Geothermal Resource Assessment for Mt. Longonot, Central Rift Valley, Kenya

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Keywords

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ABSTRACT

Africa Geothermal International Ltd (AGIL), with the assistance of Sinclair Knight Merz (SKM), is evaluating the potential development of the Longonot geothermal system located in the Kenya Rift Valley northwest of Nairobi and 10 km east of the Olkaria Domes geothermal field. Mt Longonot, a trachytic stratovolcano southeast of Lake Naivasha, is in an area of active west-to-east extension (the Rift Valley) as well as an area of crustal uplift and thinning (the Kenya Dome). Results obtained during a comprehensive geological, geochemical and geophysical field program in 2010 have been used to develop a conceptual model of this high-temperature system. The estimated power plant capacity within the area with the highest estimated power density is about 150 MWe, which is sufficient to service the project target capacity of 140 MWe. A phased drilling program is proposed to prove, delineate and develop the resource.

1. Introduction

In July 2009, the Kenya Ministry of Energy awarded AGIL a Geothermal Resource License for the 132 km^2 Longonot geothermal concession. The license allows AGIL to conduct geothermal exploration and build a geothermal power plant capable of generating 140 MWe or the maximum economically available.

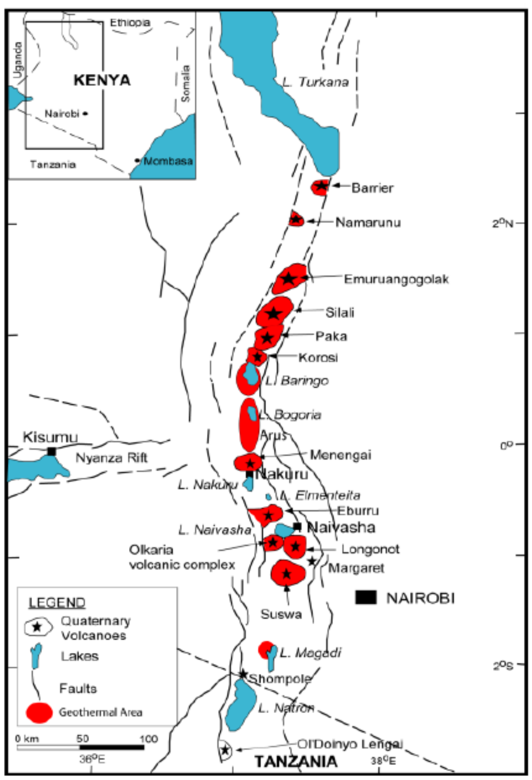


Figure 1. Map of Kenya Rift Valley showing the location of Longonot and other Quaternary volcanoes along the rift axis (from Omenda, 2008).

The Longonot concession is located in the Kenya Rift Valley, approximately 60 km northwest of Nairobi and 10 km east of the Olkaria Domes geothermal field. The Kenya Rift Valley is part of the East African Rift system that runs from Ethiopia in the north (the Afar triple junction) to Beira, Mozambique in the south. The southern segment of the Kenya Rift Valley is a unique petrological province comprising of at least four Quaternary to Recent volcanic complexes (from north to south): Eburru, Olkaria, Longonot, and Suswa (Figure 1). Although these volcanoes are located only about 50 km from each other, the eruptive rock types from each volcano are compositionally different. Active geothermal systems are associated with each of these volcanic complexes. To date, only Olkaria has been developed for power generation. The Olkaria geothermal field lays 10-20 km west of Longonot and has generation of over 200 MW already operating and expansion of about 270 MW currently under development.

2. Previous Studies

The geothermal potential of the Kenya Rift Valley was recognized in the mid-1950s. In 1956, two wells were drilled at Olkaria about 10 km west of Longonot. One of the wells reached a depth of 1035 m with temperatures up to 235°C (Clarke et al., 1990). This promising result was not followed up until the 1970s when the UNDP and the Kenya Power and Lighting Co. carried out an extensive exploration program in the Rift Valley. This survey identified Olkaria as the best candidate for exploratory drilling. By 1976, six deep wells had been drilled and the first 15 MWe generating unit was commissioned at Olkaria in 1981.

The Longonot volcanic complex was first studied in detail by Scott (1980). The study focused on the volcanic history of Longonot, in particular the establishment of the chronology and original volumes of its volcanic products.

During 1985 to 1987, a team of geologists from the British Geological Survey performed detailed reconnaissance work at Longonot and surrounding geothermal prospects between Lake Bogoria in the north and Lake Magadi in the south. This study (Clarke et al., 1990) forms the primary reference for understanding the Longonot geothermal system.

More recently, the Kenya Electricity Generating Company (KenGen) carried out a detailed geoscientific study at Longonot in 1998, which indicated a geothermal resource area of approximately 70 km^2 with an estimated power output of 128 MWe (KenGen, 1998). The KenGen report also proposed an exploratory drilling program of three wells.

3. Current Study

During 2010, SKM completed the exploration fieldwork for Longonot. Field activities included:

- Full reconnaissance of the concession including vehicular access
- Geological fieldwork including mapping and verification of surface features (alteration, structures and thermal activity) and collection of rock samples for XRD analysis
- Geochemical survey including collection of gas and condensate samples from fumaroles and completion of a soil gas flux survey
- Geophysical surveys including completion of gravity, magnetic and magneto-telluric (MT) surveys

4. Geology

The regional geology of the southern Kenya Rift Zone has been discussed in detail in previous studies, in particular, Thompson & Dodson (1963), Allen et al. (1989), Clarke et al. (1990), and Lagat et al. (2005). A brief geologic summary is given below, with updates from SKM's field work in 2010 where appropriate.

- Mt Longonot is located in the southern Kenya Rift Zone, an area of active west-to-east extension. The rift valley in the vicinity of Longonot is estimated to be spreading at 3.2 mm/year toward the east-southeast (Stamps, et al, 2008).
- The central sector of the East African Rift System corresponds to the Kenya Dome, an area of crustal uplift and thinning centered north of Longonot. As the dome formed, it stretched and fractured the outer brittle crust into a series of N- to S-trending, normal faults forming the classic horst and graben structure of rift valleys.
- The most intensive area of Pleistocene to Recent volcanic activity in the southern Kenya Rift Zone occurs near the centre of the Kenya Dome. Three large (and highly evolved) volcanic complexes (Longonot, Olkaria and Eburru) occur around Lake Naivasha.
- The volcanic activity associated with Longonot volcanic centre began 400,000 years ago. Major pyroclastic eruptions occurred over the period from about 21,000 to 6,000 years ago, which produced the major caldera structure now visible on the western flanks of Longonot.
- The present summit crater appeared about 3500 years ago. The most recent eruptions of trachyte lava on the north and southwest flanks of Mt. Longonot are estimated at about 150 years ago.
- The history and nature of the volcanism is consistent with the development and continued presence of a large magma chamber at relatively shallow depths that has been the source of the caldera-forming eruptions. The magma chamber is believed to still be molten to some extent as evidenced by the recent volcanic activity at Longonot. This is well suited to be the driving heat source for a geothermal system.
- The major NNW-SSE alignment of flank eruption centers and fissures on Longonot Volcano, which passes through the summit crater (the tectono-volcanic axis or TVA) may be the surface expression of the ongoing regional tectonics. Parallelism of major volcano alignments and regional faults at Longonot (and Suswa to the south) suggests that regional tension fractures or faults that intersect the shallow-most magma chambers are utilized as conduits for transporting magma from the chambers.
- Surface expression of faults in the vicinity of Longonot is hindered by thick deposits of pyroclastics and lava flows. A steeply-dipping normal fault, trending NNW-SSE (in line with the TVA) and dipping toward the WSW, is believed to be present from the base of the Longonot Crater to Crescent Island in Lake Naivasha.

5. Thermal Activity

Overall, there are very few thermal features at Longonot, presumably reflecting the arid nature of the area. The fumaroles that were observed by SKM have weak and diffuse steam flow. Geothermal manifestations either lie within the summit crater or on the main alignment of flank eruption centers and fissures (the TVA) or along the rim of the caldera. The manifestations along the caldera wall occur in the south where pre-caldera rocks are exposed beneath a somewhat thinner pyroclastic cover, and where it is believed that the topographic caldera rim lies very close to the ring fracture (Clarke et al., 1990). The lack of manifestations elsewhere along the rim can be accounted for by a thicker pyroclastic cover. The 2010 field observations of thermal features are summarized below. Locations of thermal features are shown on Figure 2.

Fumarole – Inside Longonot Crater, N side (SKM1, 216539E, 9899865N). Large diameter fumarole (~1-2 m dia., 3-4 m visible depth) located half way down crater on steep inside crater wall. Very slow and diffuse steam flow. Weak H_2S odor. Measured temperature = 70°C.

Hot ground – Inside Longonot Crater, N side (SKM2, 216541E, 9899831N). Large outcrop (~200 m^2) of hot rock (no steam) with reddish clay and gray sinter deposits. Weak H_2S odor. Measured temperature = 87°C.

Fumaroles – Inside Longonot Crater, N side (SKM3, 216655E, 9899914N). Several small vents with weak and diffuse steam flow on steep outcrop near base of crater. Area of altered ground (~150 m^2). Red alteration clay. No H_2S odor. Measured temperature = 104°C.

Fumaroles – Inside Longonot Crater, SW side (SKM4, 216111E, 9898716N). Several small vents with weak and diffuse steam flow on steep outcrop half way down crater wall. Unable to access – viewed from base of crater.

Fumaroles – Inside Longonot Crater, S side (SKM5, ~217100E, ~9898400). Several small vents with weak and diffuse steam flow on steep outcrop half way down crater wall. Unable to access – viewed from crater rim. Only visible on humid days.

Fumarole – Outside Longonot Crater, SW side (SKM6, 215466E, 9897642N). Steaming outcrop (30 m^2) at base of ravine high on SW outer slope of crater. Weak and diffuse steam. No H_2S odor. Measured temperature = 83°C.

Fumarole – Inside Longonot Caldera, S side (SKM7, 216016E, 9895093N). Single small vent with very weak and diffuse steam flow. On outcrop of caldera wall. Measured temperature = 60°C.

Fumaroles – Outside Longonot Caldera, SE side on lava flow (SKM8, 218095E, 9895440N). Small cavities (0.01 – 0.5 m diameter) in pyroclastic outcrop immediately adjacent to basalt outcrop. Weak and diffuse steam. No alteration. No H_2S odor. Measured temperature = 50-62°C.

Relic fumarole at base of lava dome, SE of caldera (SKM9, 218949E, 9894417N). Relic steaming ground/ relic fumarole. White mineral precipitate crust on samples. No active fumarole found.

Shallow steaming bore – SSE of caldera (SKM10, 218813E, 9890003N). Very weak and diffuse steam flow emanating from hand-dug, ~1 m dia. abandoned bore of unknown depth. No H_2S odor. Located on southern boundary of concession.

Akira Bore – SW of concession (208114E, 9890204N). Borehole (~230 m deep) discharging vigorous steam flow through well head stack. Used by Maasai for water collection. Measured temperature = ambient boiling.

6. Geochemistry

At Longonot, fumaroles within the crater typically have weak discharges while those outside the crater are steaming ground with no positive pressure, and highly impacted by atmospheric air. This limited gas sampling to collection of only one sample from inside the Longonot Crater (SKM3). Condensate sampling was limited to SKM3 (isotopes only) and Akira Bore to the southwest of the caldera. Results are shown on Table 1.

Table 1. Gas sample analytical results. Duplicate samples from SKM3 collected.

Sample	Description	Date	Temp °C	CO_2	H_2S	NH_3	He	H_2	Ar	O_2	N_2	CH_4
							Mole Percent in Dry Gas					
SKM 3A	crater	23-Feb-10	104	24.6	1.0	-	0.00040	0.03	0.82	15.6	57.7	0.19
SKM 3B	crater	23-Feb-10	104	24.0	0.3	-	0.00090	0.03	0.85	16.0	58.7	0.19
Mean Air:				0.03					0.93	21.0	78.1	
SKM 3A		air-corrected		94.8	4.0	-	0.0015	0.11	0.48	0.0	0.0	0.73
SKM 3B		air-corrected		97.5	1.1	-	0.0037	0.14	0.55	0.0	0.0	0.77

Overall, the gas data from the SKM survey adds only a little to the accumulated data of previous workers. The presence of significant H_2S is important because it is a signature gas in high temperature geothermal steam. However, the diffuse nature of the surface activity and large amount of subsurface air present in the fumaroles precluded the collection of samples good enough to determine gas-in-steam concentrations and the application of a wider range of gas chemistry interpretative techniques. The gas data are insufficient to map clear trends in chemistry across the prospect area, or to interpret reservoir processes (boiling, condensation etc).

The oxygen-hydrogen isotopic composition indicates that the Longonot reservoir is probably recharged from rainfall on the eastern side of the Rift Valley. There is no recharge from Lake Naivasha – as seen at Olkaria.

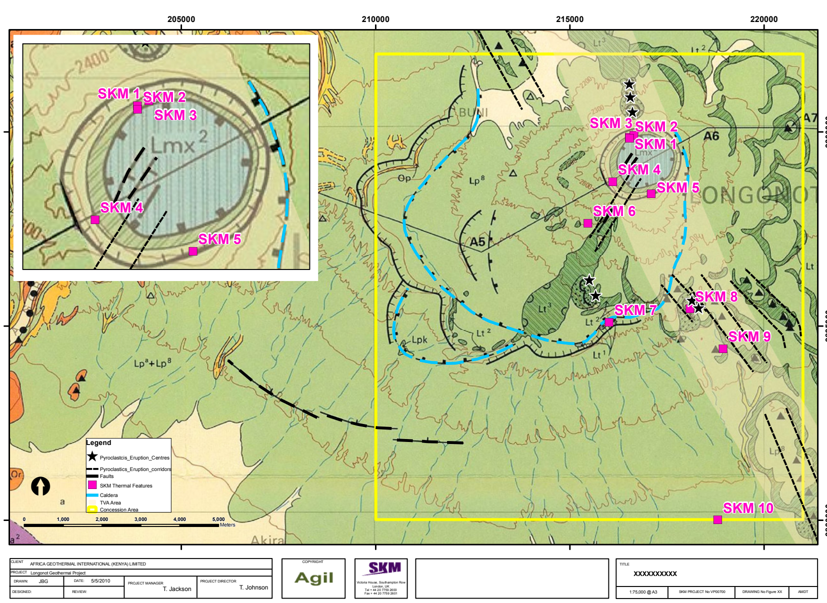


Figure 2. Thermal features verified by SKM during 2010 fieldwork. Uncertain structural margin of Longonot caldera in blue. Concession boundary in yellow. Geologic basemap from Clarke, et al., 1990.

7. Geophysics

7.1 Gravity

Previous gravity surveys in the Olkaria, Longonot and Suswa areas by Geotermica Italiana (1989) suggested that positive anomalies were related to shallow bodies made of dense lava flows and negative anomalies were related to deeper sources. Geotermica Italiana (1989) postulated that the collapsed crater of Longonot corresponds to a gravimetric low due to the possible combined effect of the light pyroclastic filling of the caldera and of the low density trachytic magma chambers.

In early 2010, SKM performed a gravity survey at Mt Longonot. Stations were confined within the geothermal concession area and included both the Mt Longonot National Park and Kedong Ranch property. Measurements were made at 101 sites, with two base stations established at Naivasha and Mai Mahiu for regional confirmation. A gravity profile of 2.1 x 10^{-3} kg m^{-3} was adopted in the calculation of terrain corrections and Bouguer anomalies as this value is least affected by terrain and is likely to represent the average density under the survey area.

Figure 3 shows a map of Bouguer gravity anomaly (in mGals), using a density of 2.1 x 10^{-3} kg m^{-3}. The map includes data collected by SKM in 2010 and regional gravity data from the Kenya gravity catalog (Swain & Khan, 1977). The eastern limits of the low anomaly is not very well defined, though the results of the gravity survey inside the geothermal concession ties in quite well with the regional data. This large gravity low could be attributed to thicker low-density pyroclastic infill inside a buried caldera structure. Some structural control is suggested by the steep gravity gradients east and northeast of the concession area, particularly along the TVA. The low gravity anomalies at the southwest area of the concession are harder to explain, though this could suggest the presence of low density plutonic bodies at depth.

The 2010 gravity survey show that the old Longonot caldera boundaries may actually lie at least 1 km outside the presently indicated caldera rim. This indicates multiple phases of caldera-forming eruptions and provides additional structural information. This structure may present some permeability targets during exploration drilling and predict areas of thicker, low density infill rocks.

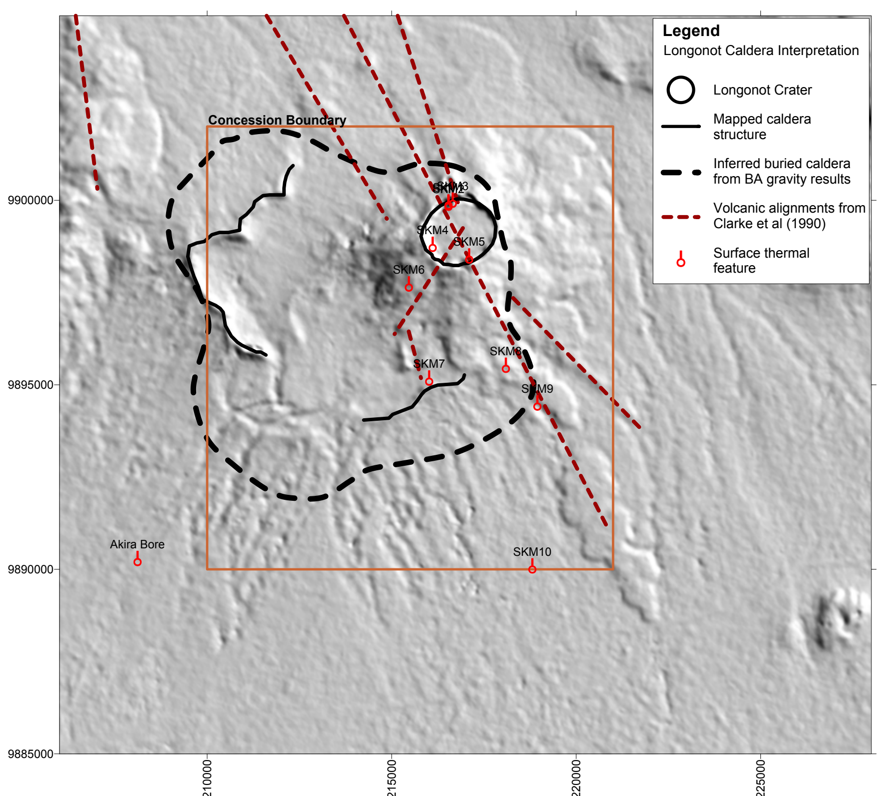


Figure 3. Map showing the extent of a buried caldera (dashed line) as inferred from Bouguer Anomaly results. The currently mapped caldera structure (solid black line) and the Longonot Crater are nested within this inferred caldera structure.

7.2 Magnetotelluric (MT)

In April 2010, SKM supervising a deep-penetrating MT survey consisting of 103 stations installed over an area of approximately 240 km^3 around the Longonot Crater. The resulting MT data collected at Longonot are of exceptionally high quality, which can be attributed to the conjunction of suitably conductive ground allowing good electrode coupling, very low electrical noise from human activities and the magnetic storm that hit the earth at the start of the survey period.

For this survey, we relied on a 3D model produced by Geosystem using their proprietary Randy Mackie 3D inversion code. We also performed some 1D modeling for cross-checking purposes. The good agreement between the outputs of the two modeling methods confirmed the viability of using 3D models. An example of a 3D model resistivity cross section along profile NS-2 is reproduced in Figure 4, as it reveals some of the distinctive patterns found below the crater and the inferred geothermal reservoir to the south.

The presence of clays due to hydrothermal alteration tends to be the dominant factor affecting resistivity patterns around geothermal systems. The smectitic clays produced by alteration processes between 50 to 200°C are highly conductive, and certainly much more conductive than the illitic clays and other high temperature mineralization that occur above 200°C. Therefore, in most high temperature geothermal systems, there is a characteristic clay "cap" that forms above the main high temperature reservoir and often on the sides of geothermal systems, particularly in outflow areas. This clay cap is readily the most dominant feature seen by resistivity surveys and so provides a useful indicator of the location and extent of the underlying higher temperature reservoir. This extensive alteration requires reasonable permeability for complete rock-water interaction and alteration, so the clay cap is dominant in shallower formations and may not be always present on the side of a system unless there is permeability to enable lateral flows of fluid.

Figure 5 shows the base of the main conductive zone at Longonot. The base of the clay cap usually marks the transition to high temperature reservoir (or, at least, reservoir at temperature greater than 200°C) and can be treated as a thermal indicator. The top of the cap typically marks the upper extent of thermal activity (about 50°C).

The resistivity picture at Longonot is complex. Although a more typical semi-horizontal conductive clay cap appears to lie above a geothermal system to the south of Longonot, the situation under Longonot Crater is not so clear.

The conductor to the south of Longonot Crater shows a dome shape and is much shallower than the conductive units east and north of the volcano, although it becomes very flat south of this dome, and very extensive too. This extensive nature of the conductive cap causes some measure of doubt to the interpretation of this feature as an indicator of the top of a geothermal reservoir for its entire extent. Indeed, we would normally expect such a feature to thicken and deepen near the edges of the system especially on down-slope outflows whereas this does not happen here. The fact that some surface thermal features are present in the southern part of this conductor reinforces our interpretation that there is some combination of a 'clay cap' and outflow of geothermal origin. In such a setting, we would normally interpret the main upflow location to be immediately below the dome structure but in this case, there is likely to be significant upflow of geothermal fluids along the conductive zone north of the dome, and along the TVA, as evidenced by the location of surface thermal features, and geothermometry.

On Figure 5, we outlined with a dashed black line the divide between the shallow conductor to the south and the other conductive bodies to the north. While the resistivity structure south of the divide is very typical of many geothermal systems, the area north under Longonot volcano is more complex and has a less certain geothermal origin.

A vertical conductor is apparent under the crater area and persists with both 1D and 3D models. Such a vertical conductor is very uncommon within geothermal systems and does not make sense in terms of any reasonable geothermal fluid salinity and porosity assumptions. It is possible that the conductor may be indicating the presence of a magma chamber under Longonot possibly rising to relatively shallow levels just south of the crater. This magma could be associated with the main heat source for the system and supports the hypothesis that the main geothermal system appears to lie south of the Longonot Crater.

The main geothermal outflow occurs towards the southwest of the survey area following the topography and generates the extensive shallow conductor seen over this whole area. The doming in the shallow conductor south of Longonot Crater probably indicates an area of preferential upflow. In this zone, the conductor is closest to the surface and thinner.

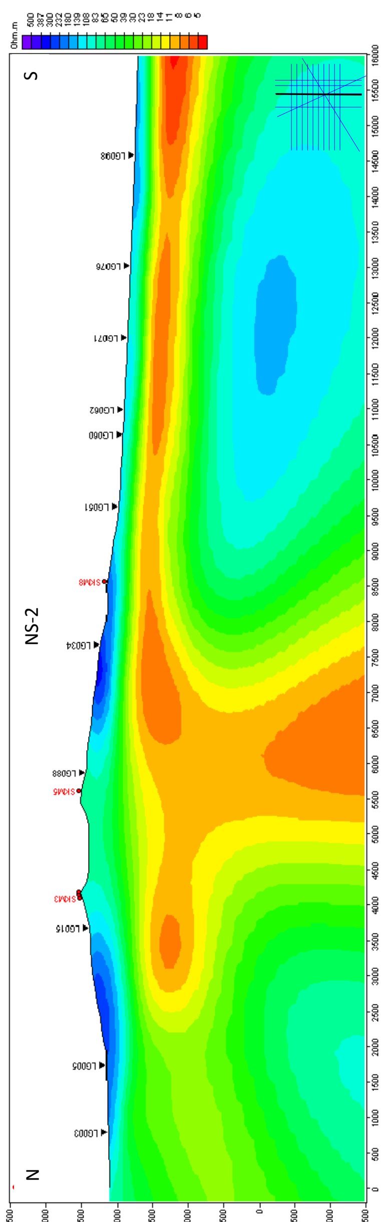


Figure 4. 3D modeled resistivity cross-section along profile NS-2 through Longonot Crater (see Figure 5). Red represents low resistivity and blue represents very high resistivity.

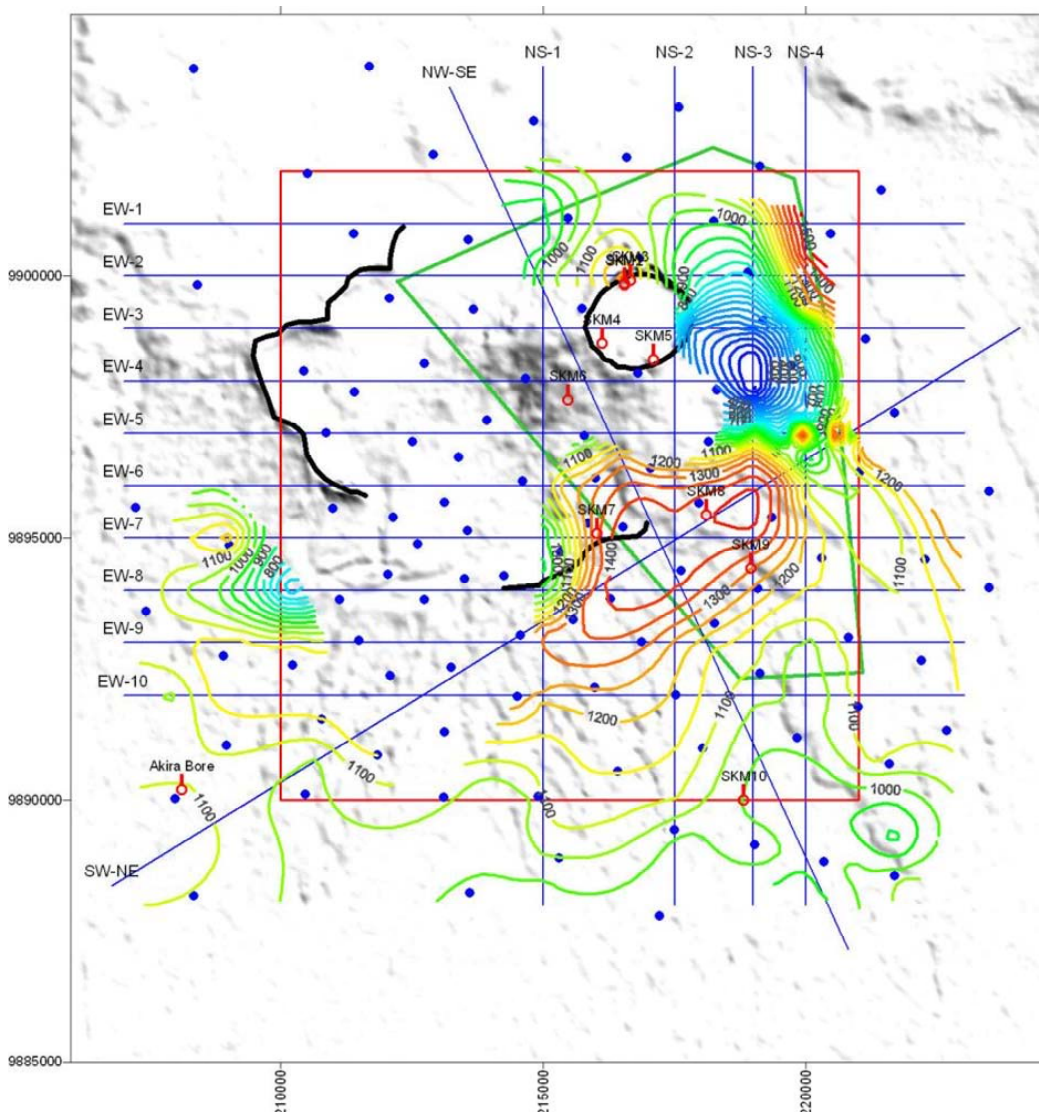


Figure 5. Contours of elevation of the base of the principal conductive bodies (50 masl contour interval). Surface thermal feature are noted in red, and MT stations as blue dots. The dashed black line is the northern extent of the conductor.

8. Integrated Conceptual Model

A geothermal conceptual hydrological model has been developed based on the interpretation of resource information in the previous sections and using analogies from other geothermal resources with similar characteristics or in similar geological settings. The key aspects of the resource that influence this model are:

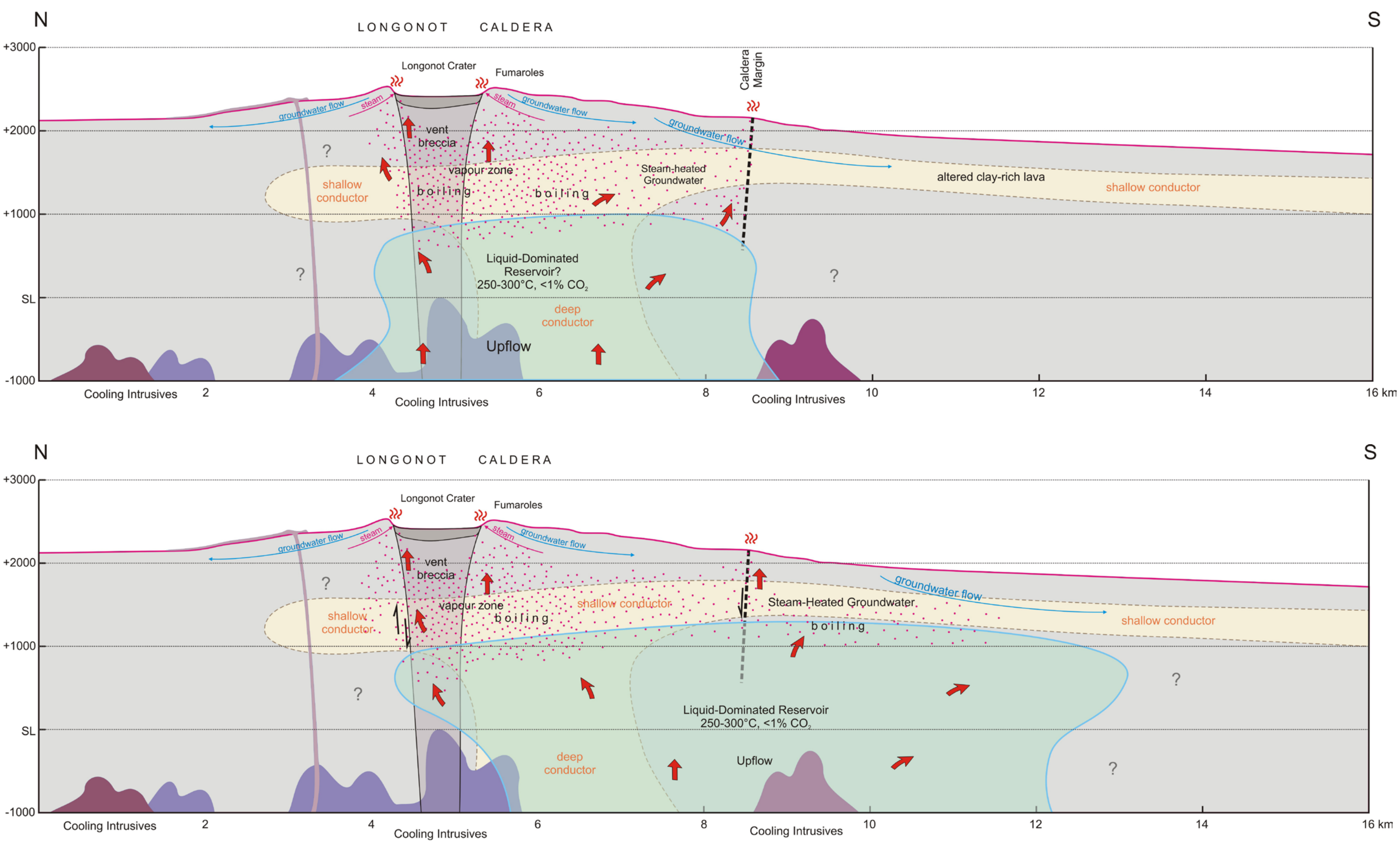
- The presence of the Longonot caldera and crater and inferred deep intrusive representing viable heat sources
- The occurrence of surface steam emissions, concentrated within the Longonot crater but present also as diffuse emissions over a wider area of the caldera
- NNW-SSE volcanic alignment associated with weak thermal activity and subsidiary minor eruptive centers
- MT survey results showing a large shallow conductor on the SE flanks of Mt Longonot
- Confirmed geothermal resource at Olkaria Domes, 10 km to the west, comprising a high temperature (max 340°C at 2200 m) and liquid-dominated resource

The chemistry and geophysics do not provide a completely consistent picture of the resource. Fumaroles within Longonot Crater point to the existence of a hydrothermal system here but the resistivity structure shows the most prospective conditions (doming shallow conductor) on the southern side of the volcano. The geophysical structure around the crater is complex indicating possible magmatic conditions, past or present (deep low resistivity), and gaps in the shallow conductor indicating removal by eruption.

On the basis of the above we propose two conceptual models as shown in Figures 6 and 7. At Longonot, perched steam-heated groundwater flows to the SSE through shallow lava flows, contributing, at least in part, to an extensive, clay-rich conductive zone. This zone may extend beyond the margins of the high-grade resource so there is uncertainty about where the southern boundary of the deep resource exists. In Conceptual Model "A" (Figure 6), the southern boundary of the resource is just south of the southern caldera. Here, the shallow conductor in the south is taken to represent surficial conditions, either an altered clay-rich lava flow or alteration caused by an outflow of perched steam-heated groundwater. In the south, the resource extends only to the caldera margin where weak steam emissions are found. In Conceptual Model "B" (Figure 7), the resource boundary is placed roughly 6 km south of the crater rim.

9. Conclusions

Interpretation of comprehensive exploration surveys conducted at Longonot present strong evidence for the presence of a substantial high temperature geothermal system on the southern flanks of Longonot volcano. The geological setting presents strong evidence for a long term heat source in the area and potential permeable zones that enable deep fluid circulation. Geochemistry sampling has confirmed subsurface geothermal conditions extend over a wide area. MT resistivity surveys have shown that geothermal alteration is pervasive across a much wider area and



Figures 6 and 7. Longonot Conceptual Model "A" (on top) and Model "B" (on bottom).

provide an indication of the likely upflow area and primary targets for exploration drilling.

Although Longonot is volcanically different to the adjacent Olkaria system which lies within a broad rhyolitic-trachytic dome complex, Olkaria provides a useful analogy for interpretation of the features seen at Longonot. Despite thermal features only being found in a small area in the western half of the Olkaria field and a complete absence of hot springs, Olkaria is proving to be one of the world's largest geothermal systems.

Based on the review of geophysical and geochemical data available at Longonot, SKM has estimated the lateral extent and outflow of the geothermal resource. Figure 8 shows a map of the Longonot resource with boundaries defined in accordance to the conceptual models. The estimated extent of the resource is shown as two different sizes in accordance to Conceptual Model "A" and Conceptual Model "B". These are interpretive and need to be proven by drilling, but are useful for deriving an exploration drilling strategy and to assist with a stored heat assessment of the Longonot geothermal prospect.

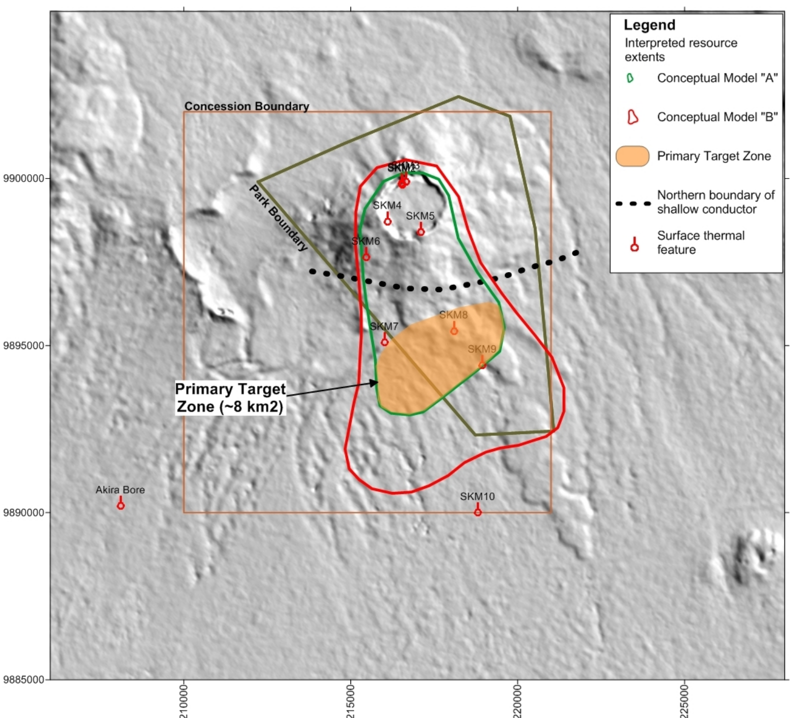


Figure 8. Primary Target Zone overlying the center of the conductive dome for Longonot geothermal resource. This area represents the most prospective part of the resource within which to focus initial exploration drilling.

The areas shown on Figure 8 are as follows:

- Conceptual Model "A" resource extent: 22 km^2 (shown in dark green)
- Conceptual Model "B" resource extent: 43 km^2 (shown in red)

The 2010 geothermal resource assessment conducted by SKM identified the following findings of particular significance to the future exploration drilling strategy:

Resource area – Surface exploration indicates a large resource area within the concession, with the most likely extent of the resource estimated at 43 km^2. It is also evident that a significant portion of the most likely resource area is within the Mt Longonot National Park.

In a general sense, the northern part of the resource surrounding Longonot crater is characterized by steep and difficult terrain. Some of this resource area can be accessed by long-throw directional wells, but for the purpose of initial well siting it is recommended that well pad and road construction focus on the resource area south of the crater. We have defined this area as the Primary Target Zone (PTZ), an area of about 8 km^2 for the most accessible area south of Longonot Crater (Figure 8). The PTZ is entirely within the concession boundary.

Depth to reservoir – Geophysical surveys indicate that the base of the clay cap (indicating about 200°C) occurs at an elevation ranging from 1450 mRL in the northern central part of the system to 1000 mRL on the sides and southern flank of the target area. Taking topography into account this means that the depth at which such minimum productive temperatures (>200°C) may occur is likely to range from about 550 mVD in the central part of the resource to up to 800 mVD on the margins of the concession. However, useful production will require temperatures greater than about 240°C and hence final production casings may need to be set deeper.

Permeability – No deep drilling has yet been undertaken at Longonot, therefore the nature of reservoir permeability is unknown, though results from Olkaria suggest zones of high permeability are likely to be structurally controlled. The alignment of surface manifestations is consistent with the predominant NNW-oriented structural trend in the rift setting and may be productive targets at reservoir depth. Fracture zones associated with east-west faulting may also represent permeable targets.

Heat source – Multiple cooling intrusives beneath the Longonot Caldera and along the NNW-SSE rift zone are interpreted to provide the heat that drives a high temperature (250 to 300°C) convecting hydrothermal system.

In order to meet the objectives of exploration drilling, proposed exploration wells will have to be located to test the range of conceptual models for the reservoir as described above. There is a high confidence that a system exists on the south flanks of Longonot crater. The primary uncertainty is about where the southern extension of the deep reservoir because shallower outflows may mask the edge of the system on the south. The southern margin of reservoir may range from just south of the southern caldera or it could extend as far as 6 km south of the crater rim. That means wells need to be located across the areas that could host the main reservoir (upstream and downstream), and that the sequence of drilling needs to have the flexibility to adapt the drilling plan on the basis of observations in the initial wells.

10. Acknowledgements

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