Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Structural Controls on Fluid Pathways in Active Geothermal Systems. Insights from Olkaria Geothermal Field, Kenya

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Keywords: geothermal systems, structures, hydrothermal fluids, ascent

ABSTRACT

In volcanically active geothermal systems, pre-existing faults structures may serve as efficient pathways for migration and ascent of deep-seated fluids in the geothermal reservoir. Review of the geological structures reveals a structural control by both rift aligned faults and the proposed caldera ring fracture. Understanding how pre-existing regional tectonic faults and caldera ring faults affect fluid flow to the surface is significant in detection of mass flow in deep geothermal wells. While it is inherent that some fault structures in Olkaria geothermal field have proved to be productive and act as efficient conduits for the ascent of geothermal fluids, others are known to be totally unproductive, in which case they act as barriers to fluid flow. This case study emphasizes the usefulness of structural features in active geothermal systems and their role in enhancing high permeability pathways for transferring hydrothermal fluids from deep to shallow levels of the system.

1. INTRODUCTION

Structural architecture of large silicic calderas (Olkaria Volcanic Complex being one of them) is largely related to the interplay among the dynamics of the magma reservoir, geological setting of the sub-stratum, stress field and the eruptive history of the volcanic system (e.g. Lipman, 2000; Acocella, 2007, and Gudmundsson, 2008). According to Cole and co-workers (2005), during the collapse of most salic calderas, rapid emission of large volumes of pyroclastic surges trigger the formation of ring faults and other associated geological structural features, extending from the surface of the volcanic edifice down to several kilometers in the crust, consequently displacing the roof of the magma chamber. The geometry of the resulting faults is strictly influenced by the shape and depth of the emptying magma reservoir. Pre-existing steep discontinuities in the crust may also have some bearing, even though to a limited extent (e.g. Kennedy et al., 2018). The geothermal system at Olkaria is located within the southern-central sector of the Kenya Rift System (KRS) (Figure 1) and connected to volcanic activity of the Olkaria Volcanic Complex (OVC). Integration of geologic data and interpretations from field observations, borehole samples and logs provide indications that faults and fractures are preferential pathways on fluid flow in this geothermal system, ultimately providing sufficient permeability in most cases. Presently, the geothermal system has an aggregate installed capacity of 775.6 MWe. This is after commissioning of Olkaria V unit 1 on Friday, 26th July, 2019.

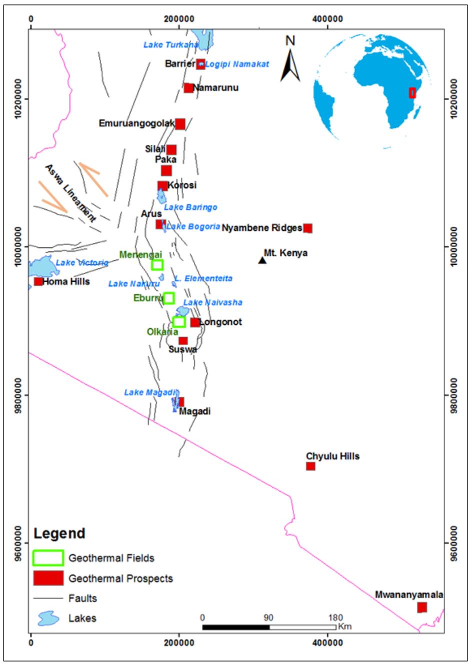

Figure 1: Simplified map of the KRS showing location of Olkaria geothermal field and other geothermal prospects (modified from Munyiri, 2016).

2. GEOLOGICAL SETTING

The geothermal field at Olkaria is located within the OVC, a relatively young (< 20 ka) silicic volcanic complex characterised by the eruption of peralkaline rhyolites (Macdonald et al., 2008). According to Macdonald and Scaillet (2006), the OVC constitutes part of the Central Kenya Peralkaline Province (CKPP), which coincides with the Kenya Dome; a ~ 300-400 km wide topographic culmination in the course of the rift. OVC is characterised by indistinct caldera system. However, scholars such as Bliss, (1979) have argued that the great thickness of comenditic lavas (at least 1 km from borehole data) may well suggest the existence of a central comendite volcano in Quaternary times. Such a view would be consistent with the voluminous outpourings of comenditic lavas observed on the surface within the OVC. Further studies by Omenda (1998) relied on a group of coalesced rhyolitic domes, forming distinct topographic features in the eastern and southern parts of the complex to infer the ring structure.

Surface geology is dominated by comenditic lavas, pumice fall and pyroclastic material (Figure 2). Clarke et al., (1990) enumerated six stages in the evolution of the complex based on their geological work. These, ranged from stage 1, which is of uncertain age, and was predominantly marked by a pile of trachytic lava and pumice to stage 6, signified by notable expression of thick comenditic flows of the Ololbutot Comendite Member (O^5). The latter is the youngest flow in the complex, dated Macdonald and Scaillet, (2006) at at 180±50 BP by ^{14}C.

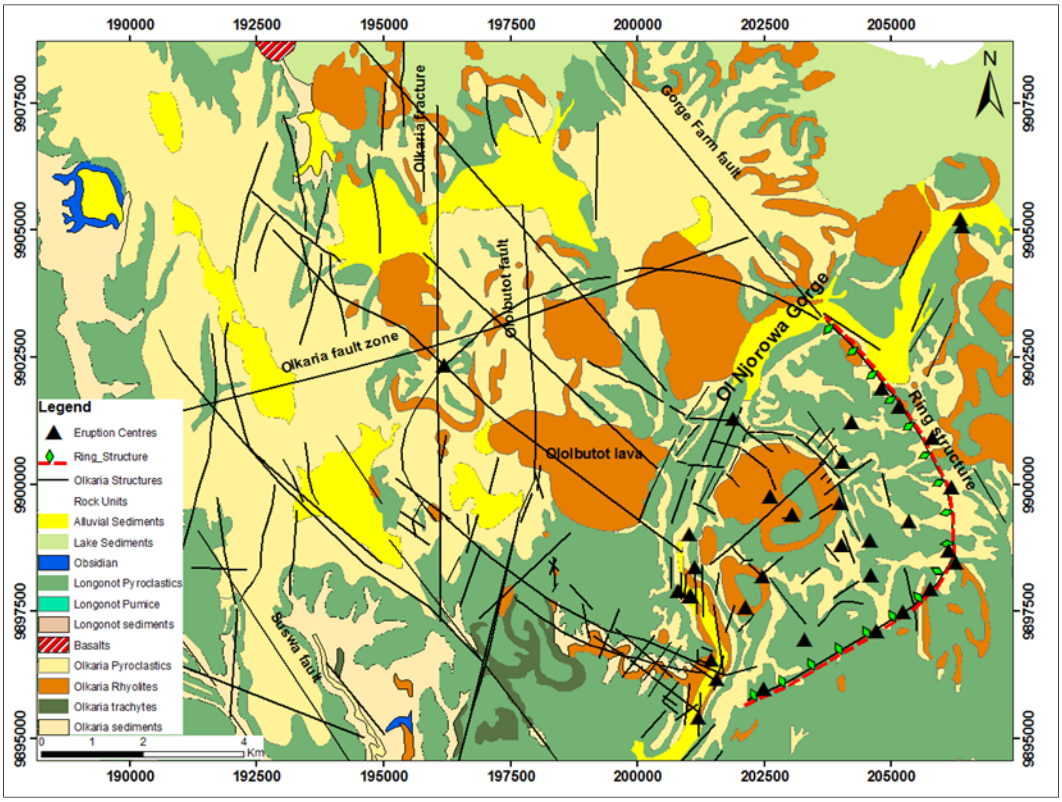

Figure 2: Surface geological map of the OVC and the surrounding area (modified from Clarke et al., 1990).

Sub-surface geology as has been deduced from data from geothermal wells can broadly be classified into six groups. The Upper Olkaria Volcanics (UOV), dated at < 0.95 Ma constitutes the youngest unit within the complex, and is dominated by pyroclastics and comendites (Omenda, 1998). Underlying the Upper Olkaria Volcanics are the Olkaria basalts which is intercalated by thin horizons of tuffs, minor trachytes and sporadic rhyolites. The basalt forms the cap rock of the geothermal field and has also been applied as a marker horizon. Olkaria basalts is preceded by Plateau trachytes, dated at between 2.1 to 1.8 Ma (Clarke et al., 1990). The unit is the reservoir rock for the East, Northeast, Southeast and Domes fields. The Mau tuffs, dated between 3.4-4.5 Ma, are the oldest rocks encountered within the complex and are of unknown thickness. The formation has been penetrated by drill holes in the west fields (Northwest and Southwest), where it forms the reservoir rock. Pre-Mau volcanics, dated at > 4.5 Ma constitute the fifth series and overlie the basement rock. The lithotypes in this series consist notably of phonolites, basalts, trachytes and tuffs. Underlying the Pre-Mau volcanics is a laterally extensive basement system comprising Proterozoic metamorphic amphibolite grade gneisses and schists, accompanied by marble and quartzites of the Pan-Africa basement system. This unit has been dated at > 590 Ma (Omenda, 1998).

3. STRUCTURAL ANALYSIS

Structural controls and their topological relationships in the OVC is instrumental in determining the reservoir fluid flow at depth, and consequently permeability distribution within the geothermal field. Whereas some structures have proved to be productive and serve as efficient conduits for the ascent of geothermal fluids, others are known to be bear limited productivity. Geological structures in OVC are divided into rift faults, ring structure, Ol-Njorowa gorge, and dyke swarms (Figure 3).

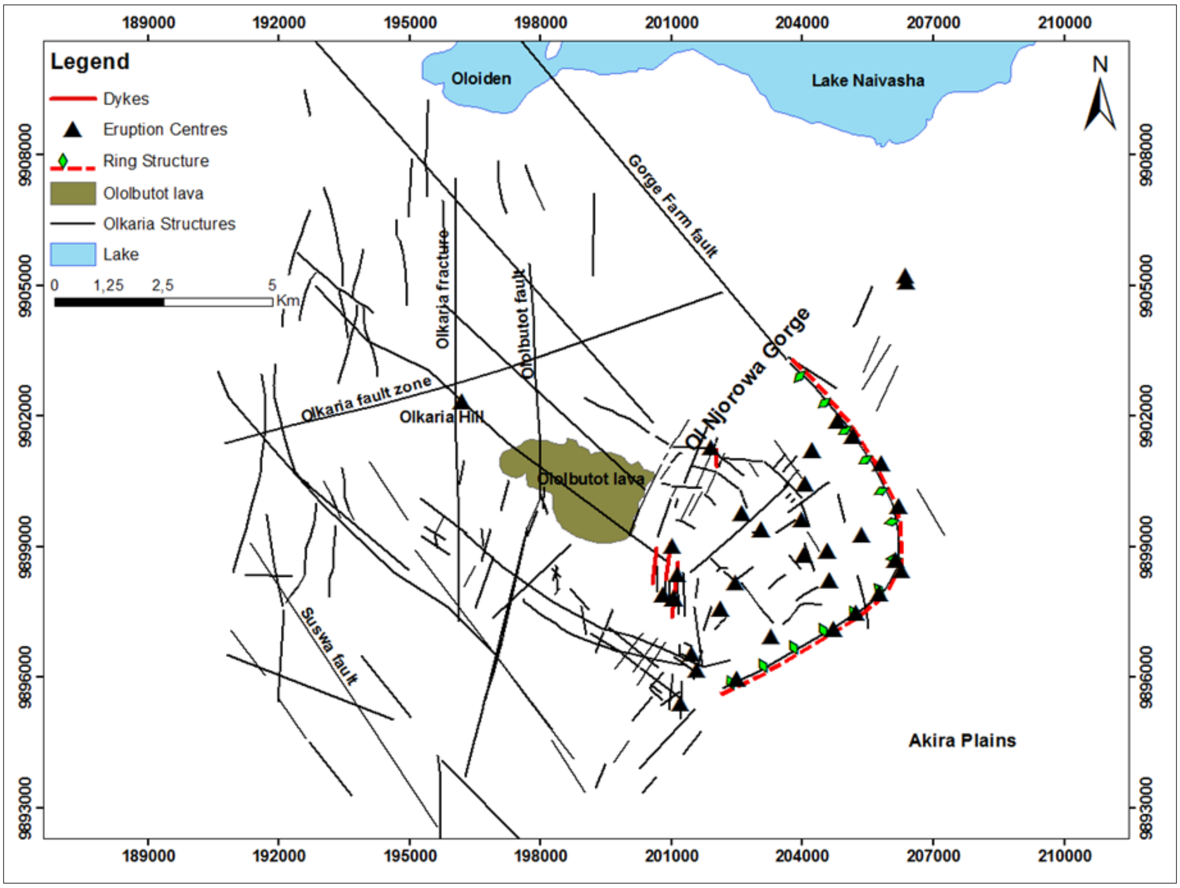

Figure 3: Summary of the structural setting of the OVC displaying orientation of the various structural characteristics (modified from Omenda, 1998).

The structural domains of are dominated by NE-SW and NW-SE striking faults, and subordinate N-S, NNE-SSW and ENE-WSW structural trending patterns (Figure 3). Other faults of variable orientation, though limited, also occur in the area and are not included in the structural map. Faults are more conspicuous in the East, Northeast and West Olkaria fields. However, their presence on the surface in the Domes area is severely limited by the substantial blanketing of the surface geology by thick, younger pyroclastic deposits (Otieno et al., 2014). The oldest faults of the complex are the NW-SE (e.g. Gorge farm fault) and ENE-WSW (e.g. Olkaria fault zone) trending faults (Omenda, 1998), and are associated with the rift formation (~ 30-45 Ma). The most recent fault systems, i.e. the N-S, NE-SW and NNE-SSW trending ones, are considered to be of a different structural regime and are thus interpreted to be associated with later tectonic activities, and perhaps, the proposed caldera collapse. The most obvious of these structures are the Olkaria fracture and Ololbutot fissure (Figure 3).

4. DISCUSSION

Structural analysis in Olkaria geothermal field largely derived from borehole data set from > 200 wells have provided sufficient information on the attributes of various structural features. The borehole data set offers systematic concept to delineate fractures and fault pattern acting as conduits and barriers. One way to ascertain which faults are preferential fluid pathways in Olkaria geothermal field was to look at their structural position and attempt to relate the same with the present-day stress field. This approach is based on the assumption that in brittle tectonic environment, faults and fractures have a specific orientation to the stress regime. The present-day stress field in OVC has not been exhaustively discussed, and as such is a matter still under active debate. Most of the structural features in OVC are normal faults with an assumed dip of near vertical.

The ENE-WSW trending Olkaria fault zone (Figure 4) has provided key permeability pathways for CO_2 rich fluids and magmatic gases to up well. Wells cutting the fault are generally good producers (average of 7 MWe) and ae characterised by sufficient mass flows. However, wells drilled close to the intersection of the Olkaria fault zone and the NW-SE trending Gorge Farm fault are characterised by incursion of cooler fluids, a possible indication that the Gorge Farm fault could be channeling cooler fluids to the system at shallower depths (i.e. between 0-1500 m). Omenda (1998) interpreted the Olkaria fault zone as an old rejuvenated structure. The fault is observable on the surface as a zone of intense geothermal manifestations that covers a width of approximately 50-100 m on the northern slope of Olkaria Hill. Most of the fumaroles here are at boiling point. Ground alteration is characterised by intense silicification and sulfur encrustations. The fault has a displacement of about 5 m with the downthrow to the north. Vertical permeability along some of the N-S fractures/faults, such as Olkaria and Ololbutot fracture zone is marked by the occurrence of strong fumarolic activity along the fracture trace. This is a clear demonstration of the active interplay of fluid-rock interaction. However, the Olkaria fracture serves as a barrier for fluid flow between the Olkaria west and east sub-fields. During geothermal drilling in Olkaria, fractures have always been observed in rock cuttings where most infilling minerals are secondary in origin. They are sometimes referred to as mineral veins, micro fractures or veins. Fractures that have been completely filled by secondary mineralisation, such as calcite, may sometimes act as barriers to fluid flow. According to Sæmundsson (2007) some of the fractures observed are actually tips of bigger fracture or fault zones that may be located much deeper. However, due to their small sizes and reduced fluid velocities, saturated fluids tend to settle and precipitate the secondary minerals depending on the reservoir temperature and pressure. Where the network of fractures display proper interconnectio, such fractures usually form fracture-parallel permeability, which may be enhanced by alteration of minerals in the host rock.

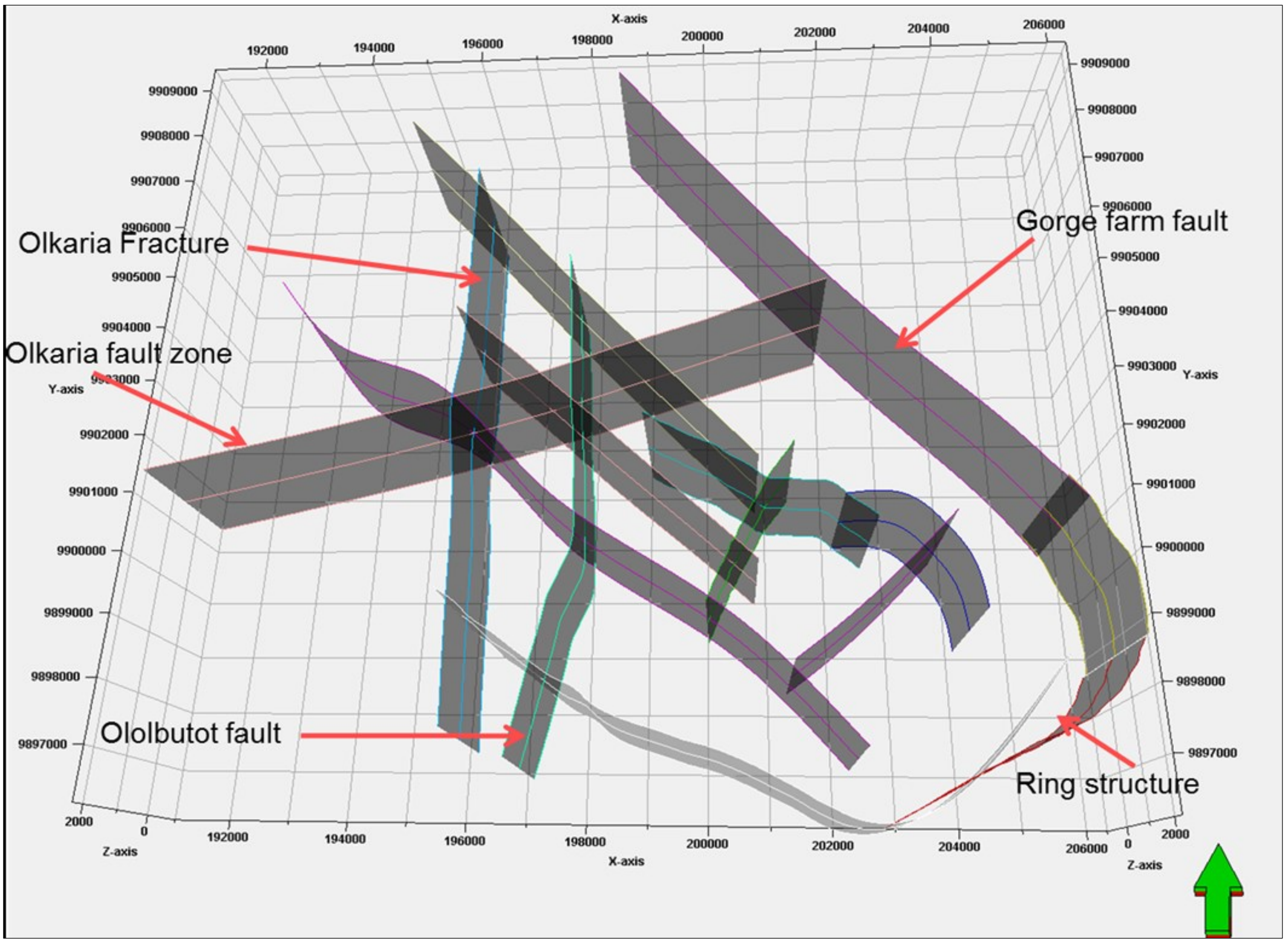

Figure 4: A 3-D presentation of the main structural features in the Olkaria geothermal system.

The ring structure, marked by an arcuate alignment of rhyolitic domes (believed to be products of resurgence) on the ground has been used by earlier researchers (Clarke et al., 1990; Mungania, 1992) to invoke the presence of a buried caldera. The ring structure is characterised by enhanced permeability at depth (> 1200 m) as has been demonstrated by drilled wells that have intersected the feature. The shallower parts of the structure (500-1000 m), is however, characterised by intense calcite deposition as has been shown by some well that have crossed the structure at that particular depth. The ring structure, is nevertheless postulated (Munyiri, 2016) to act as barrier for peripheral fluids.

5. CONCLUSION

A review of the structural geological features of the Olkaria geothermal field indicates that the geothermal activity of the system is controlled by the extensive fault and fracture networks that have served as preferential fluid pathways for ascent of geothermal fluids form the deep reservoir to the shallower levels. The N-S trending fractures represent extensional fractures within the current stress field. The fault pattern of extensional faults, depicting different orientation have also played a pivotal role in enhancing fluid flow to near the surface. Structural controls of fluid pathways in Olkaria is also exemplified by the numerous active surface geothermal expressions. The latter signify active present-day water-rock interaction processes along zones of enhanced permeability.

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