HYDROGEOLOGIC CONTROLS ON STRATOVOLCANIC GEOTHERMAL SYSTEMS

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ABSTRACT

High-temperature geothermal systems associated with stratovolcanoes (also known as composite cones) can be found at locations around the world. For example, in Indonesia, most successful geothermal developments have been completed on the lower slopes of (or adjacent to) stratovolcanoes where there are surface manifestations of a hydrothermal system.

Understanding the hydrogeology of a stratovolcano provides insight into the feasibility of developing a geothermal resource for power generation. This paper presents global examples of successful development of stratovolcanic geothermal systems, and focuses on the key hydrological and geological characteristics necessary for development of stratovolcanic geothermal systems including surface manifestations, recency of eruption, depth to basement, depth to heat source, and groundwater flow.

1. INTRODUCTION

Stratovolcanoes are steep, conical volcanoes built by the eruption of viscous lava flows and pyroclastic materials in approximately equal proportions. The layering of these products gives stratovolcanoes their other common name of composite volcanoes or composite cones. Usually constructed over tens to hundreds of thousands of years, stratovolcanoes may erupt a variety of magma types, including basalt, andesite, dacite, and rhyolite. The more viscous lavas (excluding basalt) allow gas pressures to build up to high levels, which often result in highly explosive eruptions.

Stratovolcanoes are located around the world particularly near subduction zones or rifting plate boundaries. Many stratovolcanoes have steep profiles and are topographically dominant features (due to lava viscosity and eruptive rate). According to the Smithsonian Institution Global Volcanism Program (GVP) database of more than 3000 Holocene and Pleistocene volcanic centers, stratovolcanoes are the most common type with about 1400 stratovolcanoes worldwide (about 45% of all volcano types). Well known stratovolcanoes include: Mt St. Helens, Mt Rainier, and Mt Shasta in the US; Popocatépetl in Mexico; Cotopaxi in Ecuador; Galeras in Colombia; Eyjafjallajökull in Iceland; Mt Vesuvius and Mt Etna in Italy; Mt Fuji in Japan; Pinatubo and Mayon in the Philippines; Galunggung, Krakatoa, Merapi, Tambora, and many more in Indonesia; Kilimanjaro in Tanzania; and here in New Zealand, Taranaki, Ruapehu, and Ngauruhoe.

Given that stratovolcanoes are typically towering peaks, there is a common misconception that all stratovolcanoes are obvious heat sources for high-temperature geothermal systems. However, most stratovolcanoes, especially ones located outside of volcanic arc settings, do not host producible geothermal resources due to several factors including hydrogeologic conditions, steep topography, volcanic activity, and timing (e.g., relict systems).

Perhaps, the most famous stratovolcano in the world is Mt Fuji in Japan. Fujisan, as it is commonly known, is composed of a group of 3 overlapping cones and more than 100 peripheral cones. The cones comprise interbedded ashfall deposits, lahar deposits, ignimbrites, and lava flows. The complex is about 80,000 years old, and the most recent activity occurred circa 1708 CE. Yet, despite its imposing, conical form, Mt Fuji does not host a geothermal system. This is due to several geological and hydrogeological factors including a relatively deep magma chamber (>10 km) and highly permeable young volcanic materials on the flanks of Mt Fuji, which act as the primary aquifer and allow groundwater to quickly flow along the flanks of the volcano to the base (Adhikari, 2014). Tritium analyses have revealed that water emerging near the base is not old – annually, about 77% of the precipitation flows out at the base of Mt Fuji, and another ~20% is lost by evaporation (Wohletz & Heiken, 1992). Therefore, very little of the recharge water enters the volcano's interior to be heated.

2. STRATOVOLCANIC GEOTHERMAL SYSTEMS

High-temperature geothermal systems associated with stratovolcanoes are commonly located along or near convergent plate margins, near transform plate boundaries, and within spreading centers and rifts. Stratovolcanoes allow intrusives in the form of magma chambers or dikes to reach shallow depths commonly between 1 and 10 km deep. As groundwater percolates through a faulted, permeable volcanic edifice, it may encounter a heat source (magma or hot rocks). If conditions are favorable, the interaction of the water and the magma may create hydrothermal plumes (convection cells) where hot fluids are circulated within a permeable zone. The hot fluid reacts with the surrounding country rock, dissolving the rock and adding various chemical elements to the hydrothermal fluid. Over time, the water in the system will neutralize forming a high-temperature, mature system suitable for power generation. Deeper intrusives need less time to produce neutralized waters, but require movement of a larger volume of meteoric water before a full convective cell can form (Bogie et al., 2005).

Bogie et al. (2005) proposed a classification scheme for magmatic-related hydrothermal systems based on the hydrology of a system. Subaerial systems (that is, on the land surface as opposed to submarine) can be divided into basinal, stratovolcano, and giant vapor-dominated systems. Stratovolcanic geothermal systems can be further subdivided into immature and mature systems depending both upon the depth of the intrusive driving the system and the age of the system. Younger or immature systems, such as Sorik Marapi in North Sumatra, typically exhibit surface manifestations such as acid-sulfate hot springs, and superheated solfataras. Some immature systems with associated magmatic solfataras will never evolve into mature systems, however, because they can be destroyed by volcanic eruptions, for example, Mt Pinatubo in the Philippines (Bogie et al., 2005).

Mature stratovolcanic geothermal systems commonly have thermal features with distinctive geochemical differentiation based on elevation. At high elevations, the gas chemistry of fumaroles differs significantly from that of magmatic solfataras in immature systems. At lower elevations, neutral-Cl springs are found with a HCO_3/SO_4 ratio that increases with decreasing elevation (Bogie et al., 2005). Because of topography and the hydrologic gradient, the fluids tend to flow laterally away from the volcanic center, forming hydrothermal outflows. Neutral-Cl springs occur as the lowest elevation thermal features. This is a key difference to immature systems, which can also have Cl-bearing spring waters, but at high elevations.

Stratovolcanic geothermal systems have been developed for geothermal power at locations around the world. Table 1 lists more than 30 geothermal power plants associated with stratovolcanoes with a total installed capacity of 2,300 MWe (excluding Indonesia). Almost all of these locations are in a volcanic arc setting that forms above a subduction zone. In Indonesia, more than 33 high-temperature volcanic geothermal systems (mainly associated with strato-volcanoes) have been investigated by surface exploration and drilling during the last 40 years (Hochstein & Sudarman, 2017). Of these systems, 12 fields associated with strato-volcanoes have been developed for electric power production resulting in a total installed capacity of about 1,618 MWe (Table 2). All are located within Indonesian volcanic arc segments.

Worldwide, approximately 10% of volcanoes located in convergent, volcanic arc settings currently host a developed geothermal system producing electricity, or are power-capable, and the percentage could be much higher with additional exploration and access to power markets (Stelling et al., 2016). In contrast, there are few geothermal developments associated with stratovolcanoes in extensional tectonic settings such as the East Africa Rift System.

Table 1: Geothermal Power Plants Associated with Holocene Stratovolcanic Geothermal Systems (excluding Indonesia)

Geothermal Power Plant	Installed Capacity (MWe)	Location	Associated Stratovolcano(es)	Elevation (m asl)	Last Known Eruption	Primary Rock Type
Cerro Pabellón	48.0	Chile	Apacheta-Aguilucho	5,557	unknown	Andesitic-dacitic
Boca de Pozo	15.0	Costa Rica	Miravalles	2,028	1946	Andesitic
Miravalles I-V	158.0	Costa Rica	Miravalles	2,028	1946	Andesitic
Ahuachapán	95.0	El Salvador	Apaneca Range	2,036	unknown	Basaltic-andesitic
Berlin	109.0	El Salvador	Tecapa	1,593	unknown	Basaltic-andesitic
Bouillante	16.0	Guadeloupe	La Soufrière	1,467	1977	Andesitic
Amatitlán	25.0	Guatemala	Pacaya	2,569	2019	Basaltic
Zunil	24.0	Guatemala	Volcán de Almolonga	3,173	1818	Andesitic
Hatchobaru	110.0	Japan	Kujusan	1,791	1996	Andesitic
Kakkonda	80.0	Japan	Akita-Komagatake	1,637	1971	Basaltic-andesitic
Ogiri (Daiquiri)	30.0	Japan	Karakunidake	1,700	2018	Andesitic
Onuma	9.5	Japan	Hachimantai	1,613	5350 BCE	Andesitic
Otake (Ohdake)	12.5	Japan	Kujusan	1,791	1996	Andesitic
Sumikawa	50.0	Japan	Hachimantai	1,613	5350 BCE	Andesitic
Takigami	25.0	Japan	Kujusan	1,791	1996	Andesitic
Uenotai	28.8	Japan	Kurikomayama	1,627	1950	Andesitic
Okeanskaya	3.5	Japan/Russia (Kuril Islands)	Sashiusudake (Baransky)	1,125	1951	Andesitic
Mendeleevskaya	3.5	Japan/Russia (Kuril Islands)	Raususan (Mendeleev)	882	1880	Andesitic-dacitic
Tres Vírgenes	10.0	Mexico	Tres Vírgenes	1,934	unknown	Andesitic
Kawerau	168.8	New Zealand	Pūtauaki	820	300 BCE	Dacitic
Momotombo	78.0	Nicaragua	Momotombo	1,270	2016	Basaltic
San Jacinto-Tizate	82.0	Nicaragua	Telica	1,036	2018	Basaltic
Lihir	50.0	PNG	Luise	700	unknown	Basaltic
Maibarara	32.0	Philippines	Makiling	1,090	1350	Andesitic-rhyolitic
Makban	449.0	Philippines	Makiling	1,090	1350	Andesitic-rhyolitic
Mindinao	106.0	Philippines	Apo	2,938	unknown	Andesitic
Palinpinon	192.5	Philippines	Cuernos de Negros	1,862	unknown	Andesitic
Tiwi	234.0	Philippines	Malinao	1,548	unknown	Andesitic
Pico Vermelho	11.5	Portugal (Azores)	Agua de Pau	947	1564	Trachytic
Mutnovsky	50.0	Russia	Mutnovsky	2,288	2000	Basaltic
Total:	*2306.6*					

[1] Volcano information from the database of the Global Volcanism Program

Table 2: Indonesian Geothermal Power Plants Associated with Holocene Stratovolcanic Geothermal Systems

Geothermal Power Plant	Installed Capacity [1] (MWe)	Location	Associated Stratovolcano(es)	Elevation (m asl)	Last Known Eruption	Primary Rock Type	Group [2]
Sibayak	12.0	North Sumatra	Singkut	2,181	1881	Andesitic	A
Ulubelu	220.0	Lampung	Rendingan	1,700	unknown	Andesitic	A
Salak (Awibengkok)	377.0	West Java	Perbakti-Gagak	1,699	1939	Andesitic	C
Wayang Windu	227.0	West Java	Malabar	2,343	unknown	Andesitic	B
Patuha	55.0	West Java	Patuha	2,422	unknown	Andesitic	A
Kamojang	235.0	West Java	Guntur	2,249	1847	Andesitic	C
Darajat	270.0	West Java	Kendang	2,594	unknown	Andesitic	C
Dieng	60.0	Central Java	Butak Petarangan; Dieng	2,565	2018	Andesitic	B
Karaha	30.0	West Java	Telaga Bodas	2,201	unknown	Basaltic	B
Mataloko	1.8	NTT	Inierie	2,245	8050 BCE	Andesitic	C
Ulumbu	10.0	NTT	Poco Leok	1,675	unknown	Andesitic	A
Lahendong	120.0	North Sulawesi	Lengkoan	1,202	unknown	Andesitic	A
Total:	*1617.8*						

[1] As of May 2018 (Source: ThinkGeoEnergy.com)
[2] As defined by Hochstein & Sudarman (2017): **Group A** - Young stratovolcanoes (n = about 100); **Group B** - Older, partly eroded stratovolcanoes (n = 20 compound volcanoes, and n = 15 volcanoes with caldera or maar structure); **Group C** - Volcanoes (n = a few) associated with peripheral magmatic sources that also support nearby active stratovolcanoes and young volcanic centers.

3. HYDROGEOLOGICAL CONTROLS ON STRATO-VOLCANIC GEOTHERMAL SYSTEMS

The hydrodynamic regime in an active stratovolcano depends primarily on the magmatic heat supply, the pattern and rates of precipitation, vertical and lateral recharge, and the permeability structure of the edifice (Hurwitz et al., 2003). The permeability is subject to the greatest uncertainty. In volcanic rock, permeabilities are highly heterogenous – for example, the permeability of basalt can range over 6 orders of magnitude (Wohletz, & Heiken, 1992). This huge range results largely from the variability of fracture density, aperture, and geometry, and is also strongly influenced by the degree of hydrothermal alteration and fracture filling. Also, stratovolcanoes consist of roughly slope-parallel layered lava flows and pyroclastic deposits. This implies that permeability anisotropy should be significant, at least at shallow depths.

Understanding the hydrogeology of a geothermal resource provides insight into recharge and possible outflow directions. Recent studies indicate that recharge availability exerts strong control over the heat flux of hydrothermal systems (Harvey et al., 2015). Recharge is in turn governed by permeability, structure, lithology, rainfall, topography, and proximity to a surface water supply such as a lake or ocean. The permeability structure of the volcanic edifice and underlying material is the dominant control on the water table: low permeability and high recharge lead to a saturated edifice, whereas high permeability and low recharge results in a deep water table (Hurwitz et al., 2003). When permeabilities are isotropic, water table elevations decrease with increasing heat flux. This is because high heat flow tends to decrease fluid viscosity, increasing hydraulic conductivity so that the same amount of topography-driven flow can be accommodated with a milder water table gradient. The relationship between recharge and convective heat flux is consistent with recent numerical modeling that relates system heat output to rainfall catchment area (Harvey et al., 2015).

The presence or absence of a hydrothermal plume within a stratovolcano is also relevant to the potential for geothermal resources. A hydrothermal plume requires a sufficient source of heat and magmatic volatiles at depth, strong buoyancy forces, and a relatively weak topography-driven groundwater flow system. Numerical simulations by Hurwitz et al. (2003) suggest that only under a narrow range of conditions will a high water table (thus, sufficient water for production) and a significant hydrothermal plume develop within an edifice. Hence, expensive drilling for geothermal exploration on the upper flanks of strato-volcanoes is unlikely to be productive.

4. KEY CHARACTERISTICS FOR GEOTHERMAL PROSPECTIVITY OF STRATOVOLCANOES

The characteristics of individual stratovolcanic geothermal systems are a function of site-specific variables such as the nature and depth of the heat source, the dominant heat transfer mechanism, permeability and porosity distribution, rock mechanical properties, fluid/rock chemistry, and fluid recharge rates and sources.

4.1 Surface thermal manifestations

Surface thermal manifestations (hot springs, fumaroles, etc.) located on the flanks of stratovolcanoes are one of the most prospective indications of the presence of a high-temperature geothermal system. Flank fumaroles are more likely to be associated with hydrothermal activity, whereas summit fumaroles are more likely to be, at least in part, a surface manifestation of magmatic degassing (Stelling et al., 2016). Thus, summit fumaroles are likely not indicative of an active, producible hydrothermal system.

The absence of surface thermal manifestations such as fumaroles or steaming ground makes it unlikely that an accessible high-temperature geothermal system exists beneath stratovolcanoes (although it is possible that a hidden geothermal system could exist beneath a stratovolcano). It would be a high-risk geothermal prospect if there were no surface features that can be used for confirmation.

4.2 Recency of eruption

The age of a magmatic system is an important geological parameter for evaluating geothermal prospectivity. Active and recent magmatism often indicates an excellent underlying heat source, while inactive or extinct magmatism may be associated with large-scale intrusions of igneous rock (plutons) at greater depths (>5 km depth) with remnant heat and additional heating by natural radioactive decay in granitic rock (Harvey et al., 2016).

In a recent study, Stelling et al. (2016) found that volcanic centers with eruptions within the last 900 years account for 97% of installed geothermal power plants indicating that relatively recent eruptive activity is an important characteristic for stratovolcanic geothermal systems. The strong correlation of the presence and size of flank fumaroles on stratovolcanoes can be used as an initial exploration tool to identify centers most likely to host high-temperature, power-producing geothermal systems.

4.3 Depth to basement

The use of the term "basement" usually implies a rock type that is deeper than any considered relevant to the current economic or research interest. In the context of stratovolcanic geothermal systems, the basement rock typically refers to the crystalline rock beneath the volcanic materials. The basement itself is unlikely to provide good heat storage to support a geothermal reservoir under production, so reservoirs that have a good thickness of more porous volcanic material above the basement will be more favorable for long term production. For example, the few volcanoes along the Western Branch of the East African Rift (EARS) have produced relatively low volumes of eruptive material (typically <1 km thick). In comparison, the thickness of volcanics at Olkaria (Kenya) in the Eastern Branch of EARS is thought to be on the order of 5 km. On this basis, the relatively thin volcanic cover found in the Western Branch is considered a limitation for commercial geothermal reservoir development.

4.4 Depth to heat source

The depth to a magmatic heat source beneath a stratovolcano has a direct relationship with the development of a hydrothermal plume (convection cell) capable of transferring heat to shallow depths. For example, magma bodies can be found beneath the Eastern Branch of EARS at depths as shallow as 2-6 km, a critical factor for the occurrence of high-temperature geothermal systems. In the Western Branch, magma bodies are not identifiable. Therefore, the deeper magma bodies found in the Western Branch are less likely to form hydrothermal plumes and associated geothermal reservoirs.

4.5 Groundwater flow

Stratovolcanoes with summits high above the surrounding terrain are the sites for increased precipitation and infiltration of meteoric waters that can feed hydrothermal systems, if present. Groundwater moves through the volcanic aquifer system along preferred pathways developed during lava deposition. The interbedded pyroclastic deposits and lava flows of stratovolcanoes are distinguished by high but uneven permeability. For example, the highly permeable young volcanic materials on the flanks of Mt Fuji allow groundwater to quickly flow along the flanks of the volcano to the base (Figure 1). Only a small percentage of precipitation infiltrates into the deep volcanic edifice. In many cases, high infiltration rates for rainfall and colder recharge near volcano summits can hydrologically mask any geothermal systems because the summit and slopes are saturated with cold water to depths of 500 m to 1 km (Wohletz & Heiken, 1993).

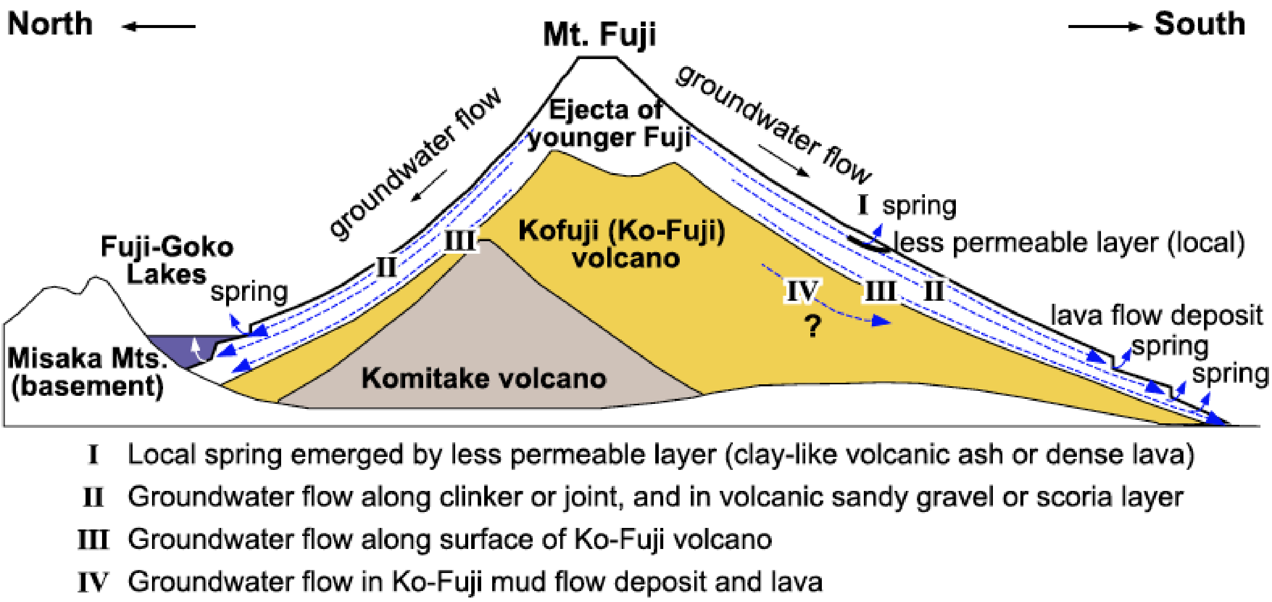

Figure 1: Generalized schematic of groundwater flow system at Mt Fuji illustrating how the vast majority of groundwater flows through the permeable deposits on the flanks of the volcano away from the central edifice (Ono et al., 2018).

5. CONCLUSIONS

Around the world, large stratovolcanoes appear to be obvious sources of geothermal heat that can be used to produce electricity. At many sites, they are – globally, more than 40 geothermal power plants have been developed using stratovolcanic geothermal resources. However, the geothermal prospectivity of stratovolcanoes must be evaluated on a site-specific basis. Key characteristics that are indicative of high-temperature geothermal potential include: (1) presence of flank fumaroles, (2) eruptions in the past 1000 years, (3) depth to basement of at least several km to allow development of a reservoir within permeable volcanic material, (4) relatively shallow depth (2-6 km) of large magma bodies capable of developing a hydrothermal plume (convection cell), and (5) relatively weak topography-driven groundwater flow, which allows infiltration of groundwater toward the center of the volcanic edifice to support development of a convective hydrothermal plume.

Development of stratovolcanic geothermal systems is dependent on understanding faulting and groundwater flow. Specific exploration techniques should include: (1) detailed structural geologic mapping, (2) petrogenetic modeling of lava samples to determine composition and depth of parent magma for heat source evaluation, (3) isotopic assessment of gas emissions and springs, (4) hydrological surveys of the field and entire catchment basin (watershed) including cold springs, streams, rainfall patterns, water levels in wells, and any information about groundwater movement, (5) stream surveys (for chloride and conductivity), and (6) deep, slimhole wells to 1000-1500 m or more.

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