

Use of hydrothermal mineralogy and geological structures in identifying drill sites in Olkaria Domes Geothermal Field, Naivasha Kenya

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ABSTRACT

Although most of the convectional geothermal systems in many parts of the world have been successfully exploited for electrical production and district heating, exploration and development of new systems is commonly limited or restricted by the risk of unsuccessful drilling. A major problem in selecting drill sites is that existing geothermal systems are generally poorly characterized in terms of favorable settings and structural-stratigraphic controls. Olkaria Domes field is one of the geo-sectors of Olkaria Volcanic Complex where geothermal activity is intense. Tectonically, four major fault systems namely; NW-SE, N-S, NE-SW and NNE-SSW are recognized from the study area. N-S and NNE-SSW are the youngest faults associated with later tectonic activities. NE-SW faults are related to the caldera formation whereas NW-SE faults are known to be the oldest faults of the system. Surface manifestations from geothermal resources are scarce due to a thick pyroclastic cover in this field. Hydrothermal alteration minerals are closely related to the interpreted intersection of faults having high temperatures, secondary permeability and the most extensive hydrothermal mineral development. Secondary permeability and the degree of hydrothermal alteration decreases towards the ring structure of the Olkaria domes field. The main geothermal reservoir appears to be located where there are fault intersections, with the highly fractured and hydrothermally altered trachytic rocks serving as the main conduits for vertical fluid flow and advective heat transport from deeper magmatic sources. Thus, correlation of hydrothermal alteration and faults signify that fluid flow in this geothermal system is structurally controlled.

1. INTRODUCTION

The Olkaria geothermal field is one of the largest geothermal fields in Kenya. The field is located within the Greater Olkaria Volcanic Complex (GOVC) in the central sector of the Kenya Rift Valley to the south of Lake Naivasha and 120 km from Nairobi, the capital city of Kenya. Olkaria is a high-temperature geothermal system, with reservoir temperatures above 200 °C with maximum temperatures of about 330°C.

Exploration for geothermal resources in Kenya began in GOVC, when two wells, X-1 and X-2, were drilled in 1956 (Kenya Power Company, 1984) and high temperatures were encountered at shallow depths of about 500 metres. Further exploration in the area commenced in 1970 through bilateral and multilateral agreements of UNDP (United Nations Development Programme) and the Government of Kenya. Drilling re-commenced at well OW-1 in 1973. Although the well intersected low temperatures, subsequent drilling 3 km northeast of the well site (OW-2) confirmed the existence of a high-temperature hydrothermal system, and further drilling was confined to this area, which is the current Olkaria East production field.

The Olkaria geothermal field is divided into seven smaller fields, namely Olkaria East, Olkaria Northeast, Olkaria Central, Olkaria Northwest, Olkaria Southwest, Olkaria Southeast and Olkaria Domes (Figure 1).

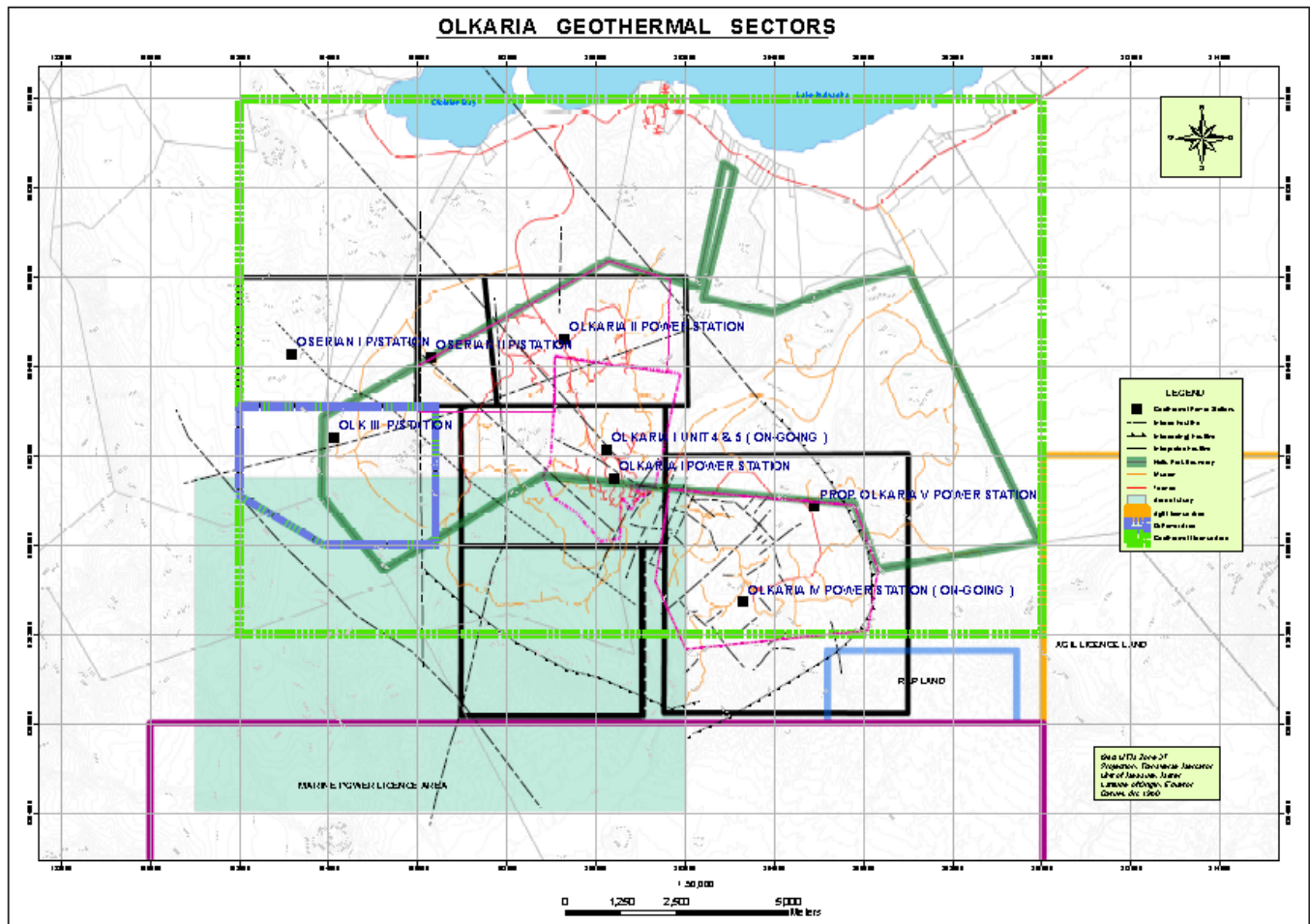


Figure 1; Map showing the location of the study area and other Olkaria fields

The Olkaria East field (Olkaria I) has been producing power since 1981 and currently produces 45 MW. The Northeast field (Olkaria II) has a plant which opened in 2003 and produces 105 MW. Two more power plants, Olkaria IV unit 1 and 2 and Olkaria I unit 4 and 5, produce 140 MW while the Olkaria Northwest field which is owned by Or power, an independent power producer with about 127 MW.

2.0 Problem Statement

The major problem in selecting suitable drill sites in Olkaria geothermal field is that the existing geothermal system is generally poorly characterised in terms of favourable settings and structural – stratigraphic controls. In order to characterize the structural controls of fluid movement in Olkaria Geothermal Field, we have to correlate the extensive hydrothermal minerals in wells drilled in this field and try and relate them with faults that have been mapped. Faults together with the topography may indicate hidden or blind geothermal fields which have no surface manifestations.

Review of existing reports and synthesis of data collected during the drilling of wells in this field can be used to determine where to drill more successful and productive wells in this field and in the process improve the geological conceptual model of the field.

2.1 Objectives

The main objectives of determining the relationship between faults and hydrothermal alteration minerals in Olkaria Domes field are;

- To identify the major structural patterns or faults controlling fluid movement in the Olkaria domes geothermal field and their relationship to the fault regime in the area.
- To identify and characterize the distribution of the main hydrothermal alteration minerals occurring in this field.
- To compare both the hydrothermal alteration minerals and structures and see their relationship.
- To compare and correlate data in order to improve the siting of drill sites and updating existing Olkaria Geothermal Conceptual Model.

3.0 Literature Review

Olkaria Volcanic Complex has previously been studied by different researchers for different purposes/objectives including academic-based research, regional geological mapping for government institutions and companies with interests in natural resources including geothermal resources. Geological work in the area with a bias in geothermal energy exploration was carried out by Browne (1984), Odongo, (1984), who analysed cores and cuttings from various wells and observed that the subsurface geology of Olkaria consists of at least 2600m of sub-aerially erupted rhyolitic, trachytic and basaltic lava and associated pyroclastic rocks. McCall (1967) has also discussed the same on the geology of Olkaria.

Naylor (1972) was the first researcher in the area to document the idea of a ring structure around a big volcanic complex in Olkaria which was supposedly destroyed by an explosive eruption followed by a collapse. He attached significant emphasis to the tectonic activities forming the north-south fracture system which he correlated with the formation of the rift scarps to the west of Olkaria.

The British Geological Survey (BGS) in collaboration with Government of Kenya's Ministry of Energy (MOE) headed by Woodhall, (1987) did some work based on regional exploration of geothermal energy in the Kenyan rift, and included geological mapping of Longonot Volcano, Olkaria Volcanic Complex (OVC) and the adjacent areas. From their geoscientific findings they concluded that the extrusion of the lava domes, which are of comendite composition, in the OVC were preceded by the eruption of pyroclastic material which mainly ash fall. The pyroclastic deposits of mainly ash fall deposits and could have erupted from Mt. Longonot volcano.

Generally, permeability is low in the West field and its distribution is strongly controlled by the lithostratigraphic contacts, fractured lava and fault zones. The fault zones show higher permeability with wells drilled within the structures having larger total mass outputs with some wells producing 16 MW (Naylor, 1972). However, N-S and NW-SE faults are mainly channels of cold water down flow into the reservoir. Well feeder zones occur mostly at lava-tuff contacts; within fractured lava flows and at the contacts of intrusives and host rocks. Naylor (1972) also noted that the ENE-WSW trending Olkaria fault which is a normal fault is considered the most important structure in the whole of Olkaria geothermal area in terms of resource exploitation. The fault with a displacement of about 20 to 50 metres transects the North-East, Central and West Fields

Omenda (1998) further observed that permeability and fluid migration in the Olkaria geothermal system is largely due to Pleistocene faults and fractures within the late Pleistocene and older formations. Reactivation of some of the older faults has provided much higher permeability due to fault intersection of the N-S and E-W fault trends. High permeability along these faults is shown by the occurrence of high temperature fumaroles and hot grounds along fault lines. Omenda (1994) also observed that vertical permeability along N-S faults/fractures is indicated by the occurrence of strong fumarolic activity. The most significant of these is the Ololbutot fracture zone where fumaroles are at boiling point of water and in places characterized by intense sulphur deposition.

Stratigraphic cross section correlations of deep drilled wells reveal basaltic flows occurring at variable depths in the wells, which has been the basis of proposing fault structures. These faults are formed later than the basaltic lava flows and may in age extend towards the age of the surface volcanic rocks. This basis has been used in creating buried fault structures as can be seen in geological cross sections in geological well reports (Muchemi, 2000; West-JEC 2009; Okoo 2013). They concluded that the level of basalt seems to be similar in the region between the East and Domes fields which may infer a tectonically quiet area, while large differences are found in the North East area which may infer NE-SW faulting.

3.1 Geological setting

According to MacDonald *et al.*, 2008, the age of the Olkaria Volcanic Complex is estimated to be between 22-20 ka BP. The caldera in domes is about 11 km x 7.5 km Although no one knows when the actual caldera formation in the Olkaria volcanic complex started, various scientists recognized six historic stages that led to its current state and it is summarized as shown below;

Stage 1; the initial pre-caldera trachytic magmatism caused the sequence exposing the Olkaria Trachyte Formation and Maiella Pumice Formation. The pumice and trachytes are wide spread and may have erupted from vents within the volcanic complex. The trachyte lavas are exposed mainly in gullies and ridges in the South West of the complex (Marshall *et al.*, 2009).

Stage 2; the trachyte eruption was followed by the caldera collapse forming a depression 11 km x 7.5 km across (Clarke *et al.*, 1990). The collapse is evidenced by the presence of a ring of rhyolite domes inferred to have intruded along a ring fault. Further evidence of collapse includes pyroclastic deposits around this structure, apparent resurgent activity within the ring structure and the distribution of the fumaroles around the collapsed caldera. This collapse has been associated with eruption of welded pyroclastic rocks of the Ol-Njorowa Pantellerite Formation.

The Lower Comendite Formation represents the post-caldera activity linked to the eruption of peralkaline rhyolitic lavas and pyroclastic rocks. The predominantly dome-building phase of the Middle Comendite Member followed, with eruption of thick pyroclastic surge deposits, Comendite Member and the most recent activity is the eruption of very thick flows of comendite from a North-South fissure zone, the youngest flow dated to 180±50 BP (Clarke *et al.*, 1990).

Stage 3; Magmatic eruptions of the Lower Comendite member of the Olkaria Comendite formation followed the caldera collapse. It is represented by rhyolite lavas and pyroclastics, dated at >9150±110 BP by the ¹⁴C method. The Olkaria volcanic complex does not have a clearly visible caldera. However, its association with the ring of volcanic domes in the east and south, and southwest has been used to infer the presence of a buried caldera (Virkir, 1980).

Stage 4; The Middle Comendite Member extrusion period was a period of ring dome formation, comprising mainly of rhyolitic lavas and the eruption of thick pyroclastic deposits which happened between >9150±110 and >3280±120 BP.

Stage 5; There was a notable resurgence of the caldera floor and the formation of thick lava flows that resulted in the Upper Comendite Member.

Stage 6; the last flow signified eruptions of very thick lava flows of comendite from a north-south fissure system. The youngest lava flow, Ololbutot comendite was dated to be 180±50 BP (Clarke *et al.*, 1990).

4.0 Structural geology of Olkaria Domes field

The structural systems in Olkaria Domes are best understood from interpretation of regional tectonic map which shows how they relate to the regional structural picture or framework. The main geological structures noted in this area include; faults, veins, vents, sills, fractures, craters, dykes, Gorge and the inferred ring structure. Identification of some of the geological structures is hindered by thick cover of pyroclastic materials; however, they are inferred from aerial photos and satellite imagery. Figure 2, shows the current updated structural map of the Olkaria geothermal field.

4.1 Faults

The major faults in the Olkaria Geothermal field may be grouped into four categories based on the strike direction; NE-SW, NW-SE, N-S, and NNE-SSW (Figure 2). The above named faults are normal faults with an average displacement of 20 to 50 metres. The NW-SE trending faults are the most visible faults in Olkaria Domes from aerial and satellite photos. The NNE-SSW faults with a strike of about 20° and a dip of almost 35° are observed to majorly cutting across the Ol-Njorowa Gorge and since there is a very thick pyroclastic cover in Olkaria Domes, these faults seem to extend into this field. Hot springs and fumaroles which are observed along the Ol-Njorowa Gorge show a similar orientation to these faults.

The NNE-SSW and N-S faults are considered most recent geological structures with NNE-SSW being associated with the doming during the caldera formation thus post-caldera faults. NE-SW faults are not visible in Olkaria Domes but are observed to the South West of the Ol-Njorowa gorge cutting across the inferred ring structure. This probably implies that they were formed after the caldera formation, hence post-caldera faults. The NW-SE faults are the most visible in Olkaria Domes and are mainly observed in the Central part of this field. These faults generally have a strike ranging between 320-330°. In regard to regional tectonics, these faults are the oldest and are associated with the rift formation since they link the parallel rift basins to the main extensional zones. Ofwona (2010) considers these faults to be older and more productive especially when their permeability is enhanced by intersecting the younger NNE-SSW faults.

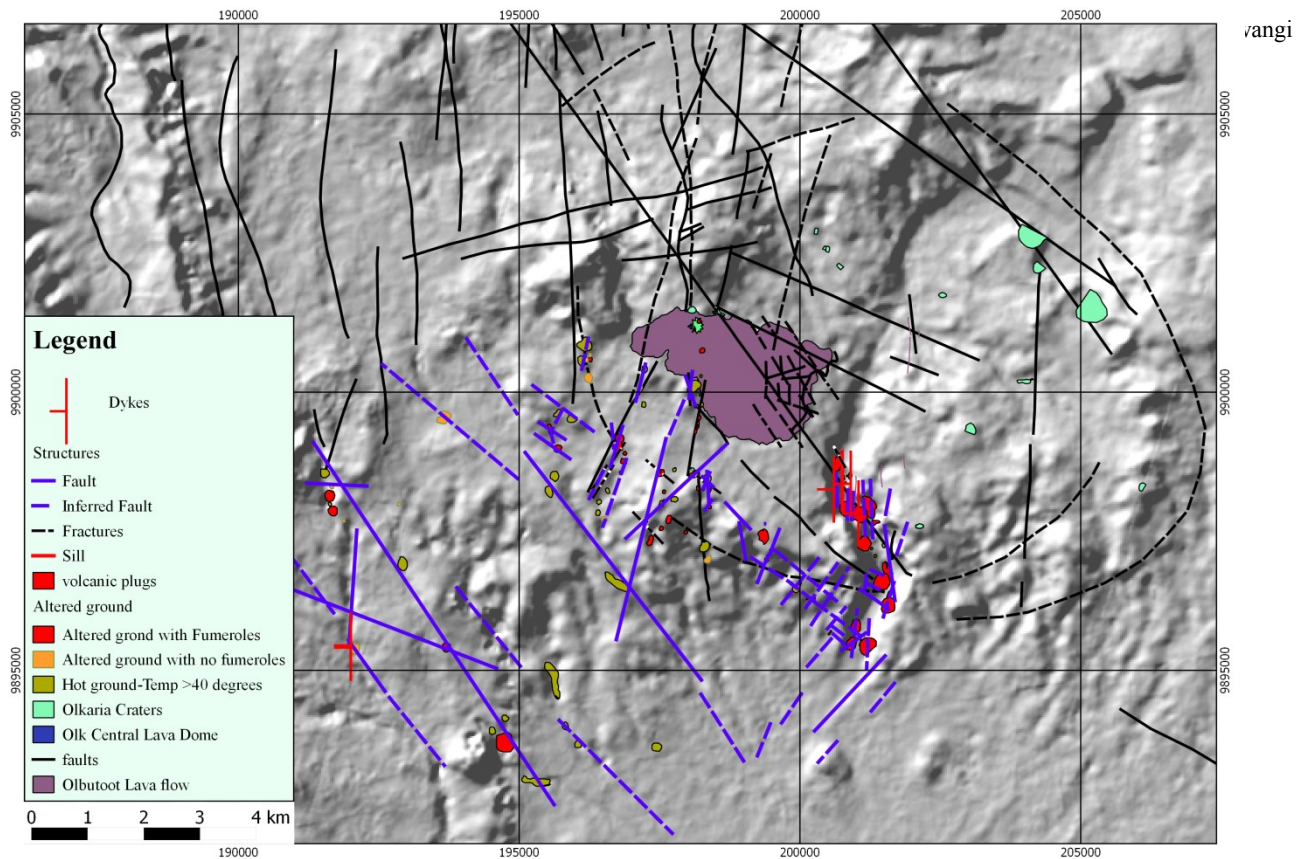


Figure 2; Updated structural map of Olkaria, faults in black colour were mapped in the past while faults in blue were mapped on June 2014

The occurrence of N-S faults is well seen in Olkaria Domes and along the gorge where they occur parallel to each. Other N-S faults in the Central section are the Olkaria fracture and Ololbutot fault and are the youngest, consequently considered to be of late tectonic activity (Omenda, 1998).

4.2 Fractures

Fractures represent discontinuities of the strata, formed due to tectonic activities and occur in close association with faults. It is believed that fractures result from brittle fracturing of surfaces near the tectonically active crust. Majority of the fractures are seen in the rock cuttings and can be associated with the intersection of the NW-SE and the NNE-SSW faults. High permeability and level of alteration is observed in these zones.

4.3 Ol-Njorowa Gorge

The Ol-Njorowa gorge is believed to have developed 9000 years ago during the catastrophic outflow of Lake Naivasha during its high levels (Naylor, 1972). The thickness of the gorge varies along its profile though appears relatively wider towards the South where the gorge terminates. Structurally, the gorge has N-S strike but it is also observed to be controlled by a system of NW-SE and NE-SW faults. This might explain the constant change in strike direction along its profile. The gorge is of interest due to the numerous structural features exposed along its walls.

For example, sections of the gorge intersected by faults are associated with extensive and high temperature fumarolic activities, with temperatures recorded ranging from 67^o to 97^o C (Figure 3). Abundant sulphur depositions around the fumaroles possibly indicate connection to the Olkaria domes area heat source. Other structures observed are dyke swarms with a more or less N-S orientation as the gorge.

4.2 Inferred ring structure

The inferred ring structure in the study area is marked by the alignment of eruption centres over the South east and the Western boundaries of the area. The ring of domes, mostly of rhyolitic composition, is thought to show the presence of a caldera that might have been formed by the magmatic stresses in the Olkaria magma chamber (Naylor, 1972). The ring structure in the Olkaria area pre-dates the north-south tectonic trending pattern in the Rift-valley zone. The Ol-Njorowa gorge cuts the suggested ring structure from north to south.



Figure 3; a section of the Ol-Njorowa Gorge with fumaroles clearly visible

5.0 Hydrothermal Alteration

Hydrothermal alteration is a general term which embraces the mineralogical, textural and chemical response of rocks to a changing thermal and chemical environment in the presence of hot water, steam or gas (Henley and Ellis, 1983). As a result of this water-rock interaction, primary minerals, which constitute the rocks, are altered into different secondary minerals, and the alteration process, together with the resulting type of alteration minerals, are dependent on the type of primary mineral altered. Factors that influence the types of mineral assemblages and distribution of hydrothermal alteration products include permeability, temperature, fluid composition (pH value, gas concentration, magmatic, meteoric), initial composition of the rocks, duration of activity (immature, mature), pressure and hydrology (Reyes, 2000).

Different alteration styles that can be recognized in the greater Olkaria geothermal fields can be broadly categorized into two types. In the near sub-surface supergene environment within a depth range of 0-450 m, majority of rocks are subjected to argillic alteration where low-temperature groundwater becomes acidic and the clay minerals are introduced, mainly smectite, zeolites and illite at presumed temperatures of $<180^{\circ}\text{C}$. Once the temperatures advances, argillic alteration pro-grades into low grade propylitic alteration normally characterized by the occurrence of chlorite, quartz, illite, intermittent epidote and wairakite with sporadic prehnite in the temperature ranges of $200\text{-}270^{\circ}\text{C}$.

This zone may vary in depth from one field to another in the range between 600 to 1500 m with the Olkaria east, west and central being much shallower than the Domes field. Epidote which is one of the main index hydrothermal minerals in Olkaria gradually crystallizes with increase of depth and temperature. In hypogene environments within the depth range of 1500-3000 m, high grade propylitic alteration advances to prophyllitic alteration characterized by mineral assemblage of epidote, chlorite, albite, illite, prehnite and actinolite at temperatures greater than 250°C . At high-temperatures $>280^{\circ}\text{C}$, amphiboles and pyroxenoids occur with actinolite and wollastonite being the most dominant alteration minerals (at temperatures $>280^{\circ}\text{C}$).

5.1 Hydrothermal Alteration in Olkaria Domes Field

Hydrothermal alteration in this field is very unique where the influence of structures is very critical. Significant hydrothermal alteration is notable in the perceived up-flow zones around wells OW-914, OW-916 and OW-915 region where the high temperature index hydrothermal alteration minerals are observed at shallow depth as compared to the proposed down-flow regions around the ring structure.

At the up-flow zones, high alteration intensity is observed from 300m bgl where the first appearance of secondary quartz is noted. Subsequent prograde alteration is characterized by first appearance of epidote at 500m bgl in OW-916 (Figure 4) and at around 600m bgl in wells OW-914 and OW-915. Actinolite and wollastonite characterize the lower parts of the well as from 1000m bgl.

Conversely, the down-flow regions show the occurrences of high temperature index minerals at depth and in some cases the high temperature index minerals may not be discerned, like in OW 917 (Figure 5) and OW 918. Certainly in such cases, calcite seems to dominate due to the possible incursion of cold flows to the system from the inferred ring structure.

The clays in this field show distinct mineralisation sequences ranging from smectite - chlorite – Illite. Four distinct alteration zones are common in this field which are defined by the first appearances of the index minerals; namely; zeolite-illite zone, chlorite-illite-MLC zone, epidote-chlorite-illite zone and actinolite-epidote-chlorite-illite zone.

A comparison of the first appearance of epidote and actinolite in this field reveals that the system is heating up at round OW-916, OW-914 and OW-915 and possible cooling where directional wells cut across the ring structure and Ol-Njorowa Gorge at shallow depths.

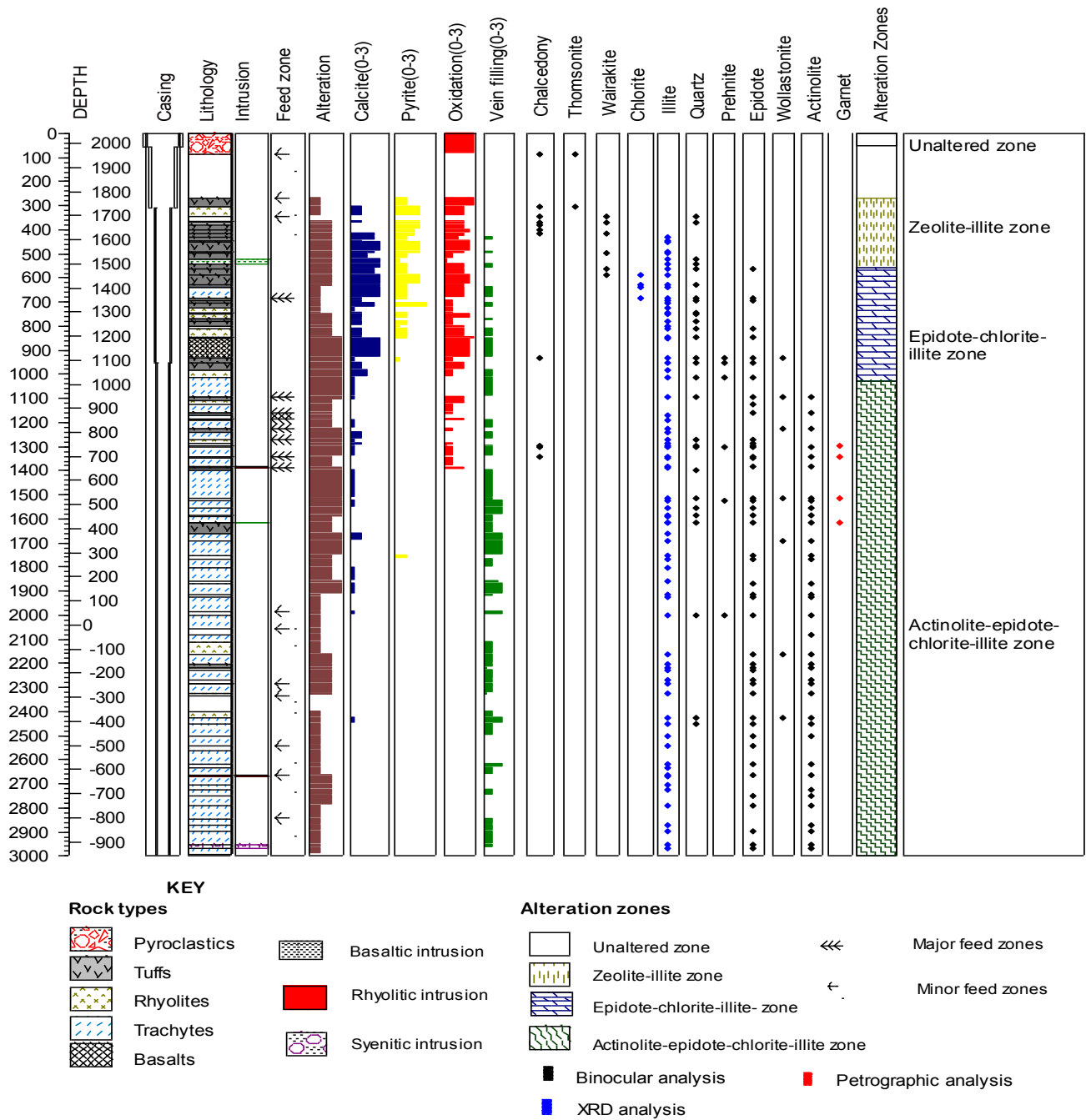


Figure 4; OW 916 Geological data

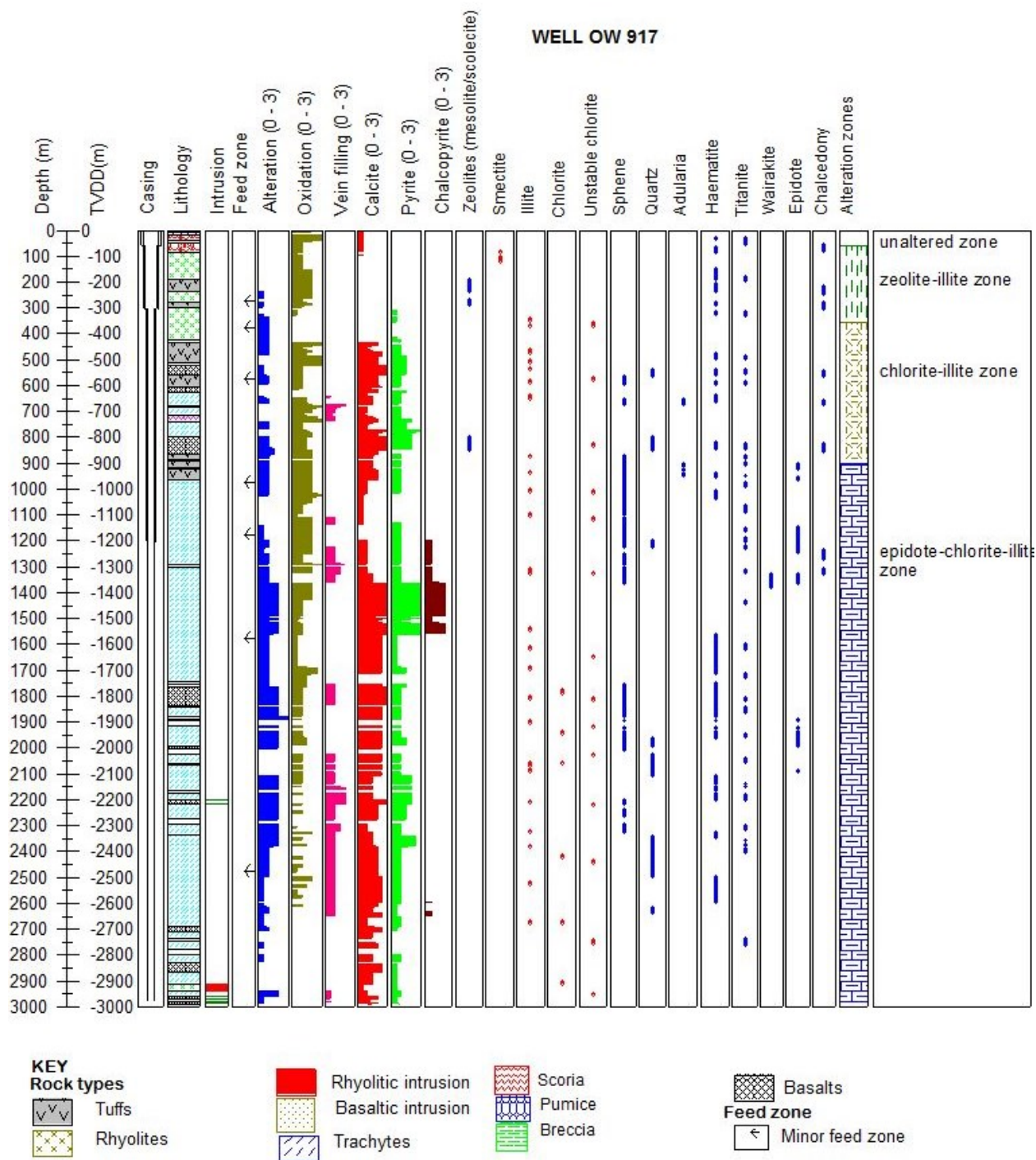


Figure 5; OW 917 Geological data

6.0 Discussion

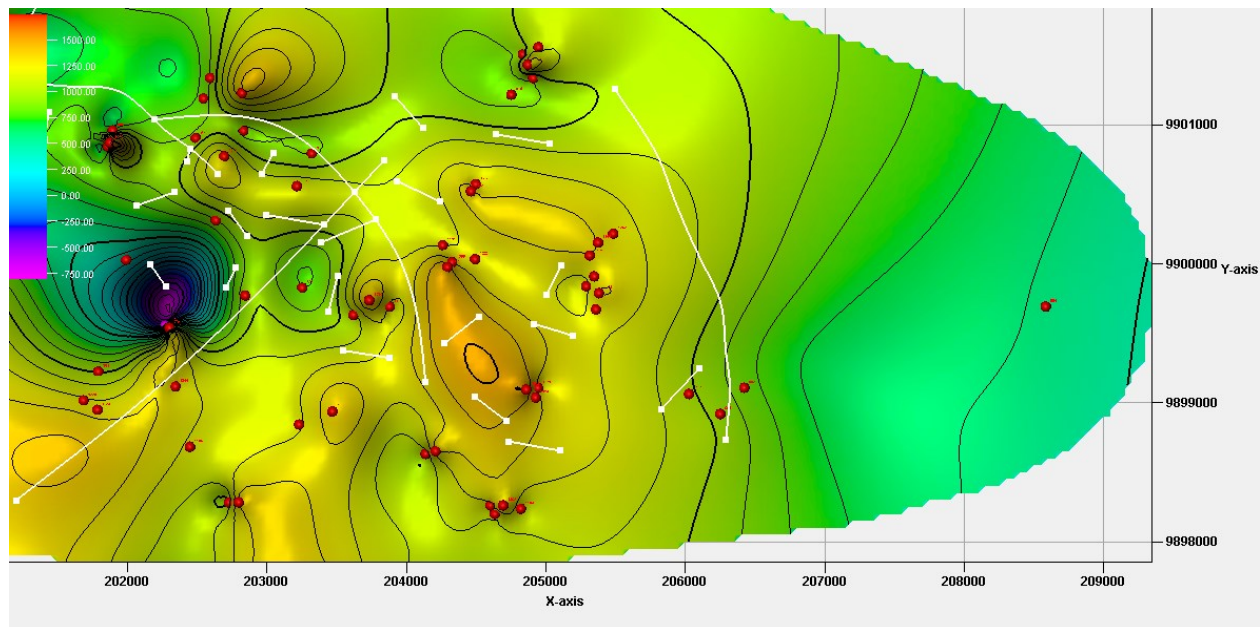
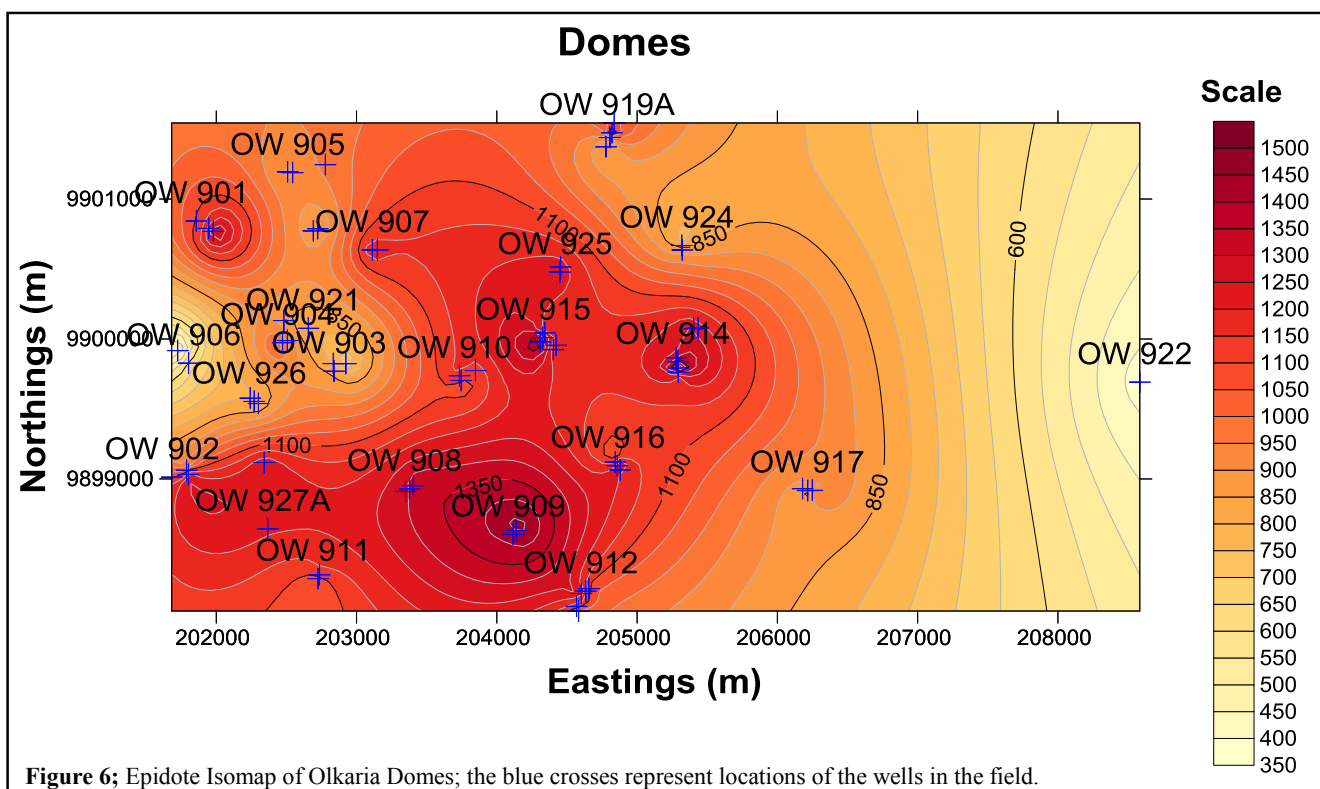
Fault systems in Olkaria Domes show orientation in NW-SE, N-S, and NNE-SSW direction, with the NNE-SSW and the NW-SE trending faults being the most common and relate to the general regional structural map of Olkaria. The NE-SW trending faults are barely visible due to a thick pyroclastic rock layer.

The NNE-SSW and N-S faulting system occurred after the caldera formation (post-caldera) while the NE-SW faults were formed during the caldera formation (syn-caldera) and are the most recent faults. Ol-Njorowa gorge is oriented in a N-S direction with many structural features exposed along its profile. The inferred ring structure which is marked by alignment of the lava domes indicates the presence of a buried caldera with Ol-Njorowa gorge cutting through it. Fractures and veins observed in the rock cuttings from the drilled wells in this field indicate high permeability if they are encountered deeper during drilling.

The most common hydrothermal alteration minerals in this field include; zeolites, clays, quartz, pyrite calcite, prehnite, epidote, actinolite and wollastonite. The influence of structures in this field is important to the hydrothermal alteration model of the area. For instance, the inferred ring structure is perceived to be the conduit for cold inflows in to the system and wells which have been drilled intercepting this structure show abundant calcite deposition with little high temperature hydrothermal alteration. Similar trends are also noted around the Ol-Njorowa Gorge which is also perceived to be a conduit for cold waters. Generally, the hydrothermal mineral assemblage around this structure show possible cooling hence subsequent incursion of hydrothermal calcite.

High development of hydrothermal alteration minerals together with high level of alteration seems to occur where the NW-SE trending faults intersects with the NNE-SSW younger faults. This can be due to a higher level of fracturing in this area and thus permeability is enhanced making these areas favourable conduits of hot fluids emanating from the magmatic source below.

A comparison of the structures and first appearance the main index hydrothermal minerals; epidote, was done for the entire Olkaria Geothermal Domes field and it clearly shows that hydrothermal alteration is closely related to the structures (Figure 6 and 7).



7.0 Conclusion and recommendation

The following conclusions can be drawn from the findings of the research carried out in Olkaria Domes field;

- Tectonically, the main fault systems in the study area show orientation in the NE-SW, NW-SE, N-S, and NNE-SSW direction, with the NNE-SSW and NW-SE being the dominant fault directions.
- Correlation between the hydrothermal mineralogy and structures shows that high alteration and highly developed hydrothermal minerals are observed where the NW-SE and the NNE-SSW faults intersect.
- Production wells and reinjection wells can be sited using both faults and hydrothermal alteration mineralogy for much better results.

Recommendations

- Detailed resistivity and geochemical work are recommended in the Olkaria Domes and should extend towards the outside this field to the East to confirm whether the resource extends outside.
- Obtain more aerial photographs and remote sensing data of the entire Greater Olkaria Geothermal Area and Longonot to aid in structural mapping and to identify whether more structures can be observed.
- More detailed geological data analysis should be carried out in this field to assess if more structures can be identified and their relationship to hydrothermal mineralogy.

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