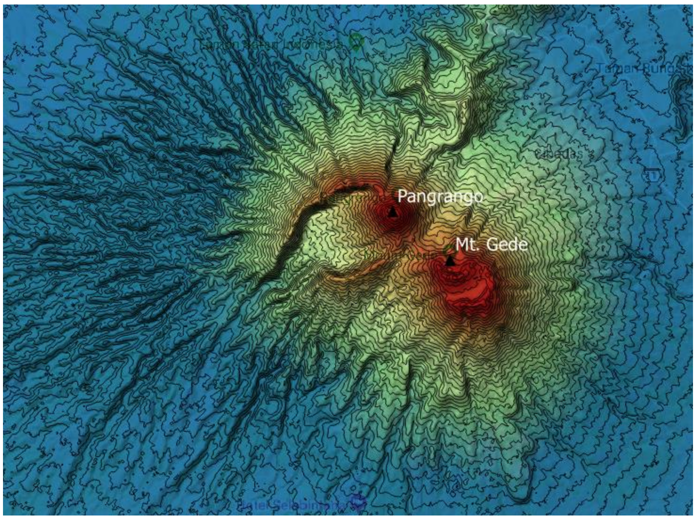
b) Landscape of a compound volcano; the image is from Patuha-Kawah Putih composite cone, with several edifices around.



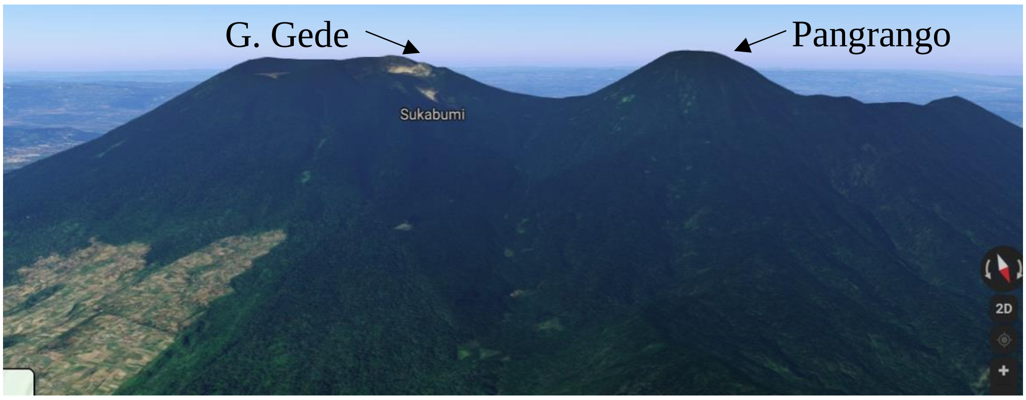


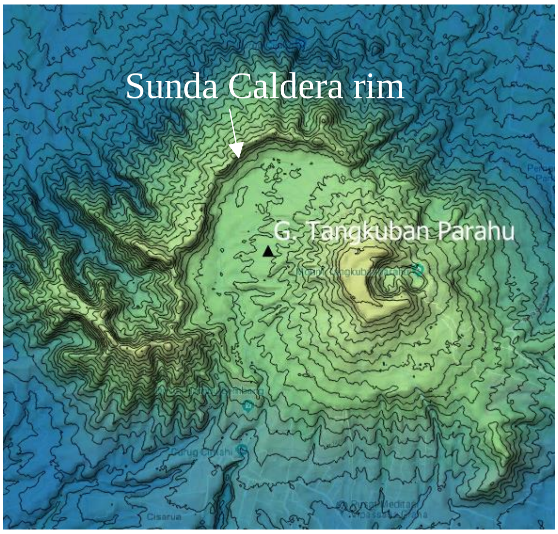
c) a compound volcano with numerous Holocene vents (the youngest being the symmetrical cone with a single active vent)





d) Landscape of Twin Volcano





e) Landscape of composite volcanoes associated with caldera

Figure 1:Various type of composite volcanoes a) Landscape of classic cone shape, b) Landscape of a compound volcano, c) a compound volcano with numerous Holocene vents, d) Landscape of Twin Volcano, e) Landscape of composite volcanoes associated with caldera

The geothermal system discussed in this paper is specific to volcanic or magmatic associated hydrothermal system, in particular andesitic volcanoes with high standing terrain. The components of this system consist of (1) heat source, (2) reservoir and possibly overlying clay cap, (3) recharge area, and (4) discharge area that includes upflow and outflow (Hochstein and Browne, 2000). This implies that one heat source is associated only with one system. But one system can have several compartment of reservoir, that each of them can have more than one upflow zone. The conceptual model of volcanic hydrothermal system is shown in Figure 2. It is shown that in a Twin Volcanoes (a variation of composite volcano) the heat source evolve and migrate from heat source 1 (HS1) to heat source 4 (HS4) based on the age from oldest to youngest respectively. In the deeper part, this volcanic neck may merge into one larger magma chamber. As magma rises to shallow level, it can produce convection of hydrothermal system shown as isothermal T1 (150^{o}C) and T2 (300^{o}C). Two magma rises to shallow level and create volcanic neck thus produce two separate convection which might not connected to each other due to the occurrence of self sealing. Reservoir is associated with every convection and might not connected each other. At the surface, fluid from reservoir emerge to the surface as surface thermal manifestation such as hot springs and flowing to lower flank of an edifice. The distribution of thermal manifestation is controlled by the volcanostratigraphy of this edifice. The thermal fluid can travel laterally and appear as outflow, indicated by bicarbonate hot or warm springs that emerge at the edge of a stratigraphic unit boundary. By understanding this concept, a hot springs that appear connected to a particular volcanostratigraphy can be interpreted as having heat source from this edifice. The geothermal system boundary can be expected to be located beyond the appearance of bicarbonate springs (or chloride bicarbonate springs or chloride springs) that relatively adjacent with cool unmixing or uncontaminated springs. It is critical that one can distinguished among different volcanistratigraphy unit in order to be able to delineate the boundary of geothermal system.

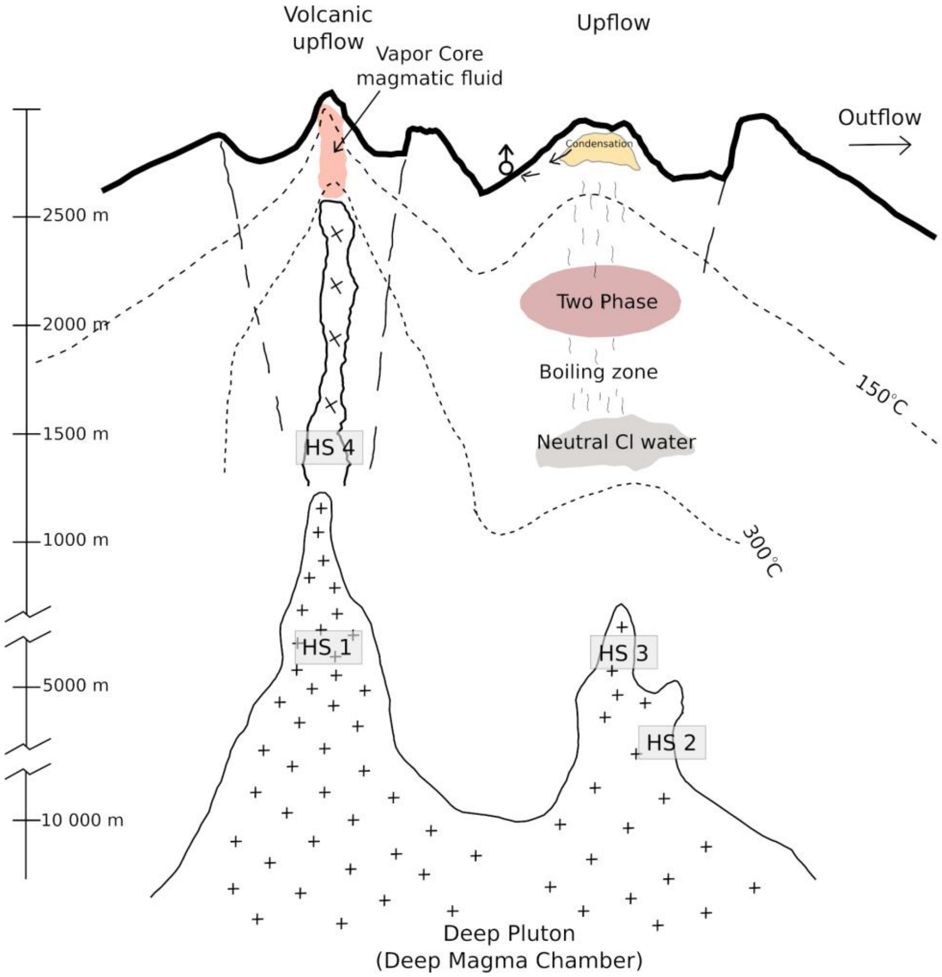


Figure 2: Conceptual model of volcanic hydrothermal system

However, field mapping in volcanic areas may be difficult because some lithologies look similar and lithology boundary of volcanic rock units may be misinterpreted and so does the boundary of a geothermal system. Thus the applicability of remote sensing can assist in delineating lithology boundary prior, during, and after field mapping. The objective of this paper is to demonstrate that the boundary of geothermal system can be interpreted from intersecting lithology unit boundary (also called volcanostratigraphy unit) with occurrence area of geothermal manifestation. This would assist in designing further exploration strategy and predicting resource assessment in particular at the early stage of exploration.

The discussion in this paper will be structured to follow the logical order of methodology. First, the determination of volcanostratigraphy and its boundary will be explain, secondly the integration with surface manifestation area will be discussed and lastly, it will be concluded with case studies and discussion of the results.

2. VOLCANOSTRATIGRAPHY

2.1. The Nomenclature

Volcanostratigraphic classification is a systematic grouping of volcanic rock/deposit bodies or strata, which enables one to make a simpler description, arrangement and determine mutual relationship among volcanic rock/deposit strata (Bronto et al., 2016). Indonesia with large amount of volcanoes has developed a volcanostratigaphy nomenclature namely Volcanostratigraphy code of Indonesia or *Sandi Stratigrafi Indonesia* or is shortly called SSI. It was developed in 1996 by Indonesian Association of Geologist (IAGI). This become formal stratigraphy unit classification in Indonesia although its application is still limited. The nomenclature of a volcanostratigraphic unit is based on volcanic source, genetic term of volcanic rocks/deposits and chronological events. Ranks of volcanostratigraphic formal units, from high to low, are respectively Arc (Indonesian name "Busur"), Super Brigrade (in Indonesia "Menggala"), Brigade (in Indonesian "Bregada"), Crown (Indonesian name "Khuluk"), and Hummock (Indonesian name "Gumuk"). Bronto et al. (2016) discussed in detail the concept of this nomenclature. For this study the applicable usage of volcanistratigraphy units are Crown or *Khuluk* and Hummock or *Gumuk*. This concepts are illustrated in Figure 3.

A Crown (Khuluk) is a basic unit in the volcanostratigraphic classification (see Figure 3). This consists of rocks/deposits produced from one eruption point or more in the case of a composite volcanic body. Composite volcanoes may erupt various rocks/deposits as products of explosive and effusive activities along with their subvolcanic intrusions. Thus, a Crown unit is applicable for single composite volcanic body which reflects a construction period resulting from a variety of volcanic activities. The Crown unit is mappable at a scale of 1:50,000 or larger. (Bronto et al., 2016).

A Hummock (Gumuk) is a part of a Crown formed as eruptive material at the volcanic Crown in the summit crater or on flanks (Letter c and d in Figure 3). However, a Crown does not always has a Hummock. In the summit crater the Hummock is known as a child of volcano or volcano children (in Indonesia: gunung api anak), whereas on flanks of the Hummock the eruptive material forms a parasitic cone(s). The volcanic body forming the Hummock is smaller than the Crown and usually consists of homogeneous volcanic rocks/deposits. These include lava cones or lava domes, pyroclastic cones (cinder/scoria cones, tuff cones, tuff rings), and maars. Monogenetic volcanoes also imply a single stage of volcanism. Due to its smaller size and homogeneous composition, an eccentric volcano can be considered as a Hummock. Eccentric volcanic eruptions are eruptions from vents near or beyond the base of the main volcanic cone The Hummock is mappable at a scale of 1:50,000 or larger (Bronto et al., 2016).

2.2. Theory and Basic Assumption

Some assumptions used in volcanostratigraphy determination using satellite imagery (or remote sensing) are described as follows:

1) A composite volcano can evolve from one eruption center that develops from small to large, or from moving eruption centers, but every time an eruption occurs, it is assumed to occur only at one location point or edifice (Letter a,b,c and d in Figure 3).

2) An edifice ejects alternating pyroclastic and lava that will accumulate and deposit around it, thus its distribution is dispersed radially from the main vent. So, by delineating the pyroclastic or lava flow product, the main eruption center or edifice where the pyrocslastic and lava are principally originated will be known. It can be observed as river channel and ridge on the mountain slope that form radial pattern centered from edifice a, b, c or d in Figure 3.

3) The sequence of events or the relative age of the volcanostratigraphic unit is determined from the law of cross cutting relationship of the features seen in satellite imagery, such as the cross cutting of some circular feature (representing crater or edifice, shown as edifice b and c in Figure 3) or cross cutting of the ridge and river alignment (are shown in white circular in Figure 3). Apart from the cross cutting relationship, the relative age of volcanostratigraphic unit is also determine by the texture of morphology that appear on satellite image. The rougher texture may reflect older volcanostratigraphy unit (compare the roughness of Crown/Khuluk 1,2 and 3 in Figure 3 that representing the oldest, mid age and youngest age respectively).

4) The active thermal manifestations associated with a particular volcanostratigraphic unit, will point to the edifice of this volcanostratigraphic unit as the heat source of the geothermal system found in the unit. In Figure 3, yellow stars symbols are hotsprings and it is associated with volcanostratigraphic unit of Hummock/Gumuk c as shown by white arrow that point to this edifice. Thus Hummock/Gumuk C is most probably a heat source that associated with hydrothermal system of these hot springs.

5) The boundary of the geothermal system will be determined from the boundary of this volcanostratigraphic unit. (yellow solid line in Figure 3)

3. INTEGRATION WITH SURFACE MANIFESTATION TO DELINEATE GEOTHERMAL SYSTEM BOUNDARY

High terrain Volcanic hydrothermal system is often characterized by active surface manifestation such as fumaroles, solfataras, acid sulfate hotsprings, steaming ground, and the product of steam heated alteration such as advance argilic alteration in the upflow zone. The acid sulphate hot springs, often found at topography level high above water table, often indicates the boiling zone beneath it. On the flank of this system, bicarbonate increase as the product of steam and gas condensation into poorly-oxygenated sub-surface groundwaters. Such fluids can occur in an umbrella shaped perched condensate zone overlying the geothermal system, and are common on the margins of fields to form outflow zone. In the farthest zone of the outflow often found hot chloride springs. Distribution of this surface manifestation is strongly controlled by topography and hydrology of this system. A cool spring may emerge above a water table where thermal fluid flow (through outflow zone) beneath it. It is possible due to local or intermediate ground water flow system. The fluid chemistry of such cool springs may be elevated due to contamination or mixing with thermal fluids. Above the outflow zone, vegetation stress maybe occur due to acid soil associated with concealed outflow, or elevated ground temperature or groundwater temperature. Beyond the concealed outflow, chemistry of cool springs or ground water is assumed to be normal because it is not contaminated or mixing with thermal fluids. The concept of distribution of thermal surface manifestation, outflow and cool spring is illustrated in Figure 4. From the figure it is expected that boundary of geothermal system A is located between the farthest contaminated cool springs or warm springs and the closest cool springs, and still within one volcanostratigraphy unit (Crown A). If warm or cool springs occur in Crown B, it is expected that another separate geothermal system is occurred at volcanoes B. In the illustration at Figure 4, the boundary is shown as blue dash line.

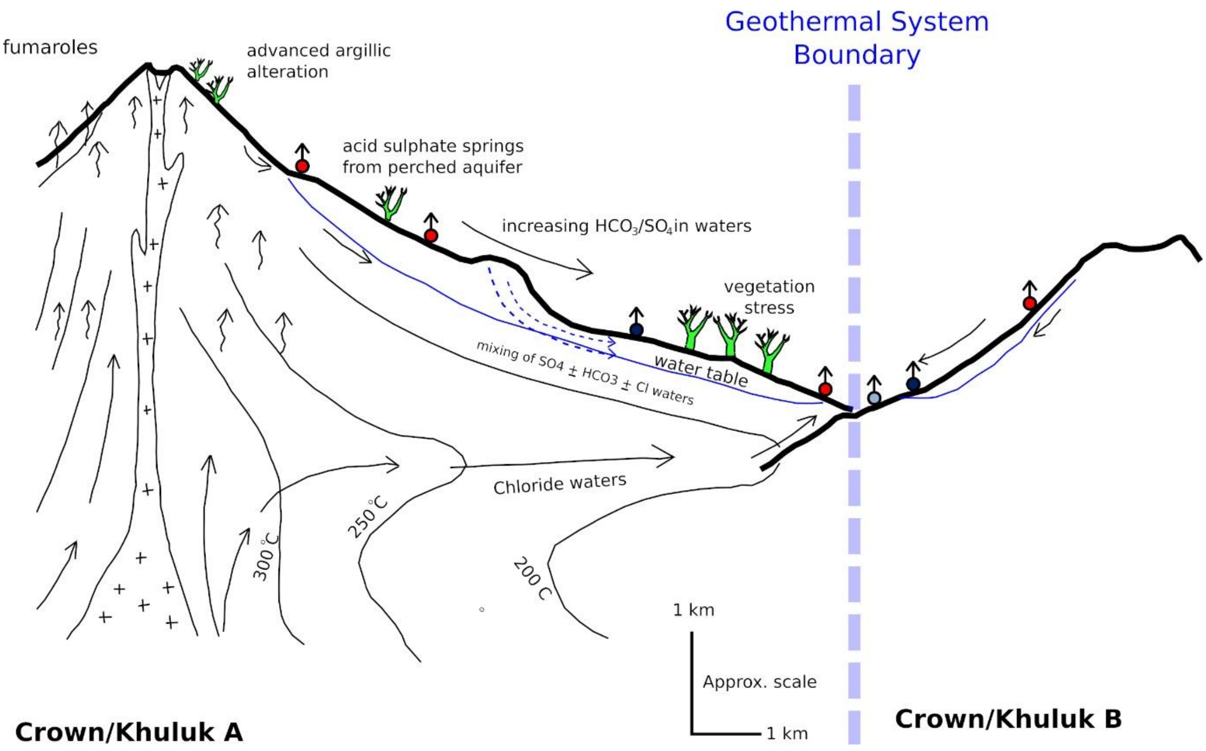


Figure 3: illustrated volcanostratigraphy unit and delineation of geothermal system.

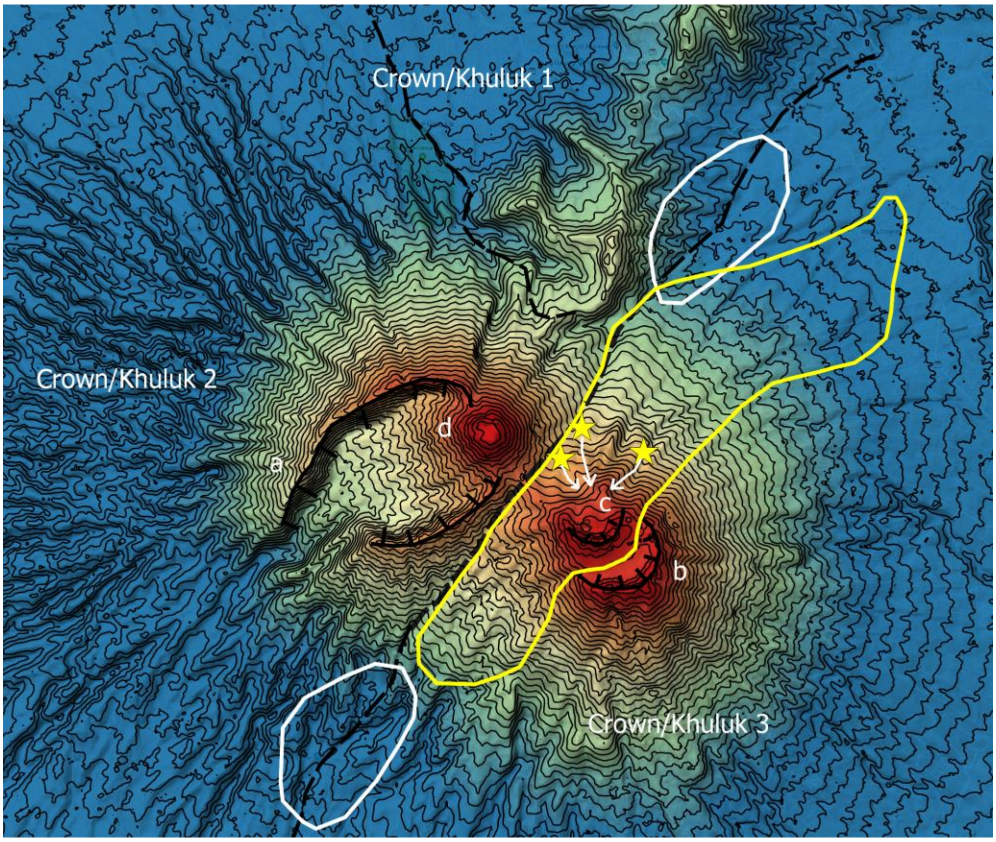


Figure 4: Geothermal System Boundary based on thermal surface manifestation distribution and volcanostratigraphy.

4. CASE STUDIES

4.1. Patuha Geothermal Systems

Patuha complex is a compound volcano with several edifices. The shape of the volcano is large circular convex. Two prominent edifices exist, those are Patuha and *Kawah Putih* (or "white crater"). Other edifice such as Kawah Cibuni, Kawah Citiis, Kawah Sugihmukti and other are small and subtle. Integrated volcanostratigrapy study and water springs (hot and cool) have been applied to delineate the northern boundary of this system. It is illustrated in Figure 5.

In the early stage of exploration survey, geothermal system boundary is determined by resistivity from DC resistivity value <20 ohm.m (Schlumberger array, AB/2 = 500 meter) and MT data with value <20 ohm.m at shallow depth. The depth of resistivity both from MT and DC resistivity is assumed to be <500 m depth since no further information is available. Purple, yellow and red circle area are cold springs that show high TDS, lower pH and elevated temperature, respectively, from average surrounding or nearby data. It is suspected that these cold springs have experienced mixing or contamination with thermal fluid from Patuha-Kawah Putih geothermal system. As can be seen that system boundary by MT resistivity 20 ohm.m cover larger area to the north up to Crown/Khuluk Cadaspanjang-Tikukur, which is an old composite volcanoe complex. This is also the same when resistivity value 30 ohm.m from DC resistivity data were used. If DC resistivity value <20 ohm.m were applied, the boundary become too small and ignoring the fact that some hot springs occur outside the boundary. By integrating volcanostratigraphy boundary (green line) and validation with hot springs and contaminated or mixing cold springs with thermal springs, the boundary become more reliable. If the data about hot and cold springs were omitted, the boundary is still applicable and not over or under estimated. Therefore in the early stage of exploration where geophysical data and possibly not many springs data available, this method is quite convincing.

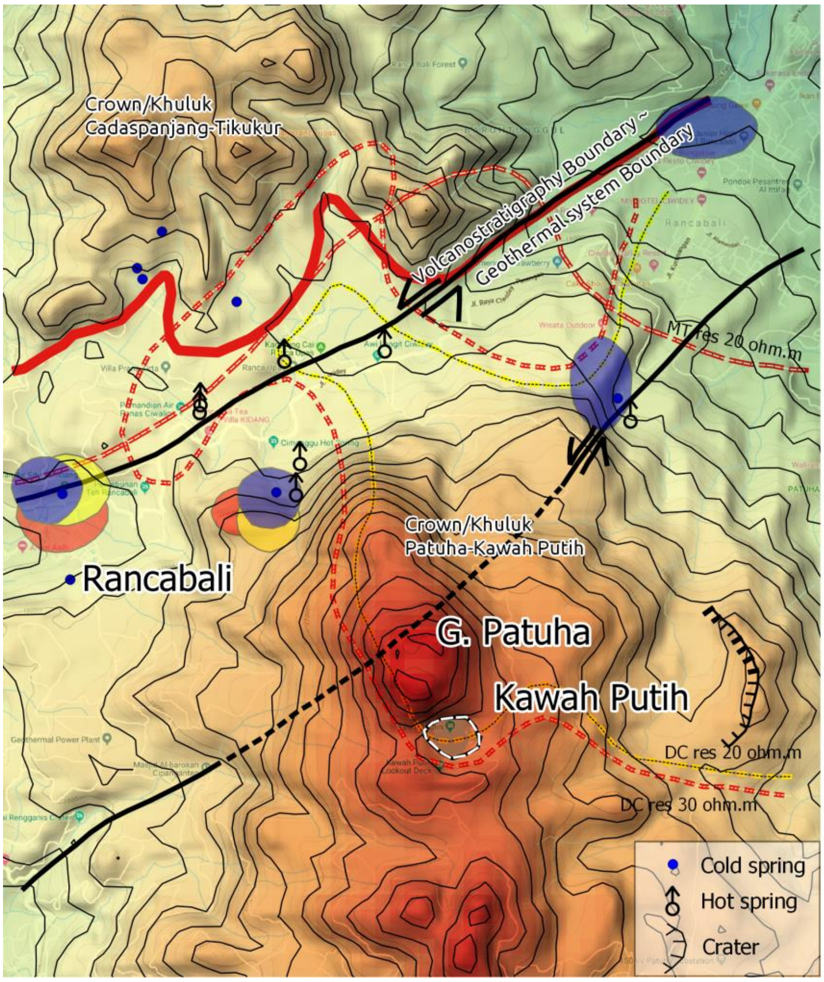


Figure 5: Northern Patuha geothermal system boundary. The figure also show contaminated cold springs indicated by elevated springs temperature (red circle), lower pH (yellow circle) and high TDS (purple circle). Red solid line is geothermal system boundary adjacent with volcanostratigraphy boundary (Modified from Suryantini et al., 2017)

4.2. Wayang Windu Geothermal System

Volcanostratigraphy of the Wayang Windu area is shown in Figure 6. Crown/Khuluk Wayang-Windu-Bedil is a composite volcanoes where the eruption centre is slightly migrate from north to south. The northern part of this crown is adjacent with Brigade Malabar-Puncak Besar. The hummock is younger toward the south, consist of Hummock/Gumuk Gambung, Bedil, Wayang and Windu. The boundary of each hummock is shown in Figure 7.

Geothermal system boundary in this field is determined by integrating volcanostratigraphy unit with water geochemistry data from hot springs and cold springs. The outermost boundary is determined by locating the area outside the farthest cold springs that are contaminated by thermal springs that shows low pH or high TDS or high cation-anion than surrounding area. The data for cold springs is taken from Igna et al. (2011). The boundary is shown as light green in Figure 7.

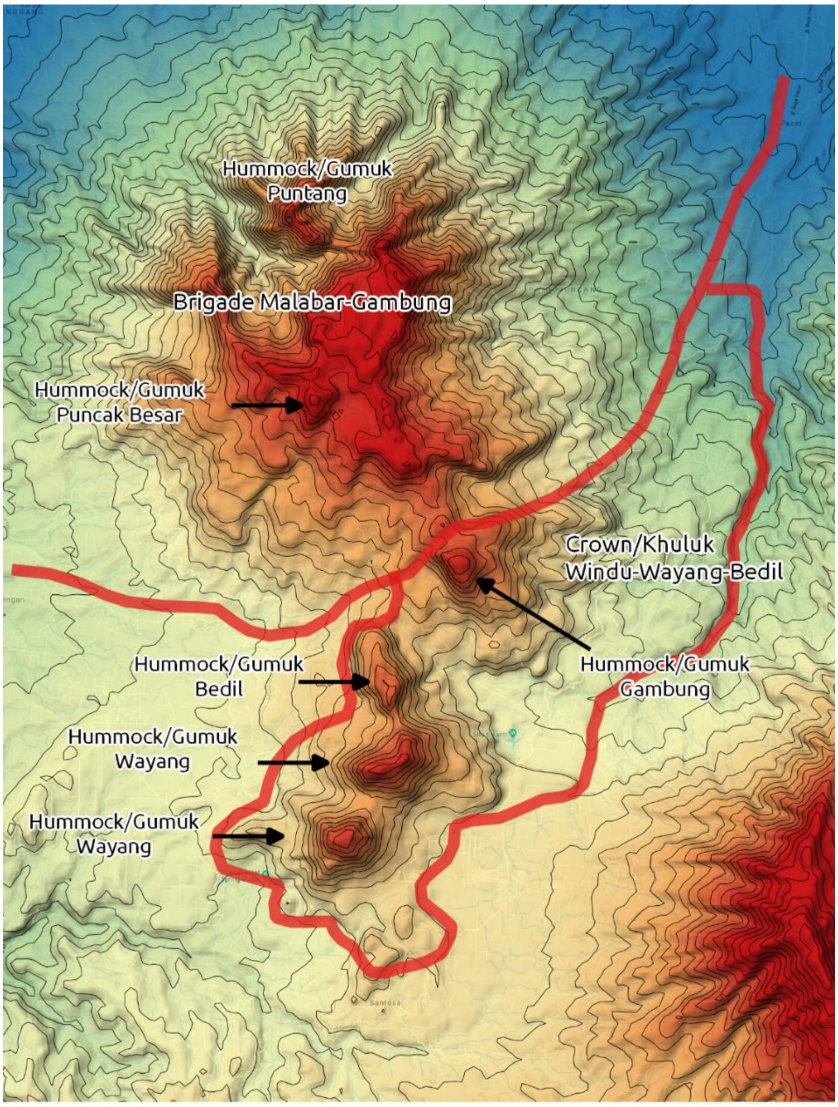


Figure 6: Volcanostratigraphy of Crown/Khuluk Windu-Wayang-Bedil

Association of volcanostratigraphy unit, surface manifestation, DC resisitivity contour <10 ohm.m (Sudarman, 1996), boreholes and reservoir boundary (UGI, 2002) are shown in Figure 7. At the early stage of geothermal survey, resistivity contour <10 ohm.m is often used to delineate reservoir boundary. Nowadays, the resistivity data used is usually MT survey. It can be seen that reservoir boundary that was determined from DC-resisitivity contour is overestimated. However, it failed to delineate the area north of Hummock/Gumuk Gambung. The reservoir area is even much smaller and the trend of the reservoir follow the trend of volcanostratigraphy unit. On the contrary geothermal system boundary delineated by integrating volcanostratigraphy unit and cool springs contamination or mixing with geothermal fluid show smaller area when compared to boundary from resistivity contour, but covered the proven production area. This boundary also suggest that the reservoir consist of several compartments controlled by hummock or gumuk in this area. Each compartment has unique reservoir fluid characteristic and has been proven by subsurface geochemistry. Those are, Windu reservoir is characterized by water dominated system, Wayang is the major upflow, Gambung is the major contribution of steam in this field from MBD Pad which is located at the border of Hummock Gambung and Kawah Burung.

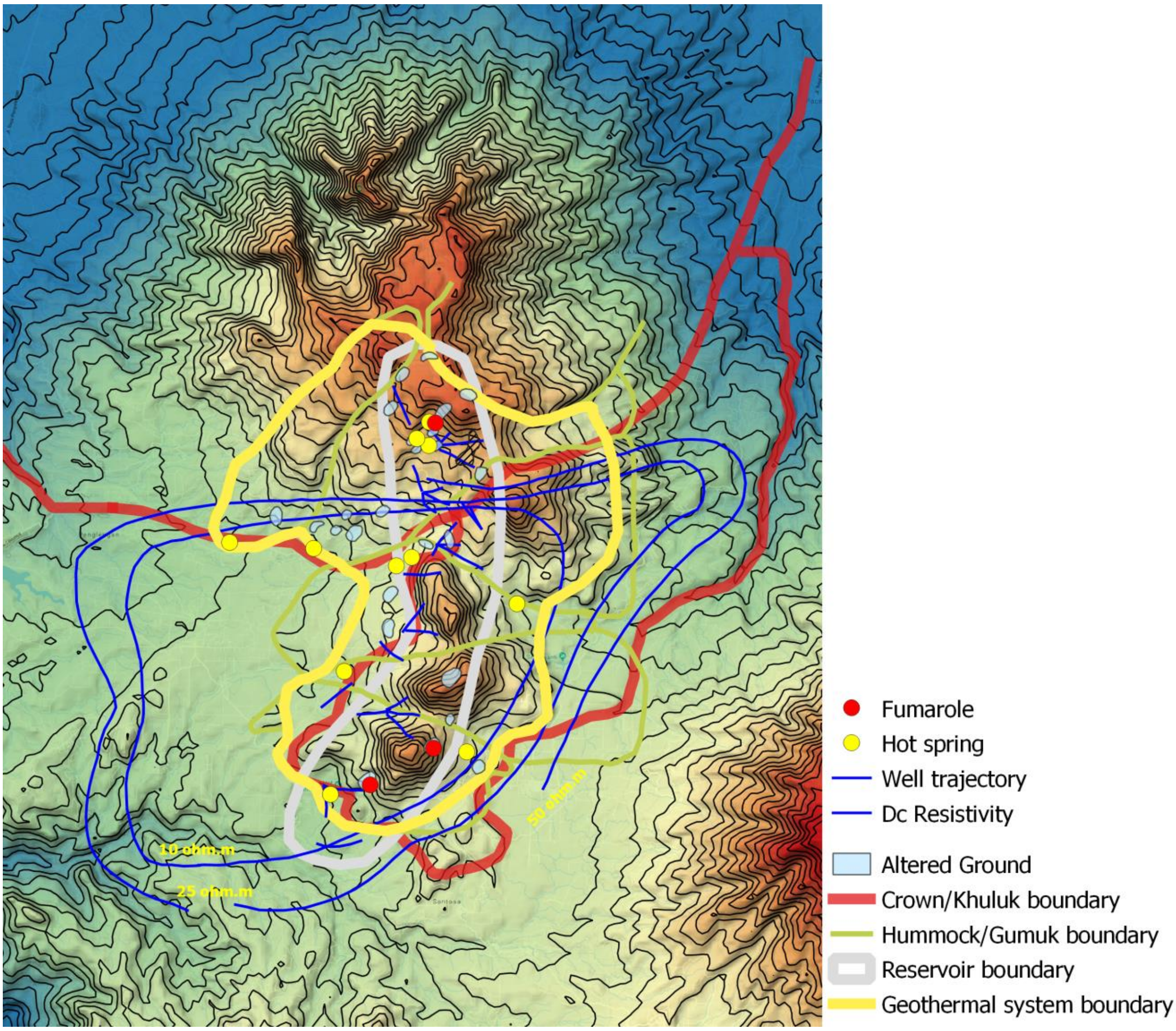


Figure 7: Association of volcanostratigraphy unit, surface manifestation, DC resisitivity contour <10 ohm.m (Sudarman, 1986), boreholes and reservoir boundary (UGI, 2002)

4.3 Karaha-Talaga Bodas Geothermal System

Karaha-Talaga Bodas Geothermal System is part of Brigade/Bregada Galunggung-Talaga Bodas-Karaha (Figure 8). The evolution of the composite volcanoes is younger toward the south. The oldest one at the north is Crown/khuluk Sadakeling, followed by Karaha, Talaga Bodas and the youngest is Galunggung. The texture of satellite image show similar trend, where to the north (Sadakeling) it is more rough than in the south or in Galunggung. Geothermal surface manifestation such as fumarola, solafataras, hot springs, cool contaminated or mixing springs occured in all crowns except at Sadakeling.

The initial conceptual model was developed based on MT resistivity data, Gravity and more than 10 wells located both in Talaga Bodas and Karaha (Allis et al., 2000; Moore et al., 2002a; Moore et al., 2002b; Moore et al., 2002c; Nemcok et al., 2007). The conceptual model is shown in Figure 9. The model extend from Talaga Bodas to Karaha without any significant barrier. Based on volcanostratigraphy study, Talaga Bodas and Karaha are actually two different crown, thus, the geothermal system in this area is supposed to be two separate system. The boundary that separates both systems is very important because it influence the reservoir volume and thus the resource and reserve. Using the model shows in Figure 9, the contract capacity is declared as 220 MWe, which mean the reserve is greater than that value (Handoko et al., 2015) however, based on reservoir simulation the reserve is only 120 MWe (Prabata, 2018). It can be concluded that the reservoir is not as big as mentioned in the initial conceptual model. One of the factor that control the volume of the reservoir is reservoir boundary that separate both system. This boundary, actually has already been inferred since early stage of exploration, even before the geophysical survey. The failure in identifying volcanostratigraphy boundary that may also control the boundary of geothermal system can affect the subsequent resource calculation.

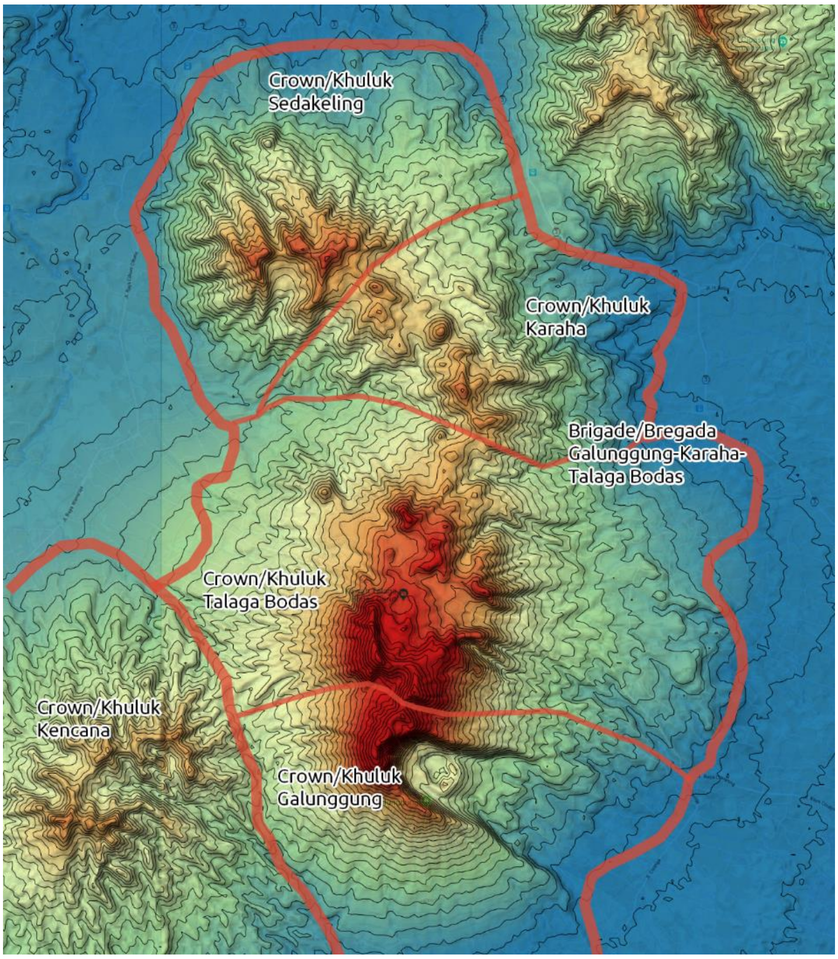


Figure 8: Volcanostratigraphy of Talaga-Karaha Bodas Geothermal System

5. DISCUSSION AND CONCLUSION

Remote sensing volcanostratigraphy is a simple method that able to show indication of geothermal system boundary, that may also imply the reservoir boundary. This method is quite powerful in particular at the early stage of geothermal exploration, even prior to geophysical survey. Integration of this data with geochemical data such as chemistry of cold and hot springs will refine the system boundary. The method is applicable to high terrain volcanic geothermal system because the understanding of hidrology and volcanic deposit unit (volcanic facies) to some extent have been understood. For other type volcanoes, the method must be reinvestigated.

The method use various remote sensing data including digital topography or Digital Elevation Model (DEM) but more important is scale of the data. Usually using scale of 1:100,000 and 1:50,000 are sufficient to resolve Crown and Hummock units. Other important aspect when using satellite data is the ground resolution, the smaller the ground resolution the better the delineation. Application of LIDAR data that has ground resolution <1 m is expected to show more detail topography but this research has demonstrated that for the purpose of geothermal system boundary such detail is unnecessary.

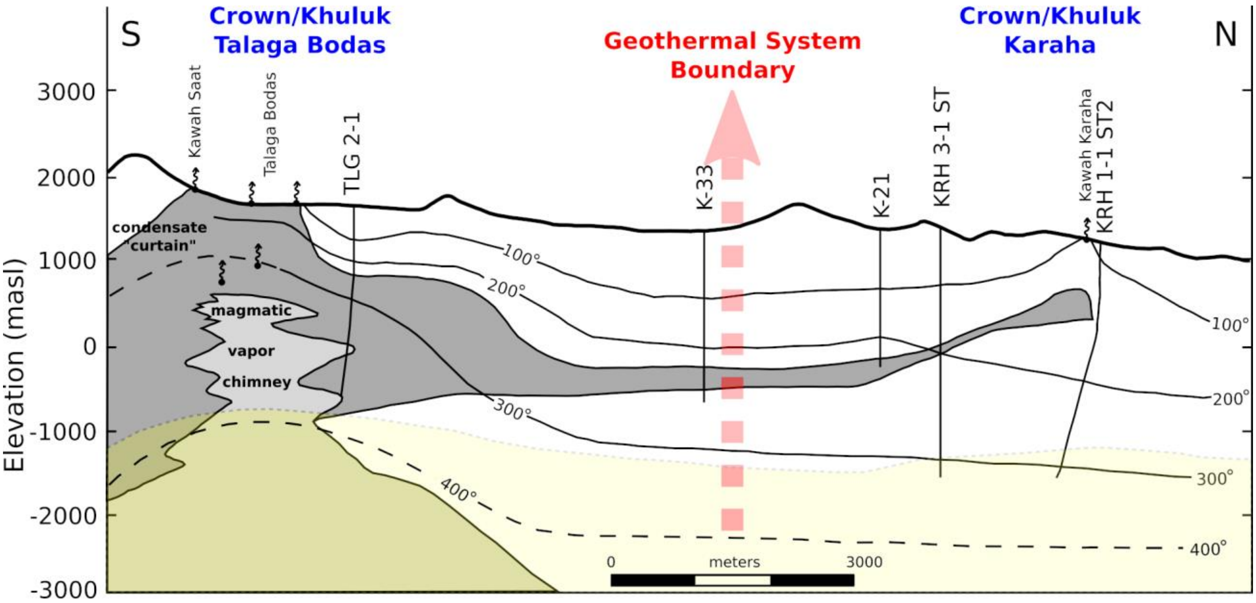


Figure 9: Intial model conceptual of Talaga Bodas – Karaha (simplified from Allis et al., 2000; Moore et al., 2000; Moore et al., 2002; Moore et al., 2004; Nemcok et al., 2007). Geothermal System boundary (Red dash line) was drawn according to the boundary of Volcanostratigraphy.

REFERENCES

Allis, R., Moore, J. N., Mcculloch, J., Petty, S., and Derocher, T.: Karaha-Telaga Bodas, Indonesia: A Partially Vapor-Dominated Geothermal System, Geothermal Resources Council Transactions, (2000), 217 – 222.

Bronto, S., Sianipar, J.Y., and Pratopo, A.K.: Volcanostratigraphy for supporting geothermal exploration, IOP Conf. Ser.: Earth Environ. Sci., (2016), 42 012014.

Davidson, J. and De Silva, S.: Composite Volcanoes, in Encyclopedia of Volcanoes, Haraldur Sigurdsson editor in chief, Academic Press, (2000), 662-681.

Handoko, B.T., Permana, J., Yosodiningrat, B., Tohari, M.A., and Satyajit, D.: History of Joint Operation Contract in Indonesia, Proceedings, World Geothermal Congress, Melbourne, Australia, 19-25 April, (2015).

Igna, H., Dyah, M., Tri, S.E., Dewi, Y.M., and Andarta, K.: KARAKTERISTIK KUALITAS SUMBERDAYA AIR KAWASAN PANAS BUMI STUDI KASUS DIENG DAN WINDU WAYANG, Prosiding Pemaparan Hasil Penelitian Puslit Geoteknologi – LIPI, (2011).

Martodjojo, S and Djuhaeni.: Sandi Stratigrafi Indonesia, Komisi Sandi Stratigrafi Indonesia, IAGI, (1996), Jakarta, 25

Moore, J.N., Lutz, S.J., Renner, J.L., McCulloch, and J., Petty, S.: Evolution of a volcanic-hosted vapor-dominated system: petrologic and geochemical data from corehole T-8, Karaha–Telaga Bodas, Indonesia, Geothermal Resour. Council Trans., 24, (2000), 24–27.

Moore, J.N., Allis, R., Renner, J.L., Mildenhall, D., McCulloch, J.: Petrologic evidence for boiling to dryness in the Karaha–Telaga Bodas geothermal system, Indonesia, Proceedings, 27th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA, USA, (2002), 223–232.

Moore, J.N., Christenson, B.W., Allis, R.G., Browne, P.R.L., and Lutz, S.J.: The mineralogical consequences and behavior of descending acid-sulfate waters: an example from the Karaha–Telaga Bodas geothermal system, Indonesia, Can. Mineral, 42, (2004), 1483–1499.

Nemčok, M., Moore, J. N., Christensen, C., Allis, R., Powell, T., Murray, B., and Nash, G.: Controls on the Karaha–Telaga Bodas geothermal reservoir, Indonesia, Geothermics, 36(1), (2007), 9–46. DOI:10.1016/j.geothermics.2006.09.005.

Prabata, T.W.: Kajian Pengembangan Lapangan Panas Bumi Karaha-Talaga Bodas dengan Simulasi Numerik, Master Thesis Program Studi Teknik Geotermal, ITB, (2018), unpublished.

Sudarman, S., Pujianto, R., and Budiarjo, B.: The Gunung Wayang-Windu Geothermal Area in West Java, Proceedings, 15th Annual Convention, Vol 1, (1986), 141-153.

Suryantini, Rachmawati, C., and Abdurrahman, M.: Geothermal system boundary at the northern edge of Patuha Geothermal Field based on integrated study of volcanostratigraphy, geological field mapping, and cool springs contamination by thermal fluids, IOP Conf. Ser.: Earth Environ. Sci., (2017), 103 012016.

UGI (Unocal Geothermal Indonesia): Wayang Windu 220 MW Feasibility Study, Report, (2002), Unpublished.