



KenGen

STRUCTURAL GEOLOGY OF EBURRU-BADLANDS GEOTHERMAL PROSPECT

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ABSTRACT

Eburru is a Quaternary volcano situated on the southern segment of Kenya Rift, an arm of the larger EARS. Eburru volcano forms the highest topography within the entire Kenyan rift at an elevation of 2800m, while Badlands lies lower to the North of Eburru massif towards Lake Elementaita. The report describes the results of structural geological mapping of Eburru and Badlands geothermal prospects. The exercise was carried on May, 2014 with objective to pinpoint the structural setting, map geothermal manifestations and mapping of alteration characteristics and identify the possible location of heat sources. The main structures observed in Eburru area include a series of fault and fracture network system with a general N-S trends and minor E-W, NE-SW and NNE-SSW trending faults, craters and ring structure. These structures play a significant role in controlling the recharge and fluid movement within the geothermal system especially at the intersection of E-W and N-S faults. On mapping Badlands geothermal prospect; distinct N-S trending faults and fractures outlining both the regional and local tectonics with minor NE-SW trending faults were noted, possibly the main control of recharge and fluid movement within the geothermal system in the area. These faults, fractures and fissures form a fissure zone of ≈ 7 -10 km wide. However, within the fissure zone at least one mini-graben was observed (≈ 2 km wide), which may be of significant geothermal interest. Geologically younger structures were noted in this area. Rock types range from mafic to siliceous rich lavas. Basalt, trachytes, rhyolites and pyroclastics are common in the Eburru area. Obsidian outcrops and pumice cover were noted at hill tops. Basalts with minor obsidian, trachyte, volcanic agglomerates, pyroclastics, tuff and sporadic trachy-andesites are the predominant rock types characterizing the Badlands geothermal prospect.

1. INTRODUCTION

The geothermal resource in Eburru was delineated by deep drilling of six wells to an average depth of about 2500m between 1989 and 1991. Of the six wells drilled, only wells EW-01, EW-04 and EW-06 (Figure 2) were productive while the rest of the wells could not discharge due to low enthalpy (Omenda and Karingithi, 1993). The Eburru geothermal power plant is utilizing steam from well EW-01 that is generating 2.5Mw from a well head generating unit that was commissioned in 2012.

1.1. Background information

Eburru volcano forms the highest topography within the entire Kenyan rift at an elevation of 2800m. The prospect area is fairly accessible as its well served by Murram road and tracks. Eburru- Badlands fields are located within Kenyan Rift which is part of the East African Rift System, an active continental divergent zone. Eburru is in the central segment of the Kenya Rift Valley, a unique petrographic province comprising of at least four Quaternary to Recent volcanic complexes running from South to North namely; Suswa, Longonot, Olkaria, and Eburru. The geothermal prospect area is located approximately 40km north of Olkaria Geothermal Field (Figure 1).

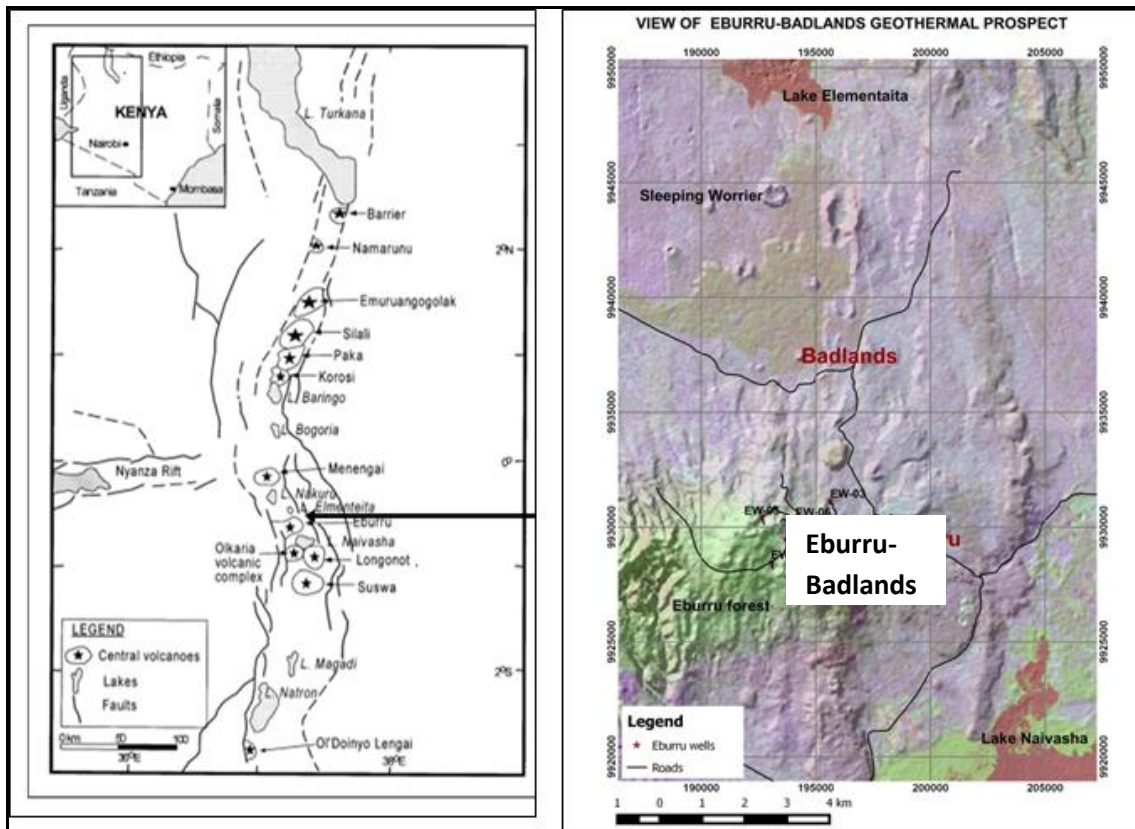


Figure 1: Map showing Eburru-Badlands area (Ofwona, 2002)

The mapped area lies within geographic location defined by; UTM Zone 37M, Northings 9916200m to 9917600m and Eastings 177700m to 202800m, approximately 40km north of Olkaria geothermal field and covers approximately 800km² (Figure 1).

2. GEOLOGICAL SETTING

2.1. Geology of Eburru-Badlands

The geology of Eburru volcanic complex is associated with Quaternary volcanism that underwent four stages of evolution (Clark et al., 1990). The initiation of activity is not precisely known but is < 0.45Ma (Clark et al., 1990). The first stage was the building of a volcanic pile at the western Eburru. Here, the exposures are poorly exposed due to blanketing effects of the pyroclastics but apparently dominated by welded and unwelded pantelleritic and pyroclastics. The second stage involved the eruption of the Waterloo Ridge fissure zone in which pyroclastic were erupted along a N-S elongate fracture that generated pumice falls and flows of Pantelleritic composition. The third stage was the building of volcanic pile at eastern of Eburru Massif in which pantellerite and pantelleritic trachytes, trachyte, pumice and ash falls are found.

The fourth stage is the axial activity at Eastern Eburru where a series of Pantelleritic lava flows and pyroclastic cones, associated with N-S fracture zone running from Olkaria volcanic complex in the south to Elementaita basalt field in the north. The geology of Eburru has also been documented by Omenda (1997), Ren et al., (2006), Velador et al. (2003) as being composed of trachytes and pantellerites. Scaillet and Macdonald (2003) showed experimentally, that strong fractionation of comenditic rhyolites from Olkaria geothermal complex generated residual melts closely resembling the geochemical composition of the Eburru pantellerites.

2.2. Stratigraphy

Stratigraphy of Eburru, based on drilled well data shows that pyroclastics have a thickness of more than 200m within the ring structure, while outside the structure to the east, thickness of less than 10 m is common. However, well EW-04 which was drilled within a crater had greater thickness of breccia >500m. The zone below the pyroclastics and extending to depths of about 1400 masl, is dominated by pantelleritic rhyolites with relatively minor occurrences of tuffs and trachytes. This zone is considered to form the shield building volcanic. The pre-shield volcanoes are dominated by trachytes, and relatively minor occurrences of rhyolite, basalt and tuffs which are interpreted to be part of the late Tertiary rift floor plateau trachyte sequence. This formation is the main reservoir rock for the Eburru geothermal system (Omenda and Karingithi, 1993). Dykes of syenitic composition were encountered in most of the wells drilled in Eburru with the shallowest occurrence at 800 masl (EW-04).

2.3. Tectonic setting of the Eburru and Badlands fields

The East African Rift System is characterized by rift segments which provide a modern analogue to understanding how continents break apart. One popular model for the EARS assumes that elevated heat flow from the mantle (strictly the asthenosphere) is causing a pair of thermal "bulges" in central Kenya and the Afar region of north-central Ethiopia (Wood, 2004). These bulges can be easily seen as elevated highlands on any topographic map of the area. As these bulges form, they stretch and fracture the outer brittle crust into a series of normal faults forming the classic horst and graben structure of rift valleys. The bulges are believed to be caused by mantle plumes under the continent heating the overlying crust and causing it to expand and fracture.

Later activity included rejuvenation of the graben step faults, until Mid-Pleistocene times, with the shattering of the graben floor by swarms of closely spaced minor faults. In the Late Quaternary, trachyte, basalt-trachyte and phonolitic caldera volcanoes built cones in the centre of the rift axis; to the east of the rift there were mainly basalt flows, some of which have continued to Recent historical times (Baker et al, 1971; Baker and Wohlenberg, 1971). The tectonics of the central rift sector has a distinction from the south and north with the rift forming faults in this area trending NNW-SSE while the southern and northern segments trend NE-SW. However, the rift floor faults in the central sector, some of which cut through Eburru, trend in near N-S and E-W direction.

3. FIELDWORK

The aim of the structural geological mapping was to expound on the structural setting of Eburru-Badlands fields, to identify parameters that support the existence of a geothermal system namely; heat source, permeability and recharge mechanism. This was accomplished by identifying and analysing the structural lineaments that control permeability such as faults and fractures, grabens and dykes, identifying volcanic eruptive centres such as caldera and craters that are possible indicators of an underlying heat source, mapping of geothermal surface manifestations such as fumaroles, hot grounds and surface alteration characteristics; which are key indicators of permeability and temperature. This exercise was carried out by KenGen geology team with help Of UNU-GTP trainers for 30 days in the month of May, 2014

4. RESULTS OF STRUCTURAL GEOLOGY MAPPING IN EBURRU-BADLANDS

4.1. Structural geology of Eburru geothermal prospect

4.1.1. Rock types

The geology of Eburru area is dominated by siliceous lavas and their pyroclastic equivalents which are common on the caldera. Trachytes and pantelleritic rhyolites are common with few obsidian and pumice. These rocks have been hydrothermally altered due to presence of geothermal fluids with elevated temperatures where the primary minerals have been altered to secondary minerals. Clays are the common alteration products noted at the surface and occasionally calcite minerals occur as replacement plagioclase in basaltic lava flows.

4.1.2. Faults and fractures

Eburru massif is characterized by series of fault and fracture network systems with general N-S trends and minor E-W, NE-SW and NNE-SSW trending faults (Figure 5). These faults are easily discernible on the surface though some are inferred from alignment of geothermal manifestations such as fumaroles. The tectonic forces acting on N-S trending faults were caused by tensile stress and strain on rock materials characterized by intense fracturing that resulted to development of E-W trending faults to accommodate the crustal extension.

The N-S trending faults are noted to have been intruded by craters and caldera features in Eburru and are closely associated with older tectonics. The much later tectonics is defined by the development of the E-W trending faults and the formation of phreatic and phreatomagmatic centres, some of which occur on the pre-existing volcanoes defining fairly circular arrangement/ structure interpreted to be the margins of a buried caldera. The E-W trending faults are of great significance as they are associated with good permeable zones where most of the fumarolic activities are evident.

4.1.3. Craters and calderas

Two calderas associated with central volcano were identified during this training. Several craters are aligned along the flanks of the smaller Caldera. The alignment of the craters forms a curve-linear structure (Figure 5). Remote sensing landsat image analysis in the Quantum GIS software confirmed the caldera existence. Some of the N-S regional faults and NE-SW faults intersect through the calderas and some craters.

The two ring structures are located at the centre of Eburru area. The bigger ring structure is approximately 3km in diameter and the smaller ring structure is about 1 km in diameter which represents small volcano-plutonic structures associated with sub-crustal magmatic activity. Faults are believed to have played a role in the formation of Eburru ring structures. The rock formation on the rims of the ring structure is composed of pyroclasts, trachytes and pantelleritic rhyolites.

4.1.4. Geothermal manifestations and hydrothermal deposits

A range of surface manifestations including altered grounds, hot grounds, active fumaroles area, geothermal grass cover and hydrothermal deposits occur in the area (Figure 2). Fumaroles and sulphur deposits are direct surface expression of hydrothermal systems in which heated groundwater is transmitted through permeable zones to the surface.

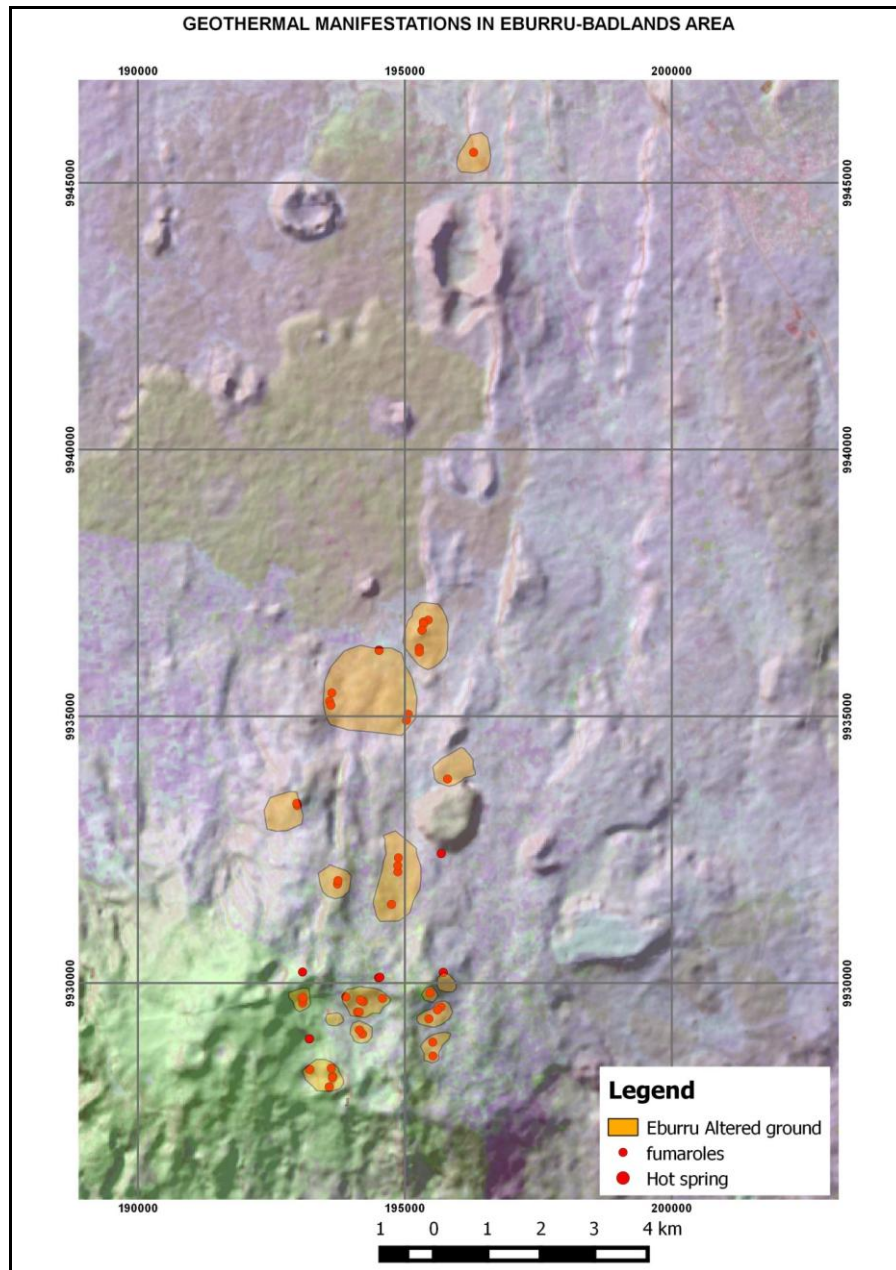


Figure 2: Geothermal manifestations

The distribution of fumaroles in Eburru is noted to be structurally controlled with most of the fumaroles aligned along the local and regional fault and fracture zones (Figure 5). A few fumaroles discharge from silicified, fractured pyroclasts and lava flows while a good number of them are in highly altered grounds. Hydrothermal deposits such as Sulphur and silica deposits are observed to be precipitated in zones with fumaroles and hot-grounds; however activity in these grounds seems to be declining.

4.2. Structural geology of Badlands geothermal prospect

4.2.1. Rock type

The lithology in this area is characterized by volcanic rocks that includes; basalt, scoriaceous basalt, obsidian, trachyte, trachy-andesite, volcanic agglomerates, pyroclasts, tuff and volcanic ash. Most of the basaltic lava flows and obsidian rocks appear geologically young and were noted to occur along the younger faults and fissure swarms.

4.2.2. Faults

This field is characterized by numerous occurrence regional and local N-S trending faults and fissures with slight deviation to the east ($\approx 10^\circ$). Tensional fractures and fissures are associated with eruption of large volumes of linear basaltic and glassy lava flows were also noted. Open fractures and fissures are noted in the area (Figure 3). Some fractures, faults and fractures observed in the field were in-filled with relatively fresh basaltic lava and obsidian outcrops.



Figure 3: Photograph of two open parallel N-S trending faults intersecting a crater in Badlands

Minor lineaments with NE-SW trending directions are evident though not extensive (Figure 5). Swarms of near vertical normal stepped faults, cracks and lineaments are evidence of rejuvenated faults where most of the geothermal manifestations are observed.

4.2.3. Craters and cinder cones

Badlands area is characterized by craters on the west region that trend north to south extending to Lake Elementaita. The craters are aligned along major N-S faults. Some of the craters in the area are intersected by the N-S faults (Figure 4 and 5); this implies that some N-S faults are geologically younger hence later tectonics in this area. A cinder cone was noted within the mini graben on the Northern part towards L. Elementaita.



Figure 4: Photograph of N-S fault intersecting a crater (Sleeping Warrior) in Badlands area

4.2.4. Graben and mini-grabens structures

Faults and fissures in Badlands forms a fissure swam approximately 7-10km wide (Figure 5). A mini graben system approximately 2.2km within the fissure swam wide is defined by series of normal stepping faults. Fumaroles within the mini graben recorded the highest temperature in the area (95.3°C). Cinder cones and craters were noted within the mini-graben structures.

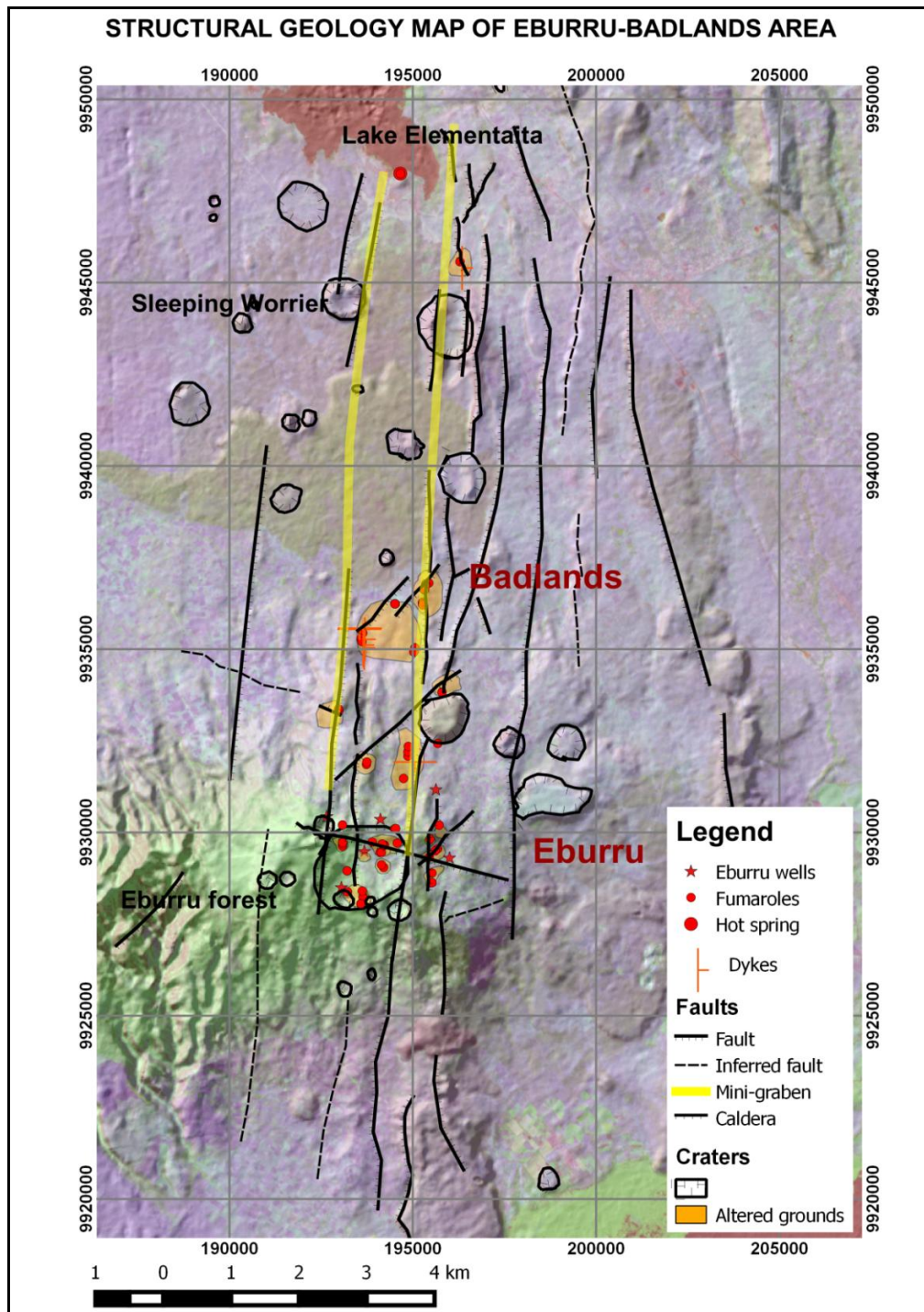


Figure 5: The structural geology of Eburru-Badlands geothermal prospects

4.2.5. Dykes

Intense volcanic eruption and up-doming resulted into a series of dykes noted in Badlands (Figure 5) east-west and north-south trending dykes are evidence of shallow intrusive in the area and are probably structurally controlled.

4.2.6. Manifestations in Badlands area

Badlands is characterized by the presence of numerous geothermal manifestations such as hot springs, fumaroles, hot altered grounds and altered grounds (Figure 2). Their temperatures were measured which gave a guide to the geothermal power potential of the reservoir of Eburru and Badlands geothermal prospects.

Fumaroles and hydrothermal deposits:

Badlands area is characterized by active fumaroles some of which emit H₂S smell. The fumaroles have variable measured temperatures with the hottest fumaroles recording a temperature of 95⁰ C at the eastern flanks of the mini graben. This temperature is near boiling point and is interpreted to imply that the principal area of up-flow is at the eastern flanks of the mini graben. Most fumaroles are noted along the E- W, NNE-SW and near N-S geologically younger faults. Most of the fumaroles in Badlands area are characterized by calcite, sulphur, silica and green and red-brown clay deposition. Silica deposits are common in fumaroles areas and were noted on the aluminium condensate equipment used by the locals to tap water from steam. It's also noted overlying the pyroclasts, lava flow and altered grounds. Silica also formed layers of sinter silica on a few scenarios.

Geothermal grass:

Geothermal grass also known also *Fimbristylis Exillis* is a small bushy grass plant which thrives well in geothermal grounds. Geothermal grass is present in most of the areas which have active fumarolic activities, hot and warm grounds as well as at altered grounds. Their sizes vary from very healthy grass to small, stunted patches. Sometimes geothermal grass can be used to track faults which are otherwise not seen at the surface.

Hot spring:

Hot spring was noted discharging into Lake Elementaita in Badlands area; probably originating from a nearby North-South fault. The temperature of the hot spring was recorded to be 47.7 ⁰C. The water is relatively fresh though with a soapy feeling. This hot spring lies by the western margin of the mini-graben

Hot altered grounds:

Hot altered grounds tend to follow a north-south structural trend and are also noted at intersection of faults where the highest recorded temperatures, averaging 90⁰C, were recorded.

4.3. Hydrogeology of Eburru and Badlands Prospects

The hydrogeology of an area is determined by the nature of the parent rock, structural features, weathering processes and precipitation patterns. In volcanic terrains, groundwater primarily occurs within fissure zones, fractures, sedimentary beds, lithological contacts and Old Land Surfaces (OLS) which characterize periods of erosion between volcanic eruptions and subsequent lava flows and are potential aquifers. Within the Eburru and Badlands fields, the groundwater movement and recharge to the system is principally controlled by the structural framework; the N-S regional faults and other localized faults, fissures or fractures have significant influence to vast movement of fluids within the geothermal system.

In both fields, the regional recharge mechanism to the system is from the Mau escarpment to the west and the Aberdare escarpment to the east. The localized fault systems recharging these geothermal prospects are mainly attributed to later tectonic episodes. In Eburru geothermal system, the E-W and NE-SE trending faults and fractures are the young tectonic features which are believed to be the possible conduits for the fluid movement. Whilst, in the Badlands field, the recharge is predominantly characterized by later tectonics which reactivated the N-S stepping faults and subsequent development of minor E-W to NE-SW trending faults and fractures.

5. DISCUSSION

5.1. Eburru geothermal prospect

Fumaroles measured temperature results in Eburru indicates high temperatures most of which were at boiling point. The temperature range of 80-96⁰C was recorded within Eburru. These temperatures indicate that the area is considerably hot and probably near heat source. Fumaroles along east-west faults cutting through the ring structure are characterized by sulphur deposits and H₂S smell which is indicative of a magmatic source

The tectonic activities in Eburru fall into three chronological categories namely; Pre-caldera, Syn-caldera and post-caldera. The Pre-caldera tectonics involved north-south regional faulting, rifting and later faulting after the rift formation. Several N-S regional faults were noted in Eburru area some of which were extended from Eburru to Badlands on the North and Ndabibi to the South. The syn-caldera tectonics involved the eruption and formation of the main volcanoes and other several parasitic volcanoes, collapse and formation of the calderas, faulting as a result of tensile stresses during the caldera collapse. Two main calderas were noted in Eburru area with several volcanoes on the wall of the caldera defining a ring structure.

The Post-caldera tectonics involved eruption and formation of craters within the caldera floor and faulting. The east-west faults in the area indicate young structures and this could be confirmed from active fumarolic activities along these faults; they also cross cut through the near North-South regional faults and the caldera. The main E-W fault cutting through the ring structure was characterized by active E-W aligned fumaroles, H₂S gas emission and sulphur deposits. This implies that they are open and of good permeability offering connectivity to a magmatic heat source.

It was noted that most of the craters inside the caldera did not show active hydrothermal activity. Most of the hydrothermal activity was noted on the rim of the caldera and outside the ring structure as characterized by active fumaroles with measured temperatures ranging from 80-95°C, this could be an indication that more geothermal potential exists outside the caldera.

5.2. Badlands geothermal prospect

The structural map shows that most of the faults and mini grabens trend north-south with a few faults trending east-west and north east-south west. Some of north-south faults are regional while a few of them are local and younger. It is noted that the entire east-west and north east-southwest are younger as they crosscut through the older regional north-south faults.

Badlands area is characterized by relatively young and active tectonic activities which is evidenced by young faults (Figure 4 and 5) cutting through the regional faults and through the volcanoes and craters. A clear chronology is noted as the N-S regional faults appear oldest in the area.

Younger near north-south faults were also noted (Figure 5) and they define mini-grabens; these faults are characterized by recent basaltic lava flows and active fumaroles some with a distinctive H₂S smell which confirms that the faults are deep and permeable. The east west faults were noted intersecting the N- S regional faults which indicate that they are geologically younger. The younger N-S and E-W faults also cut through some of the craters and volcanoes in the area.

Craters in Badlands are concentrated towards the western region and near Lake Elementaita with some craters being intersected by some of the East-West and North-South faults indicating that these volcanic centres are geologically older than the most recent faults in the area. A cinder cone was noted within the mini graben implying later volcanic activity in the area.

Generally, Badlands area is characterized by active hydrothermal activities and recent tectonic features including relatively fresh basaltic lavas along fissures, fractures and faults, fumaroles, hot altered grounds, geologically young faults, cinders cones, dykes and craters respectively. All these hydrothermal activities and geologically young structures indicate a magmatic heat source and good permeability which are the major parameters to geothermal resource potential

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

Faults identified in Eburru and Badlands are mainly N-S, NE-SW trending with some E-W. Geologically the E-W and NNE-SSW are relatively younger having been formed by later reactivating tectonics hence may be of better permeability. The faults and fissures represent the fissure swarm of the Eburru central complex, forming a graben about 7-10 km wide. However, within the fissure swarm at least one mini-graben was observed (approximately 2.2 km wide), which may be of significant geothermal interest. A localized mini-graben is observable having been defined by N-S dipping faults in Badlands. Dykes identified are E-W trending.

Geothermal manifestations are evident in the Eburru-Badlands field and are align along the structural trends. Eburru is characterized by calderas and craters whereas Badlands is characterized by craters and cinder cones and volcanic features. In Eburru, craters occur in a curvilinear pattern that defines the walls of the caldera. Surface geology is mainly characterized by pantelleritic rhyolites, trachytes, tuffs, obsidian, glassy lavas, volcanic agglomerates and pyroclastics. A geothermal system exists in Eburru-Badlands with the heat source being under the caldera and probably extending north. Permeability provided by faults and fractures with regional recharge from the Mau escarpment and Aberdare ranges

6.2. Recommendations

We recommend detailed structural geology field mapping accompanied by geophysics resistivity survey in Badlands area extending to Lake Elementaita that appears to be fractured as dominated by fissures, fractures, faults and a mini graben. Steam from selected fumaroles in Badlands should be sampled and analysed to establish possible origin and source of heat. If geophysical, geochemical and detailed structural mapping results prove positive the mini-graben should be investigated further by exploration drilling

To the south and west of Eburru central volcano, we recommend detailed structural field mapping to assess the structural and volcanic features extent to this region

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