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Structural influence of the Gorge Farm Fault to Hydrothermal Alteration, Mineral Paragenesis in the Olkaria North East Production Field: Case Study of OW 736A, OW 734 and OW 732C

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ABSTRACT

The Greater Olkaria Volcanic Complex is a high temperature geothermal field located within the Central Kenya Rift system. Exploration for this resource started in the 1950's, and development over the years has been gradual, except in the late 2000's that accelerated development took place. The Olkaria North East Field (NEPF) forms one of the production areas within the larger Olkaria Geothermal area. The influence of Gorge farm fault as one of major structures controlling hydrothermal fluid circulation is largely debatable owing to diverse results realised from recent drilled wells within its vicinity. The fault is relatively complex and fairly elusive with respect to hydrothermal alteration, mineral paragenesis and fracture permeability evolution.

This hydrothermal alteration mineralogy data from wells; OW 736A, OW 734 and OW 732C has been studied to characterize the influence of the Gorge Farm Fault as a possible conduit for both cold and hot fluids into and out of Olkaria geothermal system. The results of stratigraphic correlation of the wells show the spatial variability of lithological units apparently representing variable subsurface fault geometry. The occurrence of hydrothermal alteration minerals formed by replacement of primary minerals and by deposition shows prograde mineral zonation in OW 736A and OW 732C, while OW 734 shows zones with retrogressive zonation due to temperature reversals. OW 736A and OW 732C drilled in close proximity and also intersecting the fault zone show temperature reversals at intermediate depths, though there is an improvement at depth associated with the heat sources attributed to localised intrusions.

The study therefore concludes that Gorge farm fault plays a crucial role in recharging the geothermal system, with cooler fluids occurring within the upper zones and hotter fluids circulating at depth within the fault zone, as observed in temperature profiles across the area. Therefore, the production casing for wells drilled within the fault zone should be set at deeper levels to minimise interactions with the cooler fluids. Further studies along the entire Gorge Farm fault are recommended as to fully understand the net effects on the fluid flow patterns into the larger Olkaria Geothermal field.

1.0 INTRODUCTION

The Greater Olkaria Geothermal Area is located within the Central Kenyan Rift, approximately 120km south-west of Nairobi. The Olkaria Geothermal field, currently produces 682MWe, (KenGen, 2018). To enhance sustainable development and management, the geothermal area was subdivided into seven fields **(**Ouma, 2005) referenced with respect to the Olkaria hill, and includes

Olkaria East, Olkaria North East, Olkaria Central, Olkaria Northwest, Olkaria Southwest, Olkaria Southeast and the Olkaria Domes fields (figure 1 below).

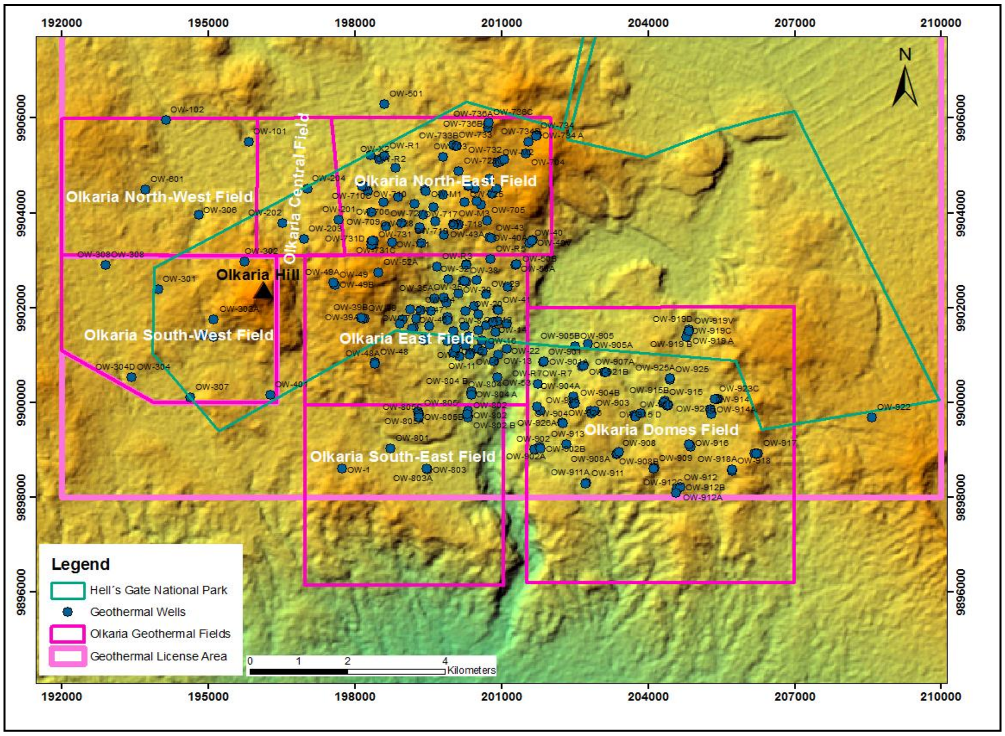

Figure 1: Olkaria Geothermal field sub-divisions (Munyiri, 2016)

2.0 Problem statement

The Olkaria Geothermal field is characterised by a series of fault systems. Faults are the major structures controlling fluid movement and magmatic/ volcanic activity, whereby the young volcanics are potential heat sources within the geothermal field. Intersection of faults may enhance fluid flow as a result of enhanced permeability, but they may also be conduits of cold meteoric waters, thus causing gradual cooling if there exists a direct channel into the reservoir.

The Gorge Farm fault trending in a NW-SE general direction, in the current area of study shows it to be a potential conduit of cold fluid incursions into the field. To fully understand its effect, the hydrothermal alteration mineralogy of drilled wells were studied, as to fully characterise the area within the fault zone. The study is envisaged to provide further/more information for optimum selection of sites as either production or re-injection wells.

2.1 Objectives

The main objectives of the study were to determine the structural controls on fluid flow and the associated hydrothermal alteration minerals in the Olkaria North East field:

- To identify the nature of fluids within the Gorge Farm fault through a correlation of hydrothermal alteration minerals within wells drilled in the area.
- To identify and characterize the distribution of the main hydrothermal alteration minerals occurring in the Olkaria North East field.
- To provide data for the update of the Olkaria conceptual model.

3.0 Geological setting

The Great Olkaria Volcanic Complex is a multi-centered volcanic field; 240km^2 in area, lying west of Longonot volcano and the western margin of the rift. The volcanic centers are at least 80 in number with most of them occurring as either steep sided domes, formed of lava and /or pyroclastics rocks, or as thick lava flows of limited lateral extent (Clarke, 1990).

Olkaria volcanic complex is characterized by comendite lava flows and pyroclastics on the surface and basalts, trachytes, and tuffs in the subsurface. The litho-stratigraphy of the Olkaria geothermal area as revealed by data from geothermal wells and regional geology can be divided into six main groups: Proterozoic "basement" formations, Pre-Mau Volcanics, Mau Tuffs, Plateau Trachytes, Olkaria Basalt and Upper Olkaria volcanics (Clarke, 1990).

The Pre-Mau formation is not exposed in the area, but outcrop on the rift scarps in the parts of the Southern Kenya Rift. Mau Tuffs are Pleistocene in age and are the oldest rocks that crop out in the Olkaria area. The Upper Olkaria formation consists of comendite lavas and their pyroclastics equivalents, ashes from Suswa and Longonot volcanoes and minor trachytes and basalts (Omenda, 1997); (Clarke, 1990); (Thompson, 1963).
The multistage model for the development of the most recent events and the associated units is as follows:
1. *Dominantly trachytic lava and pumice pile* represented by the Maiella pumice formation and the Olkaria Trachyte lava formation
2. *Caldera fracture* represented by the Ol Njorowa pantellerite formation
3. *Early post caldera activity* represented by the Lower Comendite member of the Olkaria comendite formation
4. *Ring Dome formation* represented by the Middle Comendite member which is often dome building
5. *General resurgence* represented by the Upper Comendite member well developed at the northern entrance to Hells Gate.

The youngest of the lavas is the Ololbutot comendite, which, has been dated at 250±100 yrs BP using ^{14}C from carbonized wood obtained from a pumice flow associated with lava (Clarke, 1990).

4.0 Methodology

***Binocular microscope analysis*: -** the analysis is carried out during drilling to identify the formations penetrated, the fracture intensity within the formations and to identify the intensity of hydrothermal alteration. For analysis, the samples are washed and cleaned thoroughly to remove unwanted mud/clay and other contaminants with which the sample has interacted with during the drilling operation. Samples are then placed into a petri-dish and mounted onto the stage of the binocular microscope for analysis. Important considerations during this analysis include the rock type(s), grain size, rock fabrics, primary mineralogy, alteration mineralogy, and alteration intensity (Hulen, 1981).
Petrographic microscope analysis: - a plane polarized light microscope is used to study thin sections prepared from the rock cuttings. The analysis compliments rather than replace careful binocular analysis of the samples and assists in the determination of minerals, both primary for rock identification and alteration mineralogy associated with the circulating geothermal fluids. For analysis, the samples are cut and glued on glass slide using a bonding compound and polished

down to a thickness of approximately 30 μm. The analysis gives specific information on mineral types, assemblages, mineral evolution sequences, mineral zonation in veins and vesicle fillings, and the alteration intensity of the primary minerals.

5.0 Results

5.1 Hydrothermal alteration minerals and zones

Hydrothermal alteration is a complex process affected by the interplay of a number of closely related factors. These factors include the circulating fluid composition, temperature, pressure, rock type, and the duration of the hydrothermal activity, (Browne P. R., 1978) evidenced by the occurrence of distinct mineral assemblages dependent on the interplay between these factors.

Within the study wells, the occurrence of zeolites, quartz, chlorite, epidote, prehnite and actinolite signifies the different temperature regimes changes with depth as captured in plots in figure 2, 3 and 4. These form zones within their stability ranges from the shallow to the deeper parts of the wells.

5.2 Mineral paragenesis

The sequence of mineral formation is an important concept in understanding the geological history of a particular field and also provides vital tool in studying the thermal and chemical evolution of a geothermal system over time.

The method applies the principle of crosscutting relationship where a veinlet or other feature that crosscuts another is younger. Also, the mineral deposited in the outermost boundary is the oldest while the innermost is the youngest. The deposition of minerals varies with depth depending on temperature, fluid chemistry, the rock type and permeability of the rock layer.

From the case study, low temperature alteration minerals characterize the paragenetic sequence of minerals deposited into open spaces such as vugs, vesicles and veins in the upper layer/strata below 1000m but at deeper depths high temperature minerals such as chlorite, epidote, and actinolite are noted, as shown in Table 1, 2 & 3 with a summary of the depositional sequence within the wells.

From the analysis, OW-736A shows a progressive increase in temperature with fine grained clays, zeolites, chalcedony and quartz noted from 0- 672m while chlorite, epidote and actinolite are observed from 678m to terminal depth. OW 734 between 618-648m and 2280-2288m, the mineral zonation shows decrease in temperature with chlorite forming the outer rim and quartz the innermost rim with calcite persisting to well bottom.

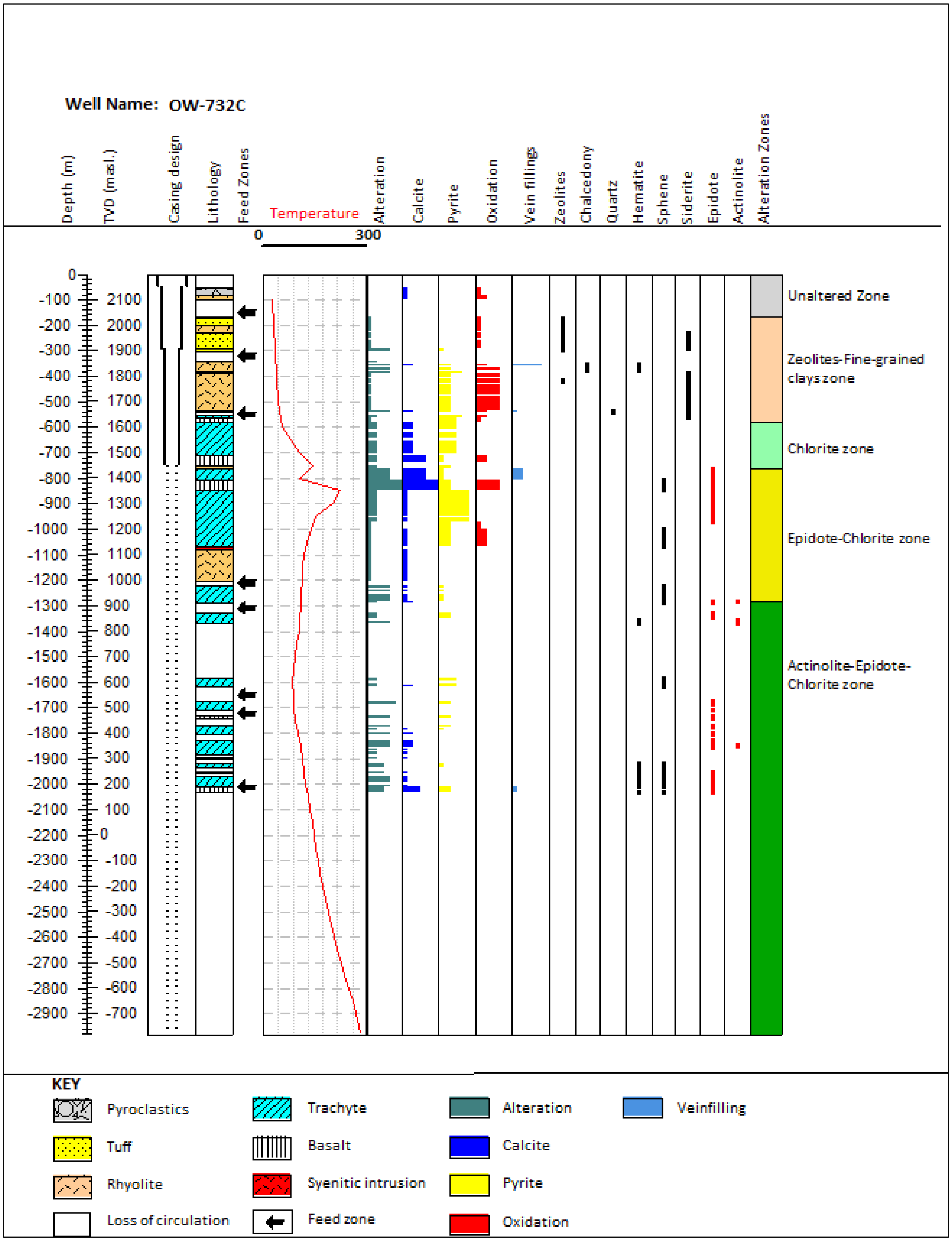

Figure 2: OW 732C alteration mineralogy and zonation plots

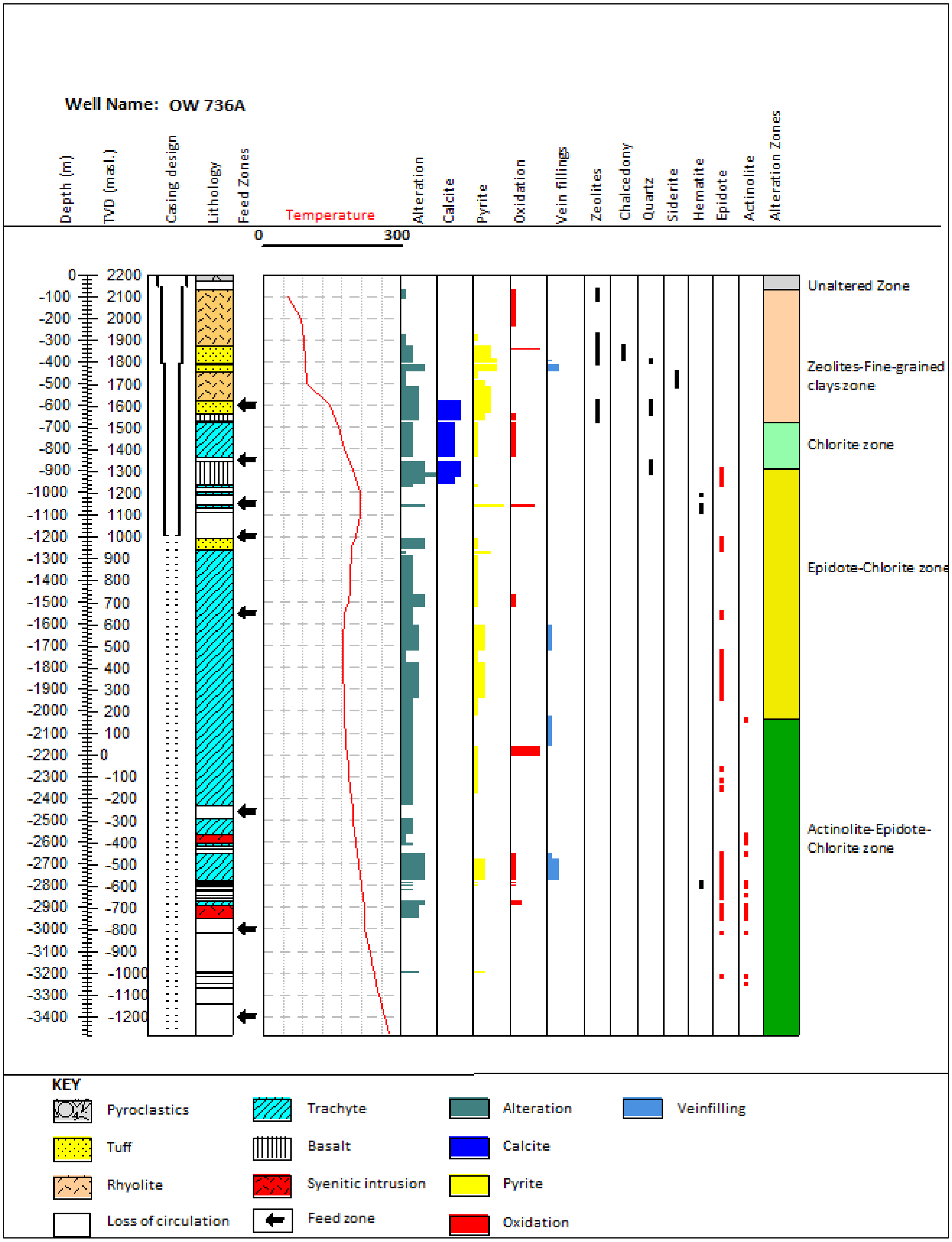

Figure 3: OW 736A alteration mineralogy and zonation plots

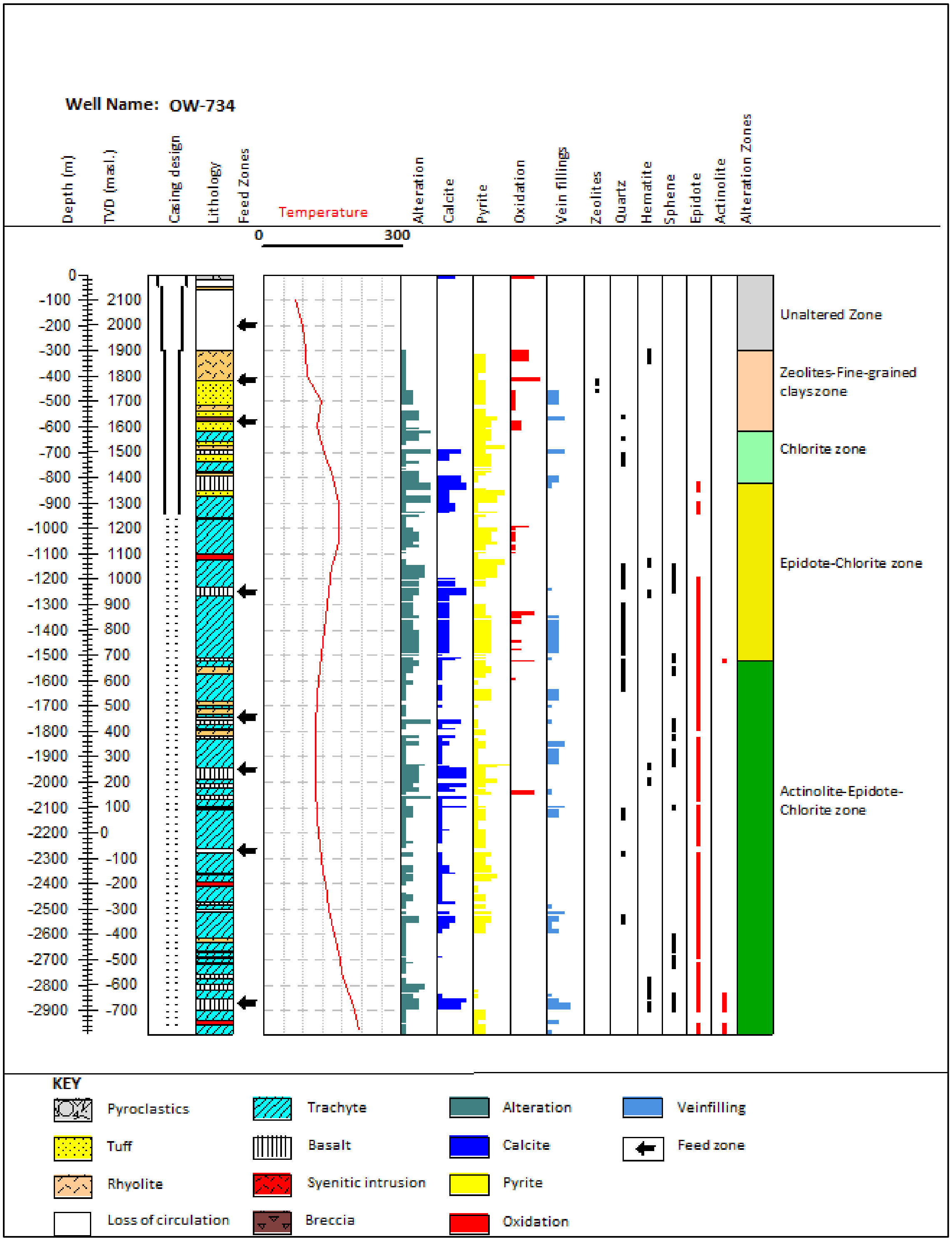

Figure 4: OW 734 alteration mineralogy and zonation plots

Table 1: Deposition Sequence in OW-736A

Depth (m)	Lithology	Alteration Intensity	Alteration Sequence Older ⟶ Younger
68 - 326	Rhyolite	Slight	Fine grained clay – Zeolites
326 - 364	Tuff	Slight	Zeolites - Chalcedony
386 - 408	Tuff	Slight	Fine grained clay – Zeolites - Quartz
578 – 672	Basalt, Tuff	Moderate	Zeolites – Quartz - Calcite
678 – 840	Trachyte	Slight	Chlorite – Calcite
860 – 928	Basalt	Moderate- High	Quartz – Chlorite - Epidote
1728 – 1942	Trachyte	Moderate	Chlorite - Epidote
2024 – 2682	Trachyte	Moderate	Chlorite - Epidote - Actinolite

Table 2: Deposition Sequence in OW-734

Depth (m)	Lithology	Alteration Intensity	Alteration Sequence Older ⟶ Younger
416 – 558	Tuff	Slight	Fine grained clay - Zeolites
558 – 618	Breccia ,Tuff	Moderate -High	Fine grained clay – Zeolites - Quartz
618 – 648	Trachyte	Moderate - High	Chlorite - Quartz
706 – 750	Tuff ,Trachyte	Slight -Moderate	Quartz - Chlorite
794 – 820	Basalt	Moderate	Chlorite - Calcite
820 – 1522	Basalt, tuffs, trachyte	High	Chlorite - Epidote - Calcite
1522 – 1524	Basalt	High	Chlorite – Epidote – Actinolite – Calcite
1524 – 1604	Trachyte, Rhyolite	Slight- Moderate	Quartz - Chlorite - Epidote
1754 – 2100	Basalt, trachyte	High	Chlorite – Epidote - Calcite
2106 – 2144	Trachyte	Moderate	Quartz – Chlorite – Epidote – Calcite
2280 – 2288	Trachyte	Slight	Chlorite – Quartz - Calcite
2328 – 2530	Trachyte & Basalt	Slight- Moderate	Chlorite – Epidote - Calcite
2530 – 2550	Trachyte	Moderate	Quartz – Chlorite – Epidote – Calcite
2856 – 2898	Basalt	Moderate - High	Chlorite – Epidote – Actinolite - Calcite

Table 3: Deposition Sequence in OW-732C

Depth (m)	Lithology	Alteration Intensity	Alteration Sequence Older ⟶ Younger
174 - 204	Tuff	Slight	Fine grained clay – Zeolites
356 – 380	Rhyolite	Moderate	Fine grained clay – Hematite - Chalcedony - Calcite
534 – 540	Tuff	Moderate- High	Fine grained clay – Quartz – Calcite
700 – 712	Trachyte	Moderate	Chlorite – Calcite
764 – 846	Basalt, Trachyte	Moderate- High	Chlorite – Epidote - Calcite
1584 – 1774	Trachyte, basalt	Slight	Chlorite – Epidote-Calcite
1802 – 1856	Trachyte	Moderate	Chlorite - Epidote - Actinolite
2010 – 2032	Basalt	Moderate	Chlorite - Epidote - Calcite

In OW 732C, mineral sequence shows low temperature alteration minerals between 0-540m and high temperature alteration minerals from 700m to well bottom.

OW 736A, measured temperatures collaborates the effect of the intersection with the fault, where cooling is observable at the depths of between 1300-1600 metres, with apparent heating up at depth due to interaction with the syenitic intrusions common within the North east field, figure 5 below.

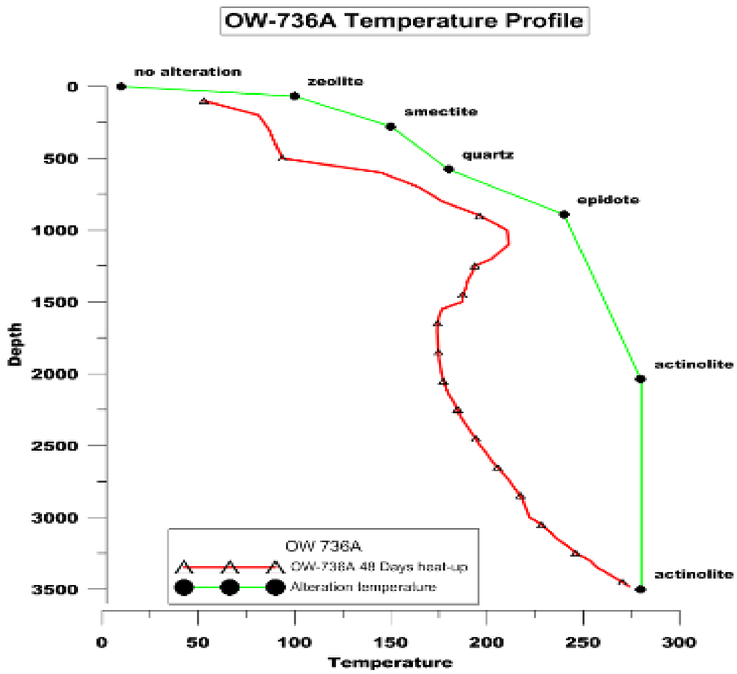

Figure 5: OW 736A Temperature data plots

A cross section from OW 102- OW 734A (west –east) shows the Gorge Farm Fault acting as a boundary fault for the geothermal system. To the west of the fault, there is an up flow zone whereas to the east is apparently the down flow zone (figure 6), as observed in results from the profile to the east, and whose data shows intense cooling zones.

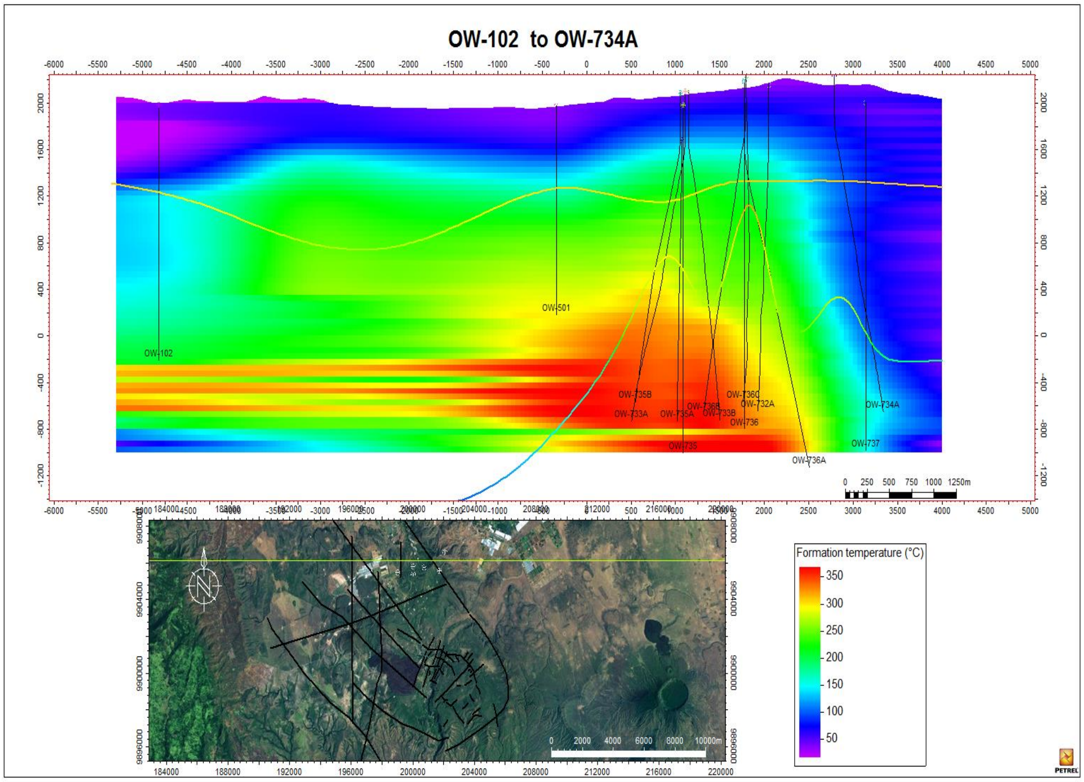

Figure 6: Temperature profile showing the effect of the Gorge Farm fault

6.0 DISCUSSIONS AND CONCLUSIONS

The hydrothermal alteration in an area provides pertinent information on the status of the geothermal reservoir through a period of time, as the different mineral associations record the changes that have occurred on the hydrothermal fluids temperature, pressure, and the rock interactions over time (Browne & Ellis, 1970).

Structurally, the influence of the Gorge farm fault is observed on both OW 736A and OW 734, as both wells intersect the faulted zone. OW 736A, at a depth of between 1500- 1600 metres bgl shows enhanced oxidation, and reversals in the formation temperature. At OW 734, drilled entirely within the fault zone, the mineral assemblage shows that calcite, pyrite and oxides persist to the bottom of the well. Also vein-fillings occur in abundance, indicating the occurrence of extensive fracturing of the formation. The mineral association for quartz, and calcite attests to the enhanced permeability within this zone (Lagat, 2009). OW 732C, intersecting the fault zone at depth, was characterised by total losses of returns (blind drilling) from 2000 to 2986 metres.

The fault is characterised by cooler fluid incursions at shallow depths, causing extensive calcite deposition within wells that intersect the Gorge farm fault. However, numerous intrusions within the area contributes significantly to the gradually heating up of fluids within the fault zone at greater depths. Thus delineating the interface between the cooled and hot zones will contribute immensely to the siting and setting of production casings for the improvement on the overall yield of drilled wells in the area.

Recommendations

- To undertake further research as to establish the nature of the Gorge farm fault spatial relations and influence on fluid flow patterns
- To undertake fluid inclusion studies on wells within the case study area.
- Tracer tests to furnish more information on the possible fluid movement in this zone.
- To set the production casing deeper for wells intersecting the fault zone as to minimise the cooling effects.

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