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Status of Geothermal Energy Exploration at Katwe Geothermal Prospect, Western Uganda

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ABSTRACT

Systematic geothermal exploration in Uganda started way back in 1993 centered first on three major geothermal areas namely: Katwe-Kikorongo, Buranga and Kibiro and later added Panyimur in 2005. The criteria employed then to select these sites for detailed exploration were, among others: the presence of geothermal manifestations in the form of hot springs, travertine mounds and volcanic ejectamenta.

The Katwe geothermal prospect, like all the others, has been explored since 1993 on the assumption that it was a volcanic – hosted geothermal system. Additionally, six (6) 200-300 m deep temperature gradient holes (TGHs) were drilled in the Katwe prospect in 2006/2007 with the aim of locating a geothermal reservoir but the results suggested that the reservoir was either deep seated or offset from the drilled sites. While some magmatic influence cannot be ruled out at Katwe, it is now clear that the prospect falls within the now recognized model for the western rift of a fault – hosted geothermal system and only analogous to those in the Basin and Range region of the US. This model has formed the basis for the UK-DFID – supported Eastern African Geothermal Energy Facility (EAGER)/Geothermal Resources Department (GRD) project to re-assess the four priority geothermal prospects of Uganda over the last two years. In this respect, a lot more progress has been achieved (with decreasing order of confidence due to some yet critical data gaps to be filled in) at Kibiro, Panyimur and Buranga, with drilling sites for TGHs already determined.

However, the Katwe prospect is still lagging behind the other three as far as the relevant data required to site TGHs with confidence is concerned. Silica geothermometry estimates a subsurface temperature of 117-126˚C which is suitable for electricity generation and direct use. To date, however, detailed structural mapping has been completed. Field data acquisition of

the target MT geophysical survey has only recently been completed alongside soil temperature and soil gas flux surveys. Data analysis and interpretation is on-going for the temperature and gas flux surveys while the MT data interpretation awaits a new software, Geotools

This paper discusses the status of exploration at the Katwe prospect, highlighting the results of the recently completed structural mapping exercise and how it is expected to influence the remaining activities. These results will be used to refine the subsurface geothermal conceptual model that will be the basis for siting the temperature gradient holes (TGHs) and the subsequent exploration and production wells. The only recommended activity still pending is the additional geochemical sampling and analysis of gas samples for CO_2, H_2S, NH_3, N_2, O_2, He, Ar, CH_4, H_2, and CO; He isotopes and C isotopes of CO_2 and CH_4. A review of previous work based on the volcano – hosted geothermal model for the prospect is jointly discussed.

1. Introduction and Background

Systematic exploration of the geothermal resources of Uganda started way back in 1993 and initially concentrated on three geothermal areas namely: Katwe-Kikorongo, Buranga and Kibiro but in due course added Panyimur. Six temperature gradient holes (TGH) each drilled at Katwe (and Kibiro) in 2006/2007 yielded disappointing results. Like at Kibiro, the temperature gradients were found to be disappointingly low, 13 to 36°C/km. This was because all the analysis and subsequent exploration were based on the assumption that this was a volcanic hosted geothermal field. While some magmatic influence cannot be ruled out at Katwe, it is more likely that the prospect follows the now more recognized model for the western rift of a fault hosted system.

The Katwe geothermal prospect is characterized by hot springs in the Kitagata crater and warm springs in the Katwe crater. Although associated with the Katwe-Kikorongo volcanic field (KKVF), the review of existing geoscience data in Hinz (2018b) indicates that the hot springs probably originate from a 110 to 126°C aquifer heated by deep-circulation. Here, permeability is associated with fault intersections and step-overs along the strike of the Nyamwamba fault system near the Kitagata crater extending 7 km to the south-southwest. Therefore, structural geology and geophysics plans for Katwe reported in Cumming (2017) and Hinz (2018b) have focused on the area of the Kitagata springs and to the southwest along the Nyamwamba fault (Figure 1).

Over the last two years, EAGER support to GRD has focused on the geoscientific and economic aspects of geothermal development including the integration of geology, geochemistry and geophysics to develop alternative conceptual models for geothermal prospects, the use of temperature gradient holes (TGHs) (and slim holes) in exploration, geothermal data management and economic modelling for geothermal prospects. While the other three prospects have progressed to the siting of TGHs, with the two: Kibiro and Panyimur already progressed to pre-feasibility studies and financial modelling, the Katwe prospect is still at the geoscientific studies level. So far, only the detailed structural geology mapping to constrain better the area of focus of the recommended geophysics has been completed. The field acquisition of the recommended geophysical data (MT) has only recently been completed concurrent with soil temperature and gas flux surveys. Data analysis and interpretation is on-going.

1.1 Location

The KKVF lies within the Queen Elizabeth Protection Area (QEPA), formerly Queen Elizabeth National Park, except for Lake Katwe and the neighbouring Katwe – Kabatoro Town Council.

The crater area is one of the tourist attractions in the Protection Area for its scenic beauty and exotic landscape (Gíslason, et al., 1994).

Figure 1: Location map of the manifestations and lakes of the Katwe-Kikorongo volcanic field from Marini (2018).

2. Regional Tectonic Setting

The Katwe geothermal prospect is associated with hot springs in the Kitagata crater and warm springs in the Katwe crater. The geothermal manifestations cover a 0.2 km^2 area, and are situated within the 30 km long by 10 km wide Katwe – Kikorongo volcanic field that straddles the Nyamwamba fault zone and locally defines the southeast side of the Rwenzori Mountains and the northwest side of the Lake Edward – Lake George basin (Figure 1) (Hinz, 2018b). The KKVF is a field of phreatic (steam-driven) and phreatomagmatic (maar) craters, tuff cones, tuff towers and distributed pyroclastic deposits that straddle the Nyamwamba fault zone. The volcanic field consists of over 70 maars and tuff cones, some very young (Pleistocene to Holocene in age), but all generally characteristic of a deep magmatic source. Of all the numerous craters, only seven (7) are deep enough to reach the local ground water table and as such, carry saline lakes (Gíslason, et al. 1994; Gíslason et al. 2008; Natukunda and Bahati, 2015).

The volcanic rocks, with a maximum thickness of a few hundred metres only, cover either a fluvio-lacustrine sedimentary sequence of Neogene age or the Palaeoproterozoic crystalline basement rocks of the Rwenzori Fold Belt (RFB) comprising of gneiss, with subordinate granite, pegmatite, amphibolite and quartzite (Bahati et al., 2002; Westerhof et al., 2014).

3. Previous studies

Initial exploration employed various geological, geochemical and geophysical (TEM and gravity) methods to assess the targets (e.g. Ármannsson, 1993, 1994; Gíslason et al., 1994 and Árnason and Gíslason, 2009). Cationic (Na-K) geothermometric temperatures of about 200°C were predicted at Katwe. Subsequent studies employed isotopic hydrological (e.g. Ármannsson, 2001; Bahati et al., 2002, 2005; Bahati, 2007) and active seismic (e.g. Stadtler, et al., 2007) techniques to understanding the groundwater flow characteristics and heat sources to the geothermal systems. Stadtler et al. (2007) noted that silica-undersaturated carbonatitic and alkali basaltic compositions of recent volcanic rocks in Uganda imply deep magmatic sources and rapid ascent of magma to the surface, consistent with the widespread maar eruptions at Katwe. Therefore, no significant shallow crustal magma chambers are expected at Katwe and indeed, at all Uganda's known geothermal occurrences, unlike those associated with high temperature volcano – hosted geothermal systems worldwide, for example, in Kenya and Ethiopia.

Surface exploration at Katwe was deemed complete by drilling six (6) thermal gradient holes. However, the temperature gradients measured were found to be disappointingly low, in the range from 13 to 36°C/km. The hole closest to the hot spring in Lake Kitagata showed a little higher temperature than the other. The estimated heat flow in the area is similar to the average heat flow in the continental crust of the Earth (av. 65 mWm^{-2}) (Gislason et al. 2008).

EAGER has had to conduct an extensive review of the dearth of data and information contained in reports and publications arising from five large geothermal assessment projects that included the Katwe area in order to develop an exploration plan for the prospect.

4. Katwe Literature review

4.1 Geology and Structure

The KKVF, which straddles the southwestern end of the Nyamwamba fault zone, is also an accommodation zone between oppositely dipping ('antithetic') normal faults on the southeast of the Lake Edward – Lake George basin. The termination of the large magnitude Nyamwamba fault and the adjacent accommodation zone creates a regional area of weakness in the brittle crust with extensive complex faulting, which may have facilitated the ascent of small volumes of magma associated with the volcanic field. The area is also cut by a number of NE- to ENE-striking faults that may be related to a change in extension direction across the Rwenzori region over the past few million years from WSW – ENE to NW – SE (Ring, 2008). It is possible, therefore, that one or more of these numerous fault segments may also host geothermal fluid associated with the Katwe geothermal area.

Based on a preliminary review of existing structural surface mapping and the structures inferred from gravity models in Gíslason et al (2008), there are hints of several possible key fault intersections and step-overs in the Katwe geothermal area. However, pyroclastic deposits form a relatively thin, but laterally extensive veneer over the respective Paleoproterozoic age crystalline rocks and Cenozoic basin – fill deposits on either side of the Nyamwamba fault respectively. As a result, many of the young Quaternary faults are variably obscured along strike and thus, more detailed mapping of the local fault distribution, dip and dip direction are needed to develop new conceptual models for the Katwe geothermal area (Hinz, 2018b).

4.2 Geochemistry

Apart from Lake Edward, the Kazinga Channel and Lake George which host low – salinity waters, other lakes of the KKVF have very high salinity due to dissolution of evaporite minerals and their peculiar water budget, in which evaporation is balanced by precipitation and inflow of groundwater of high to relatively high salinity. Evaporites are seasonally deposited in all the lakes except Kitagata, Kikorongo and Munyanyange, and their deposition is more widespread in the recent past, based on their presence in local sediments. Evaporite minerals have a remarkable influence on the chemical characteristics of local groundwaters and lake waters, with production of Na-Cl, Na-SO_4 and Na-HCO_3 type water that depend on local variations in the types of evaporites, and not on any geothermal process or an association with magmatic heating (Marini, 2018).

Several thermo-mineral and mineral manifestations and saline lakes are present in the KKVF (Figure 1). The thermo-mineral and mineral manifestations include: 1) hot springs positioned along the western shores of Lake Kitagata and below the surface, with temperatures of 39.4 to 72.1°C for only the onshore springs only; 2) the warm springs of Kabuga (40.6 – 41.8°C); and the cold high-salinity springs in Lakes Katwe (32.5°C) and Nyamununka (Marini, 2017, 2018; Nick, 2018b; Cumming, 2018). Gíslason et al. (1994) recorded 56.6 to 66.5°C on the onshore (sub-aerial) springs and 70.1°C in the sub-aqueous spring issuing from beneath Lake Kitagata(Figure 2).

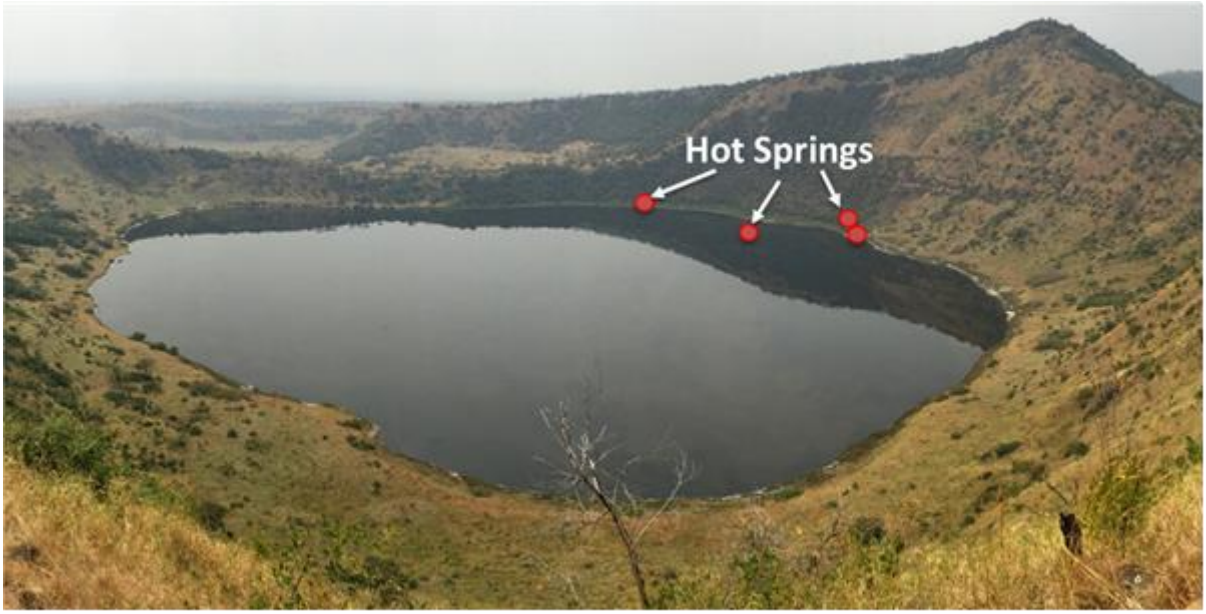

Figure 2: Panoramic view of Lake Kitagata with hot springs along the western shore. Left edge of photo is looking south, right edge is looking west.

EAGER's initial review of the existing geochemistry in the context of the structural geology analysis at Katwe suggests that the >70°C hot springs in and adjacent to Lake Kitagata are the only thermal features at Katwe that are most likely associated with a >120°C geothermal aquifer based on silica geothermometer. The Kabuga crater is less prospective, with a maximum aquifer temperature on the order of 85-90°C as indicated by the silica (quartz) and K-Mg geothermometers.

4.3. Geophysics

The initial review of geophysical data relevant to the geothermal resource interpretation at Katwe by EAGER (Cumming, 2018) utilized the following datasets:

- Earthquake hypocentres from a five – year seismic monitoring survey covering the area from Lake Albert to Lake George;
- TEM resistivity maps and profiles covering the volcanic zone at Katwe;
- Gravity maps covering a similar area;
- A 2D gravity model along a gravity profile perpendicular to the Nyamwamba fault zone near the Lake Kitagata hot springs.

The earthquake events underlying the volcanic rocks near the Katwe-Kitagata prospect mainly occur at 15 to 30 km depth, indicating a deep magma source for the volcanics. This is consistent with the geochemistry and geology indications that the Lake Kitagata hot springs are not heated by magma but by deep circulation in fracture permeability associated with the Nyamwamba fault zone.

The geophysics reports by Gíslason et al. (2008) and Árnason and Gíslason (2009) illustrate a comprehensive TEM (138) and gravity station (537) coverage of the KKVF and their interpretations are consistent with the conclusion that no magmatically – heated geothermal system exists at Katwe.

Although the previous interpretations of the resistivity structure and Bouguer gravity at Katwe are reasonable, they had been limited by their focus on a resource model associated with the volcanics. Near the Lake Kitagata hot springs, TEM resistivity data detects a moderately low resistivity veneer of pyroclastics overlying very high resistivity Palaeoproterozoic age granitic gneiss to the west of the Nyamwamba fault zone and the very low resistivity, thick volcanoclastics and lake sediments east of the fault zone (Figure 3).

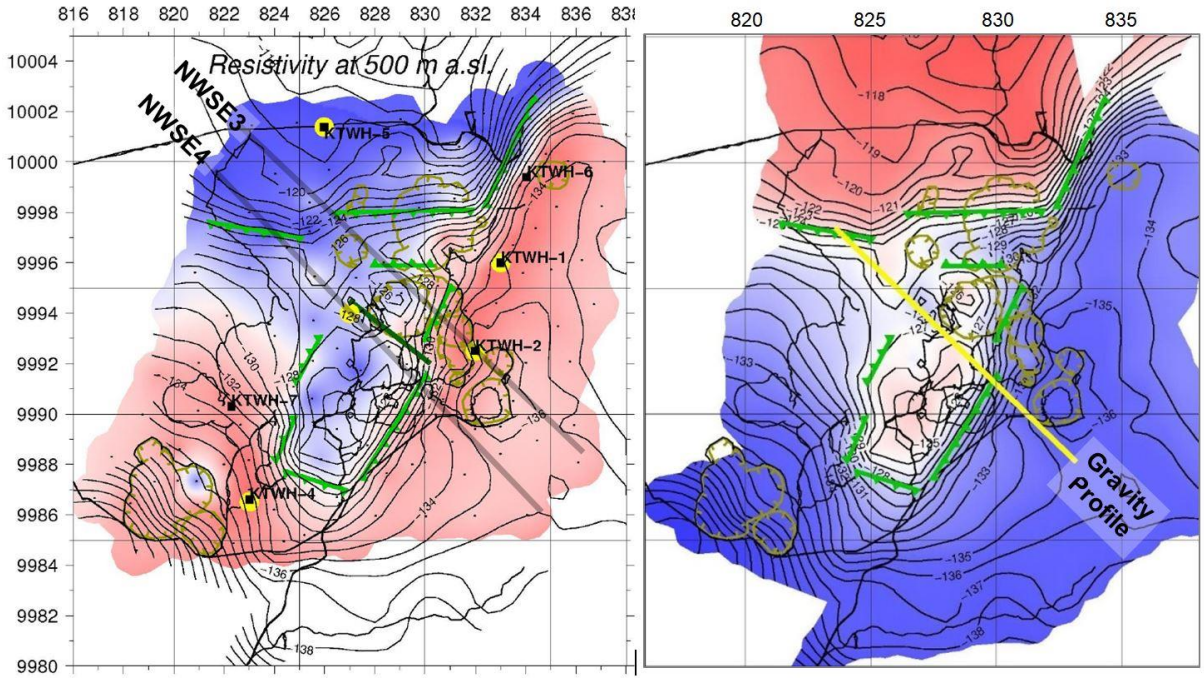

Figure 3: Map of TEM resistivity in ohm-m at 500 m a.s.l (left) and map of Bouguer gravity in mgal (right) with inferred structural trends from Gíslason et al. (2010) and UAERAUS (2004), with cross-section profiles (Different projection: UTM Zone 35 – South WGS84).

No hydrothermal alteration of the surface and borehole rocks was detected and the sediments are likely to be low resistivity due to primary clays and saline water.

The Bouguer gravity map, undoubtedly, reflects density difference between the Palaeoproterozoic basement rocks and the sediments in the graben. The steep gradients reflect the buried fault escarpment.

In the ADF project (UAERAUS, 2004), one of the dense gravity profiles was modelled (see 'yellow' line on Fig. 3) and the resulting model is illustrated in Figure 4.

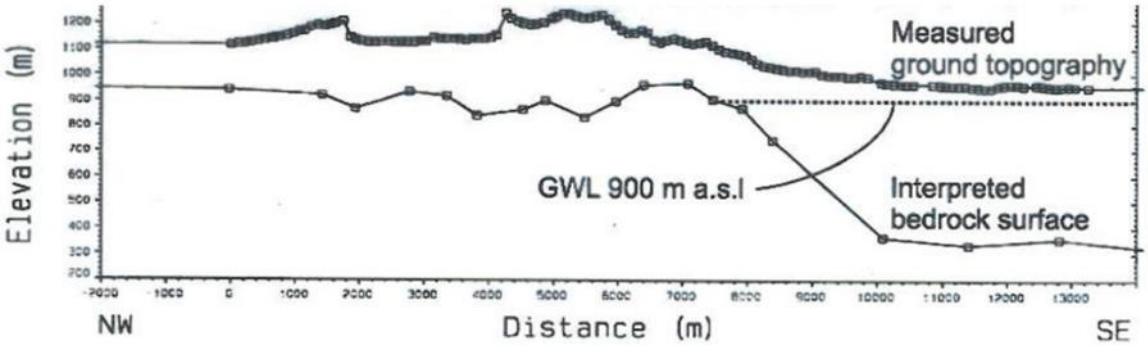

Figure 4: Gravity profile from Gislason et al. (2010) and UAERAUS (2004) with 3x vertical exaggeration showing dip on the main fault to be under 25°, much lower than inferred from surface geology.

The figure shows that to the NW of the main fault, the bedrock is at an elevation of about 900 m a. s. l. and is overlain by 200 – 30 m thick pyroclastics and sediments. The figure also shows that at the main fault, the basement is downthrown by about 550 m, i.e. from about 900 m to about 350 m a. s. l.

4.4. TGH drilling

To check the nature of the resistivity anomalies, six (6) temperature gradient holes were drilled in the Katwe prospect in 2007. The temperature gradients were found to be disappointingly low, in the range 13° to 36°C/km. The hole closest to the hot spring in Lake Kitagata (KTWH-2) showed a little higher temperature than the other. The estimated heat flow in the area is similar to the average heat flow in the continental crust of the Earth (av. 65 mWm-2) (Gislason et al. 2008).

Although Gíslason et al. (2008) and Árnason and Gíslason (2009) had concluded that 120°C would likely be reached at 2500 m depth based on a continental heat flow gradient, they did not review possibilities for a local fault – hosted upflow and related outflow.

Based on worldwide, successes with of developing deep-circulation systems in this temperature range, EAGER recommended that GRD conducts MT surveys at Katwe, with specific proposals following the completion of the structural geology survey.

5. EAGER's Work at Katwe

Further exploration at Katwe required a new rationale given the extensive geothermal exploration work already completed over a 35 year period and the disappointing maximum temperature of under 38°C encountered in the six (6) TGH wells drilled to about 300 m (Franzson, 2008; Gíslason et al, 2008; Árnason and Gíslason, 2009).

The rationale for EAGER support of additional exploration was that the previous exploration of the Katwe Prospect assumed that the target would be a magmatically-heated reservoir, whereas the preliminary EAGER analysis of the geology, geochemistry and geophysics strongly pointed to models with a deep-circulation heat source, consistent with the conceptual conclusions of Árnason and Gíslason (2009). Such deep-circulation systems (sometimes called "fault-controlled" or "fault-hosted" systems) are typically <180°C; systems that can generate power from ~100 – 180°C resources using binary power plants and direct use geothermal applications.

The proposed model for Katwe is analogous to the conceptual model and interpretation proposed by Alexander et al. (2016) and Hinz (2018a) for the Kibiro prospect, 240 km to the northeast. At both Katwe (and Kibiro), exploration and TGH drilling programmes, conducted in the period 2006 – 2007 and directed at discovering magmatically-heated reservoirs yielded similarly disappointing results. At Kibiro, a recently completed geoscience program focused on exploring for a deep-circulation reservoir has supported a new TGH drilling program targeting the basin – bounding fault within the Lake Albert basin (Alexander et al., 2016). This has been further refined recently following fieldwork focused on evaluating the structural geology and surface manifestations (Hinz, 2018a).

Therefore, although the existing shallow TG wells have significantly constrained resource models at Katwe, the new geology, structure, geochemistry and geophysics interpretations under EAGER assignments U40 (Hinz, 2018b; Cumming, 2018) and U41 (Haizlip, 2018) are reasonably likely to support geothermal resource conceptual models that could justify targeting a deep-circulation geothermal resource that might be of interest for development for power or direct use to enhance the local tourism industry.

5.1. Structural geology mapping at Katwe

The EAGER structural geology fieldwork conducted in January 2018 focused on detailed mapping of Quaternary fault scarps along the Nyamwamba fault system and of the active hot springs in the Lake Kitagata crater, which is about 1 km across. The field area is covered by poorly consolidated late Quaternary tuffs and fluvially reworked tuffs. Pre-Quaternary bedrock is not exposed in the study area.

The structural fault patterns that emerged from this mapping indicate nearly continuous fault scarps along the Nyamwamba fault zone, with local sections of this fault zone obscured by landslides and/or young tuffs. Very few fault scarps were observed west of the east-dipping Nyamwamba fault zone whereas numerous interbasinal faults were observed east of the Nyamwamba fault zone (Figure 5). Specifically, the work delineated fault intersections at the Kitagata crater and fault intersections and fault step-overs extending over 7 km to the southwest along the strike of the Nyamwamba fault system (Figures 6 and 7).

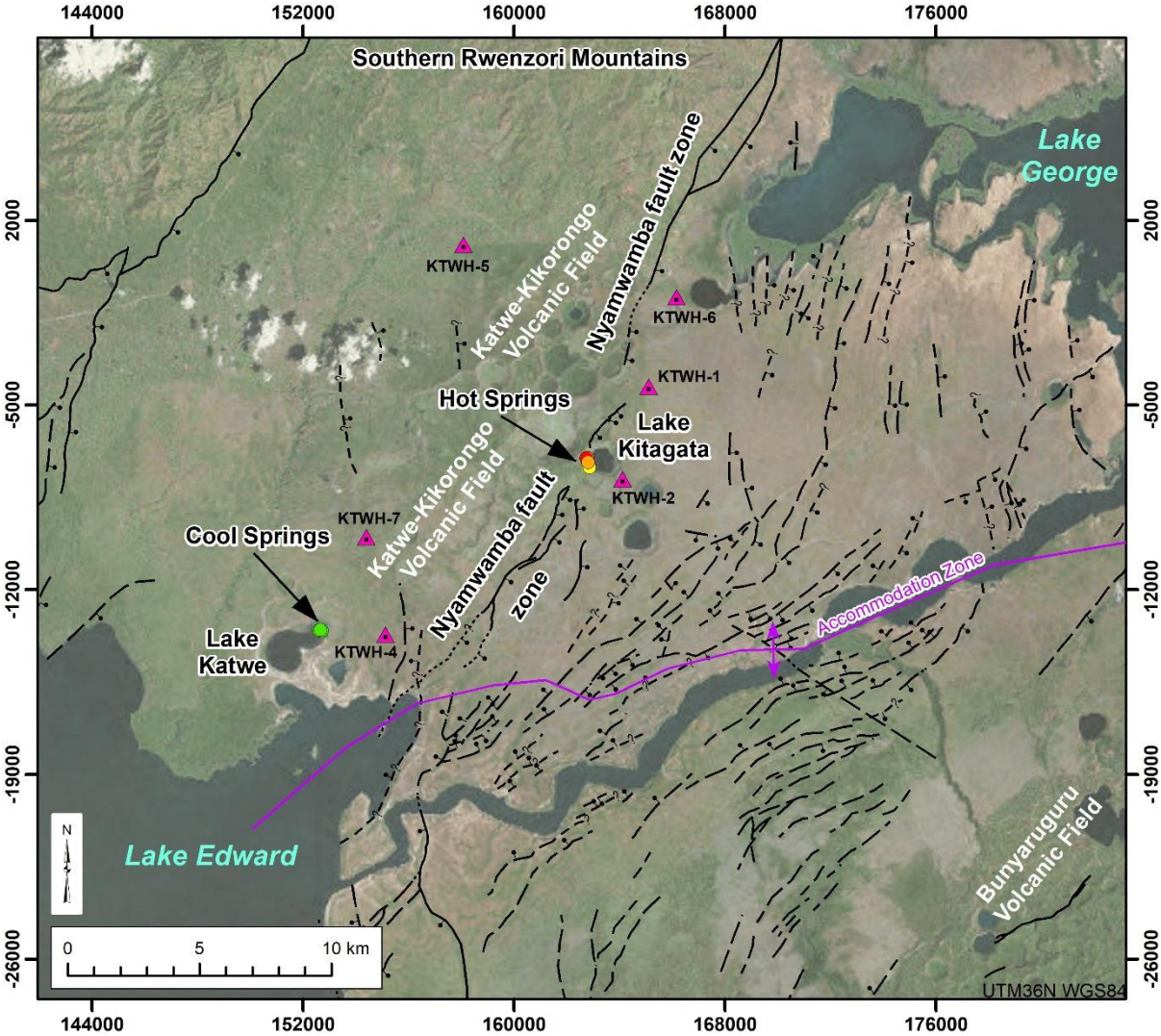

Figure 5: New mapping of active Quaternary faults by EAGER-GRD across the entire Katwe area. Purple triangles correspond to existing TGHs.

The main strand of the Nyamwamba fault system intersects the western part of the Lake Kitagata crater with apparent dips of 65 to 60° E based on the interpretation of topographic features. More reliable measurements of dip were not possible because no clear fault surfaces were observed that allowed direct measurement of the dip of the Nyamwamba fault zone or any other faults in the area. Even where the Nyamwamba fault is exposed (along the Kikorongo Junction – Bwera/Mpondwe Border road cut), the scarp is completely mantled over by volcanic tuffs. Similarly, discrete slip directions on these faults were not observed due to the lack of fault surface exposures. Regional studies of the Rwenzori area indicate that the modern-day extension direction is roughly NW-SE, nearly perpendicular to the Nyamwamba fault zone (Ring, 2008). In the Katwe area, the map patterns of the Quaternary faults are consistent with the NW-SE direction.

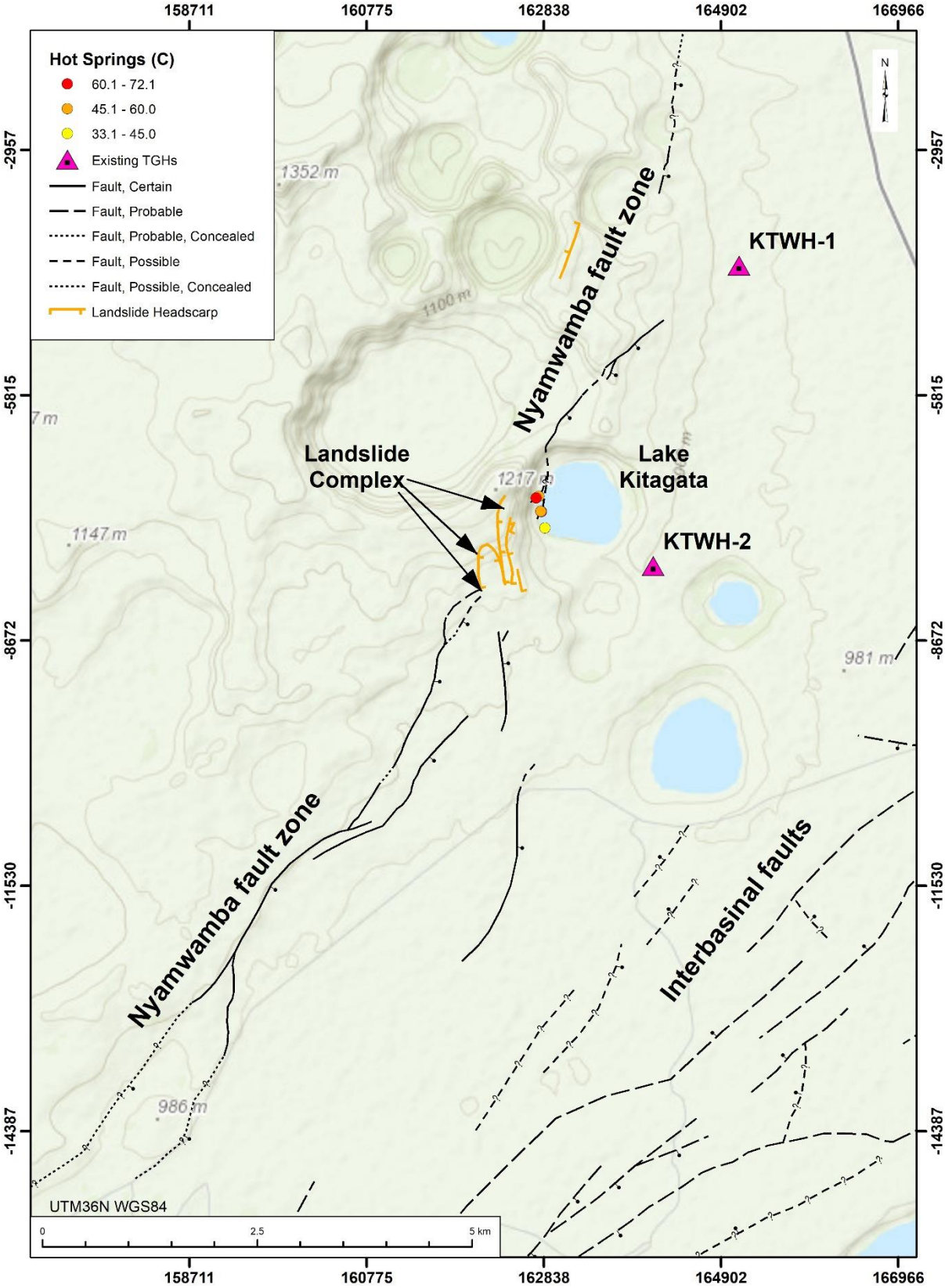

Figure 6: Lake Kitagata area with active Quaternary faults mapped by EAGER-GRD in January 2018. Ground-truthing of some of the interbasinal faults was done only on the north side of the Kazinga Channel.

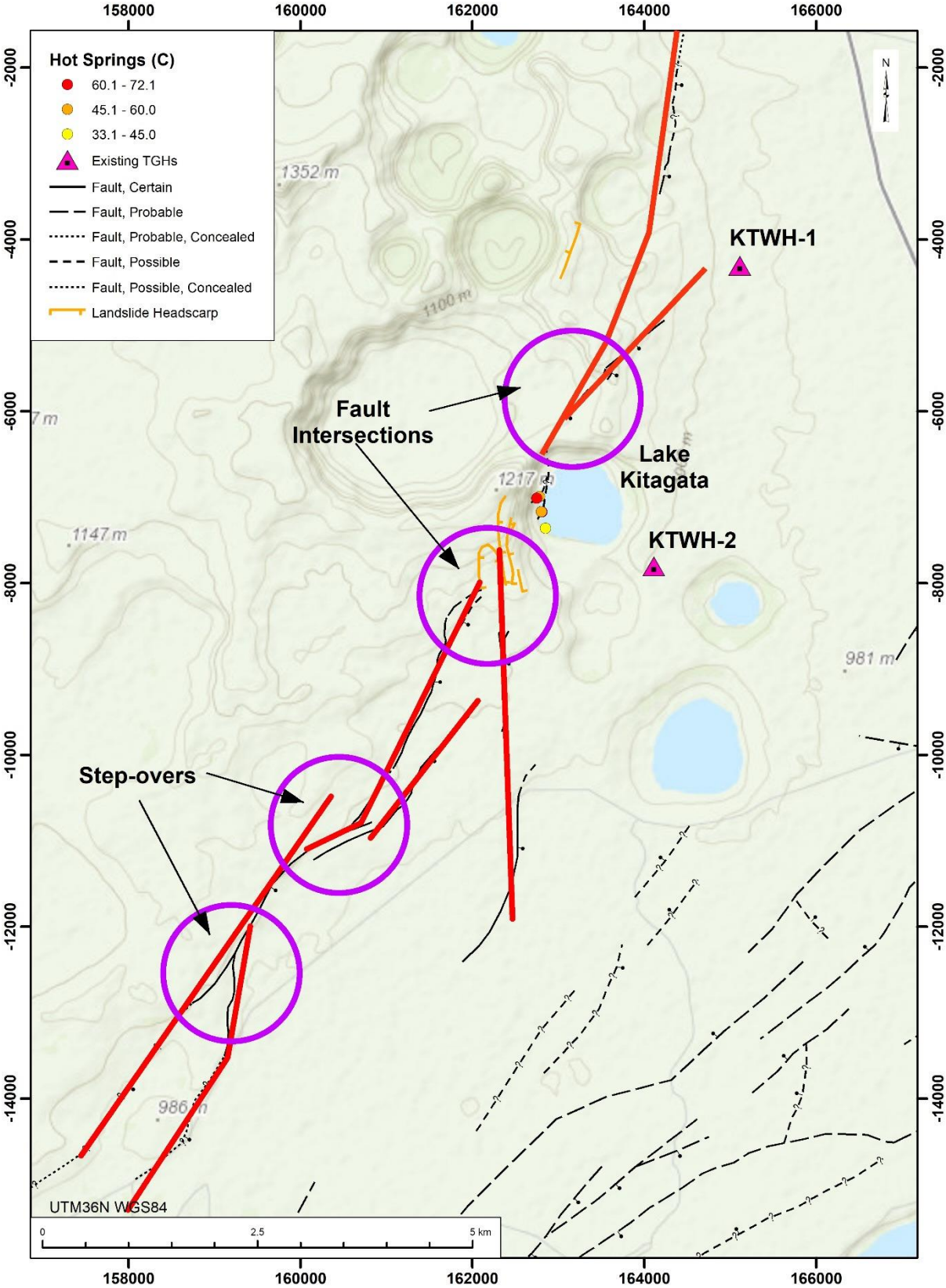

Figure 7: Structural target areas along the Nyamwamba fault zone in the Lake Kitagata area. Red lines highlight key fault segments and purple circles highlight the structural target areas.

5.2. Reinterpretation of existing Geochemistry data at Katwe

Figure 8: Subaqueous Spring in Lake Kitagata visible as a rough patch on the left side of the photo in the lake-spring #2 in Ármannsson, 1993 (yellow arrow).

Geothermometry applied to the chemistry of thermal surface manifestations at Lake Kitagata relies on a thermal end-member calculated from a mixing model rather than direct application to a thermal fluid. This approach creates some uncertainty due to the complexity and the lack of data along some of the mixing lines. At a simplified level, there is mixing between thermal water and groundwater in the subaerial springs, thermal water and lake water in the subaqueous springs and between groundwater and lake water in the lake. The thermal end member is common to both the subaqueous and subaerial springs. The lake has high salinity, which is believed to be the result of evaporation.

The primary conclusions from the evaluation of Katwe thermal and non-thermal fluid chemistry were:

- GRD should focus on Lake Kitagata as it has the only indications within the Katwe – Kikorongo area for a geothermal system hot enough for power utilization;

- The subaerial and subaqueous hot springs and Lake Kitagata waters have Na-SO4 composition and distinct Total Ionic Salinity (TIS) (see Figure 16 in Marini, 2018):

  5180 – 7630 meq/kg for lake waters probably elevated by evaporation;

  3040 – 7400 meq/kg for subaqueous hot springs (due to mixing with lake waters), and

  590 – 850 meq/kg for subaerial hot springs.

- Observed thermal and non-thermal fluid chemistry of surface waters can be explained by a dual mixing model:

  Groundwater and thermal water produce subaerial springs.

  Lake water and thermal water produce subaqueous springs.

The chemistry of the thermal water component of mixing lines is similar. Applying geothermometers to the estimated thermal water component of the dual mixing model, reservoir temperatures are estimated between 117±10°C to 127±10°C (mineral saturation index method) to 128°C (chalcedony silica geothermometer).

5.3. Recommendations for Additional Geochemistry at Katwe

The evaluation of Lake Kitagata fluid chemistry collected to-date has provided preliminary estimates of reservoir temperatures indicative of a potentially exploitable low temperature geothermal system. However, these temperature estimates are based on a mixing model rather than direct application of geothermometers. Therefore, EAGER recommends GRD conducts additional sampling and analysis to address the following objectives:

- Increase the reliability of the mixing model;
- Re-evaluate geothermometers used to date after re-evaluation of the mixing model and add some additional geothermometry from gas, possibly trace constituents (e.g. Li) and isotopes (such as sulphate-oxygen);
- Confirm meteoric source of water does not contain any magmatic component.

Geochemistry re-assessment should entail the collection of at least three (3) gas samples for analysis for CO_2, H_2S, NH_3, N_2, O_2, He, Ar, CH_4, H_2 and CO. Analysis of He isotopes and C isotopes of CO_2 and CH_4 is also recommended.

5.4. Reinterpretation of existing Geophysical data at Katwe

The results of the EAGER structural geology fieldwork and interpretation reported in Hinz (2018b) were combined with a review of the comprehensive TEM and gravity plots in Gíslason et al. (2008) from the 49 TEM and 240 gravity stations acquired in the 2004 UAERUS/MEMD survey and the 89 TEM and 297 gravity stations collected in the 2005 ICEIDA/MEMD survey. Although Gislason et al. (2008) had concluded that 120°C would likely be reached at 2,500 m depth based on a continental heat flow gradient, they did not review possibilities for a local fault-hosted upflow and related outflow.

Although all of the TEM data were reviewed, the focus of the TEM interpretation on the areas near and southeast of the Kitagata Crater was based on several factors: (1) the more favourable geochemistry of the springs at Kitagata, (2) the 38°C maximum temperature found by the ICEIDA TGH at 300 m throughout the prospect, including at KTWH-2 immediately east of Kitagata Crater, and (3) the results of the structural survey that identified fault cross-overs and intersections from the Kitagata Crater and extending 7 km to the south-southwest.

Figure 9 illustrates the combined TEM – Gravity model of the relevant resistivity profile ('yellow' line in Figure 3) across the Katwe prospect.

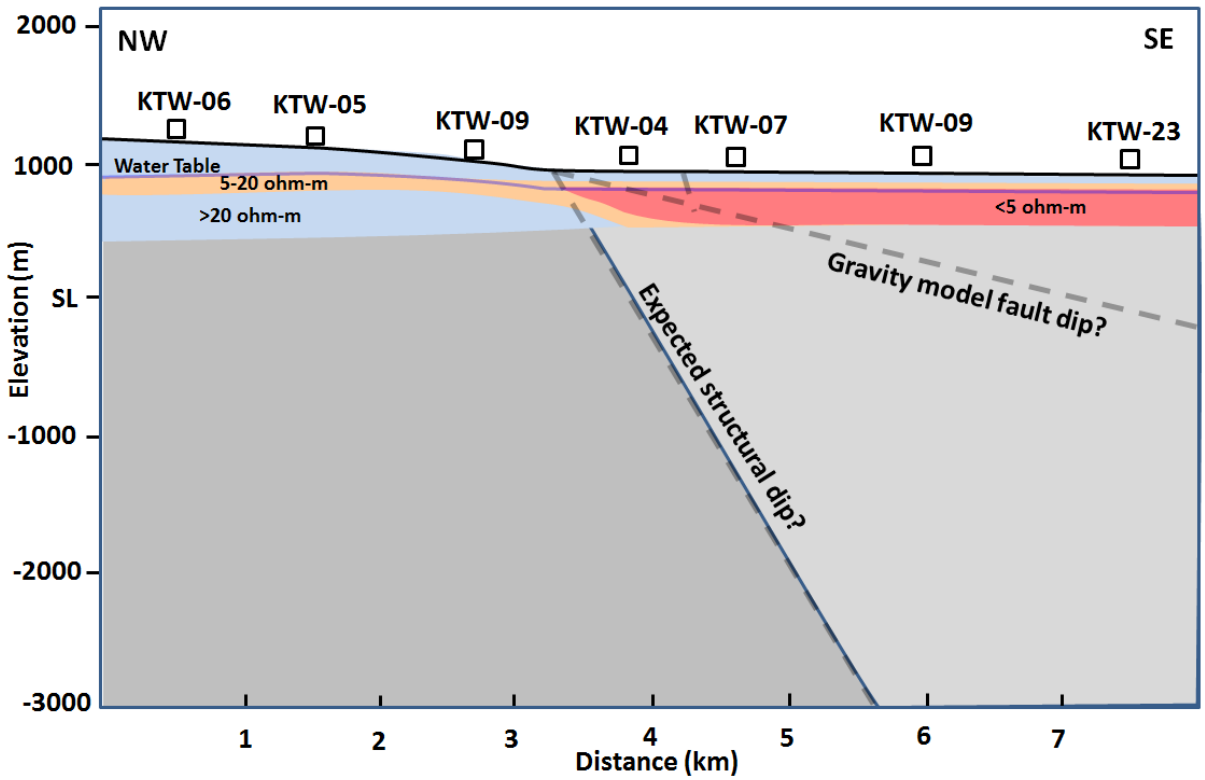

Figure 9: The TEM resistivity from the east end of Profile NWSE4 in Figure 5, together with the gravity model from Figure 8, are shown in 1:1 vertical exaggeration.

The results of the EAGER analysis of the TEM and gravity data at Katwe Prospect in the context of the revised structural geology map in Hinz (2018b) are, nonetheless, generally consistent with the interpretation by Gíslason et al (2008). A veneer of moderate to low resistivity pyroclastics and sediments overlies an uplifted N-S trending block of high resistivity Palaeoproterozoic crystalline rocks (see also Figure 4).

However, the TEM station locations shown in Figure 11 are about 2 km apart and so cannot resolve details of structures within the Nyamwamba fault zone. Moreover, the sediments are likely to be very low in resistivity due to primary clays and saline water related to evaporites, making any interpretation based on correlated low resistivity with smectite alteration intensity doubtful. Finally, the depth of investigation of the TEM is insufficient to reliably constrain the overall dip of the Nyamwamba fault zone and the density of the sediments is not well constrained, making the interpretation of the dip of the fault zone very ambiguous.

5.5. Recommendations for Geophysical surveys

Reinterpretation of the TEM and gravity data in the context of a deep-circulation system potentially connected to a lower temperature outflow near or southwest of the Kitagata hot springs was the highest priority for the EAGER-supported geophysical programme at Katwe geothermal prospect.

Although the TEM and gravity analyses were limited by the unavailability of suitable TEM and gravity digital data, the figures from Gislason et al. (2008) were sufficiently comprehensive to support replotting of a key cross-section (Figure 10) that illustrates the limitation of the TEM. Although it is compatible with an upflow in the Nyamwamba fault zone, it does not resolve an outflow due to lack of coverage and does not reliably resolve the dip of the Nyamwamba fault zone because of limited depth of investigation.

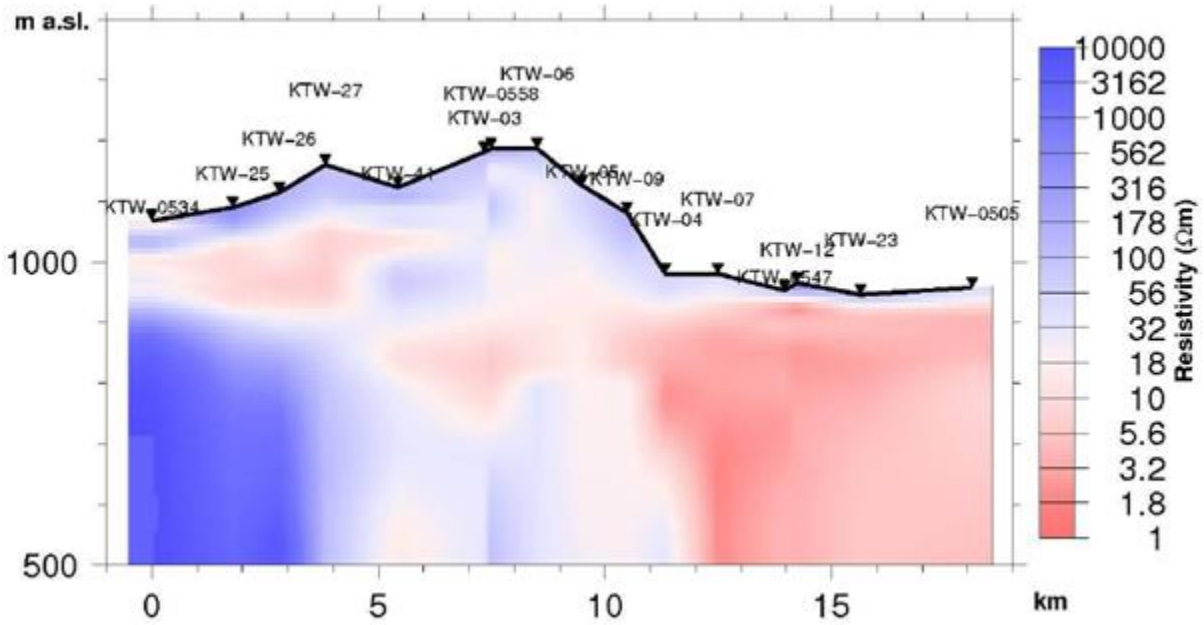

Figure 10: Profile NWSE4 with low resistivity in red and high resistivity in blue, with 14x vertical exaggeration. The dip of the Nyamwamba fault zone is ambiguous.

No further TEM acquisition is thus recommended by EAGER because of the limited depth of investigation of the TEM in the low resistivity sediments east of the Nyamwamba fault zone.

Targeting TGH in this area would benefit immensely from better constraints on the dip of the primary Nyamwamba fault, detection of low resistivity smectite alteration over hot water aquifers, and characterization of potential up-dip outflow paths. Because the GRD's Protem 57/67 was not able to reliably image the base of the sediments because of their very low resistivity, a more than 40 station MT survey has been proposed as in Figure 11.

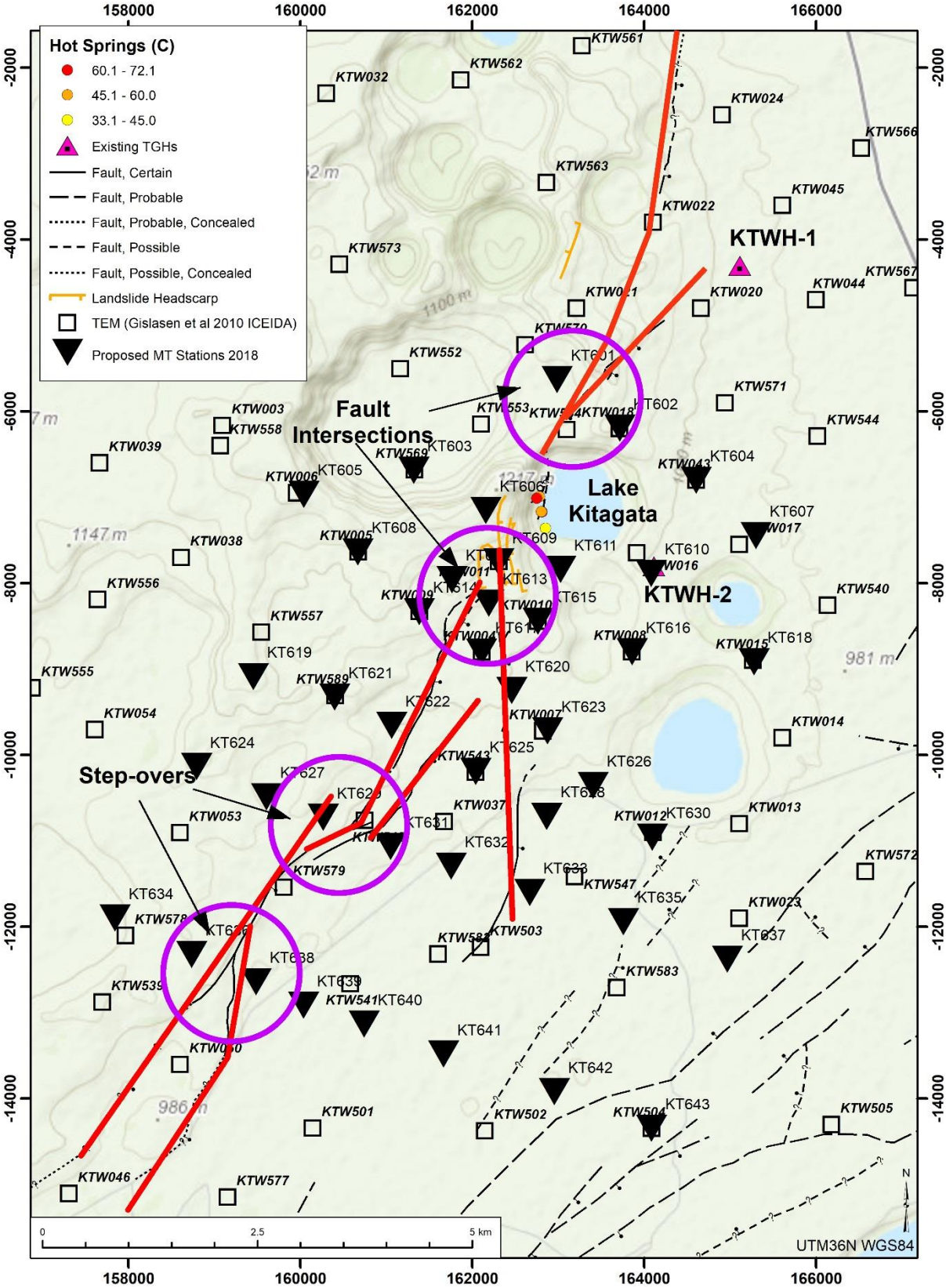

Figure 11: Proposed MT are shown as inverted solid triangles to illustrate the coverage of 43 stations. Structural target areas along the Nyamwamba fault zone are purple circles, red lines highlight key fault segments and previously acquired TEM is open squares.

6. Conceptual Models at Katwe

The interpretation of a more magmatic affinity for Katwe has been based hitherto, on the elevated salinity of their springs, the recent volcanic activity at Katwe, and earthquake evidence of magmatic activity at 15 to 30 km below the Rwenzori Mountains and speculative imaging of shallow magma at Buranga (Stadtler et al., 2007). However, all evidence from the geology, geochemistry and the relatively deep seismicity are consistent with a deep magmatic source for the volcanism at Katwe and no shallow heating by magma, as detailed in Cumming (2017).

The results of the new structural geologic mapping (Nick, 2018a) confirmed that Lake Kitagata sits along the Nyamwamba fault, a major ESE-dipping basin-bounding normal fault on the west side of the Lake George basin. Specifically, the Nyamwamba fault zone intersects the west side of the Kitagata crater in the same location as the hot springs (Figure 5). This crater is located at the north end of a 7 km-long area of complex faulting along the Nyamwamba fault zone (Figure 6). This area includes normal fault step-overs (2 nos.) and major fault intersections (2 nos.) (Figure 7), both of which are potentially capable of facilitating deep circulation of geothermal fluids based on studies of similar structural styles in the Basin and Range province of the western US (Faulds and Hinz, 2015).

The spatial extent of the Lake Kitagata thermal anomaly is bound to the E by the KTHW-2 TGH, which is located 1.5 km SE of the hot springs (Figures 5 and 6). One conceptual model for the Lake Kitagata geothermal system consists of a very small narrow upflow plume along the Nyamwamba fault that is located directly beneath the hot springs. A second model is a larger thermal anomaly hosted in one or more of the fault steps or intersections along the Nyamwamba fault zone to the SSW of Lake Kitagata (Figure 7). In this second model, the hot springs emerging at the lake's edge constitute lateral flow along the Nyamwamba fault zone from the main reservoir.

If this resource is small and only located west of Lake Kitagata, it may not be big enough to warrant development. Alternatively, if this resource is hosted in the structural target area(s) SSW of the lake, then it has the potential to be larger and could warrant development.

Given the possible conceptual range of resource size and location, a single cross-section has been developed across the Nyamwamba fault zone south of Lake Kitagata. The location of the cross-section is shown in map view (Figure 12).

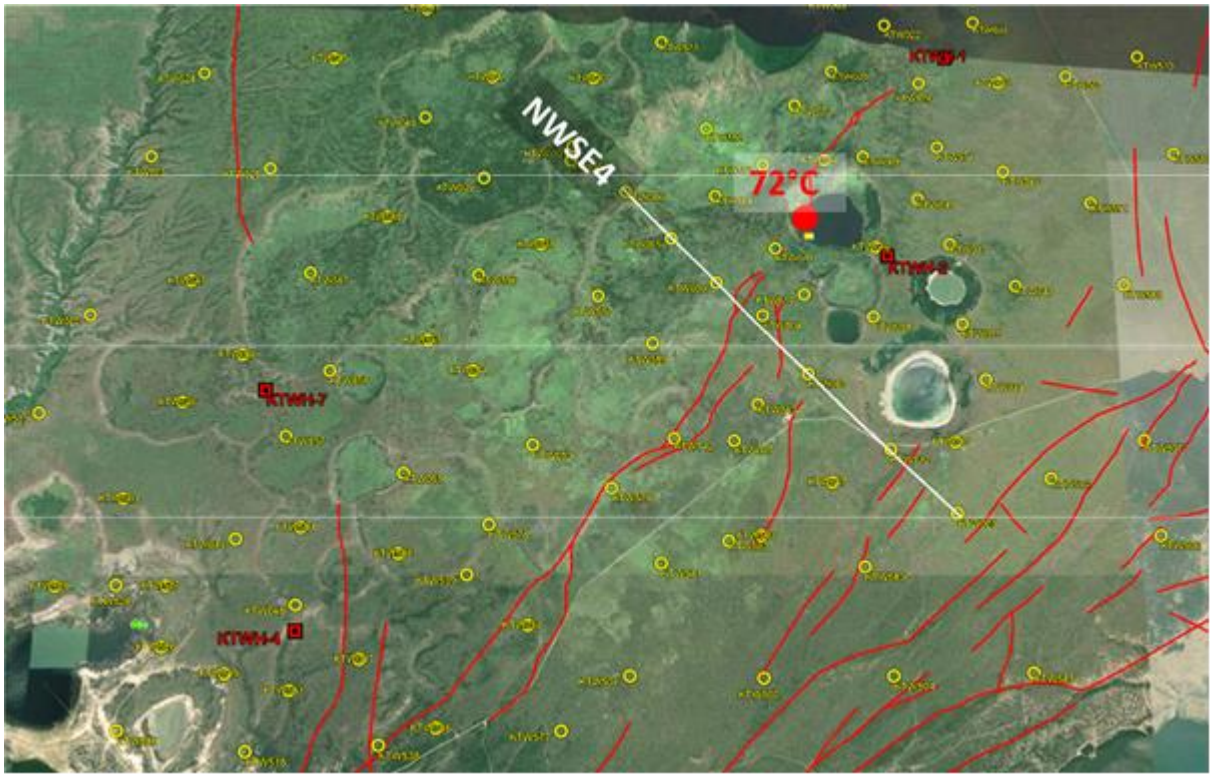

Figure 12: Cross-section location for the conceptual model Figures 13, 14 and 15.

To construct the cross-section, EAGER has attempted to define the dip of the Nyamwamba fault based on recent geologic mapping and existing geophysics zone (Figures 5, 6 and 11). The lack of fault surface exposures limited direct field measurements of fault dip. However, several 3-point calculations were made on the dip of the Nyamwamba fault zone from the new mapping. Projecting the trace of the Nyamwamba fault segment that cuts through the northwest wall of Lake Kitagata and projected through the landslide complex area on the southwest side of Lake Kitagata facilitated three dip calculations of 40°, 55°, and 60° ESE (Figure 6). The 55° calculation was made from higher confidence map input data (Hinz, 2018d). This fault zone is also clearly apparent in both the TEM and gravity models of Gíslason et al. (2008). However, the TEM models do not resolve the fault dip because the TEM has insufficient depth of investigation and this type of TEM has limited ability to resolve such steep dips (Cumming, 2018). The gravity model indicates a dip of <25° (Figure 9), but this is geologically unreasonable based on the available map data and is probably due to an inappropriate assumption for the density contrast between the volcanics/sediments and the underlying crystalline rocks. Low angle faults have map patterns that zigzag along strike and around topography and this is not the case for the Nyamwamba fault zone. Therefore, with the current data available, the 3-point calculations provide the most reliable input for the fault dip in the cross-section.

Based on lithologic logs from the existing TGHs, the volcanic rocks (mostly non-welded tuffs), have a maximum thickness of a few hundred meters and cover either Neogene sandstone and siltstone in the basin east of the Nyamwamba fault or Precambrian basement to the west of the fault. The <1 ohm-m low resistivity zone found near the surface at TEM stations KTW-552 and KTW-553 immediately west of Kitagata crater (Figure 12) is consistent with smectite alteration of the pyroclastics just west of the Kitagata hot springs. The water table is locally defined by lake levels and the cold springs that ring many of the lakes. The lakes and cold springs correspond to the upper limit of low resistivity boundaries in the TEM models and facilitate tracing the water table laterally through the model area.

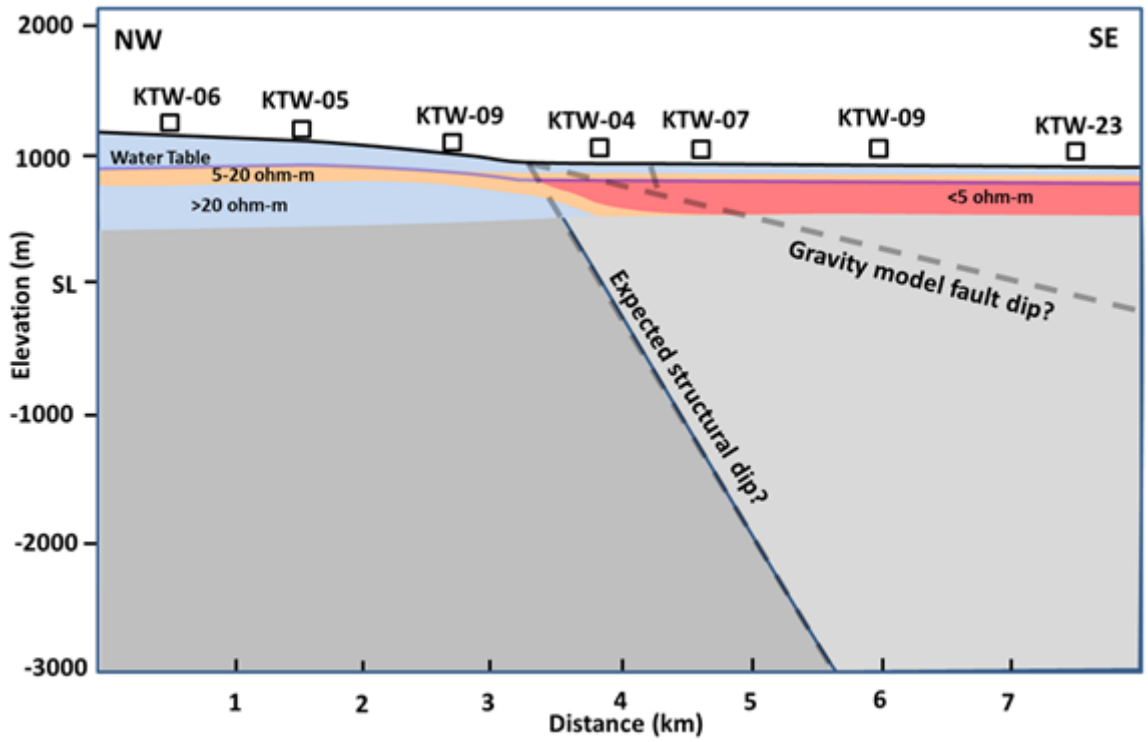

Figure 13: Cross-section base for evaluating conceptual models in Figure 14 and 15 showing TEM resistivity (red is low, blue is high resistivity, grey is not resolved).

Geothermometry for the deep geothermal aquifer discharging through the Lake Kitagata hot springs is 106 to 136°C (Marini, 2018; Haizlip, 2018). The existing TGHs that have been drilled across the Katwe area all have cool, conductive gradients. For example, the temperature logs for KTWH-2 follow a 25°C/km temperature gradient (Gislason et al., 2010). A 25°C/km temperature gradient would place the 100°C isotherm at about 3 km depth given a 25 to 30°C average surface temperature. In reality, the subsurface temperature will vary slightly due to minor differences in thermal conductivity between different strata. The 100°C isotherm will probably be shallower east of the Nyamwamba fault due to the insulating effects of the low thermal conductivity basin-fill sediments and deeper west of the Nyamwamba fault due to the denser, higher conductivity basement rocks.

The primary fluid flow pathway for the two P50 and P10 conceptual models (Figures 14 and 15) is upflow along the Nyamwamba fault zone with secondary flow to the north, along the fault zone to Lake Kitagata. In both models, the 100°C isotherm is near the surface, consistent with the >70°C spring discharge temperatures at Lake Kitagata. The major difference between the P50 and P10 models is the temperature gradient within the upflow area along the fault as is illustrated by the 125°C isotherm, which is shallower in the P10 and deeper in the P50 model. In both models, shallow lateral outflow does not extend as far east as TGH KTWH-2, however there could be outflow at shallow levels further south depending on the distribution of upflow along strike of the Nyamwamba fault.

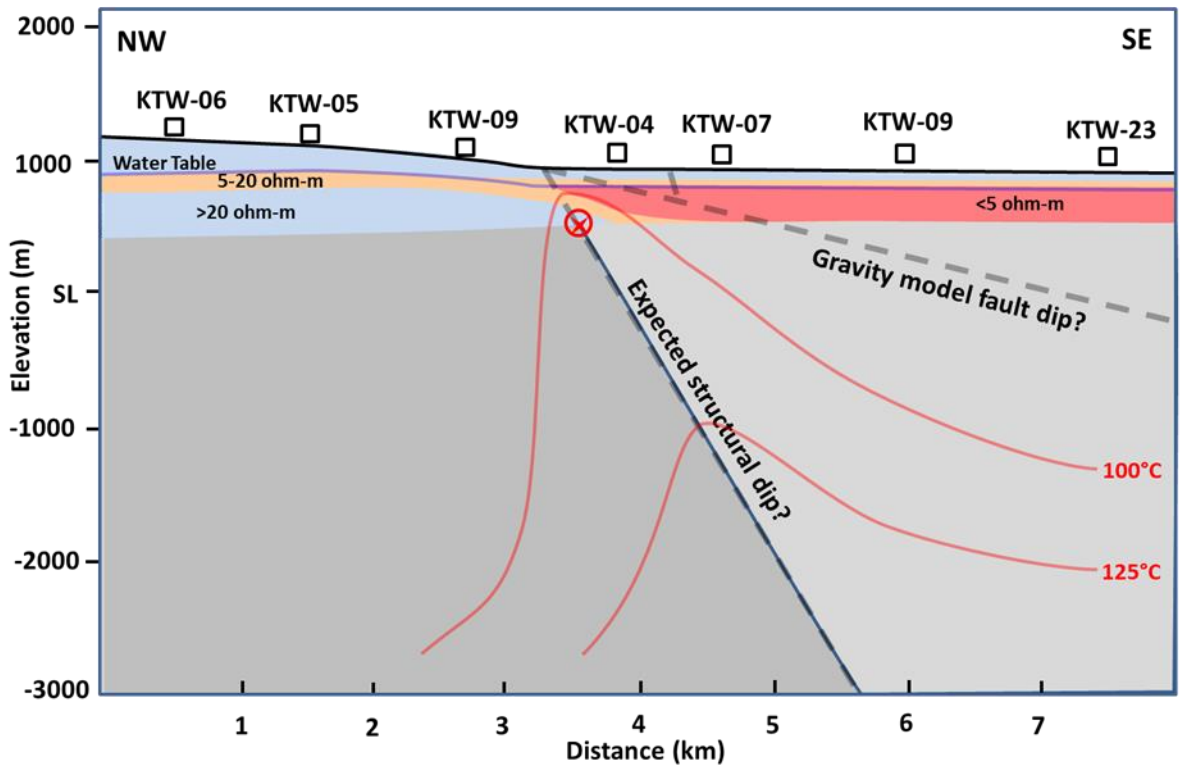

Figure 13: Conceptual model P50 along cross-section NWSE4.

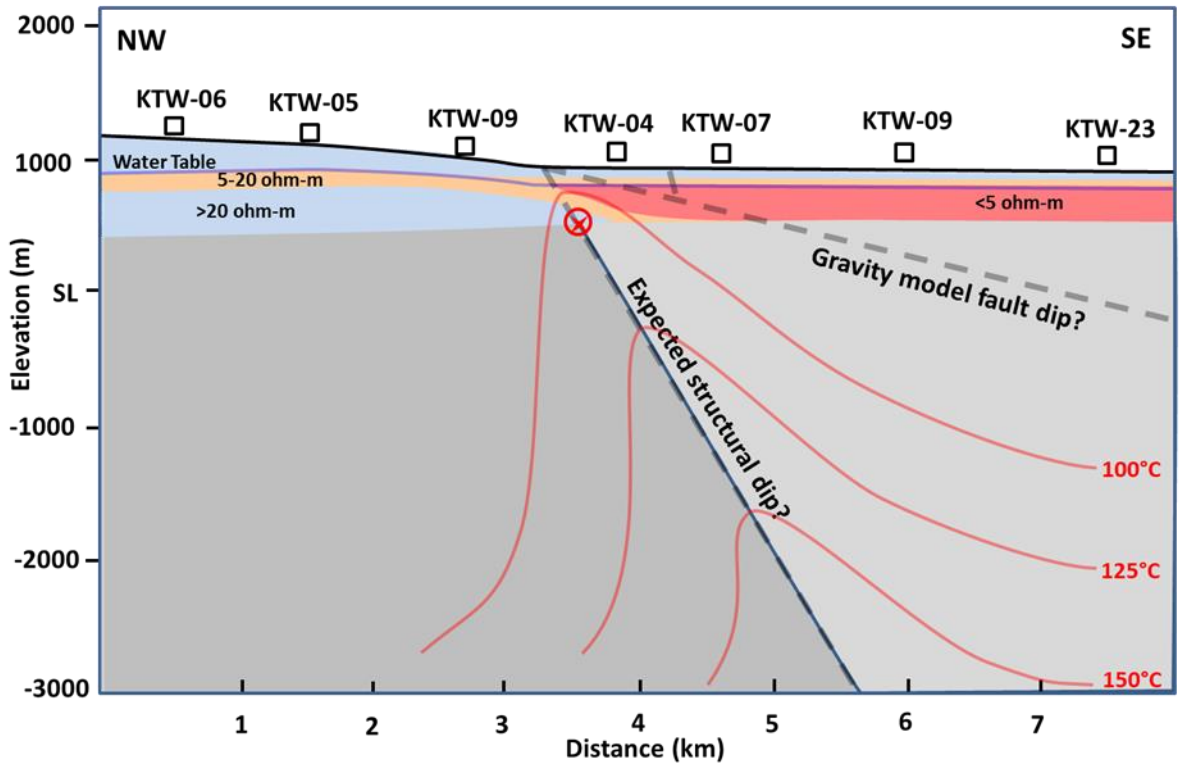

Figure 14: Conceptual model P10 along cross-section NWSE4.

7. Conclusions and Recommendations

Following three and a half decades of geothermal exploration at Katwe that has focused on volcanic models for the geothermal system, the available data, only recently acquired by EAGER/GRD during the last two years, indicate that any geothermal resource at Katwe is likely to be a deep circulation system located near Lake Kitagata. Further evaluation of the spring, lake and borehole fluid geochemistry has concluded that the hot springs at Lake Kitagata are the only thermal fluids in the Katwe area and their geochemistry indicates a probable resource temperature in the range of about 106 to 136°C. The new structural mapping has confirmed that this geothermal resource is associated with faults and specific structural settings capable of deep circulation. As such, much of EAGER/GRD's work in the Katwe area has, therefore, focused on the Lake Kitagata area. Consequently, EAGER and GRD have developed two alternative deep circulation conceptual models for the geothermal activity at Kitagata analogous to a US Basin and Range type system. The first model consists of a narrow upflow zone along the Nyamwamba fault zone just under the hot springs area while the second model consists of upflow in one or more of the fault step-overs or fault intersections along the Nyamwamba fault SSW of Lake Kitagata.

A combination of additional MT, additional geochemical sampling, and drilling TGHs can effectively distinguish between these models, and EAGER recommends that GRD apply some combination of these exploration methods to develop an updated conceptual model to guide future exploration and make development decisions (Hinz, 2018e, Haizlip, 2018).

These exploration options include:

- Additional geochemistry sampling to help clarify uncertainties regarding the mixing model used to calculate the resource temperature
- Soil gas survey to assess the existence and extent of a clay cap and leakage areas along faults in the resource area.
- A shallow 2m temperature probe survey across the target area to map out heat reaching the surface from a reservoir.
- A 43 station MT survey to establish the dip of a possible productive fault intersecting Lake Kitagata crater.
- A limited TGH drilling programme to demonstrate the presence or absence of a sizeable enough resource to warrant deeper exploration wells capable of production.

Because the existing Katwe TEM survey data was acquired using GRD's more powerful Geonics Protem 57/67 TEM system, a new TEM survey is unlikely to provide better depth of investigation or resolution of fault dip than the existing survey, especially over the low resistivity sediments to the south and southwest of Lake Kitagata. Therefore, no further TEM acquisition is recommended at this prospect.

Based on the new mapping, EAGER recommended additional MT data acquisition and further geology, structure and geochemistry assessment to target two TGH wells directed at constraining a non-magmatic deep circulation geothermal upflow with a potential formation-hosted outflow. In this regard, a 43 station MT survey has been proposed to better inform targeting of TGH with the following objectives: 1) constraining the dip of the main strand of Nyamwamba fault within the greater Nyamwamba fault zone; 2) detecting low resistivity smectite alteration over hot water aquifers, and; 3) characterizing potential updip outflow paths.

To date, options 3, 4 and 5 have been completed and data analysis and interpretation is on-going.

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