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

Hydrogeological Controls on Stratovolcanic Geothermal Systems in the Western Branch of the East African Rift System

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Keywords: Stratovolcanoes, hydrogeology of geothermal systems, Western Branch, East African Rift System, Virunga Volcanic Province, Rungwe Volcanic Province, Karisimbi, Ngozi

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.

In the Western Branch of the East African Rift System, stratovolcanoes are located in two areas: the Virunga Volcanic Province (VVP) in Rwanda/DRC/Uganda, and the Rungwe Volcanic Province (RVP) in southwestern Tanzania. Extensive geothermal exploration surveys have been performed at the stratovolcano Karisimbi in the VVP (including a 3,000-m deep well), and the former stratovolcano Ngozi (now a caldera) in the RVP, based on the tacit assumption that they host high-temperature reservoirs. The results of the exploration work completed to date suggest that neither site appears to host a high-temperature geothermal system.

Understanding the hydrogeology of a geothermal system provides insight into recharge and possible outflow directions. This paper will compare the data from recent studies at Karisimbi and Ngozi and evaluate the hydrological and geological characteristics similar to both sites including: (1) the absence of surface manifestations (hot springs, fumaroles, alteration), (2) the presence of CO_2-rich cold or tepid springs, (3) the shallow depth to Proterozoic basement rock, (4) the likely deep source of heat and magmatic volatiles, and (5) the relatively strong topography-driven groundwater flow systems. Lessons learned from Karisimbi and Ngozi are applicable to possible future geothermal resource assessments at other stratovolcanoes in the Western Branch including, for example, at Kyejo (RVP) or Kinigi (on the SE flanks of Visoke in the VVP).

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 (calc-alkaline series found in arc settings) and phonolite, trachyte, and rhyolite (more alkaline series found in rift settings). 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, Krakatau, Merapi, Tambora, and many more in Indonesia; and here in New Zealand, Taranaki, Ruapehu, and Ngauruhoe (used as a stand-in for the fictional Mount Doom in the Lord of the Rings film trilogy).

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.

Thus, 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 potential of stratovolcanic geothermal resource development in the Western Branch of the East Africa Rift System (EARS) by comparing two explored sites, and the reasons that neither prospect appears to host a high-temperature geothermal system.

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 (Figure 1). 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).

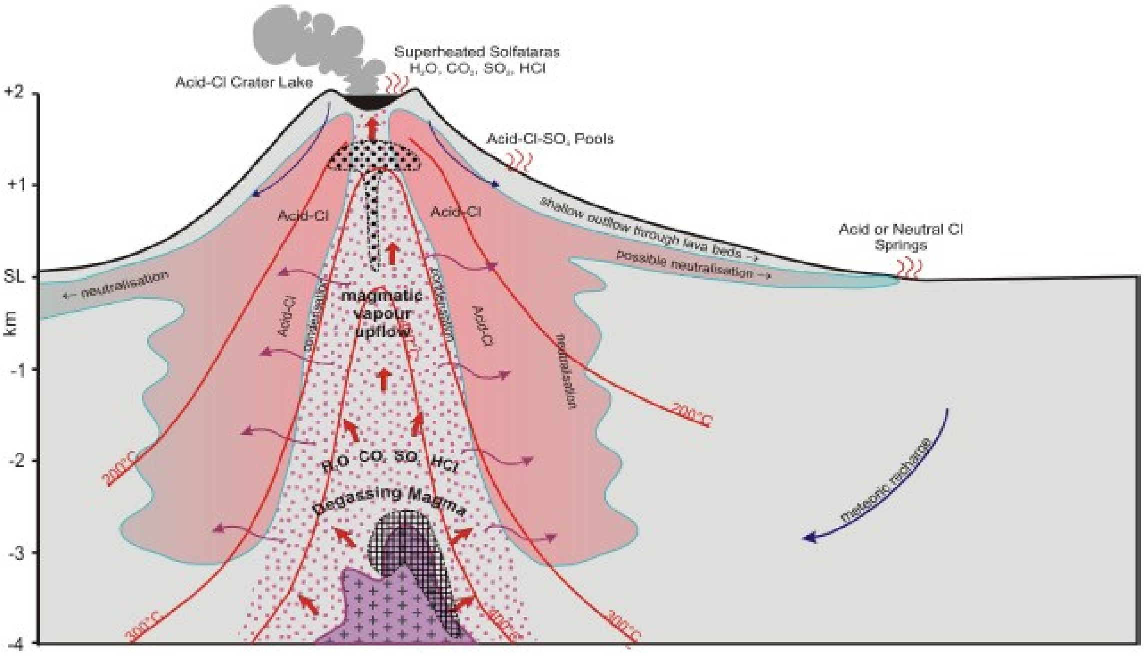

Figure 1: Schematic model of an immature stratovolcanic type hydrothermal system (Bogie et al., 2005).

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 stratovolcanoes) have been investigated by surface exploration and drilling during the last 40 years (Hochstein & Sudarman, 2017). Of these systems, 12 fields associated with stratovolcanoes 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)	Rausudan (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
[2] Indonesian geothermal power plants summarized in Table 2

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. STRATOVOLCANOES IN THE EAST AFRICAN RIFT

The East African Rift System (EARS) is an active area of extension and crustal thinning, which extends over 3000 km from the Red Sea southward to Mozambique. It crosses two regions of topographic uplift, the Ethiopian and Kenyan domes that developed as a result of mantle plume activity 30-40 Ma (Ebinger & Sleep, 1998). The Eastern Branch consists of the Afar and Main Ethiopian Rift located in Eritrea, Djibouti, and Ethiopia, and the Kenya Rift, which extends south through Kenya into northern Tanzania. A separate, Western Branch of EARS runs to the west of the Tanzanian Craton through western Uganda, eastern DRC, Rwanda, Burundi, western and southern Tanzania, Malawi, and into Mozambique (Figure 2).

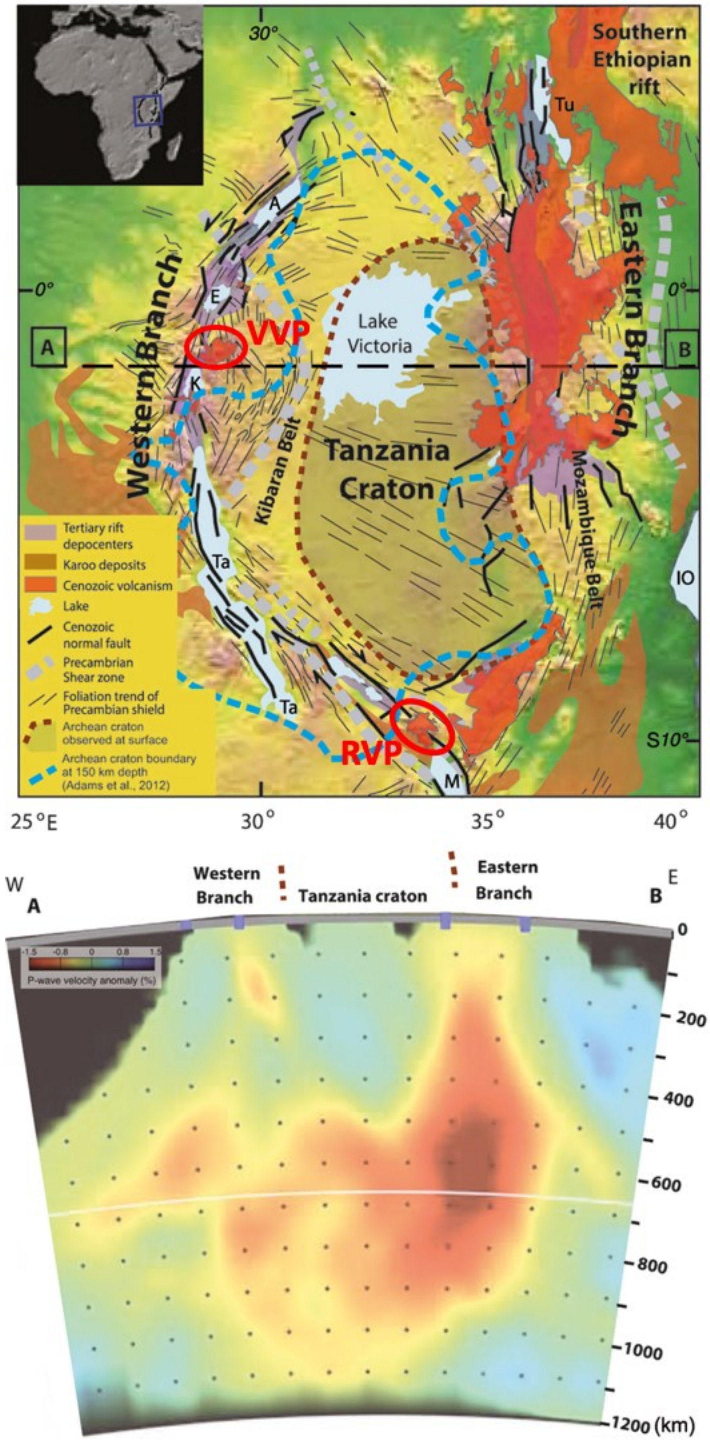

Figure 2: Top – Geological map of EARS showing the extent of the Tanzanian craton, surrounded on both sides by active rift branches, and the much higher volume of Cenozoic volcanism (in red) in the Eastern Branch compared to the Western Branch. The only stratovolcanoes in the Western Branch are located in the VVP (Virunga Volcanic Province) and the RVP (Rungwe Volcanic Province). Bottom – W-E cross section showing P-wave velocity mantle tomography observations (Mulibo & Nyblade, 2013) that illustrates the thick Tanzanian craton underlain by hot mantle material deflected towards the Eastern Branch of the EARS (Koptev et al., 2015).

The Eastern and Western Branches of EARS show marked differences in their igneous activity (especially its volume) and morphology. Intense magmatism and continental volcanism are largely present in the Eastern Branch of EARS, while the Western Branch to the west of the Tanzanian craton has only scattered Cenozoic volcanism (Figure 2). The differences in volcanism, uplift, and subsidence probably reflect the way the mantle plume was channeled underneath East Africa (Ring, 2014). The magma-rich Eastern Branch of EARS is characterized by a broad zone of shallow (5-15 km) and smaller magnitude seismicity, but voluminous Cenozoic volcanism while the Western Branch of EARS is characterized by low-volume volcanic activity, large (M>6.5) magnitude earthquakes, and hypocenters at depths up to 30-40 km (Koptev et al, 2015). In the Western Branch of EARS, there are only 4 isolated areas of Cenozoic volcanism, which are from N to S: Toro-Ankole in Uganda, Virunga Volcanic Province (VVP) and South Kivu in DRC-Rwanda, and Rungwe Volcanic Province (RWP) in SW Tanzania. As a result of the paucity of volcanism in the Western Branch, the volume of volcanic rocks is much less than the Eastern Branch: Rosenthal et al. (2009) estimates that the volume of volcanics in the Western Branch is ~100,000 km^3, considerably less than in the Eastern Branch with >900,000 km^3.

The differences in volcanism and uplift/subsidence in the Eastern and Western branches of EARS reflect different mantle temperatures, with temperatures underneath the Eastern Branch probably 100-150°C higher than underneath the Western Branch (White et al., 1987). This difference in mantle plume activity affects the geothermal gradient, degree of partial melting, magma type, and magma chamber development (Figure 2). The volcanic centers in the Western Branch are confined to the rift zones and limited age data suggest that magmatic activity occurs periodically rather than continuously (Harðarson, 2015). Also, the volcanic centers in the Western Branch are mostly fed from deep magmatic sources, with rapid ascent of magma to the surface, imparting minimal heat input to the upper crust (Hinz et al., 2018). As a result, stratovolcanoes are few and far between in the Western Branch of EARS. As summarized in Table 3, most stratovolcanoes in EARS are located in the Eastern Branch (n=29). The only stratovolcanoes in the Western Branch (n=7) are found in the VVP and RVP (Table 4). The differences in volcanic and geothermal characteristics between the two branches are summarized in Table 5, and explain why the Eastern Branch is much more prospective for geothermal development than the Western Branch (primarily due to higher heat flow, magmatic intrusions, and thinner crust).

Table 3: Holocene Stratovolcanoes in the Eastern Branch of the East African Rift System [1]

Volcano Name	Volcano Type	Country	Elevation (m asl)	Last Known Eruption	Primary Rock Type	Known or Likely Geothermal System?
Jalua	Stratovolcano	Eritrea	713	unknown	Basaltic	unknown
Alid	Stratovolcano	Eritrea	904	unknown	Rhyolitic	Yes
Dubbi	Stratovolcano	Eritrea	1,625	1861	Basaltic	Yes
Nabro	Stratovolcano	Eritrea	2,218	2012	Trachytic	Yes
Mallahle	Stratovolcano	Ethiopia-Eritrea	1,875	unknown	Trachytic	unknown
Sork Ale	Stratovolcano	Ethiopia-Eritrea	1,611	unknown	Basaltic	unknown
Mousa Alli	Stratovolcano	Ethiopia-Eritrea-Djibouti	1,993	unknown	Rhyolitic	unknown
Gada Ale	Stratovolcano	Ethiopia	287	unknown	Basaltic	unknown
Dalafilla	Stratovolcano	Ethiopia	578	2008	Basaltic	Yes
Bora Ale	Stratovolcano	Ethiopia	668	unknown	Basaltic	Yes
Ale Bagu	Stratovolcano	Ethiopia	988	unknown	Basaltic	unknown
Borawli	Stratovolcano	Ethiopia	784	unknown	Basaltic	unknown
Afderà	Stratovolcano	Ethiopia	1,250	unknown	Rhyolitic	unknown
Ma Alalta	Stratovolcano	Ethiopia	1,745	unknown	Rhyolitic	Yes
Dabbahu (Boina)	Stratovolcano	Ethiopia	1,401	2005	Basaltic	Yes
Groppo	Stratovolcano	Ethiopia	852	unknown	Rhyolitic	unknown
Gabillema	Stratovolcano	Ethiopia	1,459	unknown	Rhyolitic	unknown
Ayelu	Stratovolcano	Ethiopia	2,145	unknown	Rhyolitic	Yes
Adwa (Amoissa)	Stratovolcano	Ethiopia	1,733	unknown	Rhyolitic	Yes
Fentale	Stratovolcano	Ethiopia	2,007	1820	Basaltic	Yes
Boset-Bericha	Stratovolcano	Ethiopia	2,447	unknown	Rhyolitic	Yes
Aluto	Stratovolcano	Ethiopia	2,335	50 BCE	Rhyolitic	Yes, 7.5 MWe installed but not operating
Corbetti	Caldera / Stratovolcano	Ethiopia	2,320	unknown	Rhyolitic	Yes
Chiracha	Stratovolcano	Ethiopia	1,636	unknown	Rhyolitic	unknown
South Island	Stratovolcano	Kenya	800	1888	Basaltic	Yes
Longonot	Stratovolcano	Kenya	2,776	1863	Trachytic	Yes
Suswa (Ol Doinyo Onyoke)	Shield / Caldera / Stratovolcano	Kenya	2,356	unknown	Phonolitic-Trachytic	Yes
Ol Doinyo Lengai	Stratovolcano	Tanzania	2,962	2019	Foiditic	Unknown
Meru	Stratovolcano	Tanzania	4,565	1910	Phonolitic	Yes

[1] Volcano information from the database of the Global Volcanism Program. Note that many East African volcanoes have multiple vents and may be more accurately described as composite volcanoes.

Table 4: Holocene Stratovolcanoes in the Western Branch of the East African Rift System

Volcano Name	Volcano Type	Country	Elevation (m asl)	Last Known Eruption	Primary Rock Type	Known or Likely Geothermal System?
Muhavura	Stratovolcano	Uganda-Rwanda	4,103	unknown	Trachybasaltic	unknown
Visoke	Stratovolcano	DRC-Rwanda	3,696	1957	Trachyandesitic	unknown
Karisimbi	Stratovolcano	DRC-Rwanda	4,490	8050 BCE	Trachybasaltic	No
Nyiragongo	Stratovolcano	DRC	2,953	2019	Foiditic	unknown
Ngozi	Caldera / Old Stratovolcano	Tanzania	2,614	1450	Trachytic	unknown
Rungwe	Stratovolcano	Tanzania	2,953	1250	Trachytic	unknown
Kyejo (Kiejo)	Stratovolcano	Tanzania	2,176	1800	Trachytic	unknown

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

Table 5: Comparison of Volcanic and Geothermal Characteristics between the Eastern and Western Branches of EARS

Parameter	Eastern Branch	Western Branch
Volcano type	Central volcanoes with calderas	Rare caldera systems
Volcanic activity	Voluminous Cenozoic volcanism	Low-volume volcanic activity
Estimated volume of volcanics [1]	900,000 km^3	100,000 km^3
Depth to magma	Shallow magma bodies (2-6 km)	Deep - probable absence of shallow magma bodies
Relative thickness of lithosphere	Thin	Thick
Relative thickness of volcanics	Thick (1-5 km)	Thin (<1 km)
Primary magma type [2]	Basalt-trachyte-rhyolite suite	Potassic mafic - intermediate magmatic products
No. of Holocene stratovolcanoes	29 (Table 3)	7 (Table 4)
Relative seismicity [3]	Smaller magnitudes and shallower (5-15 km)	Larger (M>6.5) and deeper (up to 30-40 km)
Rifting type [4]	Magmatic - axial dike intrusion and faulting	Mechanical - extension along rift border faults
Relative extension rate	High	Low (1-2 mm/year)
Relative thickness of rift valley fill	Thin	Thick - more sediments and deep rift lakes
Primary geothermal play type [5]	CV1a - Magmatic or CV3 - Extensional	CV3 - Extensional or CD3 - Crystalline rock
Major hydrothermal systems (Q>10 MW) [6]	31	7
Heat discharge rate (MWth) [6]	4000	circa 300
No. of likely stratovolcanic geothermal systems	16 (Table 3)	0 (Table 4)

[1] Rosenthal, et al, 2009; [2] Omenda, et al., 2016; [3] Koptev, et al., 2015; [4] Hinz, et al., 2018; [5] Moeck & Beardsmore, 2014; [6] Hochstein, 2005

4. HYDROGEOLOGICAL CONTROLS ON STRATOVOLCANIC 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 stratovolcanoes is unlikely to be productive.

5. GEOTHERMAL EXPLORATION OF TWO STRATOVOLCANOES IN THE WESTERN BRANCH OF EARS

5.1 Karisimbi, Virunga Volcanic Province, Rwanda

Karisimbi is the largest and highest volcano (4500 masl) in the VVP, within the Western Branch of EARS (Figure 2). There is a desperate need for indigenous power sources in Rwanda, and so the possible geothermal energy exploitation of the towering Karisimbi stratovolcano has been considered for years. Exploration surveys have been performed at Karisimbi since at least 2008, when geothermal resource assessments were carried out by the German Institute for Geosciences and Natural Resources (BGR) and their MT subconsultant, KenGen. Additional surveys were completed in 2010 and 2011 by IESE-Auckland UniServices.

Surface thermal activity is limited to two hot springs, at Gisenyi and Karago (Figure 3). The chemistry of these features provides no evidence of high-temperature conditions at depth in these areas. It is possible that the features are outflows from distant high-temperature sources beneath the VVP, which would imply higher temperatures closer to the volcanic centers. However, there are no associated high-temperature manifestations to support this (e.g.: fumaroles or steaming ground). The location of viable heat sources is therefore unclear. Also, the MT data do not indicate the potential presence of any high-temperature geothermal system at the normal depth range considered economic for development (Shalev et al., 2012). Although it is possible that a hidden geothermal system exists, there are no surface features that can be used for confirmation making this a high-risk geothermal exploration project.

Despite the conclusions of the IESE report that Karisimbi did not show indications of high-temperature geothermal activity, the Government of Rwanda decided to drill three 3,000-m deep exploration wells on the SW flanks of Karisimbi under the presumption that the massive stratovolcano must have a large, shallow magma chamber and a related high-temperature reservoir. This mis-assumption was termed the “Karisimbi paradigm” by Hochstein (2015). Exploration drilling commenced in July 2013 with Well KW-01 (Figure 3). The Proterozoic granitic basement rock was encountered at a depth of about 850 m, and drilling continued to a total depth of 3,015 m – the bottomhole temperature was 72°C. Drilling of the second well (KW-03) was stopped in March 2014 at a depth of 1,367 m after the results of the Well KW-01 became known (Hochstein, 2015). Alteration mineralogy and measured temperatures in the two wells are consistent with the average continental geothermal gradient of ~30°C/km, conclusively demonstrating that a geothermal reservoir is not present under the southern slopes of Karisimbi (Rutagarama, 2018).

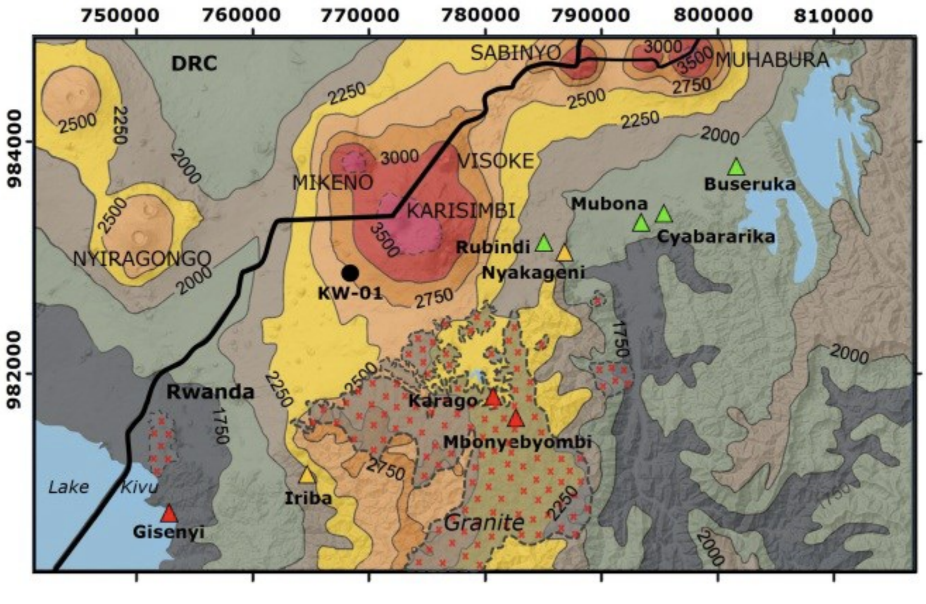

Figure 3: Topography of the Virunga Volcanic Province (VVP); thermal springs in Rwanda indicated by red and yellow triangles; cold CO_2-rich springs by a green triangle (Hochstein, 2015). Location of Well KW-03 (not shown) is approximately 1.7 km NW of Well KW-01.

5.2 Ngozi, Rungwe Volcanic Province, Tanzania

Rungwe Volcanic Province (RVP) is located in southern Tanzania on the Western Branch of EARS and represents the southernmost expression of rift-related volcanism (Figure 4). The active Ngozi volcano is one of three large, Holocene volcanoes in the RVP (along with Rungwe and Kyejo stratovolcanoes). Ngozi is a former stratovolcano formed through a variety of effusive and explosive eruptions including major, regional-scale Plinian eruptions in the Holocene that are thought to have contributed to the formation of the present-day (small) caldera (Fontijn et al., 2010, 2012). The Ngozi volcanic edifice is largely made up of basalt, phonolite, and trachyte lava flow deposits, with widespread pyroclastic deposits in the surrounding plains. The heat source of the Ngozi geothermal system is likely a trachytic magma chamber, which was replenished after the Ngozi Tuff eruption less than 1,000 years ago.

The south half of the Ngozi caldera is occupied by a 70-m deep lake. Here, the primary geothermal features at Ngozi are found on the bottom of the lake. Vertical temperature profiles identified elevated temperatures (up to 89°C) at three locations on the lake bottom. Also, visible degassing activity, accompanied by CO_2 fluxes up to 350 $g \cdot m^{-2} \cdot d^{-1}$, was detected at the surface above the high-temperature sites at the lake bottom. Geothermometry and geochemical modeling suggest the elevated-temperature fluids as having come from a >230°C geothermal reservoir (Alexander et al., 2016). These lake bottom vents are the only thermal manifestations near Ngozi with chemistry indicative of a high-temperature reservoir – no hot springs or fumaroles are known to be present on the Ngozi edifice. Two warm springs (Inyala and Iyela) occur northwest of Ngozi but the origin of the springs is ambiguous although they do not emanate from the reservoir (Figure 4). It is more likely that meteoric water is conductively warmed by the geothermal system, either by a concealed outflow from it, or by a separate upflow.

The geothermal resource at Ngozi is likely supported by a relatively narrow, deep upflow of geothermal fluids rising directly beneath the Ngozi crater lake. No exploration wells have been drilled yet at Ngozi. It is not practical to target the potential geothermal reservoir directly beneath the Ngozi caldera because the steep topography makes the vicinity of the crater lake inaccessible to conventional drilling rigs so that even a directional well would be impractical except at a cost that could only be justified by a very large resource, unlikely to be found at Ngozi. Therefore, any reservoir that could be targeted at Ngozi must extend beyond the caldera in the direction that makes it more accessible to directional drilling. The conceptual model analysis concludes that only the optimistic resource outline at a 10% level of confidence (P10) extends up to 2 km to the west of the caldera rim and could be targeted by a plausible, albeit ambitious, directional well (Alexander et al., 2016). Accordingly, it is unlikely that a commercially-producible, high-temperature geothermal reservoir is accessible beneath the Ngozi caldera lake.

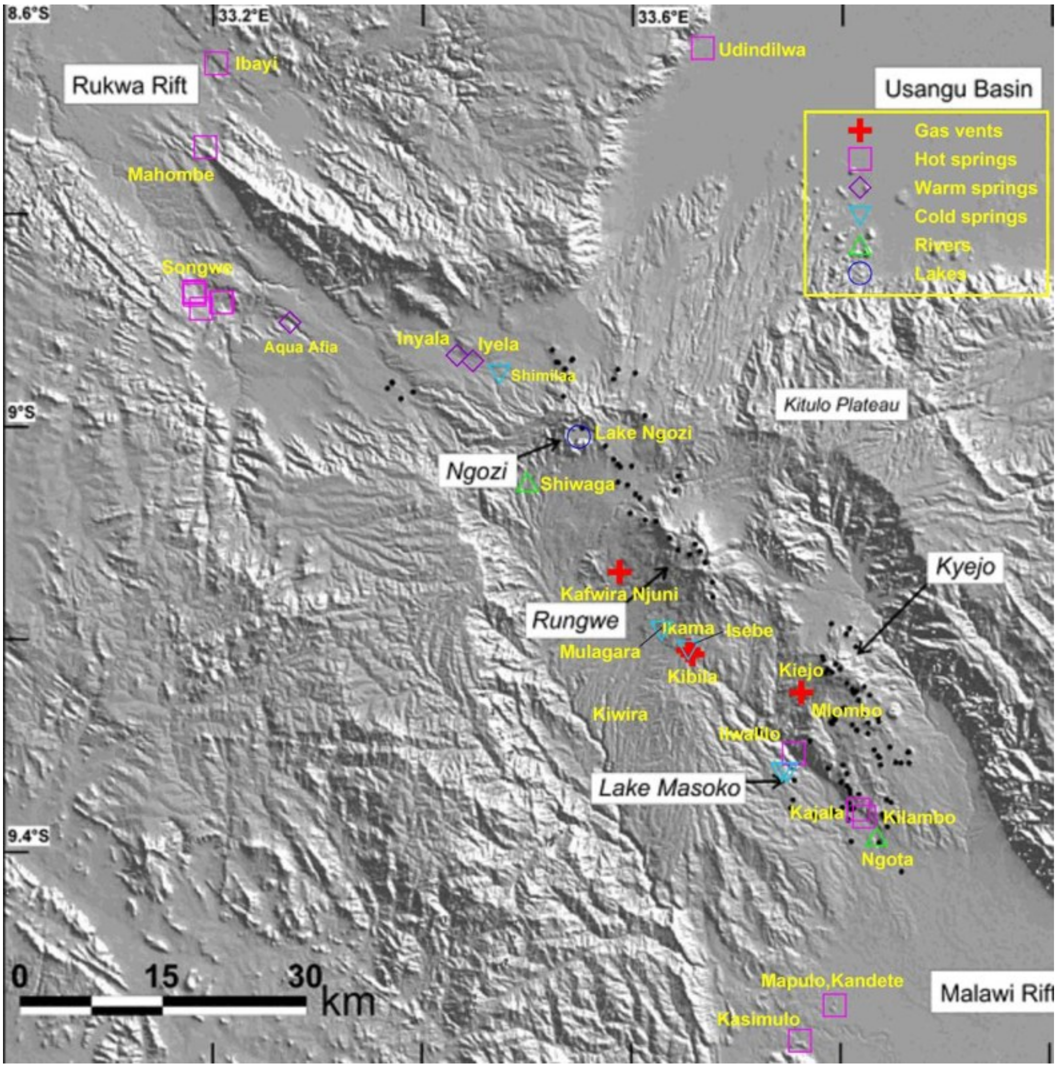

Figure 4: Map of the RVP showing major volcanic centers of Ngozi, Rungwe, and Kyejo. Basemap is SRTM shaded relief DEM of the RVP region, with its rift segments and volcanic centers (black dots) from Fontijn et al. (2010). Includes locations of known hot, tepid, and cold springs, and cold gas (CO_2-rich) vent locations. Source: Alexander et al. (2016).

5.3 Hydrological and Geological Characteristics Similar to Both Sites

Several hydrological and geological characteristics of Karisimbi in the VVP and the volcanoes of RVP are compared below to evaluate possible reasons for the apparent absence of high-temperature geothermal systems in both areas.

5.3.1 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. Neither Karisimbi nor Ngozi have active surface thermal manifestations (or even the evidence of previous manifestations or surface alteration) on the top or flanks of the volcanic edifice, except for several small gas vents at the bottom of Ngozi lake. A few warm to tepid springs are located on the lower flanks of

Karisimbi (Karago at 64°C) and Ngozi (Inyala and Iyela springs at <37°C). Note the distribution of hot springs away from the volcanic edifices (including Rungwe and Kyejo) on Figure 3 and Figure 4. This is possibly due to higher rainfall and colder recharge on the tallest volcanic centers.

The absence of surface thermal manifestations such as fumaroles or steaming ground makes it unlikely that an accessible high-temperature geothermal system exists beneath the volcanoes. The few warm springs are localized, probably fault-controlled, and do not give an indication to resource size or locations. Although it is possible that a hidden geothermal system exists, there are no surface features that can be used for confirmation making these volcanic settings a high-risk geothermal development.

5.3.2 Presence of CO_2-Rich Springs

One type of manifestation that is common to both Karisimbi and Ngozi is the presence of numerous CO_2 discharges, either as cold "mazuku"-type CO_2 gas vents or in cold CO_2-rich springs. Diffusive CO_2 degassing is widespread around Karisimbi (Hochstein, 2015). The cold Mg-HCO_3 springs E of Karisimbi including Rubindi (18°C), Mubona (19.5°C), and Buseruka (17.4°C) discharge CO_2 and deposit travertine (Figure 3). Numerous cold CO_2 vents are also found all over the RVP. Gas samples from the RVP are extremely CO_2-rich compared to samples from volcano-hosted geothermal systems and fall within the range of travertine-depositing springs from Italy and those discharging along fault systems in the western USA, consistent with extensive travertine deposits in the Rungwe region (de Moor et al., 2013 and references therein). Southwest of Ngozi at Shiwaga, several vigorously-bubbling pools (15-18°C) are present along the river banks. Other areas of gas vents are shown in Figure 4. Near the foot of Kyejo, CO_2 degassing from shallow boreholes is bottled commercially for use in soda drinks.

The presence of significant amounts of CO_2 at Karisimbi and the RVP (as well as other mantle-derived volatiles such as nitrogen and helium) are indicative of a permanent flux of deep CO_2 entering from below the volcanic edifice. The elevated flux of cold CO_2 is typical of these areas (VVP and RVP) of the Western Branch and are related to deep mantle processes, not shallow magmatism that might be associated with a volcanic geothermal system. Thus, the gas discharges at the bottom of Lake Ngozi may be a manifestation of deep magmatic degassing but are likely not indicative of an active, producible hydrothermal system.

5.3.3 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 geothermal resource development in the Western Branch of EARS, the basement rock refers to the Proterozoic crystalline rock beneath the rift valleys. At Karisimbi and Ngozi, volcanics directly overlie the metamorphic and granitic basement rock, which have inherently low porosity and permeability except where highly fractured. 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. The few volcanoes along the Western Branch have produced relatively low volumes of eruptive material (typically <1 km thick). For 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 VVP and RVP is considered a limitation for commercial geothermal reservoir development.

5.3.4 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. Magma bodies can be found beneath the Eastern Branch of EARS at depths as shallow as 2-6 km (Table 5), a critical factor for the occurrence of high-temperature geothermal systems. In the Western Branch, magma bodies are not identifiable. The type of volcanic rock is reflective of the depth of the magmatic body and the degree of fractionation (among other parameters). Felsic volcanism (silica-rich) is often associated with shallow magma chambers that can be a heat source for geothermal systems, whereas mafic volcanism (silica-poor) tends to be sourced from deeper magma chambers that are less likely to drive a shallow geothermal system.

At Karisimbi, lavas have been classified as tephrite basanites to trachy-andesites – mafic rocks indicative of differentiation within the crust (Hochstein, 2015). These rocks suggest a differentiating mafic magmatic system at a depth >10 km, originating from ultramafic mantle basanites. At Ngozi, the heat source has been postulated to be a trachytic magma chamber on the order of 5 to 7 km deep based on the analogy with Rungwe (Fontijn et al., 2013). The heat source at Ngozi is likely from fault-controlled dikes rather than large magma chambers, limiting the transfer of heat to shallow depths. Therefore, the deeper magma bodies found in the Western Branch are less likely to form hydrothermal plumes and associated geothermal reservoirs.

5.3.5 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 5). 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).

The groundwater system at Karisimbi is variously mixed cold meteoric waters and basement circulating thermal fluids. The few, isolated hot springs appear to outflow from the basement rocks, while the cold springs are associated with both basement rocks and the volcanic sequences. Similarly, in the RVP, lower temperature hydrothermal features (warm springs) are located at higher elevations on the flanks of the stratovolcanoes, whereas the hottest features such as Songwe and Kilambo hot springs are distally located from the volcanic centers (Figure 4).

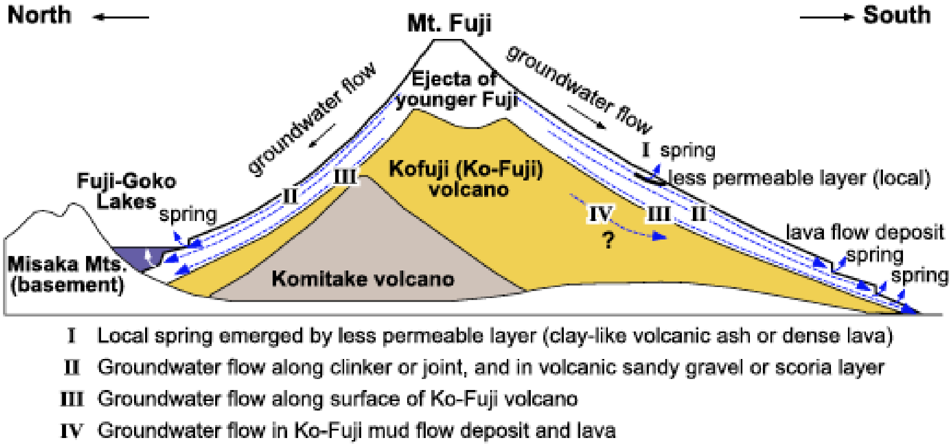

Figure 5: Generalized schematic of groundwater flow system at Mt Fuji illustrating how the vast majority of groundwater flows through the permeable deposits on the flanks of the volcano away from the central edifice (Ono et al., 2018).

6. 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, in the Western Branch of EARS, stratovolcanoes are not geothermally prospective due to a number of reasons: (1) absence of thermal manifestations on the volcano flanks, (2) prevalence of CO_2-rich gas vent or springs indicative of deep mantle de-gassing rather than shallow magmatism, (3) lack of permeable reservoir rock due to relatively shallow depths to Proterozoic basement with thin (<1 km) volcanic cover, (4) likely deep source of heat and magmatic volatiles from fault-controlled dikes rather than large magma chambers, and (5) the relatively strong topography-driven groundwater flow systems, which moves groundwater away from the center of the volcanic edifice and precludes development of a convective hydrothermal plume.

Development of stratovolcanic geothermal systems in the EARS is dependent on understanding faulting and groundwater flow. In the Western Branch, the focus of geothermal exploration of stratovolcanic systems should be on medium-enthalpy outflow areas that are accessible and may support smaller, binary power plants. Specific exploration techniques in these areas 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.

ACKNOWLEDGMENT

Constructive comments by Karen Fontijn, Mark Harvey, and Phil White were greatly appreciated.

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