Geothermal Conceptual Model of Suswa Volcano, Kenya

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ABSTRACT

Geological, geophysical and geochemical findings from a recent sampling and data collection campaign at Suswa, coupled with review of data from previous surveys allowed the development of a geothermal conceptual model of the volcano. Three models are hypothesized based on available data although in this paper, greater focus is on the favored model. The favored conceptual model includes a magmatically-heated, 250 to 300ºC, low-gas, partially two-phase reservoir associated with a large volume of hot volcanic rock overlying recent intrusions. Fracture networks have developed below the inner caldera allowing hydrothermal circulation at depth. In the favored model, the resource occupies much of the inner caldera, includes a two-phase zone at the top of the reservoir, and supports a thin 100ºC shallow steam outflow along tuff-lava contacts and faults to the north above the expected water table at about 1200 m elevation. Shallow outflow also proceeds at more limited flow rates to the south and west. Inferred reservoir conditions are expected to support commercial geothermal well flow rates. In the alternate models, the resource is deemed to occupy the inner caldera and extends to parts of the outer caldera, particularly to the north.

1. Introduction

The Suswa Quaternary shield volcano, located on the southern segment of the Kenya Rift (Figure 1), has two primary calderas; an outer and an inner caldera with an uplifted Island block at the center of the inner caldera (Central Island), surrounded by an annular trench (moat). Fumarolic activity is widespread in Suswa with fumaroles distributed in four primary areas including; the rim of the outer caldera, the traces of the inferred intermediate caldera, along the northern floor of the outer caldera, the inner caldera, and the south flank of Suswa volcano (Figure 1). Argillic alteration is associated with most of the fumarolic areas. The most intense alteration and the only sulfur deposits occur within the inner caldera.

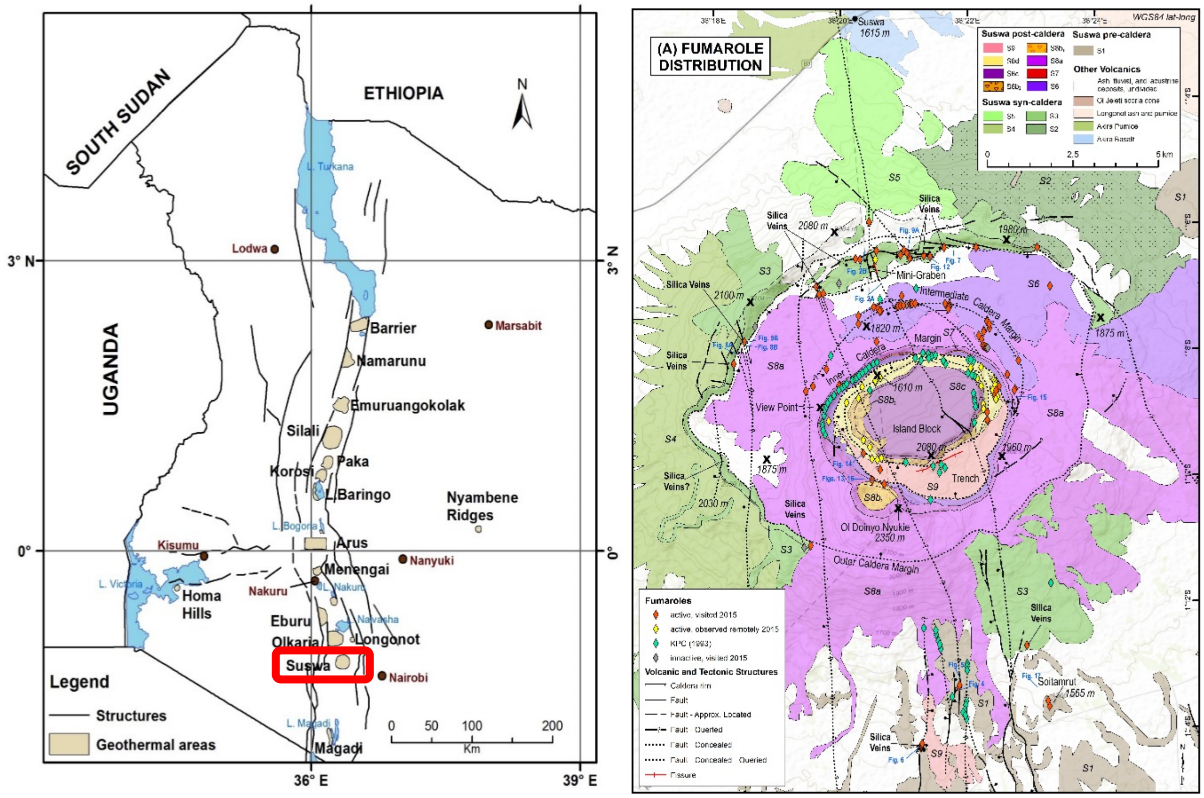

Figure 1: Map showing the location of Suswa volcano and other geothermal potential areas in Kenya (left) and the geologic map of Suswa with fumaroles added (right; Hinz, 2017)

A field sampling and data collection campaign was conducted in Suswa in 2015 and 2016 with the aim of providing additional geoscientific information for updating the geothermal conceptual model of the prospect, and to establish a well targeting program. The work comprised geological, geophysical and geochemical surveys. Geological mapping focused on integrating geomechanical evaluations with an updated assessment of stratigraphic, structural and geothermal geology. Geophysical investigations entailed MT-TEM resistivity surveys and gravity data collection and analysis. Geochemical survey mainly entailed resampling of the relatively high pressure fumaroles (and those not sampled previously, particularly those situated in the inner caldera) as well as local groundwater. The work was conducted by GDC in conjunction with EFLA Consulting Engineers (Magnusson et al., 2017). Sampling and data collection was carried out in late July to mid-August 2015 and additional field work was completed in 2016 to address some of the data issues from the 2015 survey. Available data generated from previous studies was reviewed and integrated in this study.

The field mapping, sample and data collection and analysis of results culminated in the updating of the conceptual model of Suswa. Cumming (2009) underscores that the most important element of an analysis to target a geothermal well or assess resource capacity is a resource conceptual model consistent with the available information. He further notes that the most important element of a geothermal conceptual model is a predicted natural state isotherm pattern, especially in section view. Although inferring such an isotherm pattern at an exploration stage can be challenging, many case histories show how this can be done based on surface geochemistry, resistivity, hydrothermal alteration, geology, hydrology and structures. This paper therefore presents the geothermal conceptual model of Suswa, the outcome of EFLA led survey. Available information allow three possible conceptual models for Suswa with the most promising model, with a 90% chance of geothermal resource success, being discussed in more detail.

2. Geothermal Model Aspects

Key aspects of the geothermal conceptual model(s) of Suswa are discussed below. The strength of the model(s) interpretations are dependent on congruence between the different data types.

2.1 Heat Source

The Suswa hydrothermal system expresses magmatic heat evident in high helium isotope ratios in the inner caldera (Figure 2) and the co-location of concentrated young volcanic and fumarolic activity in the calderas of Suswa Volcano. The recent, frequent, and voluminous volcanic products, re-collapsed and resurgent calderas, tectonic setting, and volcanic rock petrology suggest that the Suswa magmatic heat source occurs as a multiphase intrusive complex with persistent magma residence over long periods through the later life of the volcano. Petrology of the volcanic rocks records magma mixing based on zoning and resorption of phenocrysts that indicates episodic renewal of existing magma (Espejel-Garcia, 2009). Meanwhile the lack of recent mafic volcanic rocks is consistent with the formation of a shadow zone formed by a persistent, relatively low density phonolitic magma at depth.

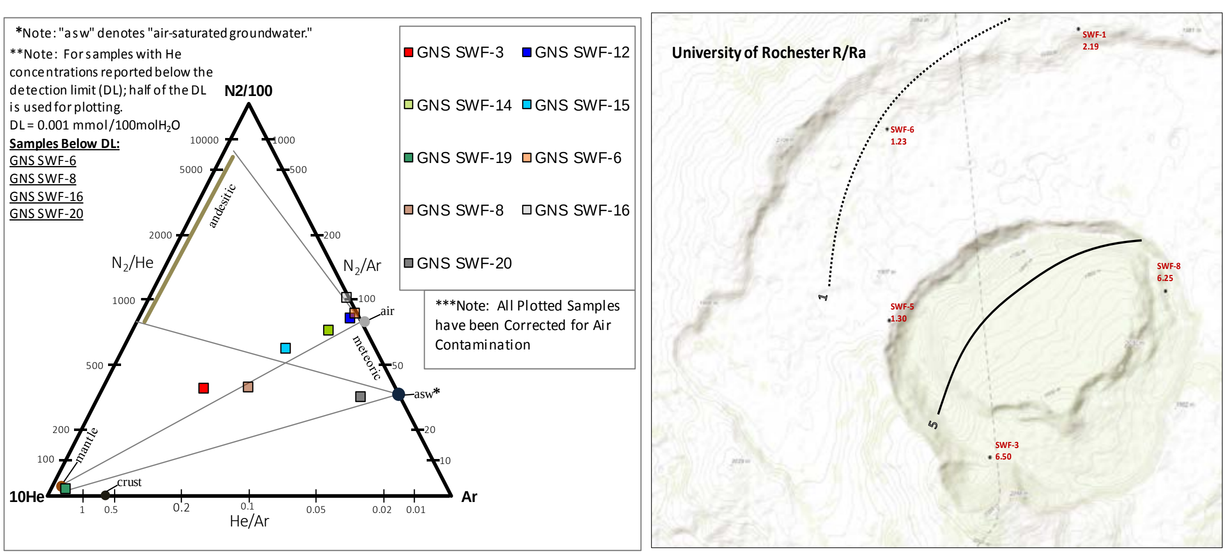

Figure 2: N_2-He-Ar ternary (left) and distribution of $^3He/^4He$ (right) suggesting magmatic helium in the inner caldera fumaroles at Suswa (Haizlip, 2017)

Magmas were emplaced at various depths. Petrologic studies by White et al (2012) estimated that fractionation of Suswa trachyte from basalt occurred at 14 km depth. Deep high seismic velocity interpreted from seismic studies (Simyu, 2010 and Simyu and Keller, 2000) along the rift may represent crystalline intrusive rock related to long term persistent deep diking above a deep magma chamber. Estimated depth to the high velocity feature is roughly 5 km. Low resistivity below Suswa extends down to that depth as shown by Cumming (2017).

Subsidence patterns measured from satellite radar interferometry were interpreted to reflect deflation at depths of 2.5 to 5 km below the inner caldera (Biggs, 2009) possibly due to active magma movement. The source of subsidence may be closer to the 2.5 km depth estimate based on the model of a subsiding or cooling magmatic sill. A more plug-shaped intrusion could be deeper. This recent intrusion is likely to dominate the highest reservoir temperatures. Caldera unrest studies elsewhere (e.g. Waite and Smith, 2002) suggest that release of over-pressured hot water can also cause caldera subsidence.

Seismicity maps (e.g. Figure 3) suggest that the recent magma may be focused under the SW inner caldera margin near the Ol Doinyo Nyukie volcano. An alternative model for the seismicity suggests that cold downflow from rainfall on Ol Doinyo Nyukie is invading along the inner caldera ring fault into very hot rock above and in the upper solidified portions of a shallow intrusion. In this case the seismicity would represent cooling-induced rock fracturing driven by tectonic and magmatic stresses. In either case the reservoir in this area would be limited either by very high temperature impermeable rock or cold rock.

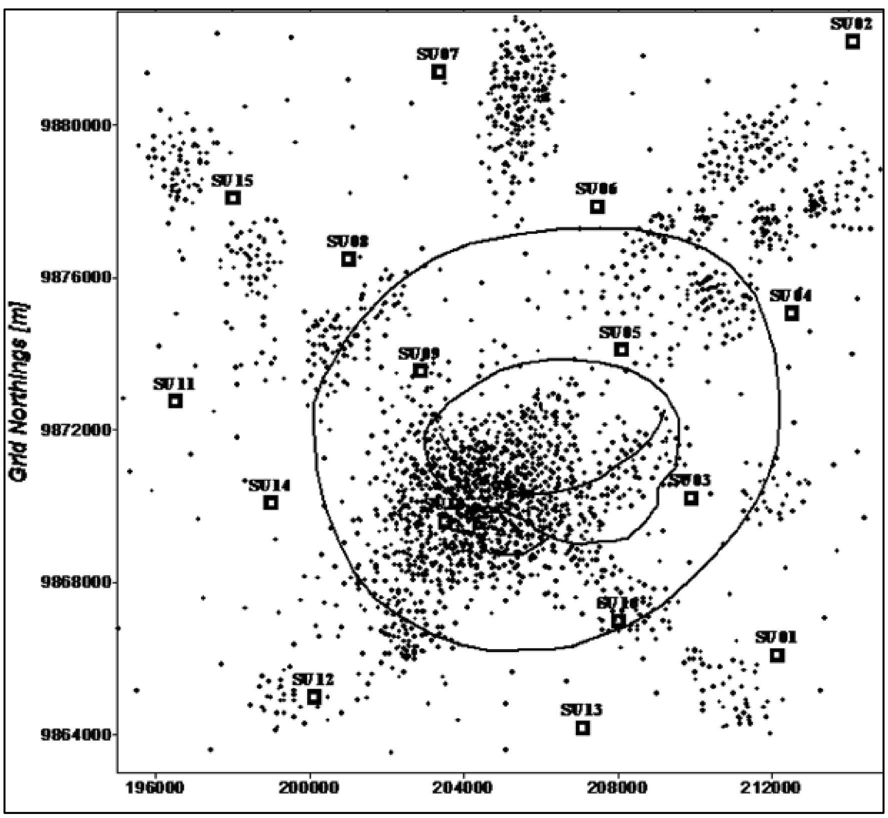

Figure 3: Map of Suswa showing event locations, inner and outer caldera and recording stations (after Simiyu 1997).

The likely magma cooling rate suggests that the volcano is currently underlain by high temperature volcanic rock focused below the inner caldera but extending below the outer caldera. The cooling time for a simple 1 km thick shallow sill should range from about 5,000 to 50,000 years depending on water convection patterns and surrounding rock temperature (Cathles, 1981). Heat from a single intrusive event of moderate size like this might support a hydrothermal system for a few tens of thousands of years (Cathles et al, 1997). After formation of the outer caldera at Suswa, five significant intrusive events related to eruptions of lava, Ol Doinyo Nyukie volcano, inner caldera collapse and resurgence, and post resurgence lavas have occurred in the last 100 ka possibly resulting in multiple overlapping hydrothermal phases.

2.2 Geomechanics

Fault irregularities are important for understanding fluid flow and are common at Suswa (Figure 4). Generally fault irregularity types include fault tips, intersections, bends, step-overs, ramps, and accommodation zones. Hot spring flow often occurs near fault irregularities. For example in a study of 300 hot springs and faults in Nevada, where magmatic heat is generally not a factor in thermal fluid distribution, 95% of all the hot springs occurred in fault irregularities in in a region with widespread occurrence of normal faults (Faulds and Hinz, 2015) suggesting that the normal faults are much more likely to be permeable where they are affected by irregularities.

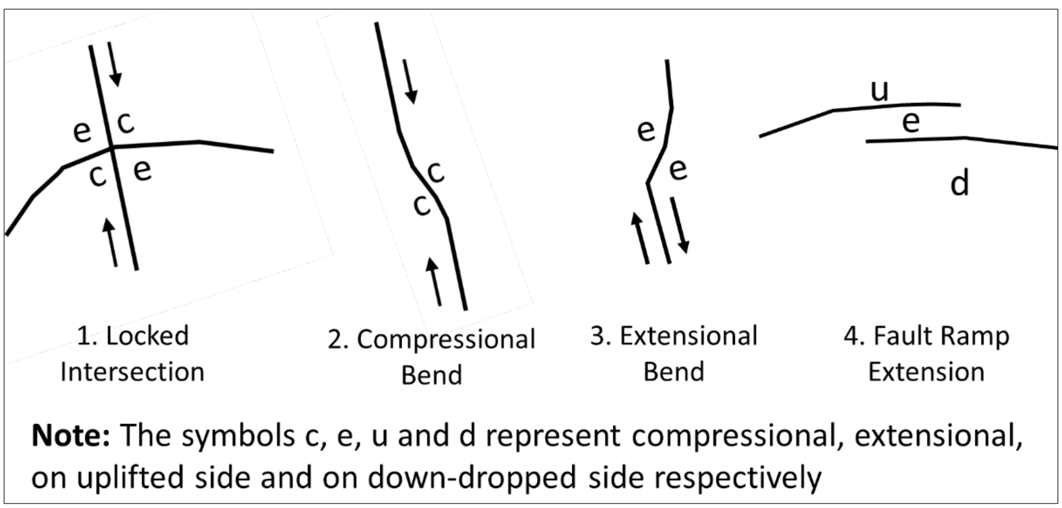

Figure 4: Fault irregularity types at Suswa (Melosh, 2017)

A worldwide study showed that locked fault irregularities in various tectonic settings dominate fracture permeability including in areas with magmatic heat (Curewitz and Karson, 1997). Examples of locking include fault tips, fault intersections with incompatible movement on the two faults, or fault bends where fault movement is across the bend. Although the two referred statistical studies do not clearly specify that hot springs occur in local extensional settings in these irregularities, well targeting experience elsewhere and mechanical theory both describe strong permeability enhancement in local extensional settings. In a locked fault intersection compressional and extensional quadrants can alternate around the intersection. Both fault and stress-strain patterns are key to interpreting locked fault patterns.

In the most recent analysis of the geology and structure at Suswa, Hinz (2017) describes the history and interpreted current patterns of strain at Suswa. In summary, he describes a regional clockwise rotation of maximum extension from NE-SW to NW-SE through time. Consequently regional NNW trending rift faults that may have been originally formed as extensional normal faults would currently show oblique normal right-lateral offset. Observed fault kinematic data at Suswa include this sense of fault motion. Lateral motion on these rift faults can lead to incompatible offsets that create locked rift fault – caldera fault intersections and extensional stress concentrations.

Local stresses at Suswa are complex. In addition to rifting, Hinz (2017) interprets local stress variations related to episodic magmatic activity as well as possible stress transfer across Suswa Volcano in a pattern that might result in development of a right-stepping extensional step-over between right lateral-normal oblique master faults to the SW and NE of the volcano. These complex stresses lead to a variety of structural patterns in the prospect.

Rift fault patterns at Suswa generally show strong, subparallel, roughly NNW trends (Figure 1-right). Two main rift faults are interpreted to cut across the calderas. A more complex set of faults near these two is mapped south of the volcano. The caldera faults include the outer and inner caldera ring faults, a ring fault around the Island Block, and intermediate caldera ring faults expressed in the northern moat of the outer caldera. The reversal of ring fault movement during resurgence developed a complex ring fault zone around the Island Block. These two main fault patterns, tectonic and magmatic, are complicated by secondary splays and local crossing faults associated with secondary strains as described by Hinz (2017).

Oblique right-lateral motion on the rift faults results in locked fault irregularities between rift faults and caldera faults. In the simplest case a NNW right lateral rift fault that intersects a caldera fault might be locked by lateral motion that offsets the ring fault or vertical ring fault motion that offsets a dipping rift fault. If the intersection is locked, extensional and compressional stress concentration quadrants may develop around the intersection consistent with the lateral sense of motion (Figures 4 and 5). Figures 4 and 6 also show stress distributions for a compressive bend in a right-lateral fault.

Stratigraphy on Suswa Volcano includes a series of tuffs and lavas over the last 240 ka overlying consistent trachyte lavas that built the original shield volcano, and flood lavas at greater depth (Figure 5). This sequence was intruded by dikes and sills. The combination of weak tuffs and stronger lavas and sills in the shallow section is likely to lead to numerous fractures associated with the differing mechanical responses to deformation between the lavas and tuffs, this may lead to stratigraphically controlled fracture zones especially along faults in the relatively young lava-tuff sequence. Meanwhile deeper parts of the volcanic section are not reported to have tuff beds but have had a longer history of faulting and may be more extensively broken. In this zone fracture patterns may be steeply dipping.

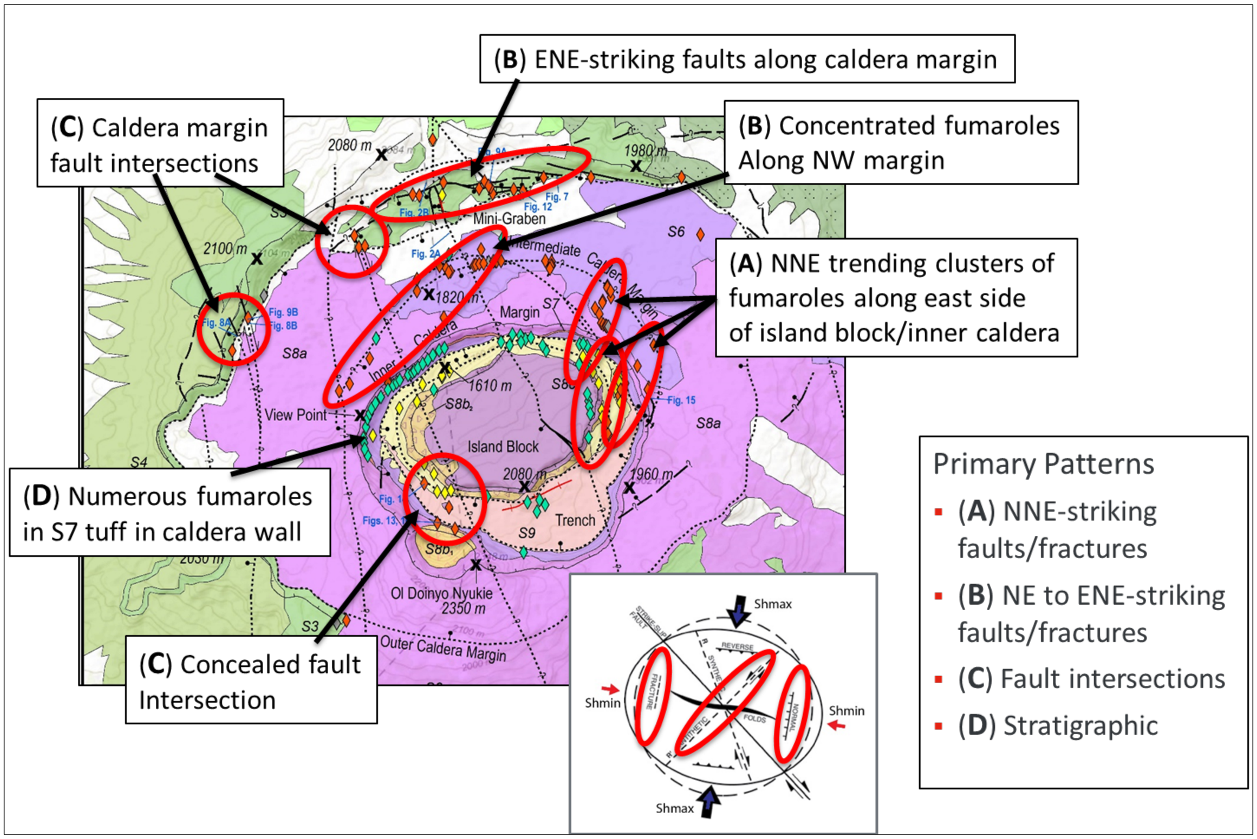

Figure 5: Geothermal structural patterns at Suswa

2.3 Permeability

Permeability evident at Suswa is dominated by two controlling factors, rift-caldera fault interactions and tuff stratigraphy. Permeability patterns are interpreted from mapped alteration, fumaroles, and gas chemistry in comparison to fault irregularities and mapped rock formations. Permeability is interpreted to extend to greater depth near fumaroles with high temperature gas chemistry and near alteration with sulfur deposition or abundant silica (in both latter cases based on inferences regarding high temperature gas chemistry in steam). Alteration with silica and sulfur is mapped separately by Hinz (2017).

The silica veins in steam vent alteration in the outer caldera at Suswa may record a previous phase of activity during which the fumaroles produced significant H_2S. KPC (1993) interpreted silica textures in the altered matrix near the fumaroles as due to acid condensate reaction with volcanic glass. This is well-supported by similar occurrences in fumaroles worldwide and has been characterized by Sillitoe (2015) as related to H_2S-bearing steam. This implies that sulfuric acid in the condensate may be required to generate this deposit. The combination of residual silica and silica veins at Suswa and their worldwide association with H_2S suggests that there may have been a previous phase of activity at these fumaroles that had greater H_2S production. Higher H_2S in the steam may in turn imply a higher temperature source. Silica veins occur in alteration areas on the northern caldera rim and in alteration near fumaroles on the south flank of the volcano.

Another structural permeability target occurs a bit farther east along the outer caldera ring fault trend (Figure 6). In this case it appears that permeability is associated with normal fault ramps – another type of fault irregularity that can result in extensional stress concentrations in secondary fractures in the ramps between the normal fault segments. Hinz (2017) suggests that the normal faults may be part of a regional step-over fault pattern in addition to caldera collapse. The occurrence of silica veins in this location indicates that H_2S was once prevalent, suggesting a relatively high temperature fluid source at that time.

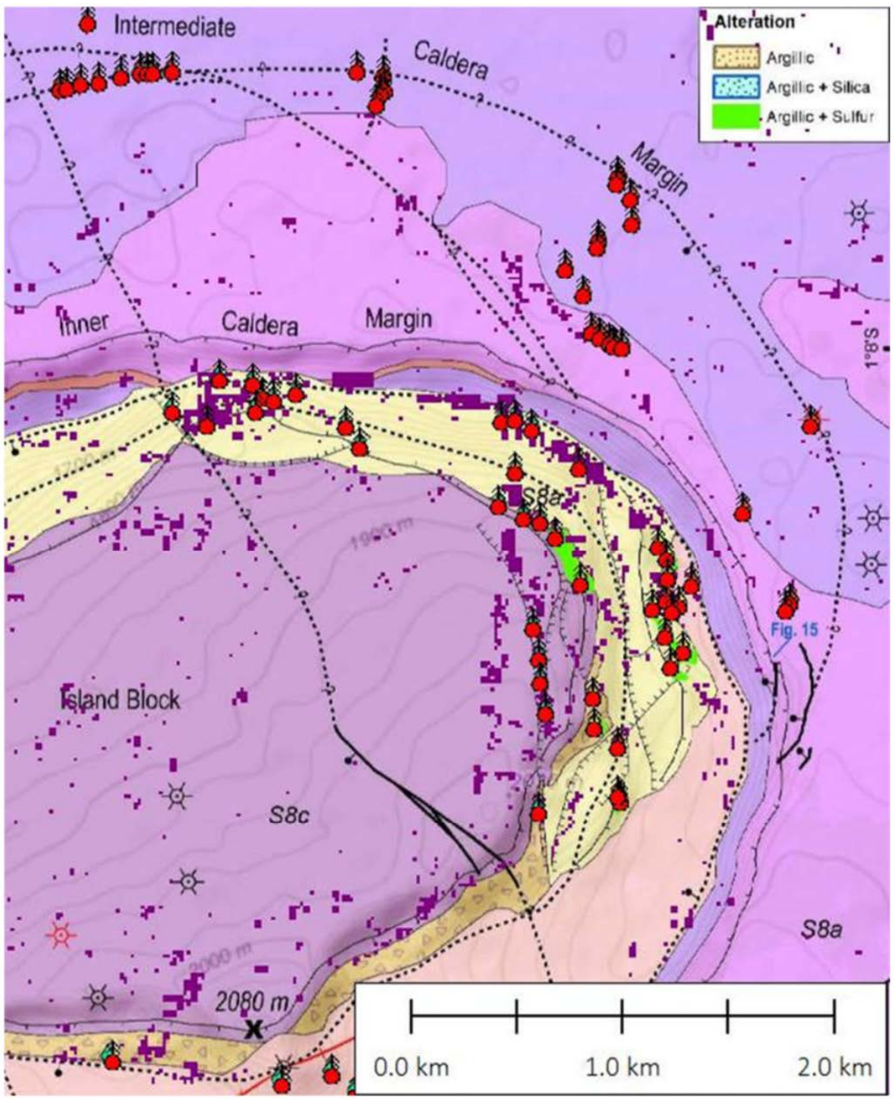

Figure 6: Suswa Geology, Alteration, and Fumaroles (from Hinz, 2017) - Landslide scarps on the east edge of the Island Block near a restraining bend in the rift fault may overlie extension in the ring fault zone. An ASTER alteration lineament (in purple) occurs on an extensional fault trend west of the landslides. A rift-ring fault intersection on the northern Inner Caldera rim shows fumaroles (red symbols) and alteration in the extensional quadrant. More ASTER alteration occurs along a possible intermediate caldera ring fault trend north of the eastern inner caldera.

Fumaroles aligned with tuff outcrops in the northwest inner caldera scarp (Figure 7) suggest that either the tuff is broadly permeable and lavas are impermeable or that the tuff-lava interbedding leads to numerous fractures in the tuff. This pattern of fumarole alignment also occurs in the caldera wall at Silali in another tuff interbedded with lava. Exploration elsewhere suggests that tuff permeability is not strongly evident in hydrothermal systems where tuffs form thick accumulations.

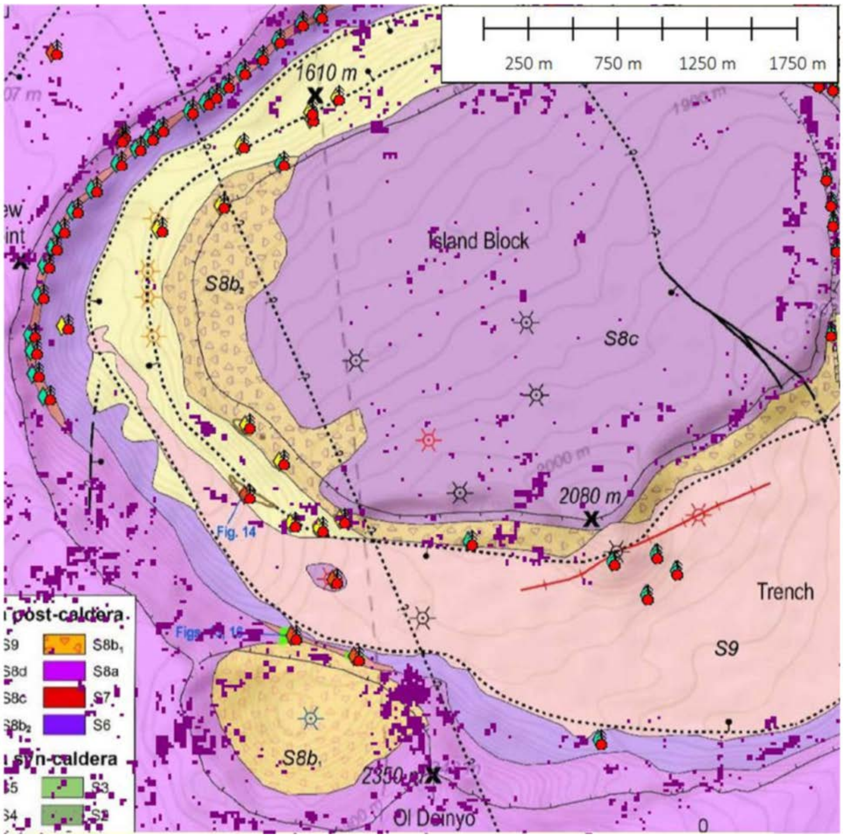

Figure 7: Western Inner Caldera Geology, Alteration, and Fumaroles (from Hinz, 2017) – Intersections of the western rift fault and inner caldera ring faults show alteration and fumarolic activity near the intersection. ASTER alteration is shown in purple. Fumaroles on the NW Inner Caldera rim align with the S7 tuff and show the impressive stratigraphic control in the lava tuff sequence.

Meanwhile extensive young lava flows cover much of the terrain and are interpreted to occur in the subsurface from geologic and geophysical data. These rocks may block vertical flow of cold water and steam away from permeable fault intersections. For example surface lavas in the largely unbroken Island Block may obstruct upward flow of steam such that there are no fumaroles on the island. MT results show horizontal buried resistors below the outer caldera especially to the north and east. These resistors may reveal unaltered lava aquicludes (Cumming, 2017).

Preference for permeability inboard of the caldera ring faults is a common theme at Suswa expressed in Figures 5 and 6. The concentrated compressional stresses outside the edge of a hole in a stressed formation can close up fractures or lead to break-outs which are then likely to collapse into the hole. This process could create more frequent fracturing inside the caldera.

These fractures could then be open in areas of localized extension due to fault-caldera intersections.

Beyond the suggestion of relatively deep permeability based on fumarole chemistry, the actual depth extent of permeability is unknown. Generally individual fracture permeability is likely to decline with depth while the number of fractures may increase due to the longer history of faulting in older rocks. Meanwhile an underlying magma and its contact metamorphic halo can heal fractures and are likely to place a limit to the depth of useful permeability.

Identifying open fracture zones at depth based on permeable extensional zones interpreted from geomechanics and alteration at the surface is clearly simplistic. Actual patterns of the faults, locked geometry, and stress build-up at reservoir depths is largely unknowable from the surface. In addition other factors such as stratigraphy and fault complexity (where extensional vs compressional zonation is difficult to interpret) are likely to be important.

2.4 Cap Rocks and Low Resistivity Seals

Suswa MT data (Figures 8 and 9) do not show an extensive, low resistivity geothermal cap rock pattern similar to many geothermal fields worldwide, perhaps because MT data could not be collected within the inner caldera. However outside of the inner caldera, a thick, moderately low resistivity zone (green-yellow in Figures 8 and 9) has been interpreted to correspond to moderately low to low permeability altered rock that seals the lateral margins of the reservoir in the inner caldera and caps a possible deep outflow to the north.

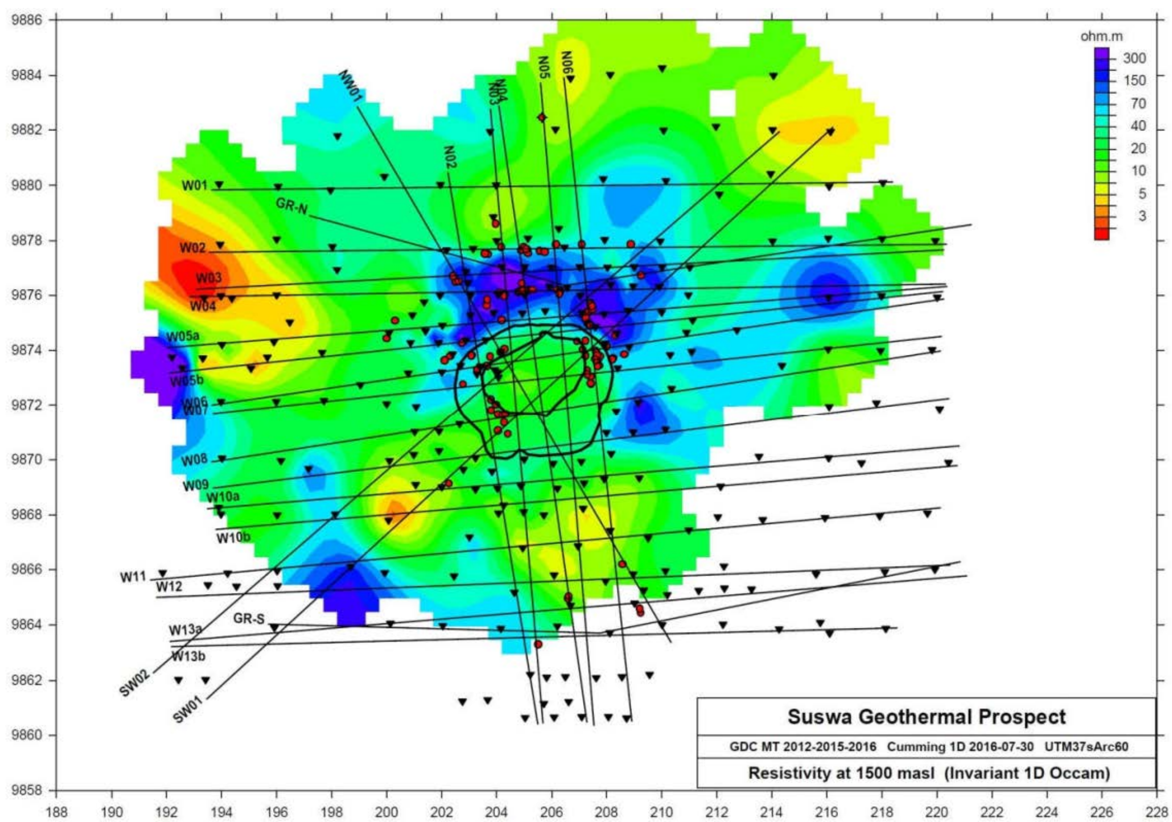

Figure 8: MT resistivity at elevation 1500 masl

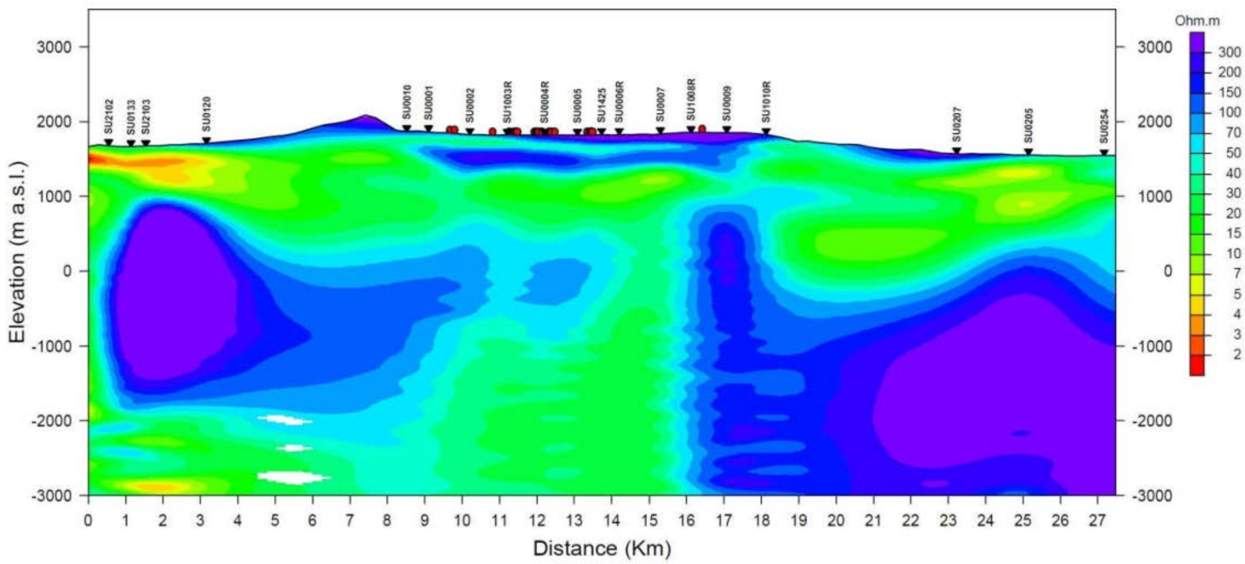

Figure 9: MT 1D resistivity profile W04 extended deeper, beyond the reliable imaging depth for a 1D inversion

A high resistivity zone (blue-purple) embedded within the moderate resistivity zone between the northern inner and outer caldera in Figures 8 and 9 has been interpreted as a dense lava that is closely correlated with the distribution of fumaroles. The extensive fumarolic activity above the margins and faulted trends of young lava flows below the northern outer caldera moat and the Island Block (Figure 5) suggest that these lavas may act as aquicludes, except where faulted. Their youth suggests that the flows may be relatively unfractured. A steam zone may be associated with a brecciated lower interface of this lava flow and the fumarole expression is related to high permeability of local fractures in the lava. Shallow recent tuffs that are not altered to clay also host steam outflows, as is shown by the numerous fumaroles that produce from tuffs in the inner caldera. The number of fumaroles with possible groundwater interaction reveals that the cap (perhaps like others in Kenya) is relatively leaky. The base of the reservoir may be formed by a low permeability contact metamorphic zone above a magma or just rapidly declining permeability due to overburden compression.

2.5 Recharge

Groundwater in the rift valley is dominated by regional flow of meteoric water from above the rift scarps to the east and west and then down the rift toward lower elevations southward to and beyond Suswa Volcano. The regional water table is expected to be about 500 m depth (1200 m elevation) below the volcano (Hinz, 2017). Significant local rainfall also occurs, including about 75 cm/year at the town of Suswa at 1600 m elevation (www.Climate-data.org). Rainfall at higher elevations on the volcano, such as Ol Doinyo Nyukie at 2200 m elevation, is expected to be strongly higher (Davies et al, 1985).

Recharge to the reservoir may be a combination of these sources. Downflow of local meteoric water is expected to encounter stratigraphic/lava flow barriers where it may perch at shallow depths before finding vertical fracture conduits near faults and intersections that deliver water to the top of the reservoir. In some cases meteoric flows may have quenched the reservoir or outflow zones. Regional water recharge is probably deeper and hotter.

2.6 Flow Pattern

The two primary sources of fluid flow are interpreted to be geothermal upflow below the inner caldera and lateral meteoric recharge from the north along the rift at depth. Meteoric input flowing vertically down from the surface of the volcano is expected to be lower volume but locally important. Flow patterns are indicated by arrows in the model drawings in the model (Figure). It appears most likely that the fractionation of water isotopes during boiling and condensation at 100°C has produced most of the variation as most samples plot along the 100°C fractionation line (Figure 10).

Geothermal upflow in the inner caldera may occur along stressed fault irregularities in a fracture network that includes the ring faults of the inner caldera and Island Block. The best candidates for deep upflow are identified at the surface based on fault patterns and fumarole chemistry at the east end of the Island Block and in the SW inner caldera moat. The breach in the cap along the inner caldera ring fault may also allow local downflow.

In the favored model (Figure 12) reservoir steam from the inner caldera flows to the north and south along the rift axis faults and in stratigraphic traps at low temperature at the top of the interpreted water level. This configuration based on the strongly expressed 100ºC condensation trend evident in the gas chemistry (Figure 9), the interpreted water table, and the overlying buried lava flow resistor in the moat that correlates with the fumarole occurrence. To the south, shallow resistors are thin, shallow, and much less extensive and fumarole activity is limited (Figure 12 and 14).

It is possible that a high temperature outflow at deeper levels to the north or a separate upflow on the northern outer caldera ring fault occurs. This speculative upflow is based on the resistivity pattern (Figure 11), a history of sulfurous alteration, and possible traces of high temperature gas chemistry (Haizlip, 2017).

2.7 Resource Conditions

The reservoir below the inner caldera is expected to include liquid and steam-dominated or two phase zones at a range of temperatures from 250 to > 300ºC (Figure 11; Haizlip, 2017, Kipngok et al., 2016). Temperatures under the eastern Island Block fumaroles are expected to follow the boiling point below the interpreted water table such that two phase conditions could cap the reservoir and extend down the upflow. Hot fluids are expected to be dilute and neutral. Acid fluids are not expected at depth based on thoroughly drilled analogs along the East African Rift. Cold dilute fluids may also be encountered in zones above and impinging into the reservoir. The generally low Soil CO_2 flux suggest a low gas reservoir in the outer caldera (Harvey, 2017).

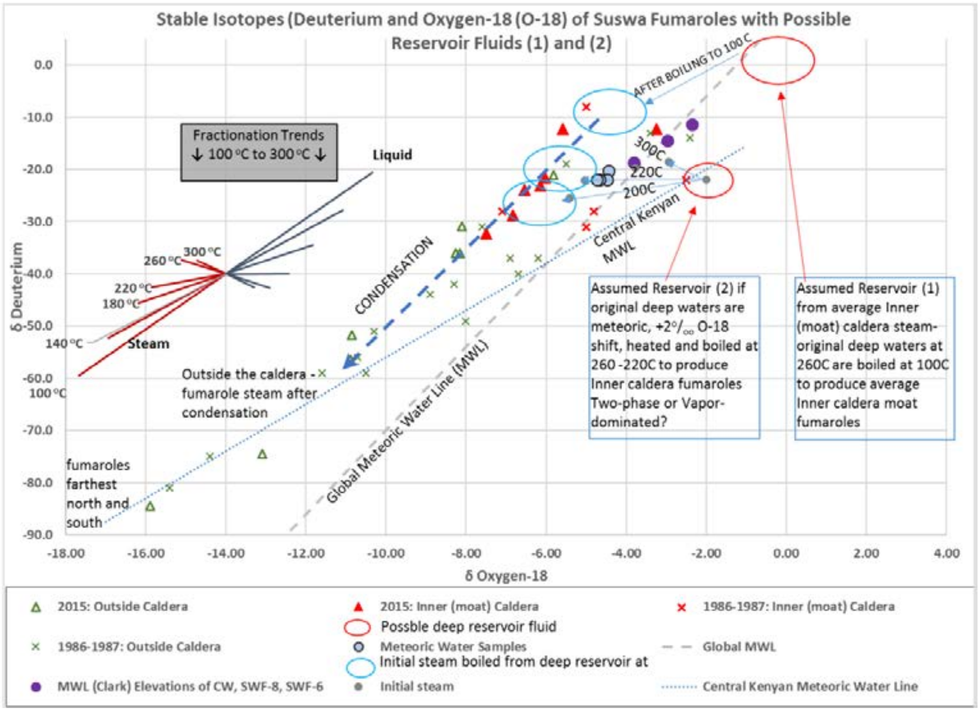

Figure 10: Stable Isotopes of water from Suswa fumarole steam and three meteoric water samples from outside the caldera from samples collected in 1986-1987 and 2015 with Interpretation of Possible Reservoir Fluids. The fractionation trends show equilibrium fractionation of Oxygen-18 and Deuterium between liquid water and steam at various temperatures. Most of the data, both inside and outside the caldera, plot on the 100°C fractionation line.

3. Suswa Geothermal Models

3.1 The Favoured Model

The favoured geothermal model of Suswa (Figures 12 and 13) suggests:

- An upflow at the east and west ends of the Island Block
- The reservoir extends below parts of the ring fault zone and Island Block-throughout the inner caldera
- An outflow below buried lava in northern outer caldera in lava-tuff sequence along faults
- A similar outflow to the south occur but shallower

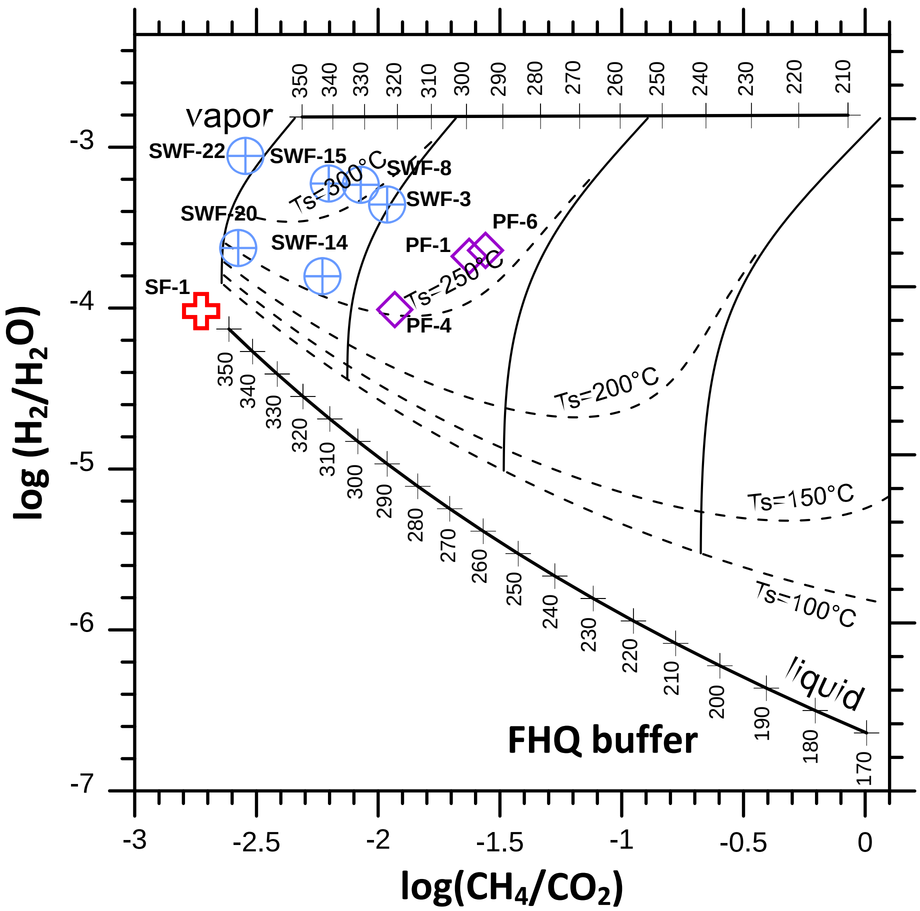

Figure 11: Diagram of log(CH_4/CO_2) vs. log(H_2/H_2O) (from Marini and Fiebig, 2005), **in which the fumarolic fluids from Suswa prospect are compared with the theoretical compositions expected for gas equilibration in a single vapor phase and in a single liquid phase (pure water) under redox conditions controlled by the FHQ redox buffer (from Giggenbach, 1987). Also shown are the effects of steam separation at temperature TS on liquids initially equilibrated at temperature TO > TS. Results from fumaroles located in the North Rift prospects (Paka; PF-1, 4 and 6) and Silali (SF-1) are also presented along with Suswa results for comparison.**

3.2 Alternate models

Features of other two possible models are briefly described below:

- The high temperature reservoir may extend across the entire inner caldera from a resource protected by the cap lavas of the island block with high enough pressure and boiling-related sealing to seal off cool shallow waters along the ring fault zone.
- Deep, high temperature outflow to the north below the thick moderately low resistivity altered cap or a separate upflow may rise at intersections and in fault ramps along the

northern outer caldera ring fault. Upflowing reservoir fluids are modified by condensation above the deep resource. In this case there is a deep and relatively hot reservoir under the northern ring fault and outer caldera moat along the rift (Figure 14). This hypothesized model is further supported by the presence of residual silica and silica veins on the northern outer caldera rim and their worldwide association with H_2S suggesting a previous phase of activity at these fumaroles that imply a higher temperature source.

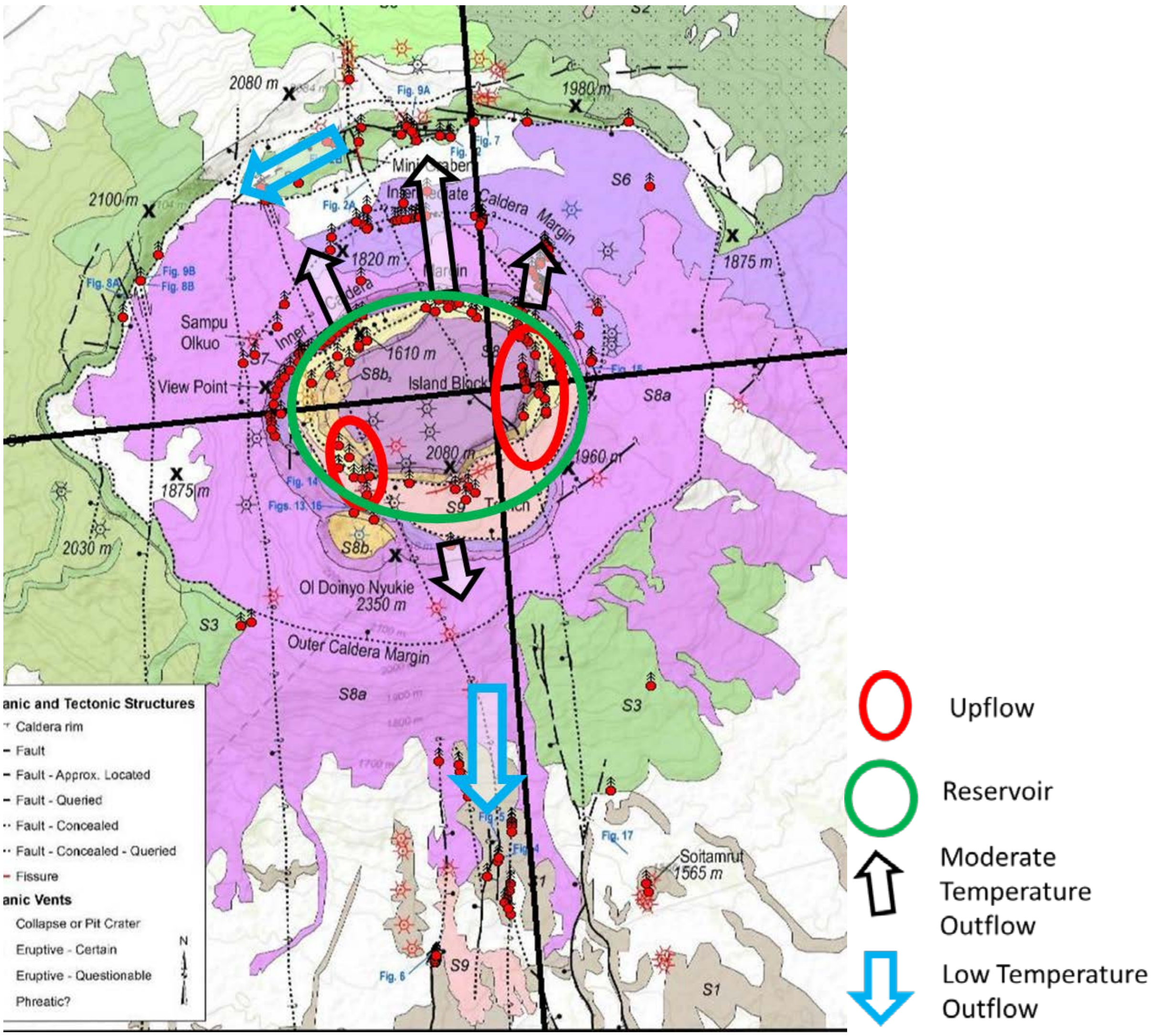

Figure 12: Suswa Caldera Conceptual Model Map (geology from Hinz, 2017; conceptual model elements from Melosh, 2017) – Upflow, reservoir, and outflow patterns are from the favored model. Bold lines show the traces of the NS and WE model cross-sections.

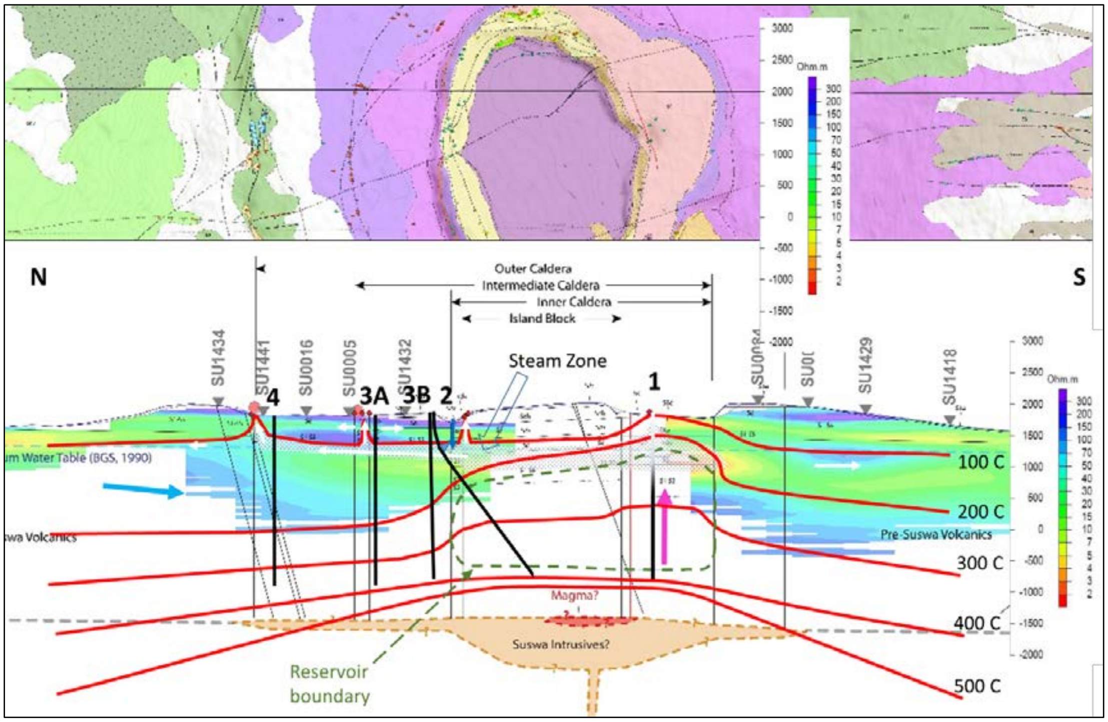

Figure 13: West-East Favored Conceptual Model Cross-Section (Melosh, 2017) – Upflow occurs below the eastern and SW inner caldera. The reservoir is confined to the inner caldera. No vertical exaggeration.

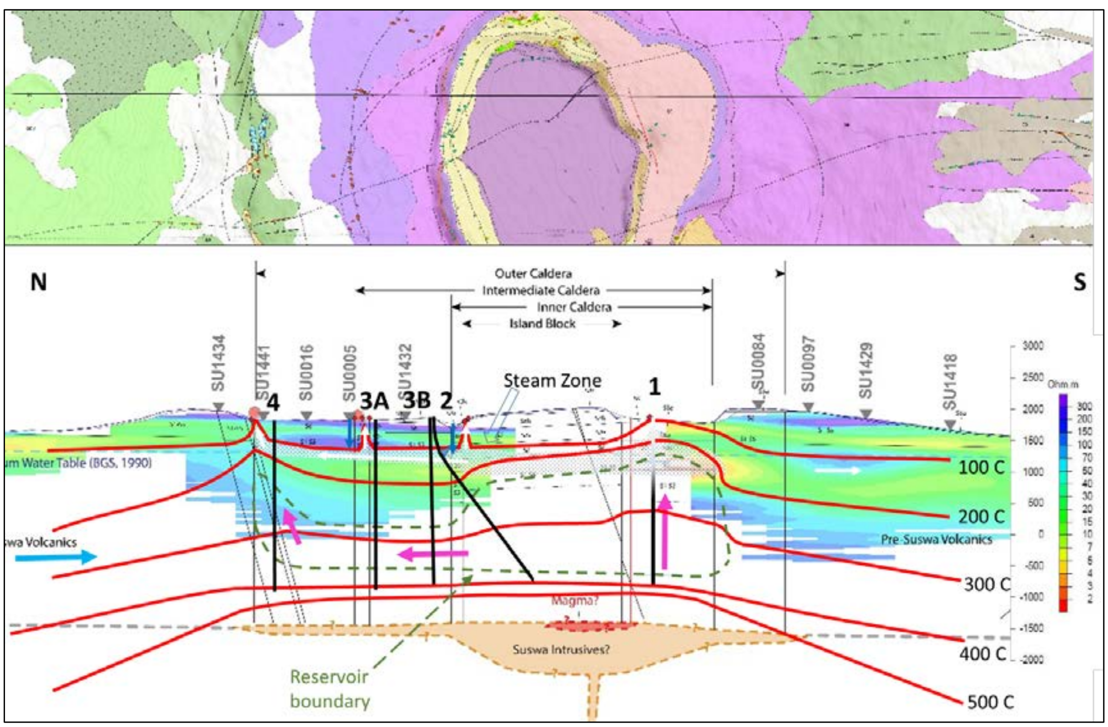

Figure 14: NS Cross-Section with Upside Alternate Conceptual Model (Melosh, 2017) – Upflow occurs on the eastern rift-ring fault zone intersection, reservoir extends under the Island Block, steam flows to the north below buried lavas, and a deep brine flows beneath the northern outer caldera and contributes to upflow on the outer caldera ring fault. The young magma extends below the northern outer caldera either as a sill or in dikes that bleed from the main body. No vertical exaggeration.

4. Conclusion

Available surface exploration data shows that Suswa is a promising geothermal prospect that can be commercially exploited. The geothermal conceptual model(s) indicate that at Suswa,

- Long term, repeated intrusion and residence of magmas have delivered heat to a large area at depth focused on the Suswa caldera complex and extending along the axis of the rift to the north and south. Renewed magma emplacement recently occurred below the inner caldera.
- Fracture networks have developed, especially below the inner caldera moat due to repeated magmatic and tectonic movements including competing offsets on concentric ring fractures around the inner caldera and Island Block and normal-right lateral rift faults.
- Hydrothermal circulation at depth below the inner caldera in the fracture networks have developed a mature geothermal circulating system that has established commercial temperatures of ~250 to >300°C, interconnected permeability, and chemical and mineralogic geothermal equilibrium in the reservoir.
- Deep permeability is localized near specific fault interactions and extends along the inner caldera ring fault zones and below the Island Block. Lavas and tuffs on faults may provide lateral conduits.
- Reservoir cap seals may be associated with lava flows, clay alteration, or veins deposited due to boiling at the top of the reservoir. The lateral boundaries around the inner caldera includes low permeability in moderately altered volcanic rock and fracture compression around the caldera.
- Recharge water is dominated by regional groundwater from the north originating in rainfall on the highlands above the east and west rift scarps. Recharge patterns also include local downward flow of meteoric water from nearby high elevation sources.

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