

The Katwe Geothermal Prospect in Western Uganda: A Deep-Circulation Fault Zone-Hosted Geothermal System?

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ABSTRACT

Motivated by a revised expectation that the Katwe geothermal prospect is more likely to host a deep-circulation rather than a magmatic type of geothermal system, new structural geology and Magnetotelluric (MT) resistivity surveys have been acquired and integrated with previous data including spring geochemistry, TEM resistivity and temperature-geology logs from six shallow wells, supporting the development of a geothermal resource conceptual model for a >125°C deep-circulation resource. The Katwe geothermal prospect is situated in the western branch of the East African Rift System (EARS) which has recently been recognized to more likely host <200°C deep-circulation types of geothermal reservoirs rather than the >230°C magmatically-heated geothermal reservoirs that have been drilled and developed in the eastern branch of the EARS. The Katwe prospect is characterized by 32.5° – 72.1°C hot springs in the Kitagata crater and warm springs in the Katwe crater within the Katwe-Kikorongo Volcanic Field (KKVF). Geochemistry at Katwe is complicated by evaporites and saline lakes in the basins adjoining the KKVF. Based on the evidence of volcanic influence from the 140 maar craters and cinder cones of the KKVF and >200°C cation geothermometry of the hot springs that had seemed consistent with a volcano-hosted geothermal model, in 2006/2007, six temperature gradient holes (TGHs) of depths ranging from 200 to 300 m were drilled but with disappointing temperature gradients of <36°C/km. From 2016 to 2018, a re-evaluation of Katwe as a deep-circulation prospect has been supported by the recently concluded, UK Department for International Development (DFID) funded, East African Geothermal Energy Facility (EAGER) – Geothermal Resources Department (GRD) project as part of the programme to re-assess the four high priority geothermal prospects in Uganda including three others: Kibiro, Panyimur and Buranga. The revised EAGER-GRD assessment at Katwe concluded thus: by modelling mixing of shallow groundwater, lake water and hot spring water, a thermal upflow water chemistry could be inferred, for which further modelling of the mineral saturation index and chalcedony geothermometry indicated that the hot springs probably originated from a 110 to 136°C aquifer heated by deep-circulation. New structural geology mapping that focused on Quaternary faults concluded that deep permeability is likely associated with fault intersections and step-overs along the strike of the Nyamwamba fault system near the Kitagata crater, likely dipping at about 55° into the basin and extending 7 km to the south-southwest. A 43 station MT resistivity survey, interpreted using 1D and 2D methods by GRD with EAGER support, extended earlier TEM resistivity imaging to greater depths, indicating that the adjacent sedimentary basin hosts only very limited shallow aquifers. GRD has also independently conducted supplementary soil temperature and soil gas flux surveys since the end of the EAGER project but with as yet inconclusive results. Based on the EAGER-GRD integration of the new structural geology and MT data with the reanalysis of existing shallow TGH and geochemistry data, a range of geothermal resource conceptual models of the Katwe prospect have been constructed indicating potential for a >1000 m deep well to encounter a >125°C deep-circulation resource. However, the location of the fault-hosted upflow remains ambiguous and so two additional shallow TGH wells have been recommended prior to considering any deeper drilling. Such a geothermal resource would be potentially suitable for pumped production for binary electricity generation and/or direct use opportunities that may be consistent with the special land use status of the Katwe area.

1. INTRODUCTION

The Katwe geothermal prospect is located in the western branch of the EARS in the KKVF (Figure 1). The KKVF lies within the Queen Elizabeth Protection Area (QEPA), formerly Queen Elizabeth National Park, but excluding Lake Katwe and the neighbouring Katwe-Kabatoro Town Council. The crater area and associated hot springs is one of the tourist attractions in the Protection Area, known for its scenic beauty and exotic landscape (Gíslason et al., 1994).

Systematic exploration of the geothermal resources of Uganda started in 1993, initially concentrating on three geothermal prospects, Katwe -Kikorongo (Katwe here after), Buranga and Kibiro (Ármansson, 1993, 1994; Gíslason et al., 1994), with subsequent investigations extending to the Panyimur prospect (Bahati et al., 2005). A series of cooperative programs between Ugandan and Icelandic government agencies focused on geothermal exploration from 2003 to 2010 and led to more extensive exploration at Katwe. The geothermal prospects given the most attention were those that had hot springs with geochemistry indications of elevated subsurface temperature.

1.1 Previous Geothermal Exploration at Katwe

At Katwe, cation (Na-K) geothermometry of about 200°C for the Lake Kitagata hot springs (Figure 1) with measured temperature of 72.1°C supported an expectation of a magmatically-heated reservoir. Subsequent studies at Katwe included isotope hydrology (e.g. Bahati et al., 2002, 2005; Bahati, 2007) to understand the groundwater flow characteristics of the system. In the mid-2000s, TEM resistivity and gravity surveys were acquired (Gislason et al., 2010). Based on the integrated interpretation of the geology, geochemistry and geophysics data sets, in 2006-2007, six temperature gradient holes (TGH) were drilled in the Katwe prospect, as part of a program that included also drilling six TGH at the Kibiro prospect, but with all yielding disappointing results.

At Katwe, the TGHs were drilled to depths of 200 to 300 m and encountered temperature gradients that were disappointingly low, in the range from 13 to 36°C/km (Árnason and Gislason; 2009). The KTW-2 well, located closest to the hot spring in Lake Kitagata, encountered the highest temperature measured in the TGHs of just over 36°C, but much lower than the 72.1°C measured temperature of the hot spring. No hydrothermal alteration was detected in the well cuttings (Franzson, 2008). The estimated heat flow in the area was similar to the average heat flow in continental crust of about 65 mW/m² (Gislason et al., 2010). These poor results were attributed to an exploration program based on the assumption that Katwe and Kibiro were magmatically-heated geothermal systems. While some magmatic influence cannot be ruled out at Katwe given its location among over 140 maar craters and tuff cones, the heat source for the prospect is more likely to fit a deep-circulation model (Gislason et al., 2010), consistent with the resource models now generally expected for the western branch of the EARS (Omenda et al., 2016).

1.2 Magmatic Context of the Katwe Prospect

Based on a regional volcanic geology and earthquake monitoring study directed at characterizing any magmatic heat sources that might be related to the western branch of the EARS in Uganda geothermal system, Stadler et al. (2007) noted that silica-undersaturated carbonatitic and alkali basaltic compositions of recent volcanic rocks in Uganda implied deep magmatic sources and rapid ascent of magma to the surface, consistent with the widespread maar eruptions at Katwe. The seismicity detected below the Rwenzori Mountains northwest of Katwe at depths of 15 to 25 km was also consistent with deep magma storage (Lindenfield et al., 2012), implying that no significant shallow crustal magma chambers were expected at Katwe, consistent with its setting in the western branch of the EARS.

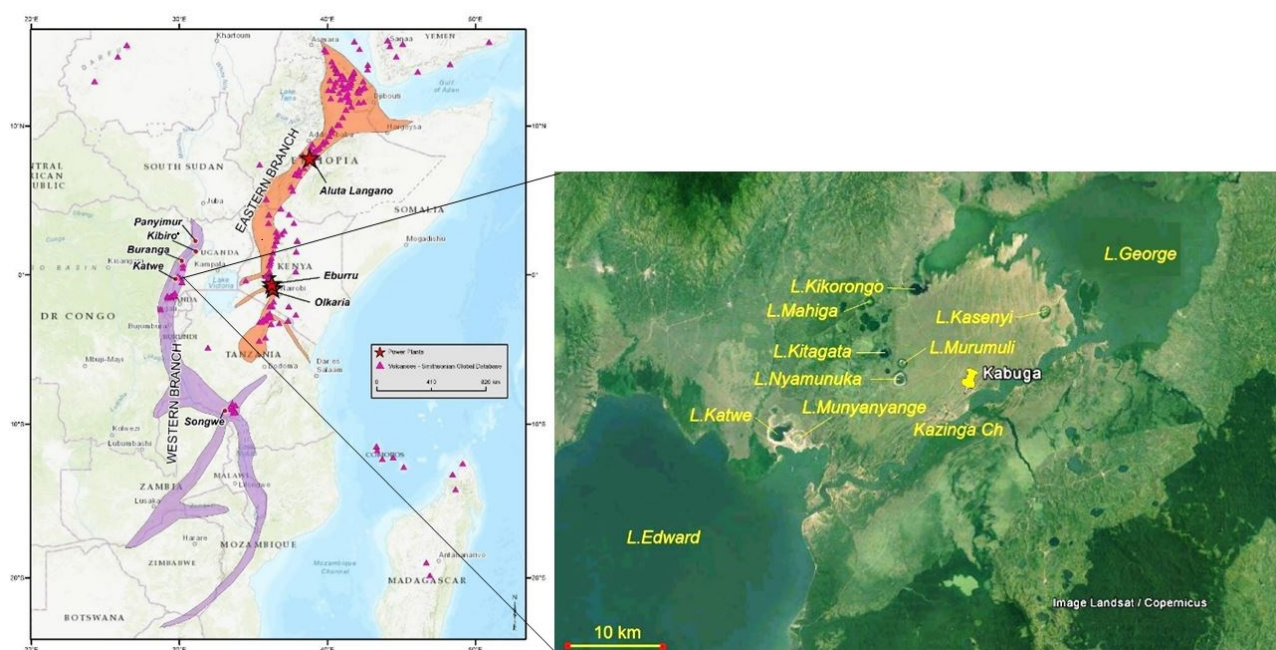


Figure 1: (A) The Eastern and Western branches of EARS (Adapted from Hinz et al., 2018); (B) Location map of the manifestations and lakes of the Katwe – Kikorongo Volcanic Field (Adapted from Cumming, 2017).

1.3 The EAGER-GRD Deep-Circulation Exploration Strategy

The new understanding of Ugandan geothermal prospects as deep-circulation systems (Omenda et al., 2016; Alexander et al., 2016), called for a new exploration strategy for geothermal prospects located in the western EARS, comparable to the recent strategies used in analogous geothermal fields in the Basin and Range region of the USA (Faulds and Hinz, 2015; Hinz et al., 2018). Such deep-circulation systems (sometimes called “fault-controlled” or “fault-hosted” systems) are typically ~100 to 200°C and, by pumping water of up to 180°C to the surface, they can generate electricity using binary cycle power plants and/or can support direct use applications.

The assessment of the geothermal energy potential in Uganda using strategies relevant to deep-circulation resources has formed the basis for the recently concluded UK Department for International Development (DFID) funded East African Geothermal Energy Facility (EAGER) that, together with the Geothermal Resources Department (GRD) in Uganda, reassessed Katwe as part of a program directed at four priority geothermal prospects in Uganda from 2016 to 2018. The collaboration of EAGER with GRD included support for the acquisition and integrated interpretation of geology, structure, geochemistry and geophysics to develop alternative conceptual models for deep-circulation geothermal prospects, the practical implementation of TGHs, slim holes and full-size wells in geothermal

exploration, geothermal data management, and the economic and financial modelling of development of <200°C geothermal projects. At Katwe, the EAGER-GRD team focused on structural geology mapping, the acquisition and analysis of a new MT survey and a reinterpretation of existing TEM and gravity data to build a range of geothermal resource conceptual models that supported a recommendation to drill two TGHs before considering the drilling of full-size exploration or production wells.

Following a summary of the regional setting of the Katwe prospect and the history of its geothermal exploration, for each geoscience discipline, a review and reinterpretation of existing data introduces a discussion of the new data acquisition and analyses completed by the EAGER-GRD team. The final section summarizes the geothermal resource conceptual models developed by the EAGER-GRD team that are informing geothermal exploration plans at Katwe.

2. KATWE REGIONAL SETTING

2.1 Regional Geology

The Katwe geothermal area is situated within the 30 km long by 15 km wide KKVF between Lake George and Lake Edward. It is a field of phreatic (steam-driven) and phreatomagmatic (maar) craters, tuff cones, and distributed pyroclastic deposits 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 volcanic field consists of over 140 maar craters and tuff cones that range in age from Pleistocene to Holocene. Of all the numerous craters, only seven (7) are deep enough to reach the local ground water table and, therefore, host saline lakes (Gíslason, et al., 1994; Gíslason et al., 2010; Natukunda and Bahati, 2015). The Katwe geothermal prospect is associated with hot springs in the Kitagata crater and warm springs in the Katwe crater. 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) to the west of it. Six (6) distinct lava flows are exposed in the western flank of the Kitagata crater walls and above the hot springs (Gíslason, et al., 1994). The RFB comprises of gneiss, with subordinate granite, pegmatite, amphibolite and quartzite (Bahati et al., 2002; Westerhof et al., 2014).

2.2 Structural Setting

The Nyamwamba fault zone is also an accommodation zone set between oppositely dipping ('antithetic') normal faults on the southeast of the Lake Edward – Lake George basin whereby 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 probable, therefore, that one or more of these numerous fault segments hosts the geothermal fluid associated with the Katwe geothermal area.

3. KATWE GEOCHEMISTRY

The Katwe geochemical database includes data from 54 samples collected in 1993/1994, 2002/2003 and 2005 sampling campaigns in the Katwe area, including water sampling from hot springs, warm springs, groundwater, river and lake water and gas sampling of hot springs (Ármansson, 1993, 1994; Bahati, et al., 2002, 2005; Bahati, 2007). Samples from thermal manifestations have been from the surface (sub-aerial) of most features and from 2 m below the surface (sub-aqueous) in many hot springs. The water and gas samples had been analysed for parameters and constituents typical of volcano-hosted geothermal systems, including physical properties (temperature, conductivity, pH, CO₂ in the field and/or laboratory), chemical constituents and isotopes ($\delta^{18}\text{O}$, $\delta^2\text{H}$, $\delta^3\text{H}$ and ^{87}Sr) (Bahati, 2007).

3.1 Geology and Hot Spring Context of Katwe 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 groundwater and lake waters, creating Na-Cl, Na-SO₄ and Na-HCO₃ type water that depend on local variations in the types of evaporites and not on a geothermal process or an association with magmatic heating (Marini, 2018).

Several areas of hot springs and saline lakes are present in the KKVF (Figure 1). The sampling from these manifestations include: 1) sub-aerial samples of hot springs along the western shores of Lake Kitagata and sub-aqueous samples with temperatures of 39.4 to 72.1°C for the onshore springs; 2) sub-aerial and sub-aqueous samples from the warm springs of Kabuga (or Muhokya) (40.6 – 41.8°C); and sub-aerial samples from the cold high-salinity springs in Lakes Katwe (32.5°C) and Nyamununka (Marini, 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).

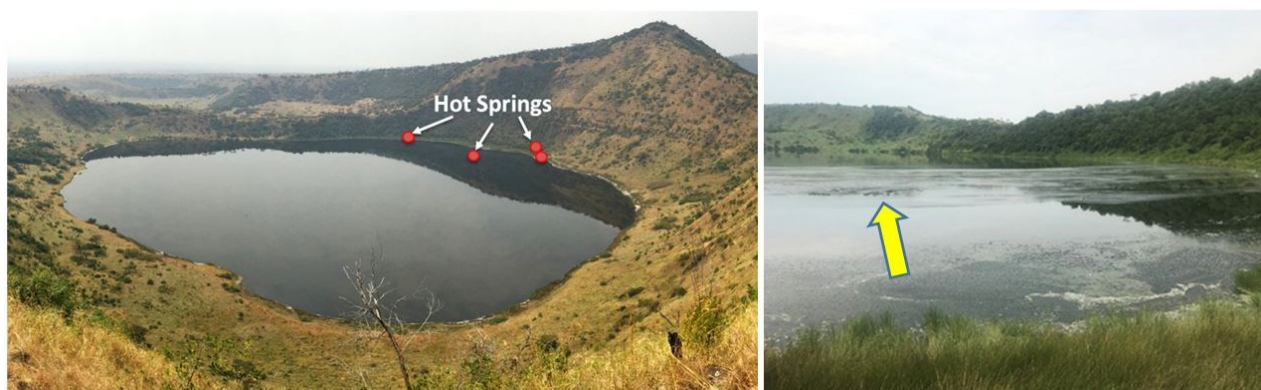


Figure 2: (A) Panoramic view of Lake Kitagata with hot springs along the western shore. Left edge of photo is looking south, right edge is looking west (Adapted from Hinz, 2018b); (B) Sub-aqueous spring in Lake Kitagata visible above the yellow arrow as a rough patch in the lake (Spring #2 in Ármannsson, 1993) (Adapted from Haizlip, 2018).

3.2 EAGER Geochemistry Interpretation of Katwe

The EAGER team's initial review of the existing geochemistry in the context of the structural geology analysis at Katwe had suggested that the $>70^{\circ}\text{C}$ hot springs in and adjacent to Lake Kitagata were the only thermal features at Katwe likely to be associated with a $>120^{\circ}\text{C}$ geothermal aquifer based on silica geothermometry (Cumming, 2017). The warm springs associated with the Kabuga crater are less prospective, with a maximum aquifer temperature on the order of $85\text{--}90^{\circ}\text{C}$ as indicated by the silica (quartz) and K-Mg geothermometers. Na-K geothermometry derived from springs in the Katwe prospect area do not reflect equilibration with a geothermal reservoir and so are not useful (Marini, 2018; Haizlip, 2018). The primary conclusions from the evaluation of Katwe thermal and non-thermal fluid chemistry were that:

- GRD should focus exploration on the upflow origin and subsurface paths of fluids supporting the Lake Kitagata hot springs, as they have the only indications within the Katwe-Kikorongo area for a geothermal system hot enough for power utilization;
- The sub-aerial and sub-aqueous samples from hot springs and Lake Kitagata have Na- SO_4 composition and distinct Total Ionic Salinity (TIS) (Marini, 2018):
 - 5180 – 7630 meq/kg for the lake waters is probably elevated by evaporation;
 - 3040 – 7400 meq/kg for the subaqueous hot springs (due to mixing with lake waters), and
 - 590 – 850 meq/kg for the sub-aerial hot springs.
- The observed thermal and non-thermal fluid chemistry of surface waters can be explained by a dual mixing model:
 - Groundwater and thermal water produce sub-aerial springs;
 - Lake water and thermal water produce sub-aqueous springs.

3.2.1 Geothermometry

Geothermometry applied to the water chemistry at Lake Kitagata relies on a thermal end-member (presumed characteristic of a geothermal source aquifer or upflow) that is calculated from a mixing model rather than direct application of a specific geothermometer to a thermal fluid. This approach creates additional 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 sub-aerial 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 sub-aqueous and sub-aerial springs. The lake has high salinity, which is believed to be the result of evaporation. A preliminary estimate of the temperature of the thermal fluid influx at the Kitagata geothermal prospect is 116 to $126 \pm 10^{\circ}\text{C}$ (mineral saturation index method) to 128°C (chalcedony silica geothermometer) (Marini, 2018).

3.2.2 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's expert team (Haizlip, 2018) recommended that GRD conduct 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.

4. STRUCTURAL GEOLOGY MAPPING AT KATWE

Structural geology fieldwork conducted in January 2018 by the EAGER - GRD team focused on detailed mapping of Quaternary fault scarps along the Nyamwamba fault system and the onshore hot springs in the Lake Kitagata crater. The field area is covered by poorly consolidated late Quaternary tuffs and fluviually reworked tuffs. Pre-Quaternary bedrock is not exposed in the study area but samples have been found as clasts deposited with tuffs in craters that erupted through the bedrock to the northwest.

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. While very few fault scarps were observed west of the east-dipping Nyamwamba fault zone, numerous inter-basinal faults were observed in the basin to the east (Figure 3). The greater area mapped constitutes an accommodation zone with its axis roughly crossing the Kazinga Channel ('Purple line' in Figure 3).

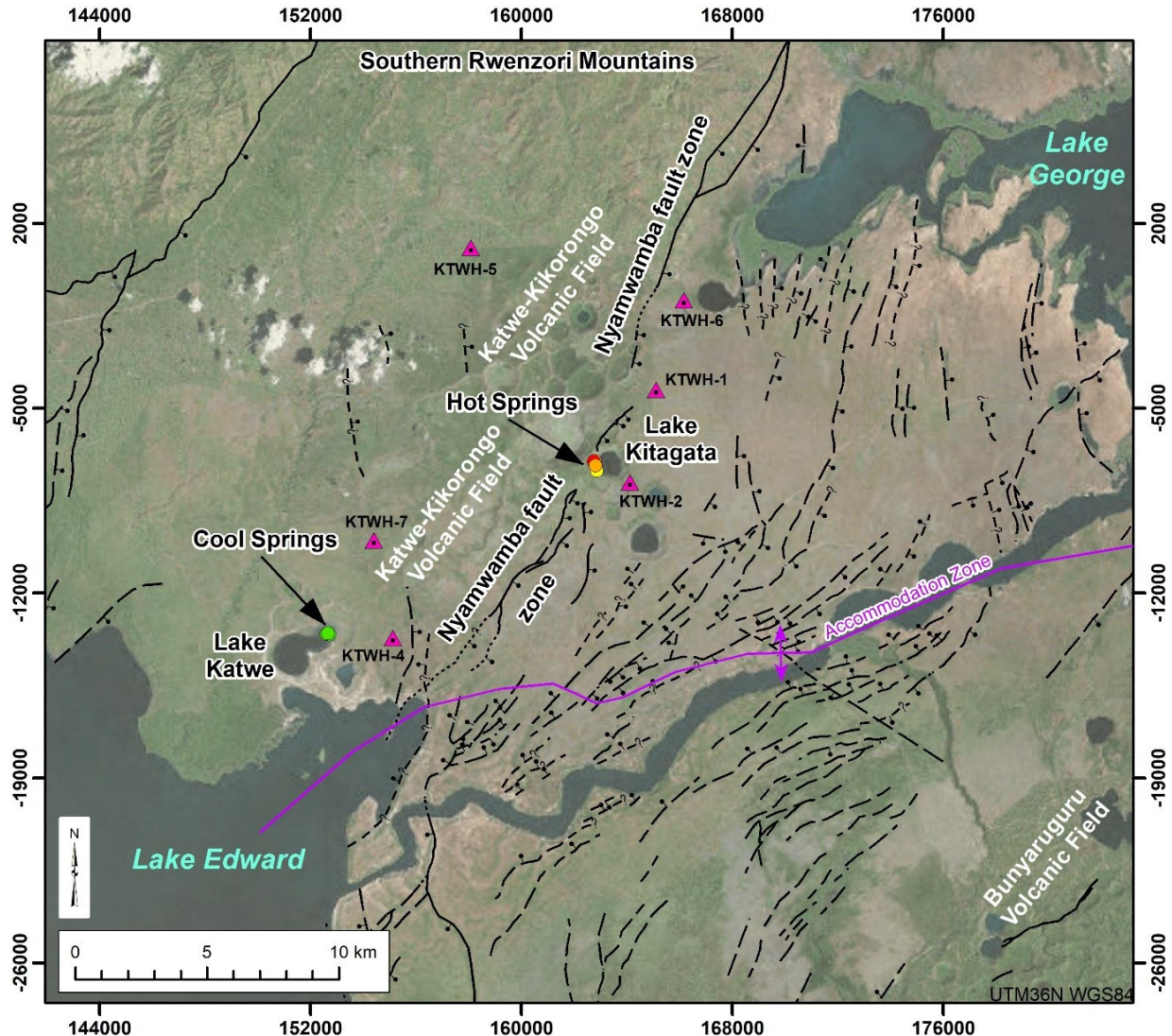


Figure 3: New mapping of active Quaternary faults by EAGER-GRD across the entire Katwe area. Purple triangles correspond to existing TGHs (*Adapted from Hinz, 2018b*).

4.1 Structural Geology Results

The EAGER – GRD field mapping 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 4 and 5). The main strand of the Nyamwamba fault system intersects the western part of the Lake Kitagata crater, where the variation of the trace with respect to elevation implies an apparent dip of 55 to 60°E (Figure, 4). The dip is unlikely to be lower than 40°, as had been suggested based on gravity models (Gíslason et al., 2010). 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. Indeed, even where the Nyamwamba fault is exposed, e.g. in a road cut along the Bwera-Mpondwe Border road just after the Kikorongo Junction, the scarp is completely mantled by volcanic tuffs. Likewise, discrete slip directions on these faults were not observed due to the lack of fault surface exposures.

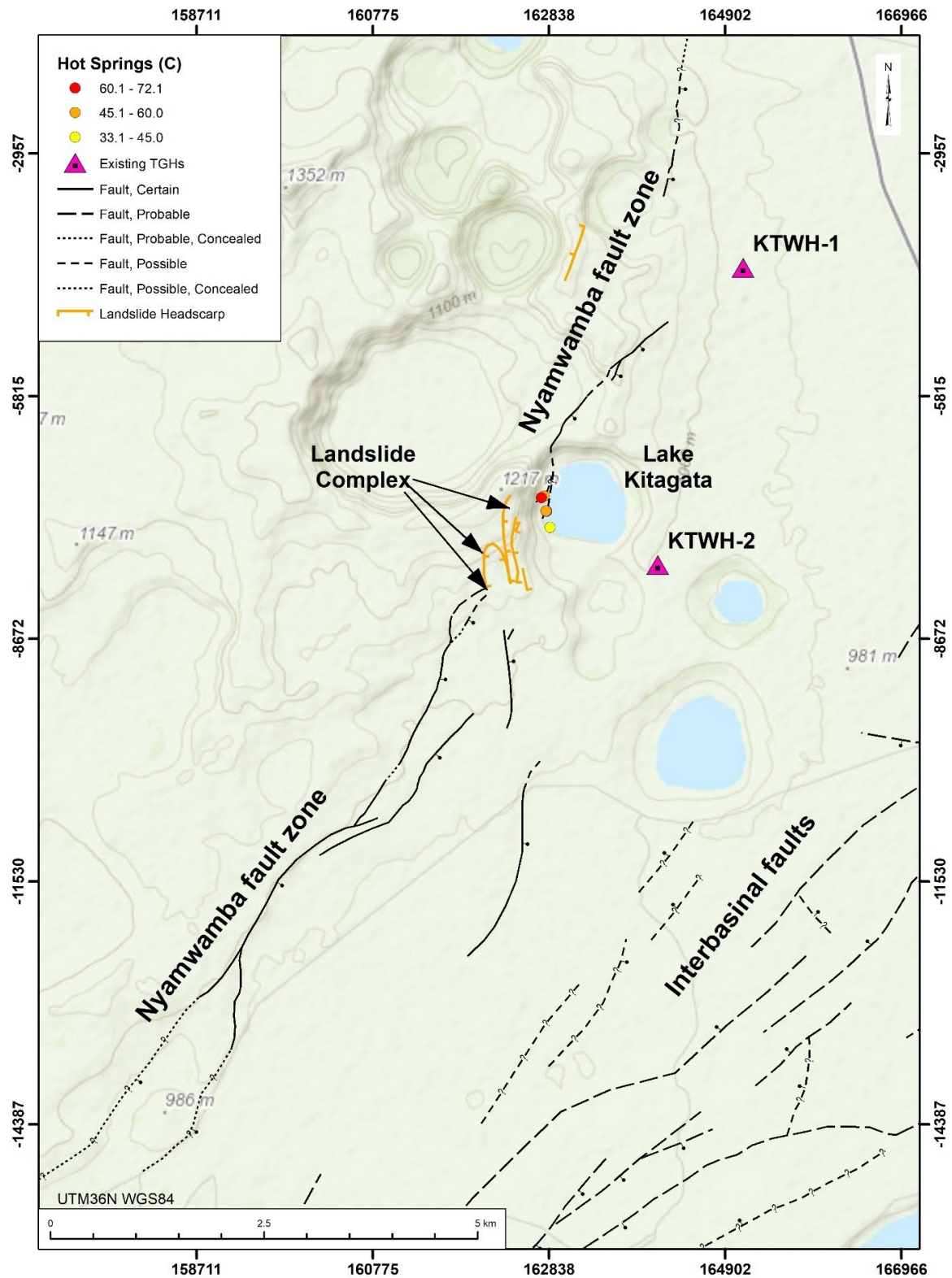


Figure 4: Lake Kitagata area with active Quaternary faults mapped by EAGER-GRD in January 2018. Ground-truthing of some of the inter-basinal faults was done only on the north side of the Kazinga Channel (*Adapted from Hinz, 2018b*).

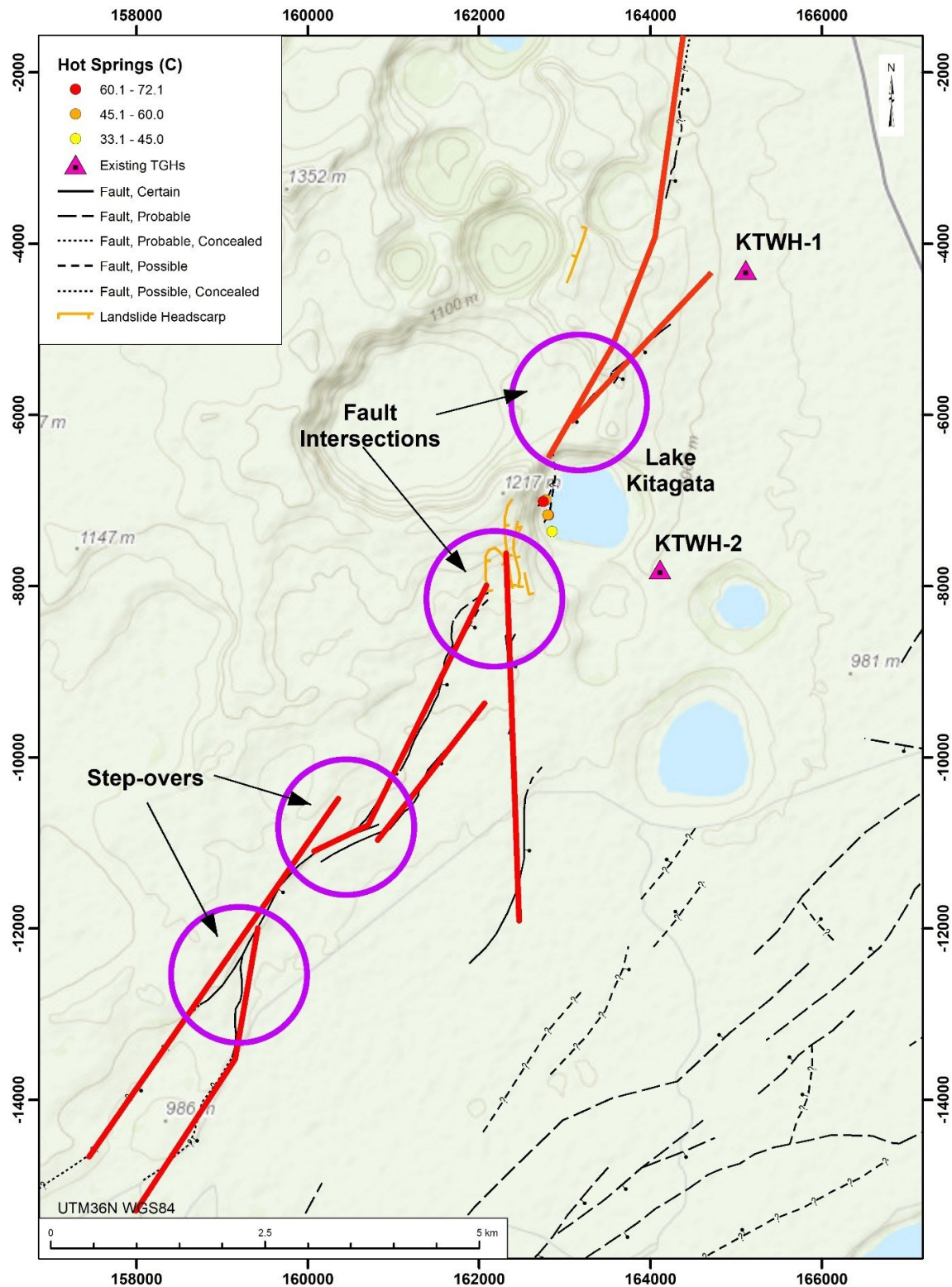


Figure 5: Structural target areas along the Nyamwamba fault zone in the Lake Kitagata area. Red lines highlight key fault segments and purple circles highlight the structural areas favorable for targeting permeability (*Adapted from Hinz, 2018b*).

3.2 Structural Geology Implications

Although the limited exposure of faults made the structural geology mapping less definitive than had been hoped, the field work did identify areas where structures within the Nyamwamba fault zone are likely to accumulate stress in a manner favorable to permeability formation (Figure 5). The complex pattern of step-overs and intersections define a fault zone at least 1 km wide. By projecting the trace of the fault that cuts through the northwest wall of Lake Kitagata and the landslide complex on the southwest side of Lake Kitagata, 3-point calculations yield dips of 40°, 55°, and 60° ESE, with most confidence in a 55° ESE dip of the Nyamwamba fault, inconsistent with much lower dip of the density contrast modeled using gravity data in a profile across this zone (UAERAUS, 2004; Gíslason et al., 2010).

4. KATWE GEOPHYSICS

The initial review of geophysical data relevant to the geothermal resource interpretation at Katwe by the EAGER-GRD team focused on the following geophysical datasets (Cumming, 2017, 2018):

- Earthquake hypocentres from a five year seismic monitoring survey covering the area from Lake Albert to Lake George (Lindenfeld et al., 2012);
- TEM resistivity soundings, maps and profiles covering the volcanic zone at Katwe (Gíslason et al., 2010);
- Gravity maps covering a similar area (Gíslason et al., 2010), and
- A 2D gravity model along a gravity profile perpendicular to the Nyamwamba fault zone near the Lake Kitagata hot springs (Gíslason et al., 2010; UAERAUS, 2004).

4.1 Interpretation of Existing Geophysics

The EAGER-GRD reinterpretation of the existing geophysical datasets at Katwe did not involve a significant change in the assessment of the survey data or its petrophysical implications but a change in focus from assessing a potential magmatic system to assessing a deep-circulation system in the context of the revised geochemistry and detailed structural geology interpretations.

From 2006 to 2011, up to 34 seismic monitoring stations were deployed along the western branch of the EARS in Uganda from Lake Albert to Lake Edward (Lindenfeld et al., 2012). Most of the detected earthquakes were located at about 15 and 25 km depth below the Rwenzori volcanics north of the Katwe area and very little seismic activity was reliably detected at shallow depths, consistent with the conclusions that the volcanic rocks near the Katwe-Kitagata prospect are sourced from deep magma chambers and that little shallow crustal heating is provided by magma.

The geophysics reports by Árnason and Gíslason (2009) and Gíslason et al. (2010) illustrate a comprehensive TEM (138) and gravity station (537) coverage of the KKVF. Although their interpretations of the resistivity and gravity at Katwe are reasonable, their focus on exploration for a magmatically heated resource provided the rationale for re-interpretation of these data in the context of a deep-circulation system. In the maps of Figure 6, the TEM resistivity pattern at 500 m above sea level detects higher resistivity (blue in Figure 6A) corresponding to shallow Palaeoproterozoic granitic gneiss to the west of the Nyamwamba fault zone and low resistivity (red) corresponding to weathered, altered volcanoclastics and saline lake sediments east of the fault zone. The gravity map shows an apparent reversal of the color pattern, with higher gravity (red) corresponding to shallow dense granitic gneiss to the west of the Nyamwamba fault zone and lower gravity (blue) corresponding to the deeper burial of the granitic gneiss below the lower density volcanoclastics and saline lake sediments east of the fault zone. Although these TEM resistivity and gravity interpretations are generally consistent with the general features of the geology – structure mapping, the structures shown as green lines in Figure 6 do not generally align with the detailed structures of Figure 4.

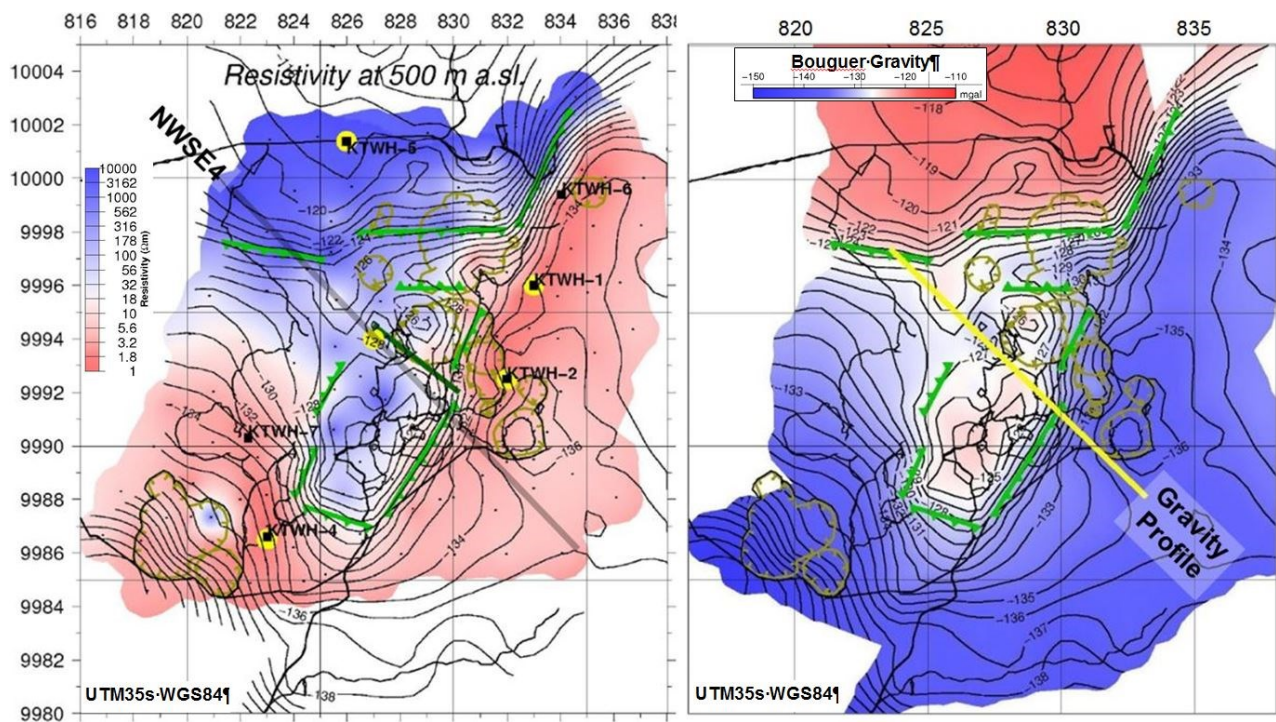


Figure 6: (A) Map of TEM resistivity in ohm-m at 500 m a.s.l (profile in gray); (B) Map of Bouguer gravity in mgal (profile in yellow). Green outlines are previous structural interpretations. (Adapted from Gíslason et al., 2010).

The TEM resistivity Profile NWSE4 cross-section shown in Figure 7 is aligned nearly perpendicular to the structural strike, as illustrated on the map in Figure 6. The cross-section illustrates more details than the map, including the moderately low resistivity (10 to 20 ohm-m in pale red) 100 m thick veneer of weathered pyroclastics overlying the high resistivity (>300 ohm-m) Palaeoproterozoic basement rocks and the low resistivity (<5 ohm-m) tuffs and sediments that fill the basin to the southeast. Because the TGH wells encountered no hydrothermal clay alteration (Franzson, 2008), the low resistivity in the basin is probably due to deposition of clay in sediments, weathering to clay below the water table and high salinity due to the presence of evaporites.

Because the high salinity might reduce the resistivity contrast between generally lower resistivity aquicludes and higher resistivity aquifers, the TEM might not resolve shallow thermal aquifers that could provide a shallower and more easily targeted reservoir zone, in the manner that has been proposed at Kibiro and Panyimur prospects (Hinz et al., 2018). Although the TEM cross-section in Figure 7 appears to resolve a steep lateral discontinuity near the location of the Nyamwamba fault zone mapped between stations KTW-09 and KTW-04, this is an artifact of its extreme 14x vertical exaggeration and, in any case, TEM soundings spaced 1 km or more apart using a central-loop geometry would not be expected to reliably resolve a lateral resistivity contrast with a dip of 60°.

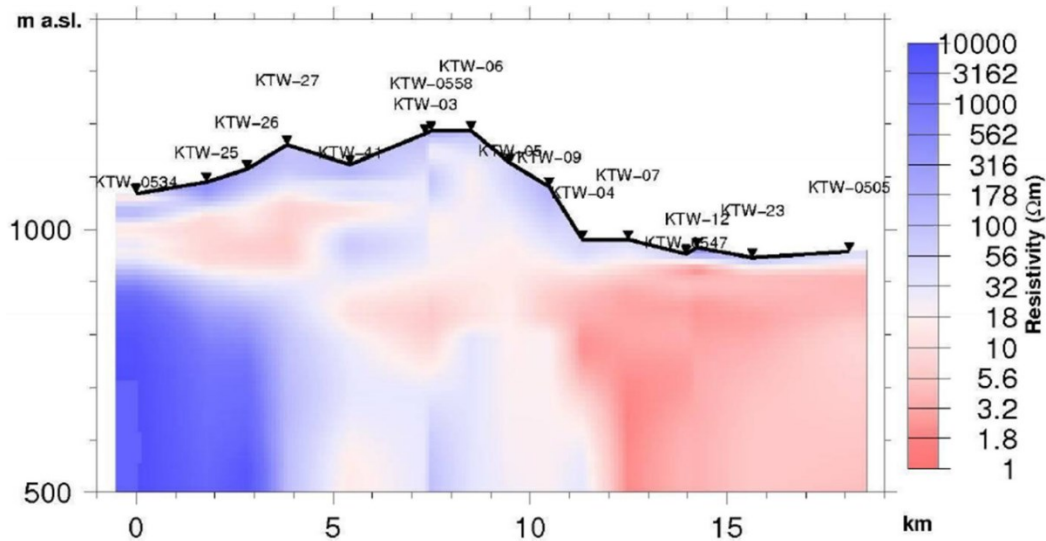


Figure 7: Profile NWSE4 (south of Kitagata) with low resistivity in red and high resistivity in blue, with 14x vertical exaggeration. The dip of the Nyamwamba fault zone is ambiguous and the base of the low resistivity sediments at >12 km is not detected (Adapted from Gislason et al., 2010).

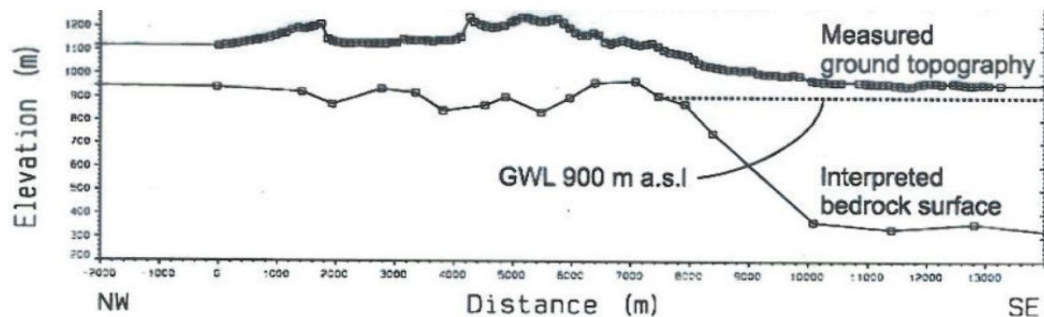


Figure 8: Gravity profile with 4x vertical exaggeration showing dip on the main fault to be under 25°, much lower than inferred from surface geology (Adapted from Gislason et al., 2010; UAERAUS, 2004).

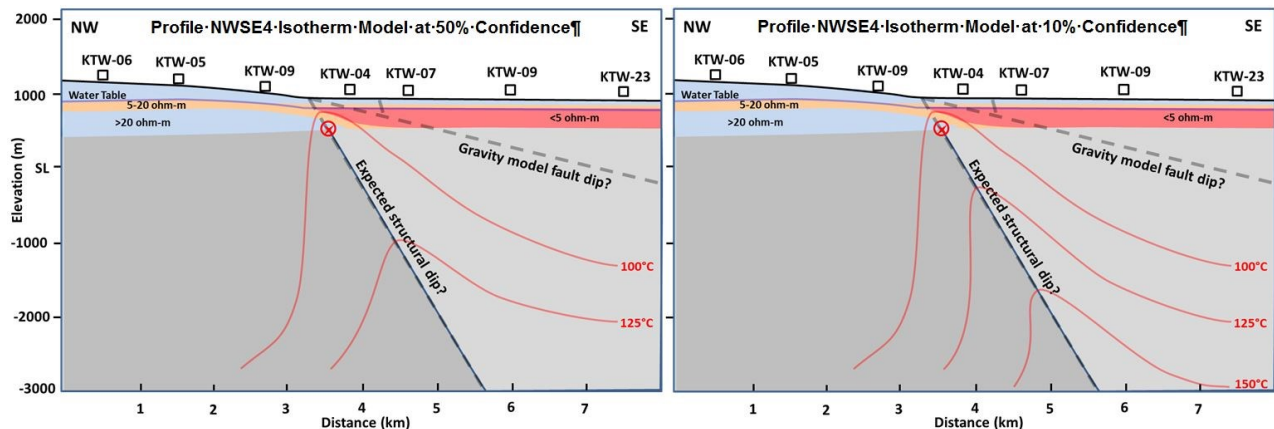


Figure 9: Preliminary resource conceptual model isotherms overlaid on TEM resistivity from east end of Profile NWSE4 from Figure 7 and gravity model from Figure 8 (1:1 vertical exaggeration) (Adapted from Hinz, 2018c).

The 2D gravity model in Figure 8 based on fitting the gravity in Figure 7B is aligned with the central part of the TEM cross-section. Although it includes a lateral density contrast where the relatively low density sediments thicken to the east of the Nyamwamba fault zone, after allowing for the 4x vertical exaggeration, the dip of the modeled density contrast is under 25°, much lower than the minimum 45° and more likely 60 to 65° dip estimated from surface exposures of the main strand of the Nyamwamba fault.

4.2 Integration of Geophysics in Preliminary Resource Conceptual Models

In order to assess the Katwe resource and better inform the next steps in its exploration, the EAGER-GRD team developed a range of resource conceptual models that considered all of the available geoscience information and illustrated the uncertainty in the resource assessment. Although the petrophysical interpretation of the TEM resistivity and gravity data by EAGER-GRD remained generally consistent with the interpretation by Gislason et al. (2010), the earlier results were not presented in a manner suitable for a conceptual integration with the revised geochemistry conclusions of Marini (2018) and the structural geology results of Hinz (2018b). To better support the development of optimistic (10% confidence), most likely (50% confidence) and pessimistic deep circulation conceptual models, the TEM resistivity pattern and gravity model were simplified and plotted without vertical exaggeration, along with the dip and location of the main strand of the Nyamwamba fault zone inferred from the geology field mapping (Figure 9). Preliminary isotherms developed for the 10% and 50% confidence models are also included in Figure 9 in order to illustrate the uncertainty in the resource assessment that led to the design and acquisition of a 43 station MT survey.

The conceptual models in Figure 9 are simplified illustrations of the following scenarios meant to illustrate the range of uncertainty in the models. An important constraint on the spatial extent of the Lake Kitagata thermal anomaly is that it is assumed to be bounded on the east by the relatively cold TGH, KTHW-2, which is located 1.5 km southeast of the hot springs (Figure 4). The thermal gradient of 25°C/km in KTHW-2 and the maximum reported gradient of 36°C/km observed at Katwe provide a range of depths required for deep-circulation heating.

Pessimistic model: A plausible pessimistic conceptual model for the Lake Kitagata geothermal system would consist of a small narrow upflow plume heated by deep circulation to <120°C at ~3500 m depth, buoyantly rising along the Nyamwamba fault and approaching the surface directly beneath the hot springs. This is not shown in a figure.

Median model: The 50% confidence model in Figure 9 assumes that an upflow illustrated by the 125°C isotherm at about 2000 m depth originates from >4000 m depth and is hosted in one or more of the fault steps or intersections along the Nyamwamba fault zone SSW of Lake Kitagata. The upflow is diverted below the clay cap and then flows at 500 to 1000 m depth north to emerge at the Kitagata hot spring. The 100°C isotherm is near the surface, consistent with the >70°C spring discharge temperatures at Lake Kitagata. In this model, the hot springs emerging at the lake's edge constitute lateral flow along the Nyamwamba fault zone from a main reservoir located in a more extensive permeable zone to the SSW.

Optimistic model: This is similar to the median model but it has higher temperature due to a higher assumed regional thermal gradient and deep circulation to >4000 m.

New data likely to resolve important uncertainty in these models would include the results of drilling two TGH wells to assess the trend in temperature at 200-300 m depth to the SSW of the Kitagata crater (Figure 4). That is, if a TGH to the SSW was significantly colder than a TGH on the west rim of Lake Kitagata, then the pessimistic model of Katwe would be more probable. However, drilling TGHs was not within the scope of the EAGER-GRD program. Therefore, investigation options short of drilling were reviewed. The EAGER team recommended several survey options that might better constrain the models, including acquiring and analyzing new gas samples of the hot springs and conducting soil gas flux, 2 m temperature probe and MT surveys.

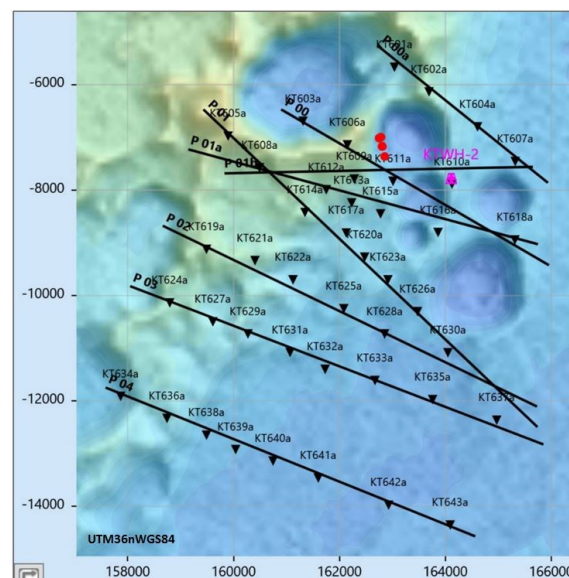


Figure 10: Map of Katwe MT profiles, hot springs and TGH KTHW-2 (Adapted from Heath and Cumming, 2018).

A new MT survey at Katwe seemed likely to resolve resistivity to greater depth than the TEM and to potentially constrain the dip on the Nyamwamba fault. The TEM resistivity data at Katwe was acquired using a relatively powerful Geonics Protem 57 TEM system and still did not reliably resolve the base of the low resistivity tuffs and sediments east of the Nyamwamba fault. In any case, central-loop TEM soundings would not be expected to reliably resolve a fault dipping 40 to 60°, whereas GRD's MT resolved the 60° dip of the basin-bounding fault at the Kibiro prospect (Hinz et al., 2018). Meanwhile, the Katwe gravity results are ambiguous. Therefore, a 43 station MT survey programme was proposed by EAGER-GRD to better assess whether further drilling was justified and constrain the targeting and the design of any further TGH. The field layout is shown in Figure 10. Specifically, the MT survey might help constrain the dip of the main strand of Nyamwamba fault within the greater Nyamwamba fault zone by better resolving the base of

the low resistivity zone in the basin, it might detect a relatively resistive hot water aquifer below the low resistivity smectite cap in the basin, and it might characterize potential updip outflow paths.

4.3 Magnetotelluric (MT) Survey Results

The 43 station MT survey recommended by EAGER for Katwe was acquired by GRD in 2018. The locations of the MT stations (Figure 10) were mostly planned to be coincident with the earlier TEM stations to facilitate the correction of MT static distortion. Data quality was generally high, with a few noisy stations caused by interference from wild animals and, in a few cases, high electrode resistance. No dedicated remote reference was feasible so noise was mitigated using a local remote reference, which resulted in acceptable data quality at the MT frequencies of interest for geothermal exploration above 0.01 Hz. As a first pass analysis, 1D inversions of the MT invariant mode were conducted by GRD with assistance and review from EAGER and eight resistivity cross-sections through all of the stations were prepared (Figure 11).

The Katwe MT resistivity profiles in Figure 11 detect a consistent pattern of resistivity relative to the Nyamwamba fault. The 1 – 5 ohm-m zone corresponds to the recent tuffs altered/weathered to clay, with a top consistent with the water table, as illustrated by Profiles 00 and 00b in Figure 11, on which the water table is indicated by the Lake Kitagata hot springs at about 920 m a.s.l. The base of this low resistivity zone dips at a relatively low angle from the fault into the basin and extends to about 500 m a.s.l. The MT resolves the abrupt transition to resistivity higher than 5 ohm-m at 800 m a.s.l. west of the fault. This transition deepens east of the fault into the basin and extends to about 500 m a.s.l. over a distance of about 2 km. This compares well to the resistivity and gravity analyses reported by Gíslason et al. (2010) and summarized in Figure 9.

It is likely that the detail of the resistivity and density variation are aliased by the MT, TEM and gravity at the fault (insufficiently sampled), and that multiple offsets occur over a zone rather than at a single fault, which is consistent with the multiple strands shown in Figure 7 (Hinz, 2018b and Cumming, 2018). With respect to the smectite clay alteration detected by the MT, the clays are particularly low resistivity updip from the hot springs at Kitagata, as shown in Figure 11 Profiles P-00 and P-01b, consistent with shallow outflow of warm water from a local outflow conduit that meets the water table near the hot springs. Figures 11 Profiles P-00 to P-04 show a pattern of generally higher resistivity near the fault to the southwest. The MT does not detect deeper structures or alteration consistent with a more extensive upflow to the southwest of Kitagata. Therefore, although the MT did not resolve the complex geometry of the Nyamwamba fault zone SW of the hot springs at Kitagata, the overall pattern of alteration detected by the MT is more consistent with the model with a local upflow closely associated with the hot springs.

5. GEOTHERMAL RESOURCE CONCEPTUAL MODEL CONCLUSIONS

The interpretation of the magmatic affinity for Katwe has been based hitherto, on the elevated salinity of the springs, the recent volcanic activity associated with the maars and cones, and the earthquake evidence of magmatic activity below the Rwenzori Mountains (Stadler et al., 2007). However, the high salinity is more reliably attributed to evaporites, the petrology of the recent volcanic rocks indicates a deep magma source, and the depth of the seismicity at 15 to 30 km below the Rwenzori Mountains is consistent with a deep magmatic source for the volcanism at Katwe, implying that there is no evidence of shallow heating by magma (Cumming, 2017) and, therefore, the hot springs water is likely heated by deep-circulation.

The Katwe geothermal prospect is characterized by hot springs in the Kitagata crater and warm springs in the Katwe crater. Although then elaborate mixing model proposed by Marini (2018) to infer subsurface temperature at the Kitagata geothermal prospect is made more uncertain by its complexity, the estimates of the temperature of the subsurface thermal fluid influx of 116 to 126±10°C based on the mineral saturation index method and 128°C based on the chalcedony silica geothermometer improve confidence given their consistency.

Although associated with the 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 probably associated with fault intersections and step-overs along the strike of the Nyamwamba fault system near the Kitagata crater. The crater is located at the north end of a 7 km-long area of complex faulting along the Nyamwamba fault zone (Figures 4 and 5), including normal fault step-overs and major fault intersections which are potentially capable of facilitating deep circulation of geothermal fluids based on studies of similar structural styles in the Basin and Range of the western US (Faulds and Hinz, 2015).

The results of the new structural geologic mapping (Hinz, 2018a) confirm 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 6). Surface geology indicates a dip of 40 to 60°. The more modest dips implied by the geophysics are due to ambiguity in the gravity and, more significantly for the MT and TEM, aliasing (insufficient sampling) across multiple fault steps in a complex zone over 1 km wide. The MT confirms the impression given by the gravity and TEM that the total throw on each strand of the Nyamwamba fault zone is relatively small.

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 6 and 7). The pessimistic conceptual model for the Lake Kitagata geothermal system consists of a very small narrow updip flow plume on the Nyamwamba fault that is located directly beneath the hot springs. The overall resistivity pattern detected by the MT is consistent with this model. More optimistic models have a hotter upflow zone located to the SSW of Lake Kitagata in one or more of the fault step-overs or intersections along the Nyamwamba fault zone and outflowing to the NNE to the hot springs emerging at the lake's edge (Hinz, 2018c).

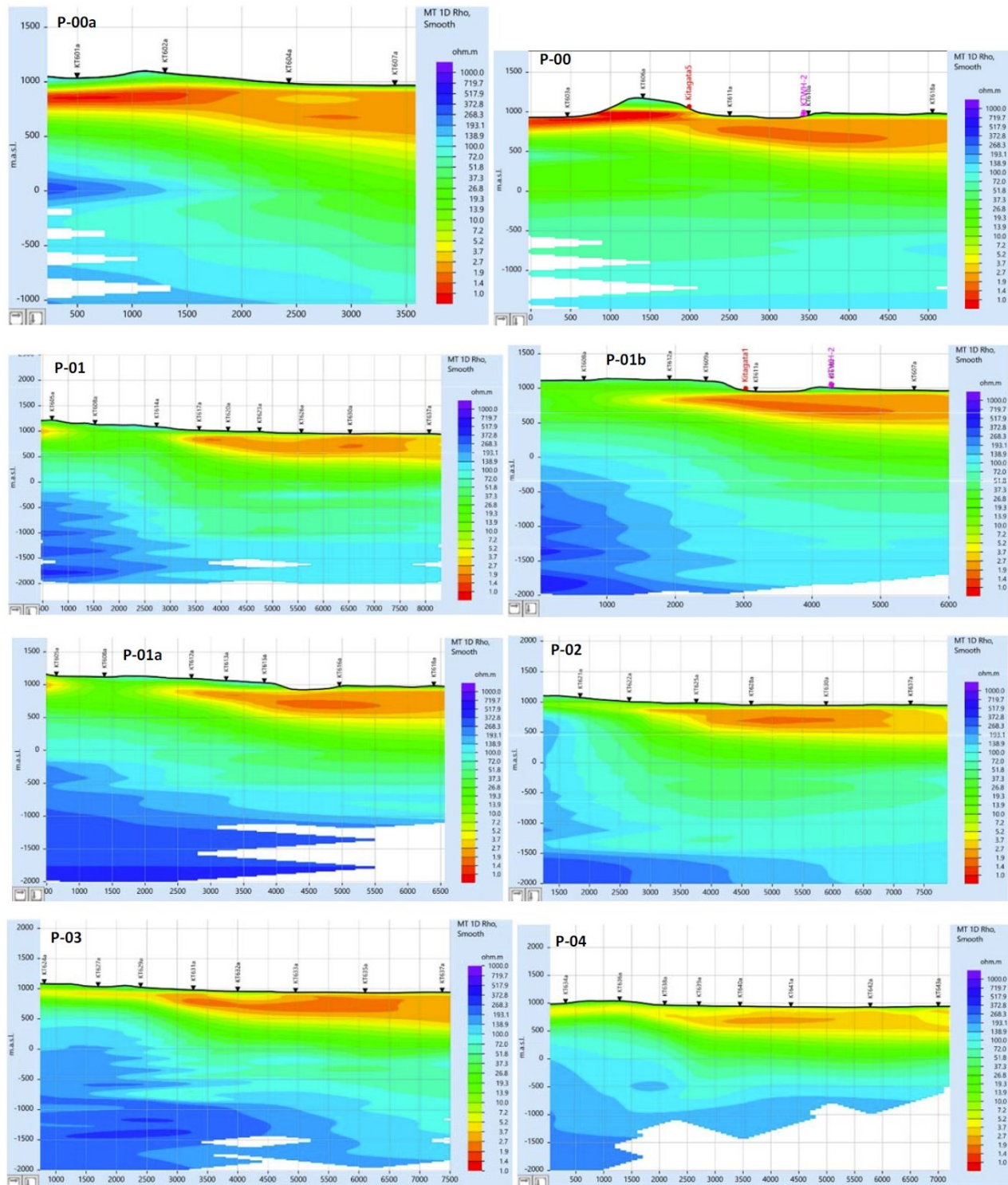


Figure 11: Katwe MT Profiles 00a, 00, 01, 01b, 01a, 02, 03 and 04 (*Adapted from Heath and Cumming, 2018*).

6. CONCLUSIONS AND RECOMMENDATIONS

Following three and a half decades of geothermal exploration at Katwe that has focused on volcanic models for the geothermal system, new interpretations of existing data and new data acquired and processed by GRD with the support of EAGER during the last two years, indicate that a conventional geothermal resource at Katwe is likely to be a deep circulation system located near Lake Kitagata. New structural mapping has confirmed that this geothermal resource is associated with fault geometry likely to promote the formation of deep fracture permeability and deep circulation. 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 between 107 to 136°C. Consequently, EAGER and GRD have developed several alternative deep circulation conceptual models for the geothermal activity at Kitagata that are analogous to US Basin and Range type systems (Hinz, 2018c). The alternative models include; a narrow upflow zone along the Nyamwamba fault zone just under the hot springs area, or a larger upflow in one or more of the fault step-overs or fault intersections along the Nyamwamba fault SSW of Lake Kitagata. The ambiguity regarding these models, one intersection and one step-over, could be reduced by targeting two temperature gradient wells to test whether a hotter system is likely to be found to the SSW of Lake Kitagata. Additional geochemical sampling

for water and gas chemistry and stable isotopes has been recommended by Haizlip (2018) to support a more complete understanding of the source of the Kitagata hot spring fluids. Soil gas surveys and 2 m shallow temperatures probe surveys could be used to assess evidence of shallow heating not directly associated with hot springs. Following the acquisition of new data, conceptual models should be updated to facilitate decisions, for example, for targeting TGH drilling if that proves to be compatible with the special status of this area.

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