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Conceptual Model Update of the Sokoria Geothermal Field, Flores, Indonesia

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ABSTRACT

At the Sokoria Geothermal Field on the island of Flores in Indonesia, five wells have discovered a 200 to 225°C reservoir and the integration of well results with supplementary geology, geochemistry and geophysics surveys have supported the revision of conceptual models to guide the development of the reservoir for power generation. Previous Sokoria conceptual models have included a proposed >250°C neutral hydrothermal system with an upflow located near the Mutubusa fumaroles at elevation 1280 masl on the southwest flank of the Kelimutu volcano, with an outflow extending below a low resistivity clay cap toward chloride hot springs 3 to 6 km to the south below 600 masl. Gas chemistry had suggested a relatively neutral water chemistry below the Mutubusa fumarole compared to the chemistry expected below the magmatic acid lakes 5 km to the northeast at the Kelimutu summit. Since 2017, PT Sokoria Geothermal Indonesia has drilled five directional wells to depths of 1650 to 2100 m from Pad-A at 1070 masl located about 1.4 km south of the Mutubusa fumaroles. To extrapolate reservoir parameters beyond those constrained by the temperature, production test and geoscience data from the wells, new surface surveys have been completed, including LiDAR-supported structural geology studies, surface alteration and lithology mapping, surface manifestation resampling, and MT resistivity and gravity surveys. The integrated interpretation of these data indicates a 200-225°C southward outflow, about 600 to 800 m-thick extending south from the Mutubusa fumarole area and overlying a linearly increasing (conductive) temperature gradient. The well stratigraphy consists of a thick sequence of Kelimutu volcanics. The shallow portions of the wells (0-600m) were drilled through tightly interbedded alternating andesitic tuffs and lavas. Within the intermediate and deep sections of the wells, primarily andesitic lithic tuffs and tuff breccias were encountered without the interbedding of lavas. The permeable zones of the Pad-A wells occur within these tuffs. The water table is relatively deep, at about 500 m below the surface. The new mapping facilitated by LiDAR coverage detected no significant Quaternary fault scarps; nor did it support the existence of a previously interpreted fault zone roughly following the axis of Loworia River, where extensive clay alteration is exposed 600 to 1200 m east of Pad-A. Coincident with the exposed alteration, the low resistivity zone becomes a thin veneer and gravity is much higher, and so this zone is now interpreted as dense relict high temperature phyllic/propylitic alteration that is close to the surface where an earlier smectite clay cap has been removed by erosion. A well targeted on this feature is likely to encounter cooler and lower permeability rocks than those found in the drilled outflow. The permeability encountered by the Pad-A wells is interpreted as associated with faults and fractures at a scale too small to be mapped at the surface and within tuffs of the Kelimutu volcanics. These conceptual elements are presented in maps and cross-sections that illustrate the resource conceptual models developed to analyze the uncertainty, risk and opportunity in the Sokoria resource.

1. INTRODUCTION

The Sokoria geothermal field (Sokoria) is located on the south margin of the Kelimutu Volcano National Park (KVNP) in Nusa Tenggara Timur Province on the island of Flores, Indonesia (Figure 1). The resource was initially identified in the 1990s based on a study of the thermal manifestations (Harvey et al., 1998). Three previous conceptual models were developed to support earlier stages of exploration (Harvey et al., 1998; Cumming et al., 2011; FEDCO, 2016); these models relied primarily on surface mapping, surface chemistry, geophysics, simple LiDAR interpretation and limited slim hole data. The updated Sokoria conceptual model described in this paper integrates previous data with new results from the five wells drilled since 2017 from Pad-A, including temperature logs, production test analyses, cuttings descriptions and analyses, and geochemical samples from the Pad-A well production. New data acquired since 2017 to support and extrapolate the reservoir parameter estimates beyond the wells include a more detailed LiDAR interpretation of structure supported by field mapping, a gravity survey, and an expansion of the earlier MT resistivity survey. The revised conceptual models provide a more reliable basis for targeting new wells, assessing resource capacity and setting priorities for further data acquisition. Following an overview of earlier conceptual models for Sokoria, the new well and surface data sets are summarized and a map and two cross-sections illustrate how the data have been integrated into a revised conceptual model.

2. EXPLORATION HISTORY AND PREVIOUS CONCEPTUAL MODELS

Geothermal exploration started at Sokoria in the 1990s with geochemical analysis and mapping of surface manifestations (Harvey et al., 1998; Harvey et al., 2000). The existing geologic mapping available to these early studies included regional 1:250,000 scale by Suwarna et al. (1989) (Figure 2). This mapping showed multiple volcanic centers (QTv, Qhv) overlying Miocene marine sediments (Tmk), and one NNE-trending lineament extending across the edifice. Harvey et al. (1998) termed the previously unnamed lineament the Lowongopolo Fault, and this feature has been included in subsequent reports, influencing exploration activities and resource models. The initial conceptual model presented by Harvey et al. (1998) included a high temperature reservoir with an extensive steam cap based on the distribution of boiling point thermal features across an area >80 km^2, the high boron content in one of the crater lakes, gas geochemistry of the fumaroles, fluid chemistry of the springs and lakes, and the geometry of the clay cap from a Schlumberger vertical electrical sounding (VES) survey. Gas geothermometry was interpreted as indicating a geothermal reservoir >300°C and fluid cation geothermometry up to 260°C. In the Harvey et al. (1998) model, the Mutubusa fumarole (Figure 3) was located along the southwestern edge of the high temperature geothermal system.

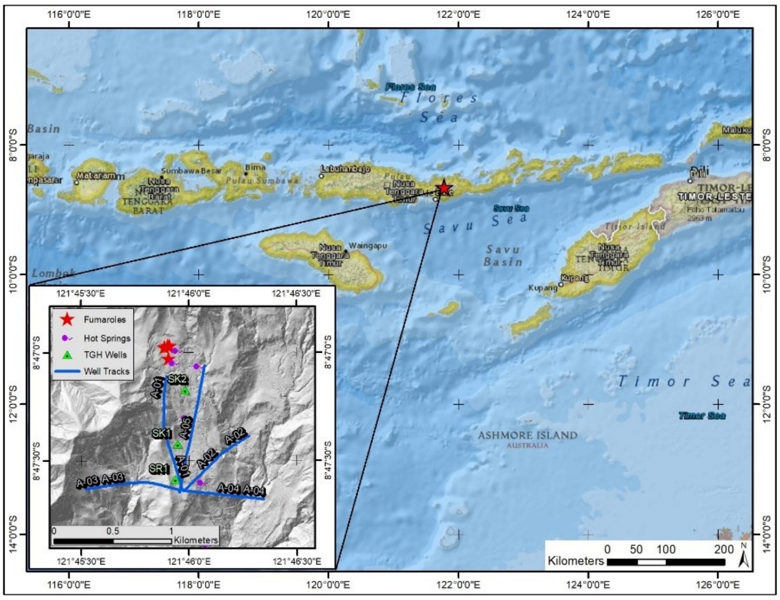

Figure 1: Location of Sokoria in the context of the Flores Island (ArcGIS Online image base) with inset showing a subset of the manifestations and wells.

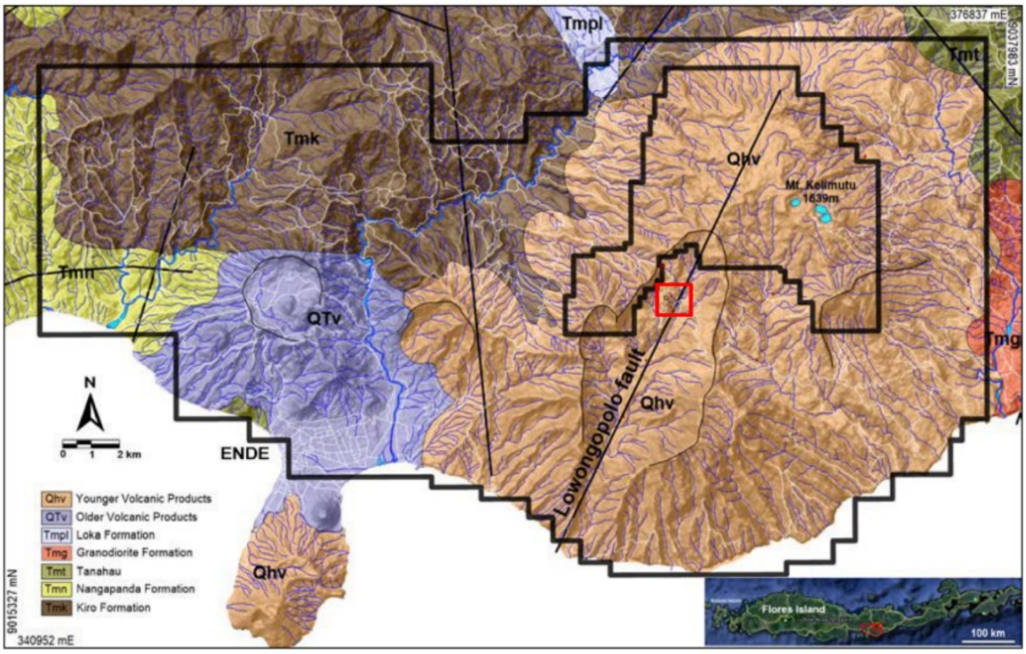

Figure 2: Regional geologic map from FEDCO (2016) with geologic units copied directly from 1:250,000 scale mapping by Suwarna et al. (1989). The outer heavy black outline is the license area held by SGI. The inner black outline is the boundary of Kelimutu Volcano National Park (KVNP). The small red box shows geothermal area near the SW boundary of the KVNP.

In the 2000s the Indonesian government drilled two temperature gradient holes (TGHs), SK-1 and SK-2, to 160m and 127m depth respectively, and one slim hole well, SR-1, to 500m depth (Figures 1 and 3). These wells had temperature gradients higher than background and did not encounter temperature reversals. The slim hole well, SR-1, reached 185°C at 500 m TD (total depth). In addition to the drilling at Sokoria, WestJEC-Elnusa acquired 35 magnetotelluric (MT) stations in a 3 x 3 km area covering the Mutubusa fumarole and extending 3 km to the south. In 2011, Cumming et al. (2011) integrated the TGH and slim hole results and the geophysics, geochemistry and limited surface geology data into a conceptual model interpretation to support an assessment of resource capacity and exploration well targets. The 2011 model concluded that a magmatic vapor core system was hosted beneath the summit acid lakes and a neutral or at least partially neutralized >250°C hydrothermal system existed beneath the Mutubusa fumarole area with a conductive clay cap extending south of slim hole SR-1 toward the chloride springs (Figure 3).

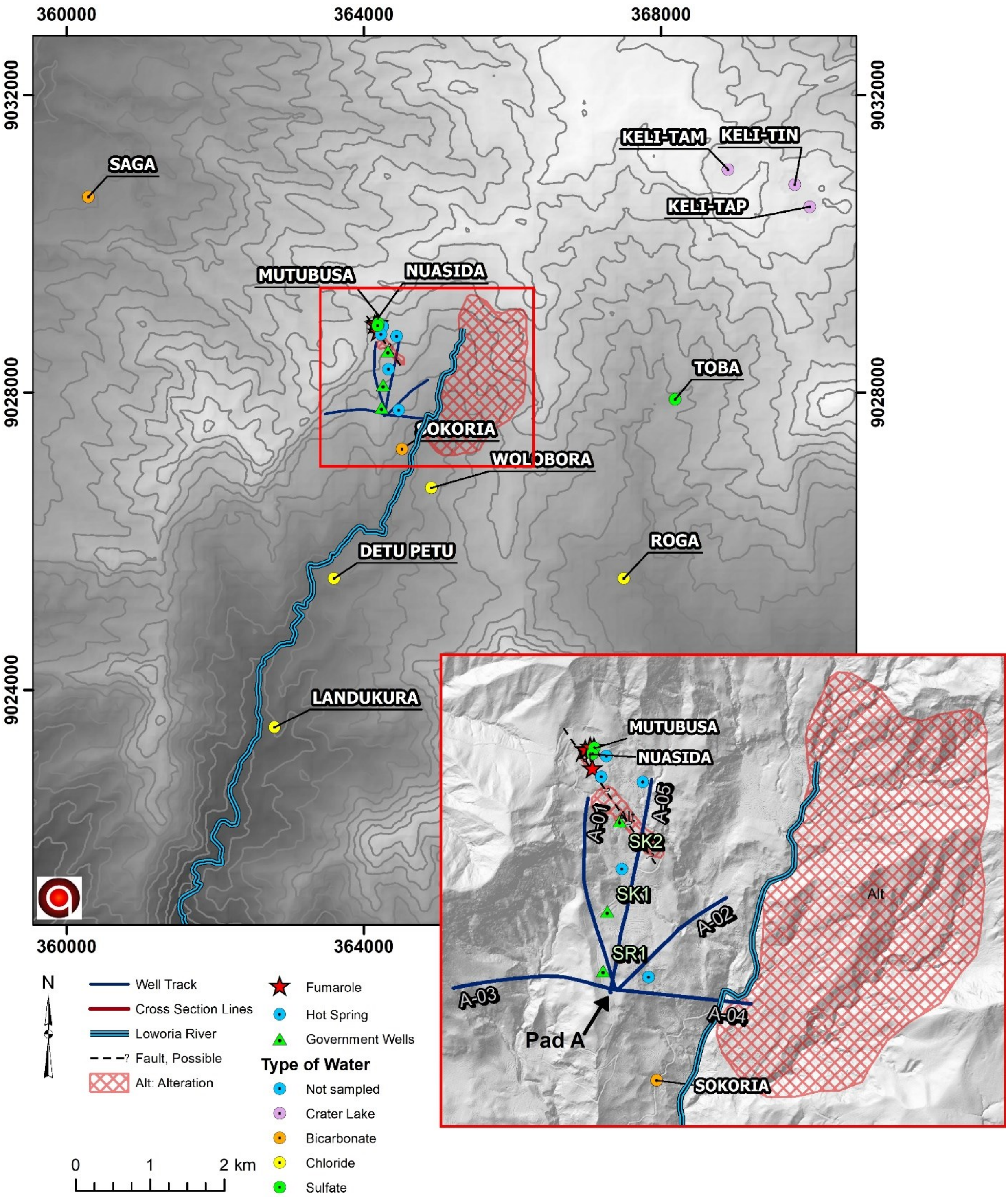

Figure 3: Surface manifestations, alteration, and existing wells in the Loworia River area of the Kelimutu volcanic edifice.

In 2016, SGI contracted Filtech Energy Drilling Corporation (FEDCO) to complete additional exploration at Sokoria including a review of the geochemistry, acquisition and lineament analysis of LiDAR, acquisition of additional MT and gravity data, and completion of a joint MT-gravity inversion. In their 2017 geochemical and geohydrological model, FEDCO proposed that two main types of fluid would be encountered in the prospect: (1) those associated with the acid core and overlying summit lake system and (2) those associated with the Mutubusa fumarole. The latter of these fluids was interpreted to be an outflow that had been neutralized along a long flow path from the acid system. The Lowongolopolo lineament was interpreted as a boundary that limited more direct flow between the two reservoirs (FEDCO, 2016). This led to the drilling in 2017-2018 of five wells completed to measured depth (MD) of 1925 m and 2505 mMD, all drilled directionally from the single well Pad-A, which is located 1200 meters south of the Mutubusa fumaroles (Figures 1 and 3). The deep wells encountered a 200-220˚C resource with moderate permeability.

Although the updated median case conceptual model includes many elements of earlier models, interpretations of the new well data together with the structural, MT and gravity data imply a much higher risk of targeting wells to the east and the new well data have better constrained the reservoir thermodynamics south of the Mutubusa fumarole.

3. DATA USED IN THE CONCEPTUAL MODEL UPDATE

3.1 Geology

New geology data available for this conceptual model update include Quaternary fault mapping from reanalysis of the LiDAR and field evaluations, updated mapping of surface manifestations and new mapping of alteration, and logs from five deep wells drilled from Pad-A.

LiDAR reanalysis prior to conducting new field mapping determined that most of the lineaments identified in previous studies were probably not faults. The initial reassessment was based on lineament patterns inconsistent with surface traces of faults (e.g., most trended straight across topography or followed streams). Subsequent field observations did not detect offsets characteristic of faults (Geologica, 2018). The LiDAR features most likely to be associated with Quaternary faults were identified for field checking but the field work did not encounter reliable evidence of Quaternary fault scarps, including along the Lowongolopolo lineament. Geologica (2018) reported that it is possible that vegetation and surficial deposits (landslides) may obscure some larger faults that do not have a surface expression (i.e., offset of depositional or erosional surfaces).

Although faults with a small magnitude of offset were observed in road and stream-cuts (Figure 4), these are too small in scale to appear in anything but very local maps of, for example, landslides or local construction hazards and are, therefore, unlikely to project to reservoir depth or to provide predictive value for targeting wells (Geologica, 2018). Preliminary kinematic analysis of fault surface data for these small magnitude faults indicates N-S shortening and E-W extension. This is consistent with the regional stress data available for Flores Island region in the World Stress Database (Heidbach et al., 2016).

Argillic alteration, consisting of clay, and localized distribution of iron oxide, disseminated pyrite, and calcite have been observed in three areas (Figures 3 and 5). These areas include: (1) in the Mutubusa fumarole area, 100 m x 40 m, elongate NW-SE and surrounded by localized areas of alteration < 25 m^2; (2) a 450 m x 100 m area that is not associated with active surface manifestations, elongated NW-SE near TGH SK-2 and alongside the main road; and (3) east of Loworia River, a 2 km x 1 km, elongated NNE-SSW area that is also not associated with active surface manifestations. The first area of alteration is due to the active presence of geothermal gas and heated bicarbonate and sulfate water at the surface. The second area is coincident with the NW-striking fault zone observed extending through the fumarole area and along the road near well SK-2. Although small-magnitude, the location of this fault suggests that it could be related to a deeper seated structure that might control the upflow of heated fluids that discharge in the surface manifestations, resulting in the alteration observed along the fault; however, because the alteration in this area is inactive, some erosion has occurred and the area may be mostly relict. The third and largest area of exposed alteration has not been reported in earlier geologic model descriptions and is identified as clay (pending further XRD and thin section analysis) with pyrite, calcite, and iron oxides. This extensive exposure of relict argillic alteration has undergone erosion, and MT resistivity and gravity suggest it is a veneer over higher rank alteration (see section 3.2 Geophysics). This could be related to either a relict geothermal system analogous to the current neutral Mutubusa resource to the west or a relict part of the acid core of Kelimutu volcano. Because the smectite cap is thin or absent and all of the alteration in this area is inactive, either the underlying higher rank alteration is low permeability or it is associated with downflow of cooler surface water. The lower permeability and slightly lower temperature of the easternmost well track, A-04, is consistent with the interpretation that the area beneath the large exposure of alteration associated with the Loworia River is unlikely to be prospective.

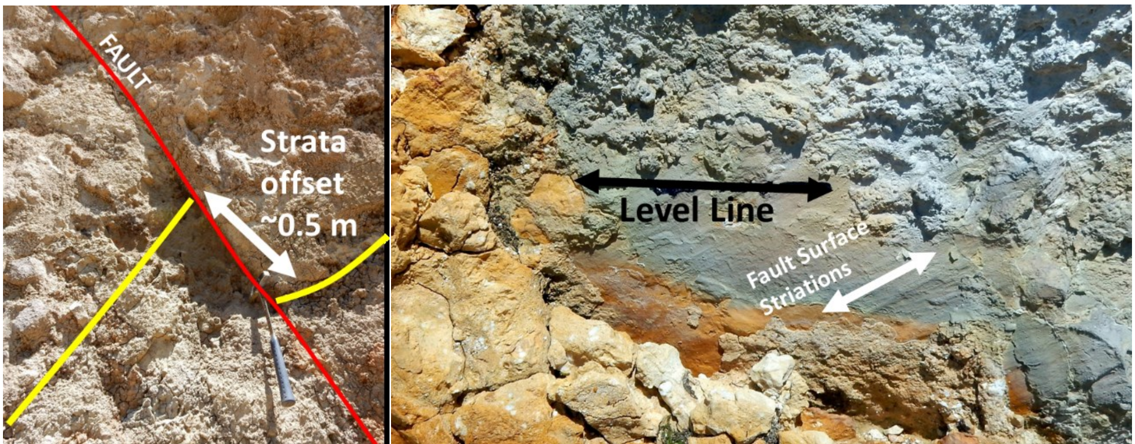

Figure 4: Left: Example of a small magnitude fault (red line) observed in Sokoria roadcut exposure offsetting a contact (yellow line) in andesite volcaniclastics. Right: Example of fault surface striations locally observed in the Sokoria fumarole area.

Figure 5: Outcrop of argillic altered andesite in the 1x2 km area of broad alteration east of the Loworia River.

The reservoir lithology has been interpreted from wellsite cutting descriptions of the five deep wells at Sokoria (Figure 6). Based on well completion reports (e.g., SGI, 2017), all the Pad-A wells at Sokoria have penetrated a thick sequence of Kelimutu volcanics. The shallow portions of the wells (0-600m) were drilled through tightly interbedded alternating andesitic tuffs and lavas (Figure 6). Within the intermediate and deep sections of the wells, primarily andesitic lithic tuffs and tuff breccias were encountered without the interbedding of lavas. The permeable zones of the Pad-A wells occur within these tuffs. Limited petrography and XRD are available for three of the wells (A-01, A-02, A-03) to support these observations (PT CoreLab Indonesia, 2018).

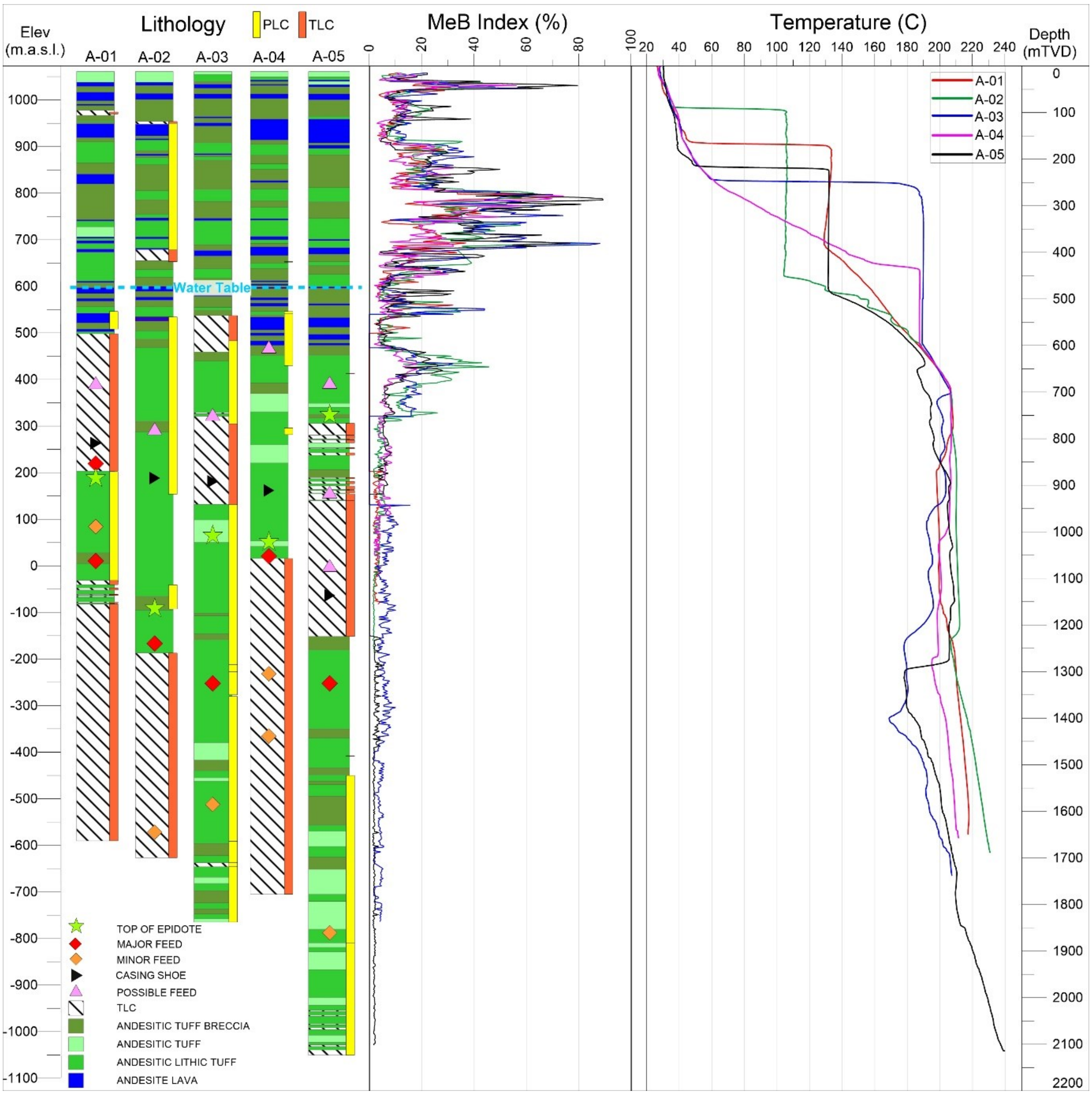

Figure 6: Lithologic units and well temperatures from deep wells at Sokoria. Total loss zones have not been tested above the casing shoe and those below the water table are possible production zones.

3.2 Geophysics

The geophysical data sets that provide the most reliable constraints on the conceptual model are the two MT surveys conducted in 2007 by WestJEC-Elnusa (35 stations) and in 2016 by PT Tunggal Buana Utama (TBU) (30 stations). The 2016 MT survey was conducted in order to both infill and extend the station coverage of the 2007 survey. In 2016, Compagnie Generale de Geophysique (CGG) computed a three-dimensional (3D) inversion of the combined 2007 and 2016 MT data sets (CGG, 2016). In addition to the 3D inversion, an independent analysis and 1D inversion of the MT was completed for quality assurance. The results of the 1D and 3D models show a low resistivity layer within the survey area, with the highest conductance near Pad-A (Figure 7). The 2016 and 2007 MT surveys provide good coverage near Pad-A but did not extend to the likely full extent of the low resistivity clay alteration, limiting the reliability of its constraints on the overall resource geometry. Based on the 3D resistivity inversion and methylene blue results from Pad-A wells, the cap is approximately 350 m thick with a base at approximately 500-600 m below Pad-A (Figures 6 and 8). Comparing the cuttings from Pad-A wells to the MT resistivity in cross-sections, the base of the conductor correlates well with the deepest occurrences of smectite recovered from the wells. The cap is interpreted as andesite volcanic rocks altered to low resistivity, low permeability smectite clay, which is typical of the impermeable caps of almost all geothermal reservoirs in a volcanic setting. Moreover, the low resistivity (1.5-10 Ωm) correlates closely with the linearly increasing temperature gradient in the impermeable section between about 350 and 600 m depth in the Pad-A wells, TGHs, and slim hole. A higher resistivity gradient corresponding to a change to resistivity >15 Ωm appears to correlate with the base of the clay and the top of the reservoir which occurs at approximately 600 m depth (Figures 6 and 8). The base of the low resistivity cap tends to follow topography to the north where the low resistivity zone has a shallower base and slightly higher resistivity of 5-7 Ωm beneath the Mutubusa fumaroles (Figure 8).

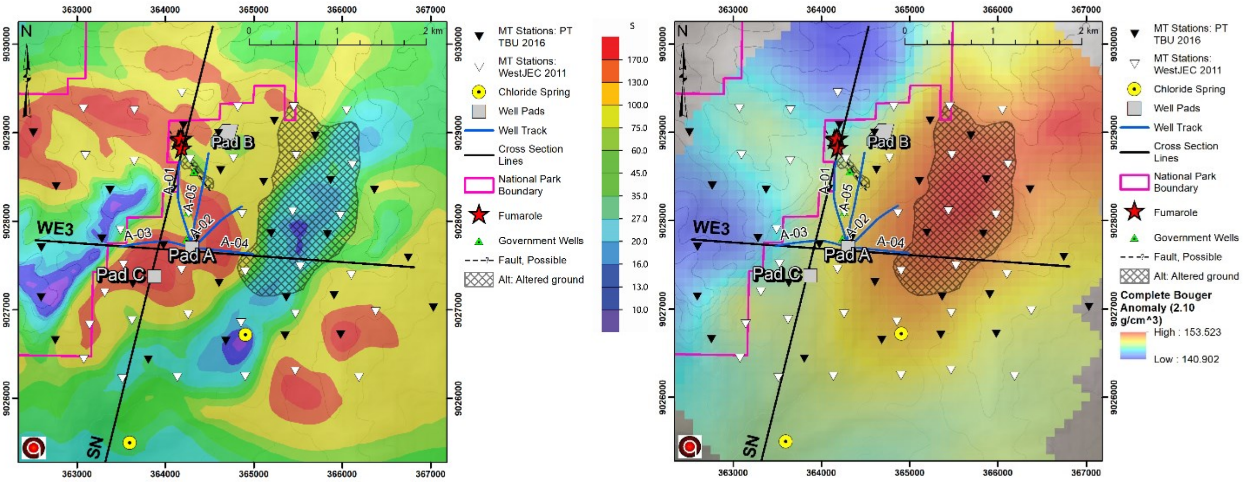

Figure 7: Left: 3D Conductance (siemens) to 500m depth with the existing Pads-A and C, the Pad-A wells, the planned location for Pad-B, alteration, chloride hot springs, the Mutubusa fumarole field with red stars, and the conceptual model cross-sections WE3 and SN (Figures 7, 13 and 14). Right: Same figure as left but showing Complete Bouguer Gravity instead of MT resistivity.

A large gap in the <10 Ωm clay cap occurs about 600 to 1200 m east of Pad-A (Figure 7). This correlates with the large area of argillic surface alteration (see Section 3.1) and the relatively high gravity (Figure 7). The pattern is illustrated in the cross-section shown in Figure 14. The shallow zone of over 10 ohm-m resistivity is interpreted as a zone of shallow, higher resistivity, high density, relict higher temperature (>230°C) alteration underlying an area that lost most of its lower temperature smectite clay cap due to erosion.

The lowest resistivity part of the clay cap at Pad-A is above the water table, a feature commonly observed in cases where a reservoir is boiling or had boiled (Figure 8). Because alteration minerals like epidote, typically characteristic of temperatures over 250°C, are found in the wells with measured temperatures <225°C, it is likely that both the epidote and the shallow smectite alteration above the water table were formed during an earlier period when the reservoir at Pad A was higher temperature and boiling at >240°C near its current top (Figure 6). This is consistent with a conceptual model in which the Sokoria reservoir was formerly larger and hotter than in its present state.

3.3 Well Temperature and Permeability

All five deep wells at Sokoria have thermally conductive temperature profiles through the clay cap overlying a nearly isothermal section from <700 to >1400 m depth (400 masl to 300-500 mbsl, depending on the well), with temperatures ranging from 200-225°C (Figure 6). Such profiles are consistent with a permeable and well-connected outflow zone. Currently, the maximum measured temperature below the productive reservoir is 240°C, consistent with cation geothermometry temperatures (see Section 3.4). The well temperatures below the isothermal section are still re-equilibrating for wells A-03 and A-05 and, to a lesser extent, A-02 and A-04.

Permeability data from well tests show low to modest permeability exists in the 700 to 900 m-thick isothermal zone, which may be associated with primary stratigraphic permeability in tuffs or fractures in lavas, and/or with ambiguously oriented faults with small offset, similar to those observed at the surface. Possible feed zones at >200°C occur up to 450 m above the cemented production casing; however, currently these are untested. Pad-A wells encounter the water table at approximately 600 masl (about 460 mTVD). Collectively, the probable and possible feed zones in the five Pad-A wells are relatively evenly distributed in 3D space and do not appear to follow major contacts or faults.

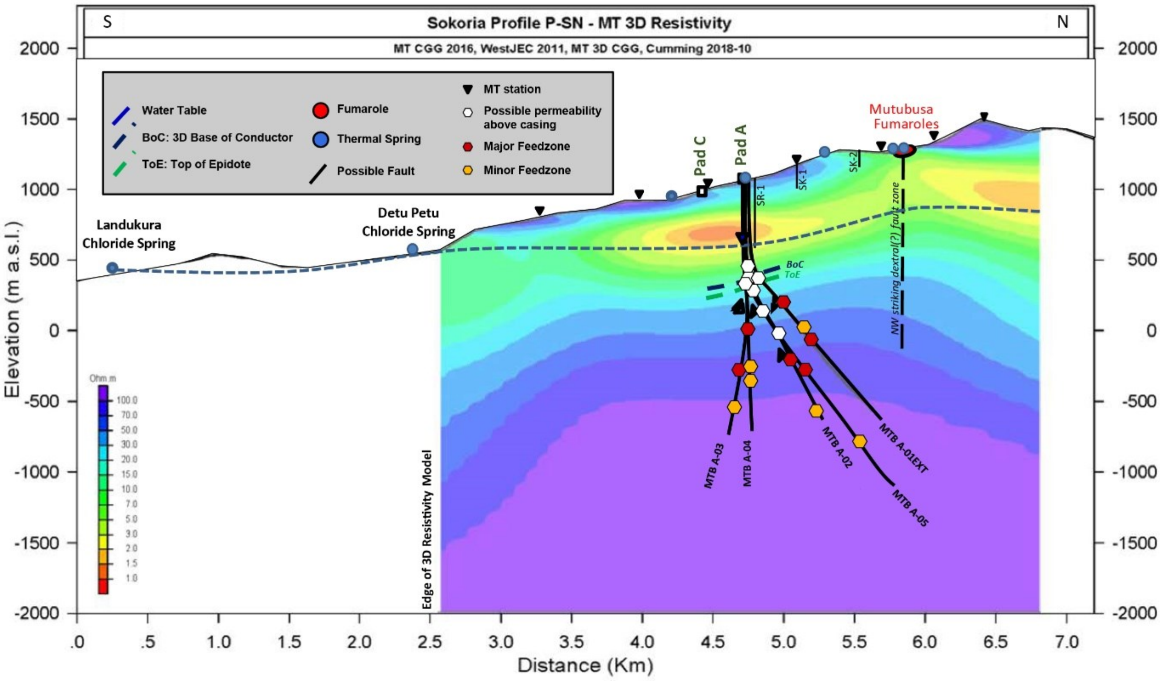

Figure 8: North-south cross-section through 3D MT resistivity model. The base of conductor (BoC) in the vicinity of Pad-A was determined by the 3D resistivity geometry and the drilling results (methylene blue and cuttings). The full extent of the cross-section trace is shown in Figure 12.

3.4 Geochemistry

New geochemical data for the Sokoria reservoir includes laboratory analysis of brine and steam (gas) samples from A-01 and A-02. The geochemistry from surface manifestations (Figure 3) is all from previous studies (Harvey, et al., 1998; Harvey, et al., 2000; Cumming, et al., 2011; Panax, 2012; also summarized in Huelsmann and Sagala, 2017).

The Mutubusa fumaroles and associated hot springs are probably the result of high temperature boiling of reservoir fluid (high SO_4, low Cl, Figure 9). The hot springs (Mutubusa hot springs, Nuasida, Saga and Sokoria) in the immediate vicinity of the Pad-A wells are either (a) conductively-heated neutral bicarbonate (HCO_3) springs (Saga and Sokoria) or (b) steam-heated acid sulfate (SO_4) springs (Mutubusa hot springs and Nuasida) (Figure 10). Several unsampled springs close to Pad-A likely have a similar composition to Mutubusa HS, Nuasida, and Sokoria. The crater lakes at the summit of Kelimutu and the thermal spring Toba are all highly acidic (pH<3), likely because of a connection with the inferred high temperature vapor core that is presumed to exist beneath the crater lakes. Chemistry of thermal springs to the south and southeast may indicate reservoir outflow in that direction (Detu Petu, Landukura, Roga, and Wolobora), but they appear to be conductively cooled and/or mixed with cold, neutral waters (**Error! Reference source not found.**). These neutral springs to the south have elevated chloride (~600-1400 mg/kg) and above-ambient temperature (~40-50°C), indicating a likely connection with the drilled reservoir.

Reservoir fluid for wells A-01 and A-02 is dilute (TDS~3000 mg/l) and major constituents are Cl = Na > SO_4 (Figures 9, 10, 11). Both wells have similar chemistry, aside from pH (A-02 and A-04 reservoir fluid is more acidic). The Na-Cl-SO_4 brine chemistry is typical of high temperature volcanic-hosted liquid-dominated geothermal reservoirs and is easily distinguished from the low TDS SO_4 warm springs, low TDS calcium (Ca)-magnesium (Mg)-bicarbonate (HCO_3) warm springs and the low TDS mixed waters.

Silica geothermometry temperatures near the feed zones of A-01 and A-02 are >220°C, slightly higher than measured temperatures at those feed zones. Cation geothermometers are ≥240 °C. As these waters are not mature Cl-type waters (see the Na-K-Mg ternary diagram in Figure 11), cation geothermometry predictions may not be applicable, however, deeper measured temperatures in the wells are also >240°C. The immaturity of these waters may be related to either (a) mixing with meteoric water, (b) low water-to-rock ratios typical of low permeability systems, or (c) both.

Produced waters from Pad-A wells are similar except in pH and sulfate concentration. The pH of brine from A-02 is lower (pH ~4) than A-01 (pH 5.5). Recent geochemistry analyses of fluids from A-04 indicate that it is also lower pH. A possible source of the acidity are acidic fluids related to the magmatic gases discharging at the summits of the Kelimutu volcanoes; however, differences between the acidic and non-acidic well discharge cannot be attributed to magmatic influx and is unlikely related to downflow of condensate. Besides the lower pH and higher sulfate, the produced brine from the Pad-A wells have no isotopic differences. Thus, it is likely that acidic fluids are sourced from acidified meteoric water, related to the influence of sulfide minerals. Additionally, given that the summit lakes require low permeability boundaries, it is unlikely that the acidic fluids from A-02 and A-04 is sourced from the acid core that feeds those lakes.

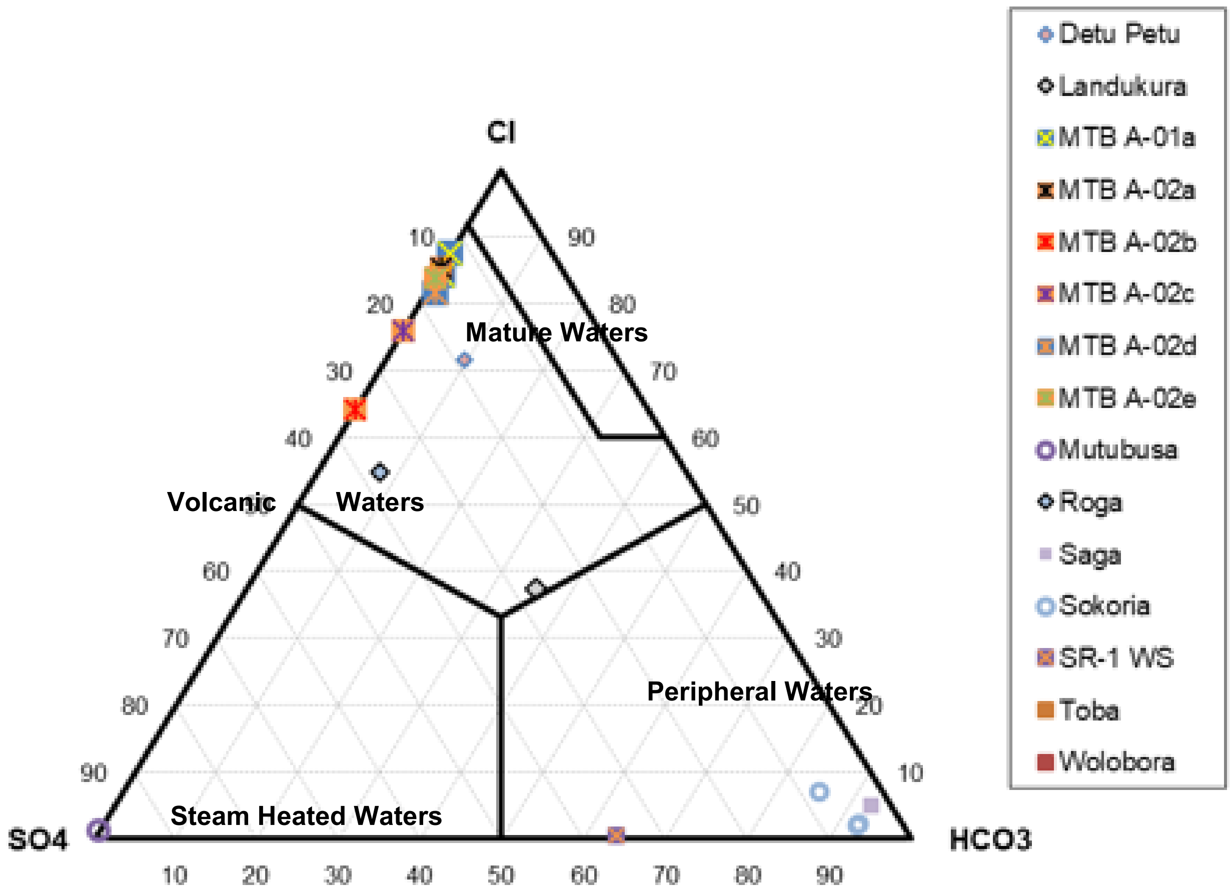

Figure 9: Cl-SO_4-HCO_3 trilinear diagram for Sokoria fluid samples and regional samples. The Nuisida sample is missing HCO_3 analysis and is not included as a result.

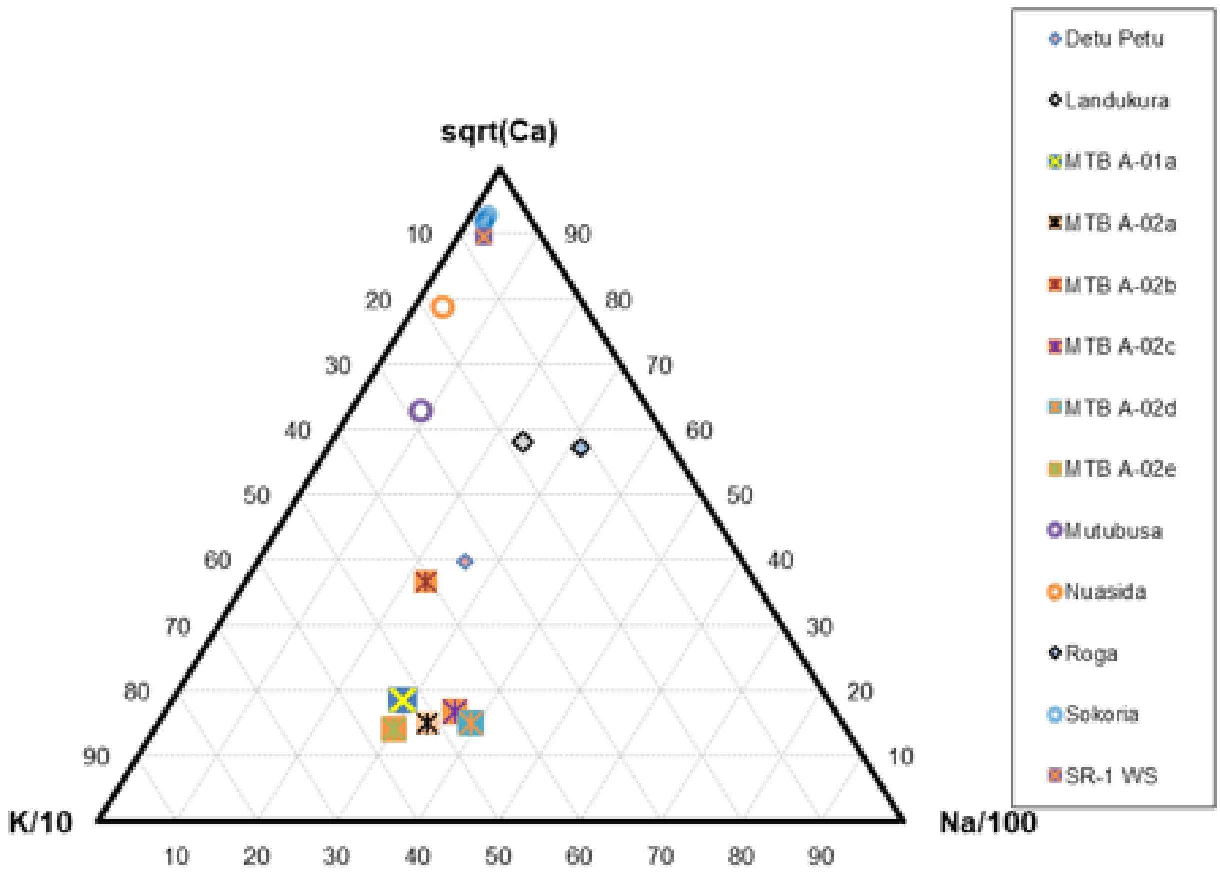

Figure 10: Na-K-Ca trilinear diagram for brine analysis of Sokoria fluid samples and regional thermal springs.

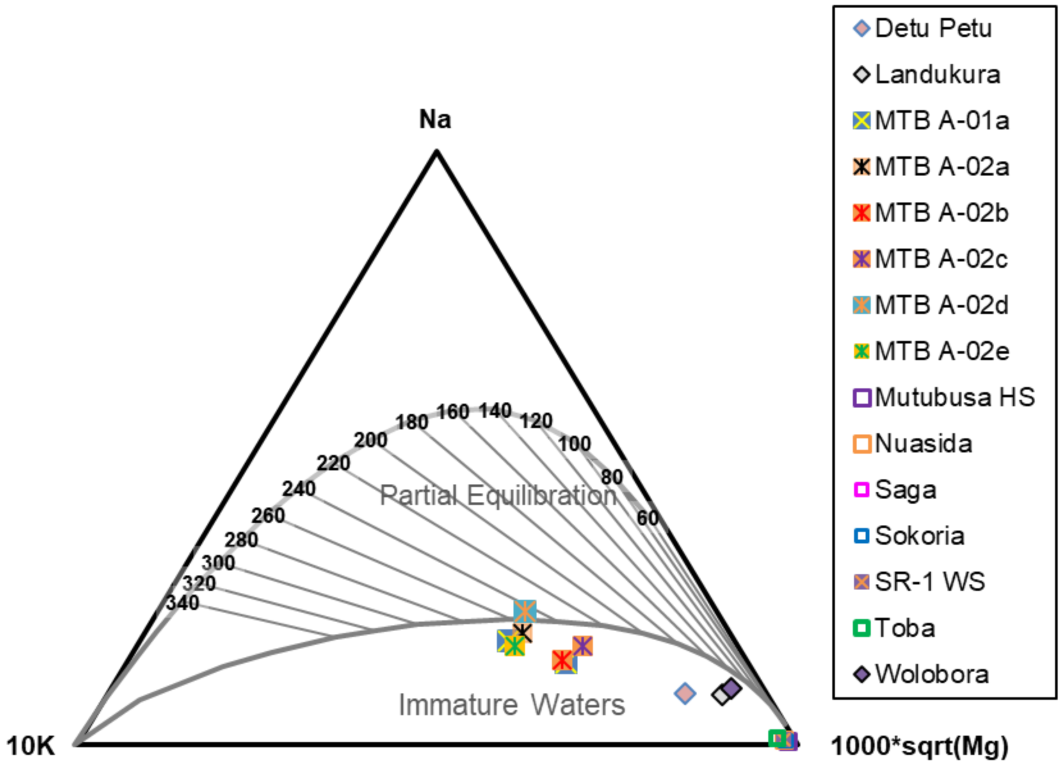

Figure 11: Na-K-Mg trilinear diagram for Sokoria fluid samples and regional samples. The Roga sample is missing Mg analysis and is not included as a result.

4. CONCEPTUAL MODEL

The revised geothermal resource conceptual model for Sokoria is illustrated in map view and two cross-sections in Figures 12, 13, and 14. Consistent with previous models, upflow is modeled to the north of the Pad-A wells with outflow generally south toward the chloride springs. The specific location of the upflow has not yet been confirmed by drilling and the MT available for this analysis has a limited extent north of the Mutubusa fumaroles. The near-isothermal (200-220ºC) well temperature profiles with feed zones spanning a zone of 1 km vertical thickness (Figure 6) are consistent with tabular outflow constrained by stratigraphy as well as structure towards the south (Figure 12). The vertical extent of this outflow is constrained at the top by the base of the low resistivity clay cap and at bottom by the transition between the convective, isothermal temperature regime to an underlying conductive temperature regime. Based on the well data, geology and resistivity patterns, outflow at Sokoria could be modeled as multiple discrete zones with slightly different temperature within a 700-900 m-thick section or as a single 700-900 m-thick zone of isothermal reservoir fluid.

The ~700-900 km-thick, 200-225°C lateral outflow has been confirmed by drilling at least 700 m to the north, east and west of Pad-A and an extension to the south would be consistent with the MT resistivity indication of an extension of the clay cap. The southern chloride springs have been interpreted as the maximum distance for which a >200°C outflow is likely to reach based on their silica geothermometry of <150°C (Figure 12). The lateral extent of the permeable neutral outflow is likely to be limited to the east of Pad-A. The most direct evidence for an eastern barrier is the pressure fall off test of MTB A-04. This is consistent with the interpretation of a relict reservoir zone underlying the extensive alteration exposed at the surface on the east side of the Loworia River and corresponding trends of high MT resistivity interrupting the conductive cap and high gravity in the same location. These patterns are consistent with the interpretation that a clay cap was stripped from a now relict reservoir zone in this area. There is no indication of an analogous barrier to the north or west. Possible options for the origin of the alteration zone include: 1) an exhumed composite clay zone consisting of the clay cap over the Mutubusa fumarole-Pad-A reservoir to the west and a clay mantle typical of the flank of vapor core volcano to the east that is both old and ongoing, mainly consisting of recent volcanics altered by leakage from the lakes and by gas lost during dike injection, or 2) an exhumed clay zone from an earlier, larger and hotter semi-neutral Sokoria geothermal system extending along the south flank of the Kelimutu volcanic massif, or 3) an exhumed clay mantle typical of the flank of vapor core volcano that the younger Sokoria geothermal system to the west is now conforming to (i.e. the cap is inherited).

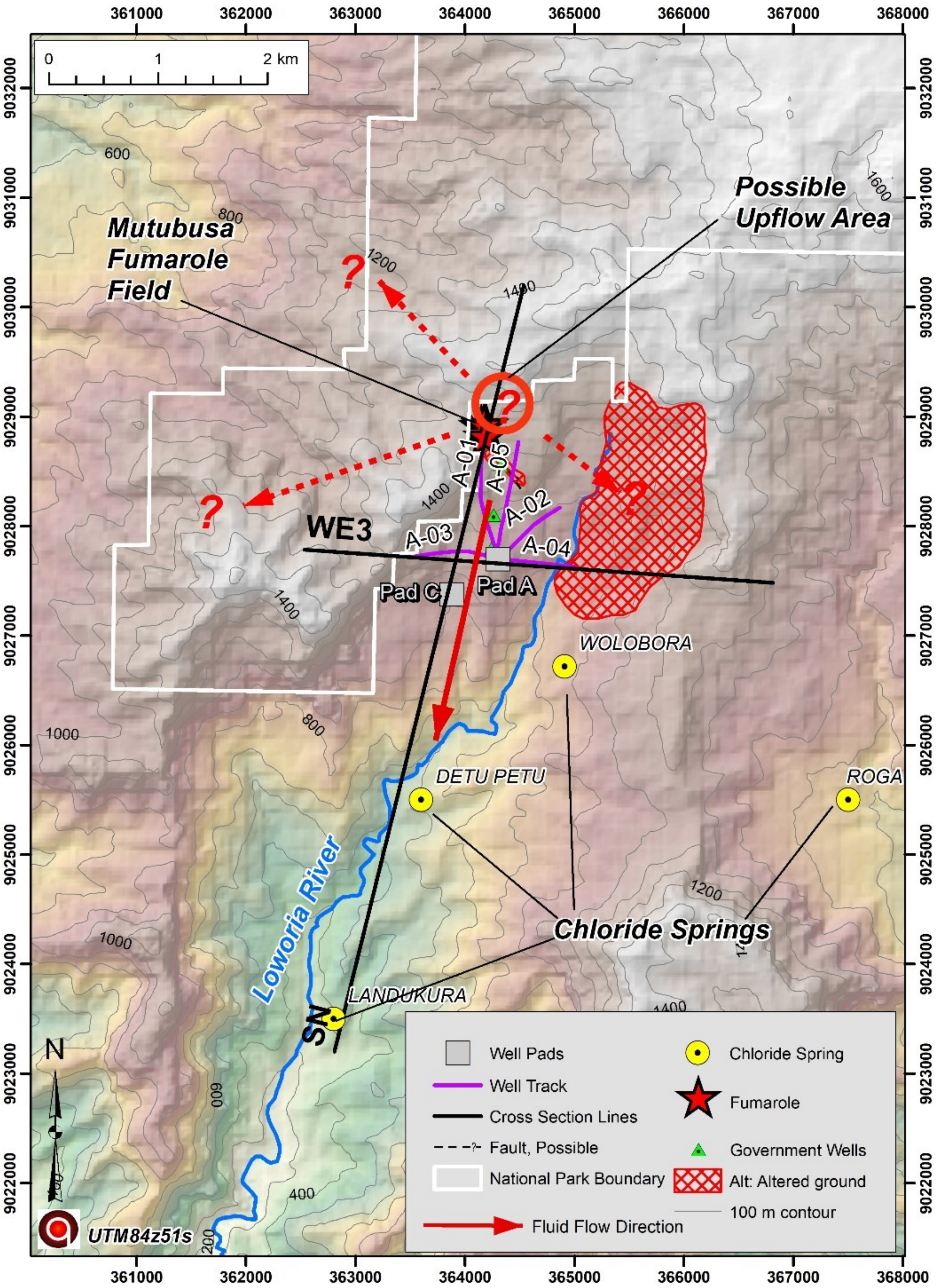

Figure 12: Map view of conceptual model with upflow possibly located north of Pad-A, and outflow likely flowing predominantly south towards the observed chloride springs. Cross-sections correspond to Figures 13 and 14.

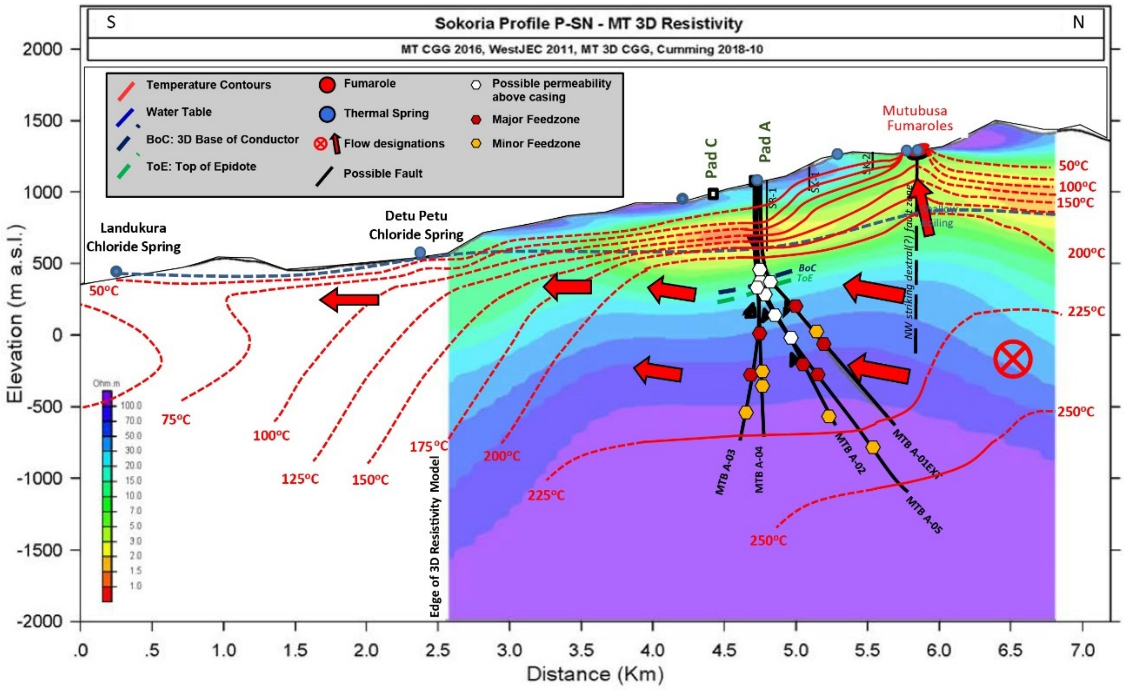

Figure 13: North-south cross-section through the conceptual model showing neutralized flow into the cross-section in the north, upflow beneath the Mutubusa fumarole and outflow to the south towards the chloride springs Landukura and Detu Petu.

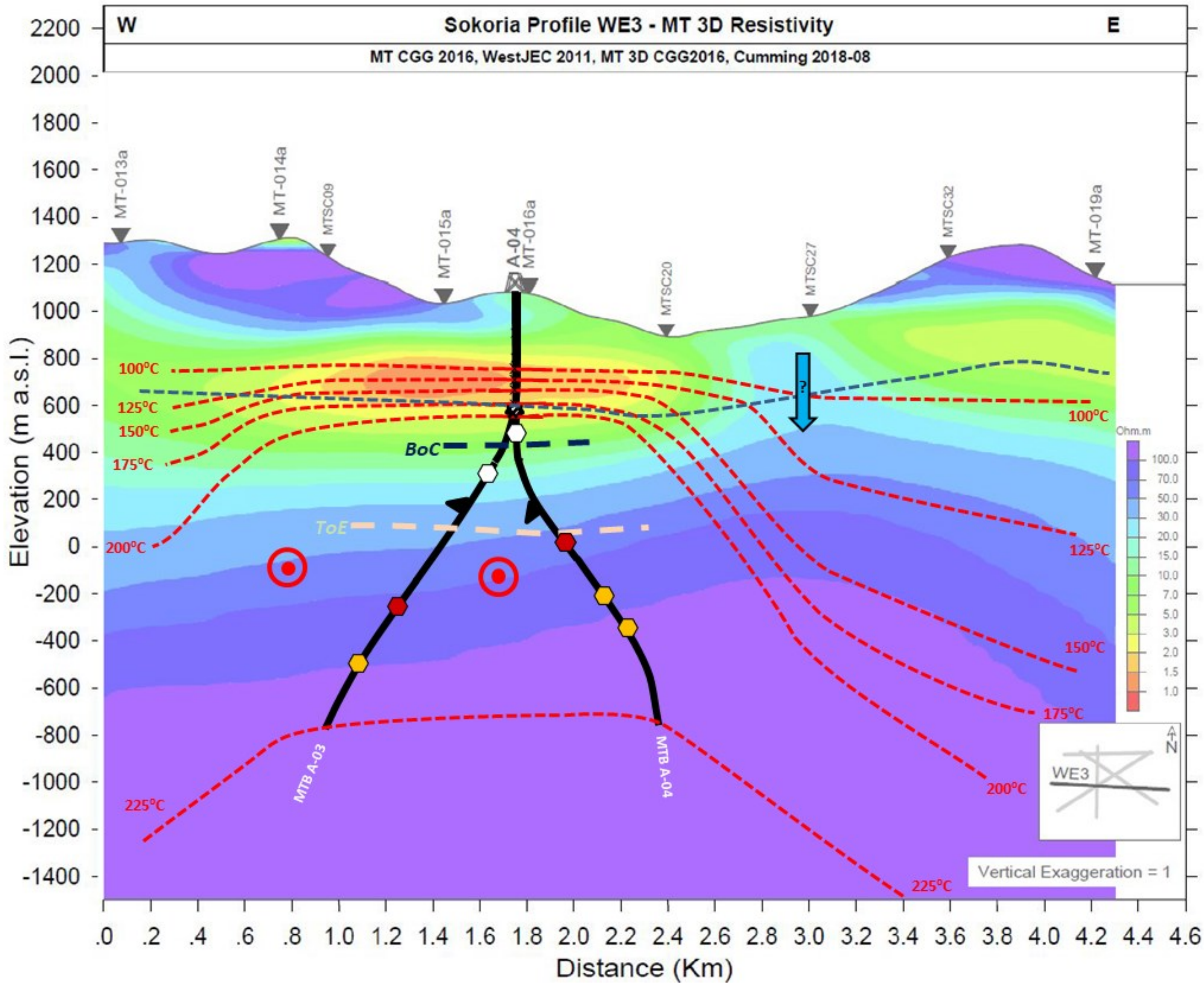

Figure 14: East-west cross-section through Pad-A with wells MTB A-03 and A-04 projected onto the section. The flow designations show outflow coming out of the cross-section plane beneath the conductive clay cap.

5. CONCLUSIONS

A revised interpretation of existing and new geology, geochemistry, MT and gravity data and integration with new geoscientific data from five deep wells has supported an update of earlier conceptual models for the Sokoria field, which includes a >240˚C upflow near the Mutubusa fumaroles with outflow toward the south and southeast. The recent deep drilling has discovered a 200-220˚C outflow about 1 km thick with moderate permeability. The extent of the 200-220˚C reservoir has not been defined by current drilling and the resistivity indications are ambiguous, in part due to the limited survey extent to the north. Vegetation and surficial deposits may obscure larger deep faults that do not have a surface expression; however, the permeability of individual feed zones is likely controlled by a combination of smaller faults and fractures and the properties of stratigraphic units and contacts within the volcanics. Acidic fluids in wells A-02 and A-04 indicate that the neutral reservoir may not be isolated from more acidic zones and there is a risk of influx of acidified meteoric water if pressure is reduced by production.

Based on well test data from well A-04 and the interpretation of exposed alteration, MT resistivity and gravity data, the conceptual model includes lower permeability east of Pad-A. The geological evolution of this altered area is ambiguous but includes options that would associate it more closely with the neutral Mutubusa reservoir to the west or with the Kelimutu vapor core volcano to the northeast.

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