Volcanostratigraphy for supporting geothermal exploration

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Abstract. Volcanostratigraphy is stratigraphy related to volcanism and its products. This includes stratigraphy for a general scoping of a regional area and detailed analysis in a local area. On the basis of Indonesian Stratigraphic Code 1996, from low to high rank, volcanostratigraphic units are Hummock (*Gumuk*), Crown (*Khuluk*), Brigade (*Bregada*), Super Brigade (*Manggala*), and Arc (*Busur*). For more detailed stratigraphic study these ranked units can be classified into genetic rock units based on source location, processes and absolute age. Genetic processes include transportation and cooling or deposition mechanisms. These lead to physical- and chemical-properties of the volcanic rocks and provide the history of volcanism and potentially geothermal processes in an area. For many areas in Indonesia the understanding of the volcanostratigraphy is an important dataset for geothermal exploration.

1. Introduction

Based on the investigation of Geological Agency, Ministry of Energy and Mineral Resources Indonesia has 29 Gwe potential geothermal energy that is estimated to be associated with active or dormant volcanic system in volcanic arcs having 6,000 km length [1]. One of important factors in geothermal exploration associated with a volcanic terrane is defining the area's volcanostratigraphy. This is the stratigraphy relating to volcanism and its products, to understand the volcanic history and characteristics of the volcanic deposits or rocks. Principally, volcanostratigraphy deals with the spatial and temporal arrangement, relationship and origin of volcanic strata, or volcanic rock/deposit bodies in an area [2]. The terminology for volcanostratigraphic units in Indonesia was originally proposed in mid-1996 [3] which was then accepted by Wirakusumah et al. (1996) [4], and finally adopted in Stratigraphic Code of Indonesia [5]. A volcano is both the place or opening from which molten rock or gas, and generally both, issues from the earth's (or a planet's in the case of planetary geology) interior onto its surface, and the hill or mountain built up around the opening by accumulation of the rock material [6] (Figure 1).

Molten rock and gas are often referred to as magma, and the location of the opening from which magma emanates onto the surface of the earth is called a crater having diameter (Ø) < 2 km, or a caldera (Ø ≥ 2 km) if it is circular in nature or a fissure if it is linear. Based on planetary research volcanoes are presence in other planets. As such, a volcano is redefined as an opening, or rupture, in a planet's surface or crust which allows hot magma, ash and gases to escape from below the surface.

Figure 1. Mayon Volcano in Philippines as an example of a volcano that is an opening, or rupture, in a planet's surface or crust which allows hot magma, ash and gases to escape from below the surface. (Source: Philippines Institute on Volcanology and Seismology)

2. Scope of Volcanostratigraphy

Volcanostratigraphy can be applied to the regional and local setting of an area. In a regional area it covers more than one volcano whereas in local area it is used for a single volcano. Regional volcanostratigraphy in eastern most Java, for example, volcanic systems are divided into two groups, namely Tertiary paleovolcanoes and Quaternary volcanoes (Figure 2). The second group includes Iyang-Argopuro volcanic complex, and Ijen volcanic complex. The Ijen volcanic complex is comprised of Ijen composite volcano and some volcanic cones appearing after Ijen caldera forming event. In both cases, the volcanism may have developed over time producing old to young stages. Figure 3 shows the development of Soufriere St. Vincent from old to young stages. In Indonesia, there are many single composite volcanoes that have developed from one to two or more conical volcanoes. For instance, Merapi and Slamet volcanoes in Central Java, Lawu volcano in the boundary between Central and East Java, Lamongan Volcano in East Java, and Gamalama volcano in Ternate island, North Maluku.

On representative exposures of volcanic units very detailed volcanostratigraphy is necessary for measuring the thickness of units (Figure 4) and collecting samples for physical and chemical analysis. This may be useful for correlating volcanostratigraphic sections in an area, either having a single volcanic cone or comprising more than one volcanic cones or volcanic complexes.

Paleosol or erosional surface may be observed in the measured section. This indicates that the volcano was inactive during a certain period (dormancy), or volcanic deposits had not been deposited in that area. Figure 5 presents three paleosoil layers in Krakatau, Setu Patok and Mount Patiayam volcanic areas.

Before applying volcanostratigraphy, geologists need to understand basic volcanology, e.g. volcanic geology concepts, genetic volcanism, volcanic landscapes, variation of volcanic rocks, volcanic facies, paleovolcanoes, and super-imposed volcanism. On the basis of a principal in geology, i.e. the present is the key to the past, a volcanic geology concept emphasizes that there is a continuous processes from magmatism through volcanism to sedimentation.

Genetically, magma erupting to the surface creating volcanism. Effusive eruptions produce either lava domes/plugs or lava flows as extrusive igneous rocks. Explosive eruptions yield pyroclasts/hydroclasts with varying intensity depending on volcanic explosivity index [7]. Based on the deposition mechanism the pyroclastic/hydroclastic deposits are divided into falls, flows, surges and pyroclastic density currents

[8, 9, 10]. Another important volcanic material results from slope failure, known as Mount St. Helens type, Bezymianny type and Bandai-san type, are called volcanic debris avalanches or rockslide-avalanches [11, 12, 13, 14].

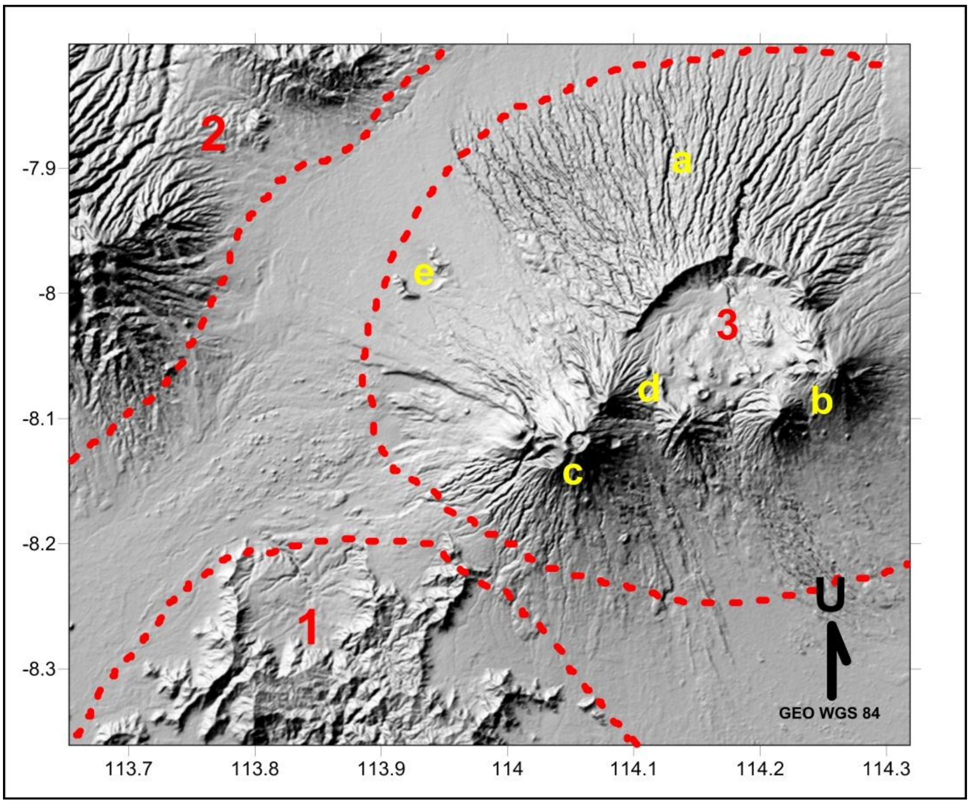


Figure 2. Regional volcanostratigraphy in eastern most Java. Volcanic systems are divided into two groups, namely Tertiary paleovolcanoes (1) and Quaternary volcanoes (2-3). The second group includes Iyang-Argopuro volcanic complex (2), and Ijen volcanic complex (3). The Ijen volcanic complex is comprised of Ijen old composite (a), Marapi volcano (b), Gadung-Raung volcano (c), some smaller cones in the caldera depression (d), and a parasitic cone (e). (Source: Satellite image by US Geological Survey)

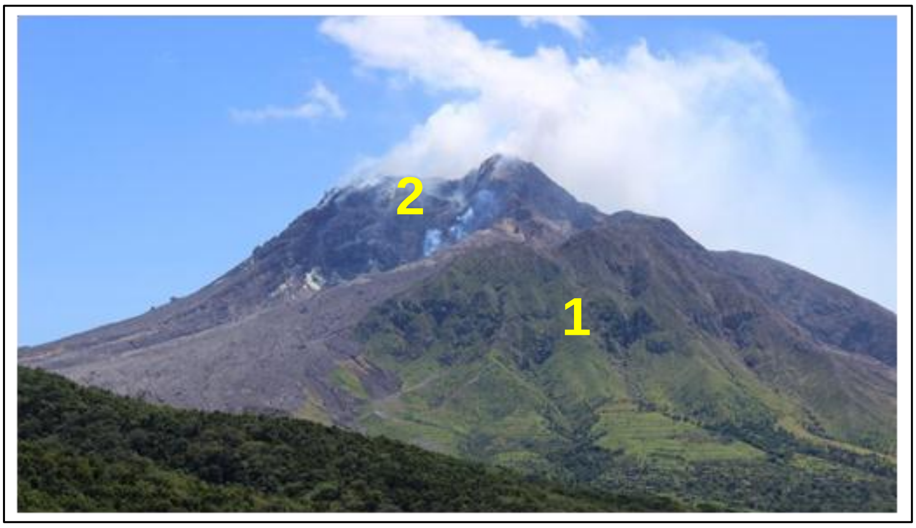


Figure 3. Volcanostratigraphy of a single volcano comprised of old (1) and young (2) volcanic cones of Soufriere St. Vincent. (Source: http://www.mnialive.com/articles/video-montserrat-20-years-after-the-first-eruption-by-martinique-television)

(a)

(b)

(c)

Figure 4. Very detailed (measured sections) volcanostratigraphy on the wall of Rakata volcano (a) in Sunda Strait, Galunggung volcano (b) in Tasikmalaya-West Java, and Setu Patok maar deposits (c) in Cirebon-West Java. Photo by: Sutikno Bronto

The magma related to surface volcanism that remains beneath the surface forms intrusive bodies, such as dikes, sills and cryptodomes in the near-surface to intermediate depth and these would overlie a plutonic body or batholith, depending on size, at deeper depth [15]. These shallower intrusions are commonly located over the deeper solidified magma body (e.g. pluton) and are referred to as subvolcanic intrusive rocks. These rocks may be connected to the surface volcanic bodies such as lava plugs/domes by volcanic necks. Ejected magmatic material are referred to as pyroclastic deposits or tephra. Magma at the surface or the near-surface interacting with surface or ground water results in violent explosions due to the formation of steam and produces an explosive volcanic material called hydroclastics.

(a)

(b)

(c)

Figure 5. Paleosol beneath: (a) The pumice-rich 1883 Krakatau deposit, Rakata Island; (b) Setu Patok maar deposits, and (c) Mt. Patiayam, Muria Penninsula, Central Java. Lower part of the Patiayam hydroclastic deposit is greenish geothermal altered mudstone, whereas the upper part is brownish gravely mudstone. (Photo by: Sutikno Bronto)

Soon after deposition of the loose volcanic material, it immediately erodes and is redeposited as syn-eruptive volcaniclastics [16], such as lahars. Texturally and compositionally, this is a non-epiclastic reworked deposit resembling pyroclastic-hydroclastic deposits, but structurally may be comparable with sedimentary siliciclastic rocks. Volcanic vents (craters or calderas) may situated on land or in the ocean floor, and the erupted material can be deposited separately, or continuously from land to the sea, especially for island volcanic activities.

Volcanic processes form many different types of volcanic landscape. Polygenetic volcanoes may form composite, compound, caldera, somma and shield types, while monogenetic volcanoes form lava domes or pyroclastic cones [17]. Among volcanologists, genetic terms of volcanic deposits/rocks are very familiar, although descriptive names should be mentioned. The genetic names of volcanic material are closely related to volcanic facies classification, namely vent facies, proximal (or near vent) facies, medial facies and distal facies [18].

Volcano stratigraphy is also applied to paleovolcanoes. These are volcanoes that were active in the past, but are now extinct or even been eroded away, so their physical features are not as clear as recent active volcanoes [19]. In Indonesia, generally, paleovolcanoes were active during Tertiary or even pre-Tertiary ages. In some cases paleovolcanoes having Paleogene age were superimposed with Neogene ones and Quaternary volcanoes.

3. Volcanostratigraphic Units

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. There are two types of volcanostratigraphic units, i.e. formal and non-formal names. Formal names are volcanostratigraphic units that follow the Indonesian Stratigraphic Code requirements. Non-formal names do not fulfil this code requirement. Naming of informal volcanostratigraphic units should not create confusion in relation to the formal names. Ranks of volcanostratigraphic formal units, from high to low, are respectively Arc, Super Brigrade, Brigade, Crown, and Hummock.

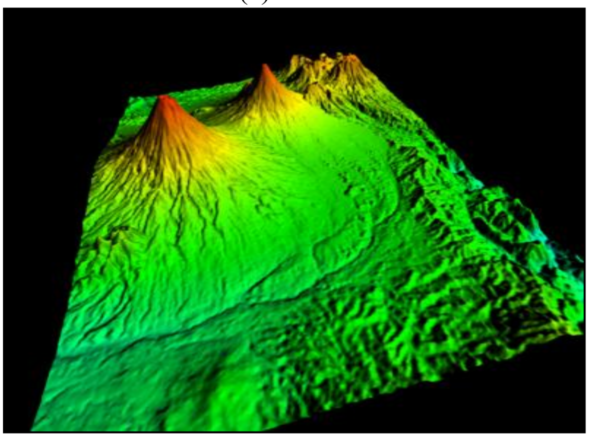
A Crown (in Indonesian: Khuluk) is a basic unit in the volcanostratigraphic classification. This consists of rocks/deposits produced from one eruption point (Figure 1) or more in the case of a composite volcanic body such as, Merapi Crown (Figure 6). Composite volcanoes may erupt various rocks/deposits 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.

Figure 6. Merapi Crown in Central Java, consisting of volcanic rocks/deposits accumulation erupted from a composite volcanic body. (Photo by: Oystein Lund Andersen)

A Hummock (in Indonesian: Gumuk) is a part of a Crown formed as eruptive material at the volcanic Crown in the summit crater or on flanks. 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 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 excentric volcano can be considered as a Hummock. Excentric volcanic eruptions are eruptions from vents near or beyond the base of the main volcanic cone [6]. The Hummock is mappable at a scale of 1:50,000 or larger.

A Brigade (in Indonesian: Bregada) is a volcanostratigraphic unit covering the distribution of volcanic rocks/deposits resulting from two or more volcanic Crown units, or that is related with a caldera formation, e.g. Sumbing-Sindoro Brigade and Tambora Brigade (Figure 7). Compound volcanoes are included in a Brigade, and these indicate double or multiple construction periods of composite volcanoes. The presence of a caldera system reflects a destruction period of a previous composite volcano. Thus, a Brigade always has a volcanic Crown(s) or a caldera system, and is mappable at the scale 1:100,000 or larger.

(a) (b)

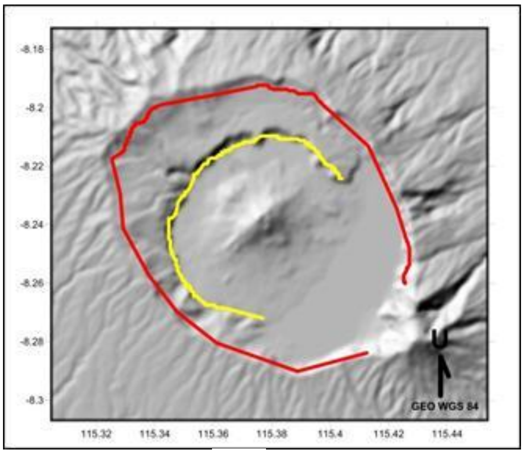


(c)

Figure 7. (a) Tambora Brigade in Sumbawa Island, having a caldera with 6 km in diameter. The caldera was formed in 1815 AD and in 1847-1913 eruption a volcanic child of Doro Afi Toi Hummock was formed. (Photo by: Chris Hooke). (b) Rinjani Brigade in Lombok Island, having a caldera with 4.5 km x 3.5 km in size and Barujari Hummock within the caldera. Source: GVP (Global Volcanism Program). (c) Sumbing-Sindoro Brigade in Central Java, composing of Sumbing Crown and Sindoro Crown. (Photo by: I. Pratomo)

A Super Brigade (in Indonesian: Manggala) is a volcanostratigraphic unit covering the distribution of volcanic rocks/deposits resulting from more than one caldera at one or more volcanic cones. In other words, each (composite) volcanic cone has one or more caldera(s), e.g. Kintamani Super Brigade in Bali Island and Tengger Super Brigade in East Java (Figure 8). Krakatau volcano in Sunda Strait, which has had two prehistoric calderas [20] and the 1883 caldera is also included into Super Brigade unit. A volcanic complex having many volcanic cones, craters and even calderas is also included in the Super Brigade. For example, Dieng Super Brigade in Central Java and Bandung Super Brigade in West Java. A Super Brigade has always two or more Brigade and is mappable at the scale of 1:100,000 or larger.

An Arc (in Indonesian: Busur) is a volcanostratigraphic unit composing many Crowns, Brigades and Super Brigades which have similar tectonic setting. The Arc is mappable at a scale of 1:1,000,000 or larger. The naming of Arc to Quaternary Indonesian volcanoes has been defined, i.e. Sunda Arc, Banda Arc, North Sulawesi–Sangihe Arc and Maluku Arc.



a

b

Figure 8. (a) Air photo of Kintamani Super Brigade in Bali Island, showing two caldera features with a new cone of Batur Crown in the center; (b) Tengger Super Brigade in East Java, comprised of Ngadisari Caldera and Sandsea (Lautan Pasir) caldera with Hummocks of Bromo, Batok and Kursi in the center and Semeru Crown in the background. (Photo by: Andika Permana)

4. Nomenclature of A Volcanostratigraphic Unit

Volcanostratigraphic units from Hummock to Super Brigade, or even Arc, provide a general view of volcanism on a volcanic geological map. In more detailed geologic mapping, e.g. 1:50,000 scale or smaller, rock units based on genetic terms are necessary. These, together with their succession, are very useful in analyzing the character and evolution of each volcano. Table 1 presents an example correlation of volcanostratigraphic units in a volcanic geological map, e.g. Geological map of Soputan volcano, North Sulawesi [21].

The nomenclature of a volcanostratigraphic unit is based on volcanic source, genetic term of volcanic rocks/deposits and chronological events. These use three characters in succession as a combination between a letter and a numeral. Letters refer to the name of the volcanic source (in capital letter) and genetic name of a volcanic rock/deposit (in small letter). Numerals indicate chronological events. For a volcanic source that has no name, the closest and easily recognize geographic name can be applied.

In geothermal exploration, lahars, either explosion lahars or rain-generated lahars, and other reworked deposits may be less important compared with other volcanic rocks/deposits. This is due to their deposition environment that located in the distal area of the source volcano, far away from the volcanic center.

By developing study on physical volcanology, the terminology of pyroclastic density currents [10, 22] should be added to the primary rocks/deposits in Table 1. Other problems are volcanic avalanche (gv) and phreatic explosion (fr) deposits. These are included in secondary rocks/deposits. It may be correct if the avalanche was triggered by non-magmatic processes, such as occurred at Mt. Unzen (Mayuyama) in 1792 [14]. However, for volcanic debris avalanches triggered by either magmatic (known Bezymianny Type) or geothermal (known Bandai Type) processes should be considered as primary rock/deposit units, e.g. the 1980 Mount St. Helens rock-slide avalanche [12] and the 1772 Papandayan avalanche [23, 24]. In addition, volcanic avalanches or glowing avalanches due to dome collapse, such as occurred on Merapi volcano, are also considered are primary rock units.

In volcanic areas, a phreatic explosion can be initiated by a magmatic intrusion into older rocks containing a significant amount of meteoric water (e.g. an aquifer) or a long-lived geothermal system producing very high pressure steam beneath the surface. Both processes yield hydroclastic deposits. Although not directly, this geothermal phenomenon is also related to magmatic processes under the reservoir of geothermal fluid. So, phreatic explosion deposits related to geothermal-magmatic system should be considered primary deposit units. Phreatic deposits classified as secondary deposits are those produced by secondary explosions of hot lava flows or pyroclastic flows entering into a body of surface water, such as a river, lake and sea. Secondary explosions producing secondary phreatic deposits may also occur during a heavy rain fall on top of hot pyroclastic flow deposits, lava flows and lava domes. Usually, the two first events occur on slopes or flanks and along river valleys, while the third one located in volcanic crater.

Table 1: Example correlation table for volcanic map units

AGE		ACTIVITY PERIOD	VOLCANOSTRATIGRAPHIC UNITS				ERUPTION CENTER	ROCK UNIT										REMARKS
								PRIMARY ROCKS/DEPOSITS							SECONDARY ROCKS/DEPOSITS			
RELATIVE	ABSOLUTE		Mg	Br	Khu	Gm		k	l	j	a	s	ll	f	gv	lh	fv	

Explanation:

Mg	Super Brigade	k	lava dome	ll	explosion lahar
Br	Brigade	l	lava flow	f	phreatomagmatic explosion
Khu	Crown	j	pyroclastic airfall	gv	volcanic avalanche
Gm	Hummock	a	pyroclastic flow	lh	rain-generated lahar
		s	pyroclastic surge	fv	phreatic explosion

5. Role of Volcanostratigraphy in Geothermal Exploration

Volcanostratigraphy presenting various volcanic rock/deposit units and chronologically arranged is useful to understand the genetic processes of volcanism. This is an important strategic step in geothermal exploration [25]. Volcanostratigraphic units from Hummock through Crown to Brigade and Super Brigade could represent intensity and timing of volcanism. The Hummock unit indicates low intensity and short life volcanism. On the other hand, Brigade and Super Brigade units imply very high intensity and very long-lived volcanism. Low intensity volcanism and short-life time may reflect a small sized magma reservoir which could be the heat source for a geothermal system. This, together with a small recharge area and minimal groundwater supply would cause a limited life to the geothermal system. However, a large group of Hummocks distributed over a very wide area, as monogenetic cones, could produce a long-lived geothermal system. Very high intensity and very long-lived volcanism yielding Brigade or even Super Brigade units, mainly a caldera or multiple caldera systems, suggest a large magma reservoir(s). This, together with very large recharge area and voluminous groundwater supply may able to produce very long-lived geothermal system.

Volcanic source of the youngest volcanostratigraphic units may indicate the position of the heat source or magma at depth. Principally, heat energy flows conductively depending on characteristics of the volcanic rocks or deposits in the absence of open structure(s) which would be conduits for convective heat transfer. Massive coherent lavas are a very good conductor. Those cover subvolcanic intrusive rocks, volcanic necks, lava domes and lava flows beneath the surface. It is thought that intrusive rocks containing rich in heavy metallic elements, e.g. iron and magnesium in basic- and ultra basic rocks, would be better conductor than that having poor ones. Whereas, volcaniclastic deposits with high porosity and permeability, and rich in liquid (meteoric-and or magmatic water) will play in convective role through their porosity and permeability. These two end member cases should cover the distribution of volcanic geothermal system to be encountered.Genetically, potential volcaniclastic deposits for geothermal reservoir are pyroclastics, hydroclastics, autoclastics, and cataclastics because relatively they are loose material and commonly are good in porosity and permeability. Pyroclastic and hydroclastic deposits are produced by magmatic- and phreatic eruptions, respectively. Autoclastic rocks or blocky lavas are formed during super cooling processes of either lava domes or lava flows. Cataclastic deposits are yielded by deformation due to tectonic- or volcanic activities, namely fault breccias, volcanic debris avalanches or rockslide avalanches. Voluminous hydroclastic deposits may suggest an area containing ample meteoric water.

The study of volcanostratigraphic units, their volume, physical- and chemical-characteristics and stratigraphic successions will assist the interpretation of potential candidates for reservoir and cap rocks/deposits. These are important to estimate the location and size of a potential geothermal system.

6. Conclusion

Volcanostratigraphic classification is a systematic grouping of volcanic rock/deposit bodies or strata. Ranks of volcano-stratigraphic formal units, from high to low, are respectively Arc, Super Brigrade, Brigade, Crown, and Hummock. A Crown is a basic unit in the volcanostratigraphic classification. Hummock unit may reflect a short-lived geothermal system, but Brigade and Super Brigade units could imply a very long-lived geothermal system. These are important parameters in understanding the genetic processes related to volcanism and the potential size and viability for development of a geothermal system.

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