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

Alteration Mineralogy of Well KW02 in the Karisimbi Geothermal Prospect, Nyabihu District, NW-Rwanda

Ngaruye, J.C.

Rwanda Mines, Petroleum and Gas Board, P.O.Box 937, Kigali, Rwanda

jclaude.ngaruye@gmail.com

Keywords: Rwanda, Democratic Republic of Congo, East-African Rift System, well logging, geothermal, alteration mineralogy, Virunga Volcanoes Range, Karisimbi volcano

ABSTRACT

Karisimbi is a "dormant" strato-volcano of the Virunga volcanoes range (VVR). It is located at the border between Rwanda and the Democratic Republic of Congo and is the highest (4,507m asl) of the eight major volcanoes of Virunga massif of the western branch of the East African Rift System. Two active volcanoes, Nyiragongo and Nyamuragira are located nearby this volcano. The rocks of VVR are dominated by under-saturated series comprising K-rich basanites, hawaiites, mugearites, benmoreites and trachytes with rare micro-syenite. Apart from trachytes, the remaining rocks contain quartz-feldspar dominated xenoliths remobilized from Mesoproterozoic basement. ~~The~~ K-Ar dating showed that the Karisimbi lavas are younger than 0.14±0.06 Ma (De Mulder, 1985). The alkalinity of the Karisimbi lavas was also confirmed by Browne (2011) who reported strong alkalinity shown by the high content in total alkalis, TiO_2, Ba, Rb, Sn, La and Ce.

Mackey et al. (1997), using the Spaceborne Imaging Radar C (SIR-C) interferometry topography, realized that lava flows of the Karisimbi are 40-60 m thick (up to 140 m) and extended NS to a length of 12 km. De Mulder (1985 and 1981) reports that the volcanic products from Karisimbi volcanic activity are essentially fluid-rich lavas with mafic to intermediate magmatic suites. Recent geothermal surface exploration around the volcano and the two exploration wells, KW01 and KW02, provide new data on the geology of the area (Rwabuhungu and Ngaruye, 2016; Ngaruye, this paper). The current paper intends to focus on the newly gained knowledge on alteration mineralogy of the Karisimbi area. Investigations on hydrothermal alteration processes was used to understand the new insights on the geothermal reservoirs. From drill cuttings samples analysis using binocular stereo-microscope, the presence of alteration minerals generated by both ascending magmatic fluids and leaching cold meteoric waters are reported.

1. INTRODUCTION

Karisimbi is the highest of the Virunga volcanoes at 4507m and it covers an area of about 600 km^2 on the Rwandan side. It is located in the same range with 8 other volcanoes among which only two are still active: Nyiragongo and Nyamuragira.

Karisimbi comprised three main parts: a summit cone of pyroclastic and viscous lavas flows, a one kilometre of diameter and a 150 m deep pit crater of Muntango lying immediately south of the summit cone and a two kilometers diameter and 40m of deep Caldera Blanca. The volcano is formed by gently sloping lava plain of some 400km^2 (De Mulder, 1985). The volcanic cover is ca. 800m thick and underlain by a basement of Mesoproterozoic age (Ngaruye, 2015). This basement comprises meta-sedimentary rocks which during the Kibaran Orogeny were intruded by two generations of granites (Tack et al., 2010; Dewaele et al., 2011).

Figure 1: View of Karisimbi shield-volcano (seen from SE).

The tectonic features are materialized by NW-SE, N-S and NE-SW trending faults. The NW-SE and N-S features are older and likely associated with pre-rift, Mesoproterozoic basement structures. The NE-SW faults are the youngest generation of fractures and are buried below the young volcanic rocks (Jolie et al., 2009).

Surface comparative surveys were carried out by BRGM (1989), Jolie et al. (2009), Kengen (2010) and Uniservices (2012) and showed that, from the perspective of geology, geochemistry, and geothermal manifestations, the following conclusions might be drawn:

- A convective magmatic heat source possibly exists under or in the neighborhood of Karisimbi volcano. The heat source possibly exists at about 10-16km depth as evidenced from occurrence of evolved magma products associated with Karisimbi volcano including trachyte and trachy-andesite magmatic types.

- The lack of surface manifestations at Karisimbi was raised by some experts as a negative fact against the presence of heat source. However, the presence of recent trachyte (age of 10Ka), was thought to suggest that magma chamber is large and still hot. The lack of these manifestations could be due to high rainfall and high permeability of the >400m thick basaltic cover resulting in hydrological sweeps.

- The extensive travertine deposits along N-S depressions of the Musanze area and in the Burera District may indicate outflows from an old geothermal system in the neighborhood of Karisimbi.

- Little hydrothermal alteration observed on erupted rocks in and around the Karisimbi volcano. Structural patterns of the area with joints and cracks associated with rift tectonics is a sign of good permeability in the reservoir at Karisimbi. The cap rock for the geothermal system has not been clearly defined from initial conceptual model.

- The geothermal system is hosted within the Proterozoic granites. Similar in this respect to Coso (California) where the reservoir is hosted within granite. Therefore, the preliminary results indicate that a medium-temperature geothermal system might exist in the southwest of Karisimbi Volcano.

- Three exploration wells were drilled in Karisimbi geothermal prospect with the aim of providing further information on the existence of geothermal resource. The first exploration well KW01 was sited at UTM (E 768745, N 9828070) with elevation of 2675 m. The aim was to intersect the most important tectonic structures in the area, which are likely to control the fluid flow of the region. The exploratory well reached 3.015km deep depth. Well KW02, located at (E 767182, N 9829357) with altitude of 2622 m a.s.l., was drilled to 1.4km. Both were vertical. The drilling sites were selected basing on the following criteria: low resistivity, gas emission (radon and CO_2) map, vicinity to the heat source (Karisimbi volcano), geological features (adventive cones/craters, faults, lineaments and fractures), accessibility to the sites and environmental impact (distance from the National Park, low population density). Samples were taken every two meters, analysed using a binocular microscope and then ~~after,~~ sent to the EWSA laboratory for petrographic investigations.

This paper will discuss different geologic features at Karisimbi using the data gathered during the exploration drilling project and specifically information gathered from well KW02.

2. GEOLOGICAL SETTINGS

The Virunga volcanic field belongs to the western branch of East African Rift System (Figure 1). The western branch contrasts with the eastern branch in that volcanic rocks are much less abundant, mostly K-rich and the grabens themselves are narrower than those of the Eastern branch. Hence, it may be considered that the western branch which hosts the Virunga region is less mature than the eastern branch and the Virunga volcanic rocks may therefore be the initial products of the magmatic evolution of a continental rift over a mantle plume (Ebinger and Furman, 2002).

The Virunga province comprises two active and six extinct but recent volcanoes and numerous small volcanic cones (De Mulder, 1985 and Rogers et al., 1998). The basement of the Virunga consists of three important blocks: the D.R.Congo block and the Rwanda block which is separated from the Uganda block by the Bufumbira depression (Figure 9). The N-S Virunga fault separates the western active volcanoes from the central and eastern volcanic fields (Figure 9).

The age and duration of Virunga volcanism are subject of debate, with ages ranging from <100ka to 12 Ma. The volcanic activity of the Karisimbi area has been dated between 0.03 and 0.14Ma. However, no recognized volcanic eruptions were reported in the Karisimbi area during historic times (De Mulder, 1985).

The most recent ages of Karisimbi lavas vary between 240,000 and 90,000 years (Rancon et Demange, 1983). They are silica under-saturated but K-rich basanites, hawaiites, benmoreites and trachytes.

The geology of Rwanda and the neighboring parts of D.R.Congo and Uganda is dominated by the Kibaran mobile belt which evolved between ca. 1.4 and 1.3Ga, with two phases of anorogenic granite intrusions (Peralkaline S-type granites) and syenites dated between 0.9 and 1.375 Ga (Tack et al., 2010).

According to Jolie et al. (2009), the most favorable part (of the Virunga massif) for geothermal potential in Rwanda is the Eastern part of the accommodation zone bounding the Butare complex, roughly southeast of the Karisimbi volcano. The main geological structure dominating this zone is the Muhungwe WSW-ENE fault (Rogers et al., 1998).

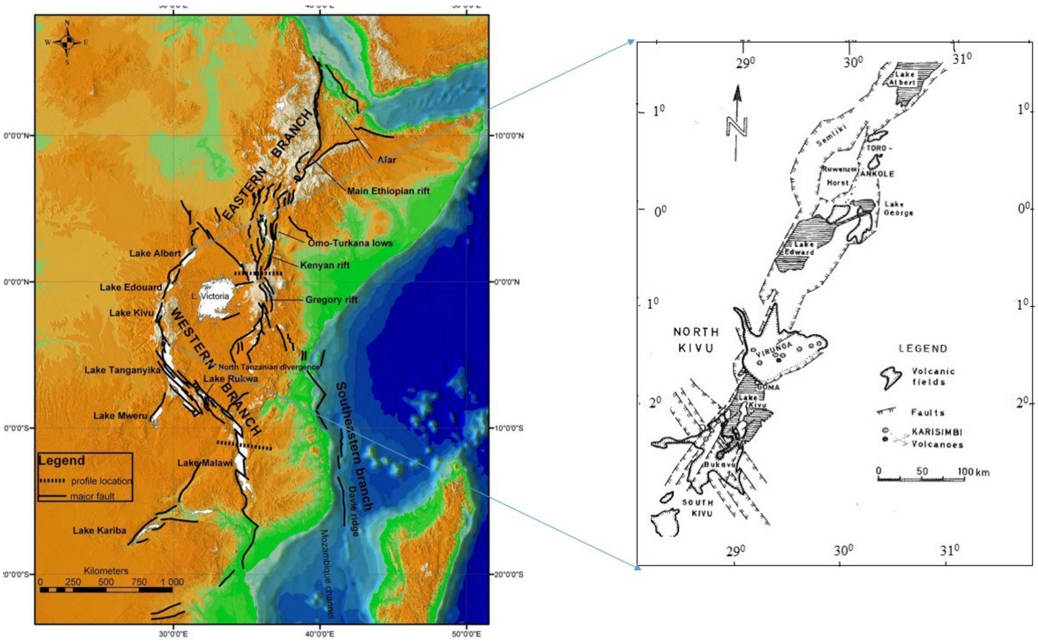

Figure 2: Volcanic field and geological feature in the western rift Valley of Africa (modified after De Mulder, 1985 and Chorovicz, 2005).

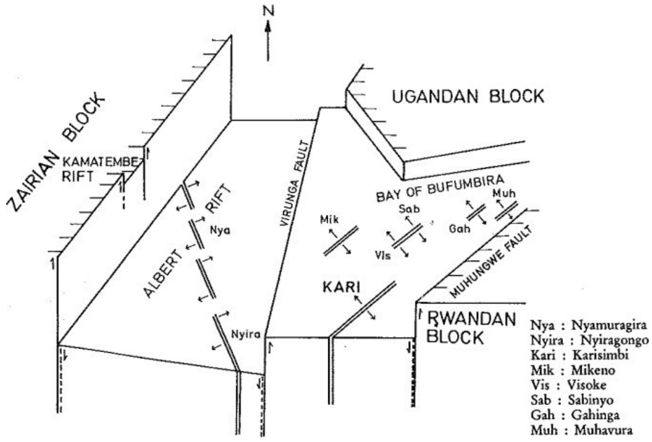

Figure 3: Block diagram of the Virunga basement (De Mulder, 1985).

Other major structures of the region are defined by NW-SE, N-S and NE-SW structural trends (Figure 4). The old structures predominantly trend NW-SE and N-S and are associated with the pre-rifting period. The NE-SW fault pattern is younger and is associated with the western rift. Other important structures include the NE-SW inferred accommodation fault zone (Jolie et al., 2009).

Volcanic ashes, lapilli (Figure 5), bombs (Figure 6) and aphyric lava flows-pahoehoe in most cases- (Figure 13) are common. They have been slightly weathered (Figure 7). The thickness of soils was estimated to be between 0 and 2m.

The field investigations confirmed the existence of the geological structures within the Karisimbi prospect (Jolie et al., 2009). These are mainly N-S trending faults which are delineating narrow grabens with 50 to 180m widths. This is eivident by the existence of several NE-SW trending depressions filled by the lava flows (Figure 8) and the presence of lava tubes. Moreover, Karisimbi prospect exhibits a series of cones/craters.

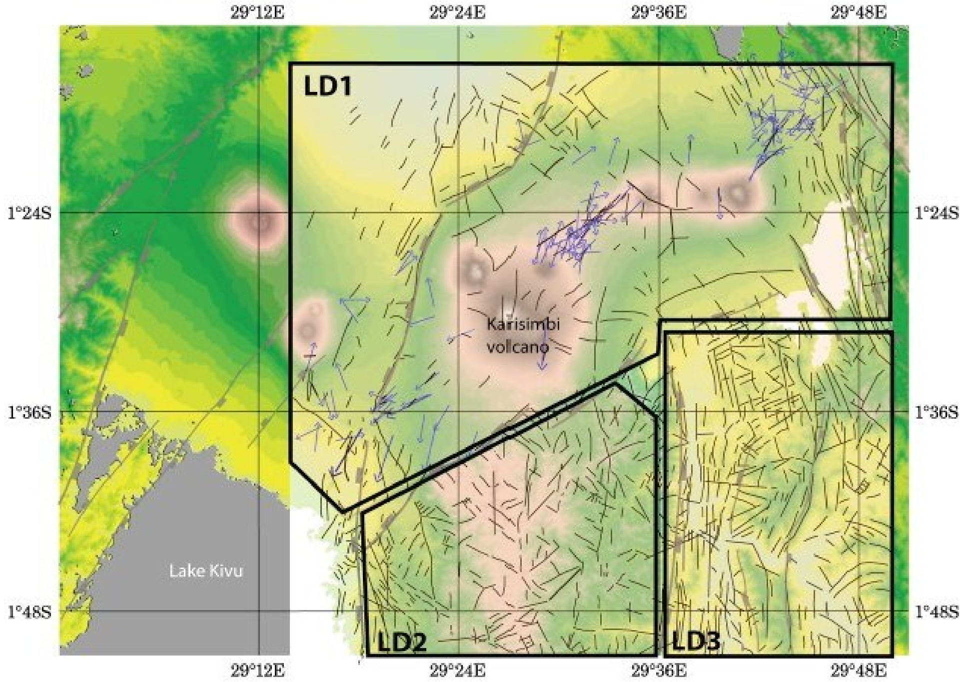

Figure 4: Key structures of the investigated area (Jolie et al., 2009).

Figure 5: Volcanic aphyric bomb.

Figure 6: Slightly altered ashes and lapillis.

Figure 7: Pahoehoe nearby Karisimbi volcano.

Figure 8: NE trending micro graben.

3. KW02 WELL STRATIGRAPHY: PREDICTED GEOLOGICAL SETTINGS & ROCK FORMATION (FIGURES 9 AND 10).

The local stratigraphy using existing geological data from the area and from data gathered during the KW01 geological logging is as follows:

0-2m K-Basanite volcanic rock

Massive and fine to medium grained lava flow. The rock has a porphyritic texture with pyroxene, olivine and feldspar phenocrysts. The rock is rather hard.

3-238m Volcanic rocks with vesicular and scoraceous materials and lava caves

Layers of volcanic lava: they possibly consist of scoria-lava, often hosting lava caves that formed, when gas rich fluid lavas were drained and escaped away from beneath. They hardened to form pahoehoe surfaces with lava tubes or lava caves. Lava caves between layers of scoria are be denser in 56m - 88m depth interval.

Fine-grained to glassy vesicular lavas and vesicles rich scoria which were found between 56 m and 238 m in well KW01 are also expected at the same depths in well KW02. They are porphyritic rocks with phenocrysts of clino-pyroxene, olivine, Fe-Ti-oxides and feldspar.

238-324m K-Hawaiite volcanic rocks

Light grey, medium-grained lava flow, rather dense with porphyritic texture and dominant feldspars, olivine, pyroxene and biotite phenocrysts. The rock is rather hard at the edge and a bit softer between 266-317m.

324-961m Fractured volcanic lava rocks.

Subsequent different scoriaceous lava layers with lava caves. Therefore, high circulation losses are expected in this section.

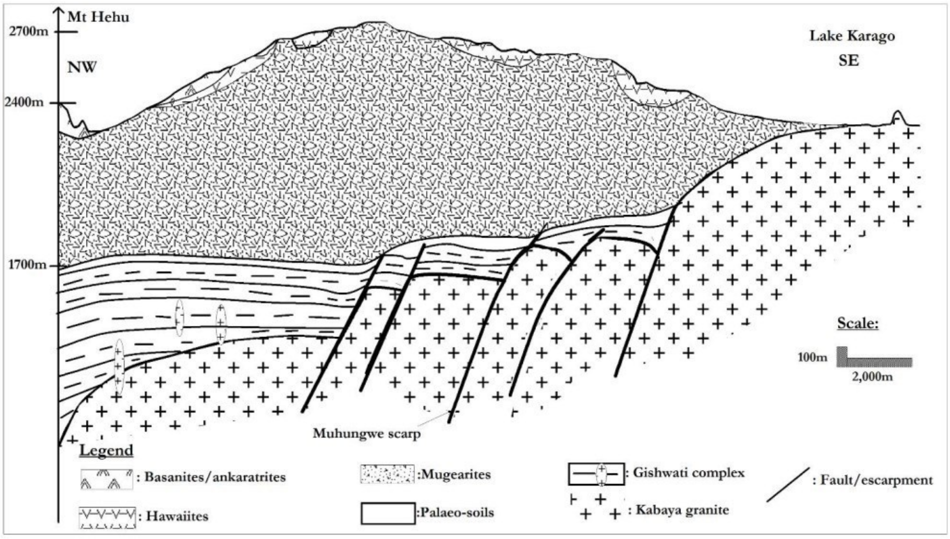

Figure 9: Hehu-Karago geological cross-section (EWSA, 2013).

961-1300m Pegmatite intrusions

Highly crystallized and feldspar-dominated felsic rocks with muscovite, biotite, tourmaline and various forms of quartz as primary minerals.

1300-3000m Granite

Fine to medium grained, hard granitic formation, along with pegmatite lenses. A small amount of basanite dykes and fracture zones filled with alteration minerals like calcite, zeolites, limonite and hematite between 2000 m and 3000 m.

3000-3500m Mafic intrusion through granite batholiths

Dense and hard layers of light grey, fine to medium porphyritic felsic rock (granite batholith). Dense network of fractures intruded by basanites and K-hawaiites dykes/sills with feldspars phenocrysts.

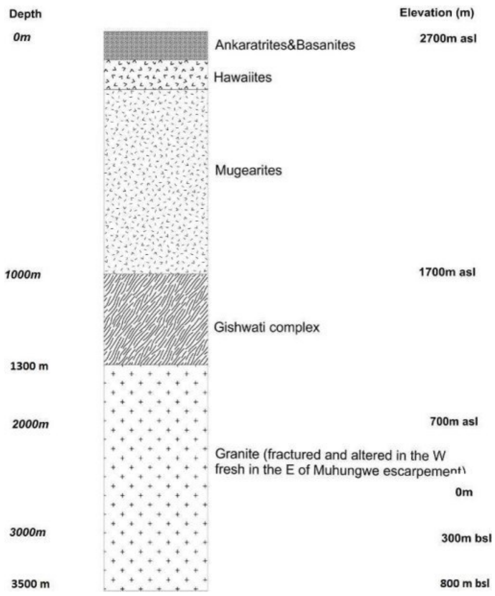

Figure 10: Predicted rock types in well KW02 (EWSA, 2013).

4. MAIN FINDINGS

4.1 Geology and Hydrothermal alteration

Well KW02 was drilled at well pad #3 in the Karisimbi prospect. The lack of any sign of hydrothermal alteration in the cuttings resulted in the halting of the drilling operations before reaching the targeted depth (TD) of 3,500m. Therefore, the hole was stopped at only 1367m. Three geological facies have been identified during the drilling operations of KW02: 0 – 67m, 67-790m and from 790 to TD.

a. **0-67m:** The surface geology of well KW02 shows four types of young eruptive rock units:

1. *Pyroclastites comprising pumice and fresh tuffaceous materials*. Volcanic ashes are the main component of all the volcanic cones/craters found within the investigated prospect. The tuffs are partly lithic and partly crystal tuffs. Its main components are aphyric fine-grained clasts, occasionally coarse-grained and occasionally medium-sized volcanic bombs.
2. *Aphyric volcanic rocks* which are hard, massive and dark to black colored. They are fine-grained and porous. They have been identified in the south-western to southern part of Muntango pit crater.
3. *Volcanic rocks with plagioclase phenocrysts:* these are fresh lava flows which show small to big plagioclase phenocrysts.
4. *Lava flow embedding xenoliths:* numerous lava flows and pyroclastic rocks of Kabatwa area enclose bedrock inclusions. Majority of these inclusions are quartz xenocrysts-rich.

The area hosts also volcanic cones/crater of Musamura, Ngo, Bugeshi I and Bugeshi II for which the key rock types are thick layers of volcanic ashes. These light volcanic ashes produced by explosive activity cover 0 to 3m thick paleo-soils. On the top of the ashes, fertile soils were developed. The upper geological formations consist of hard and dense volcanic rocks. This is the reason why the contractor for civil works was using explosives during the drilling site preparation. NE-trending narrow graben expressed as depressions extending from Kabatwa zone (2700m high) to Lake Kivu (1460m high) dominate the topography. Several steps at different elevation levels are identified within those grabens. The basement was dissected by NW and NE trending normal faults. The most important tectonic features which are possibly controlling the fluid flow in this area are open N-S to NE- SW faults. This is evidenced by the absence of springs, rivers or any other water point in the Gisenyi town - Kabatwa axis where the annual rainfalls range between 1600 and 1800mm. The rain water seems to flow through those fractures to Lake Kivu. The throw of the faults is often difficult to measure, but range up to hundreds of meters. The faults that dissect the study area are more common in the basement than in the younger lavas where they followed the former micro-grabens dissected in the basement.

b. **67m-790m:** This part consists of mixture of light to dark grey, vesicular and oxidized volcanic rocks with olivine, clino- pyroxene, plagioclase and biotite as the main rock-forming minerals. Frequent scoria, pumice and mixture of volcanic ash, lapilli and hard boulders are found. Common xenolith phenocrysts are also abundant. Fragments of aphanitic volcanic glasses are present. Frequency of zones of total losses: 87-100 m, 151-229m, 232-237m, 282-366m, 376-380m, 381- 404m, 447-451m, 465-470m and 646-650m intervals.

c. **790m-1367m:** Rare pegmatite bodies in upper section and light greyish, fine to coarse-grained and slightly oxidized granite with variable amounts of quartz, feldspar, muscovite and biotite.

The rock type, the rock-forming minerals, the context of mineral deposition and alteration minerals in KW02 were identified. The result is that most of the rocks of upper parts of KW02 (0-790m) are K-Basanite, K-Hawaiite with oxides, olivine, clino-pyroxene, plagioclase and black micas as primary minerals. The deep sections (below 790m) are comprised of coarse-grained pegmatite intrusions and/or fine to medium grained, light grey, slightly oxidized granite with variable amounts of quartz, feldspar, muscovite and biotite.

4.2 Detailed stratigraphy of KW02 (Figures 7, 8 and 9)

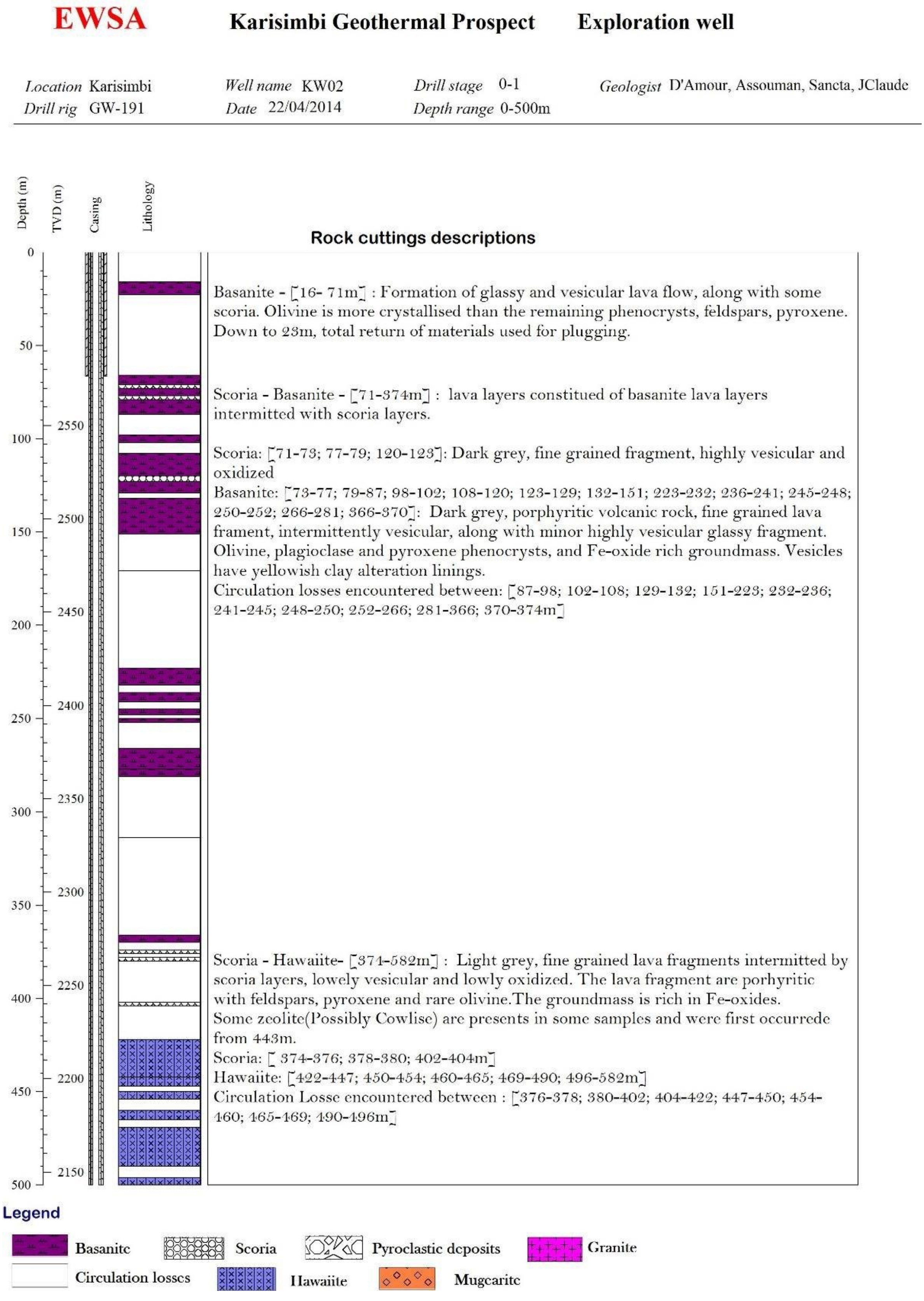

Figure 11: Stratigraphic log of well KW02 from 0 to 500m.

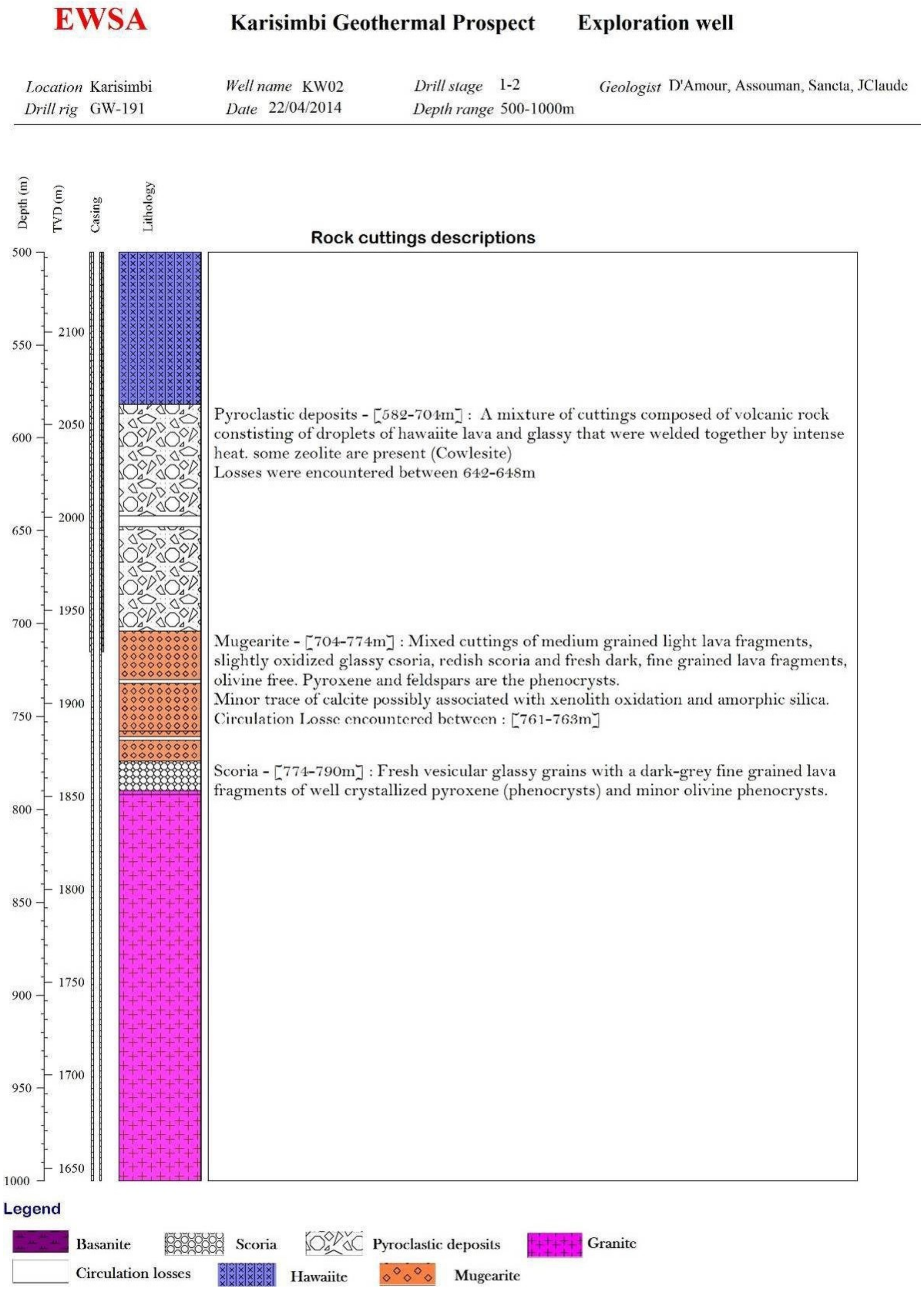

Figure 12: Stratigraphic log of well KW02 from 500 to 1000m.

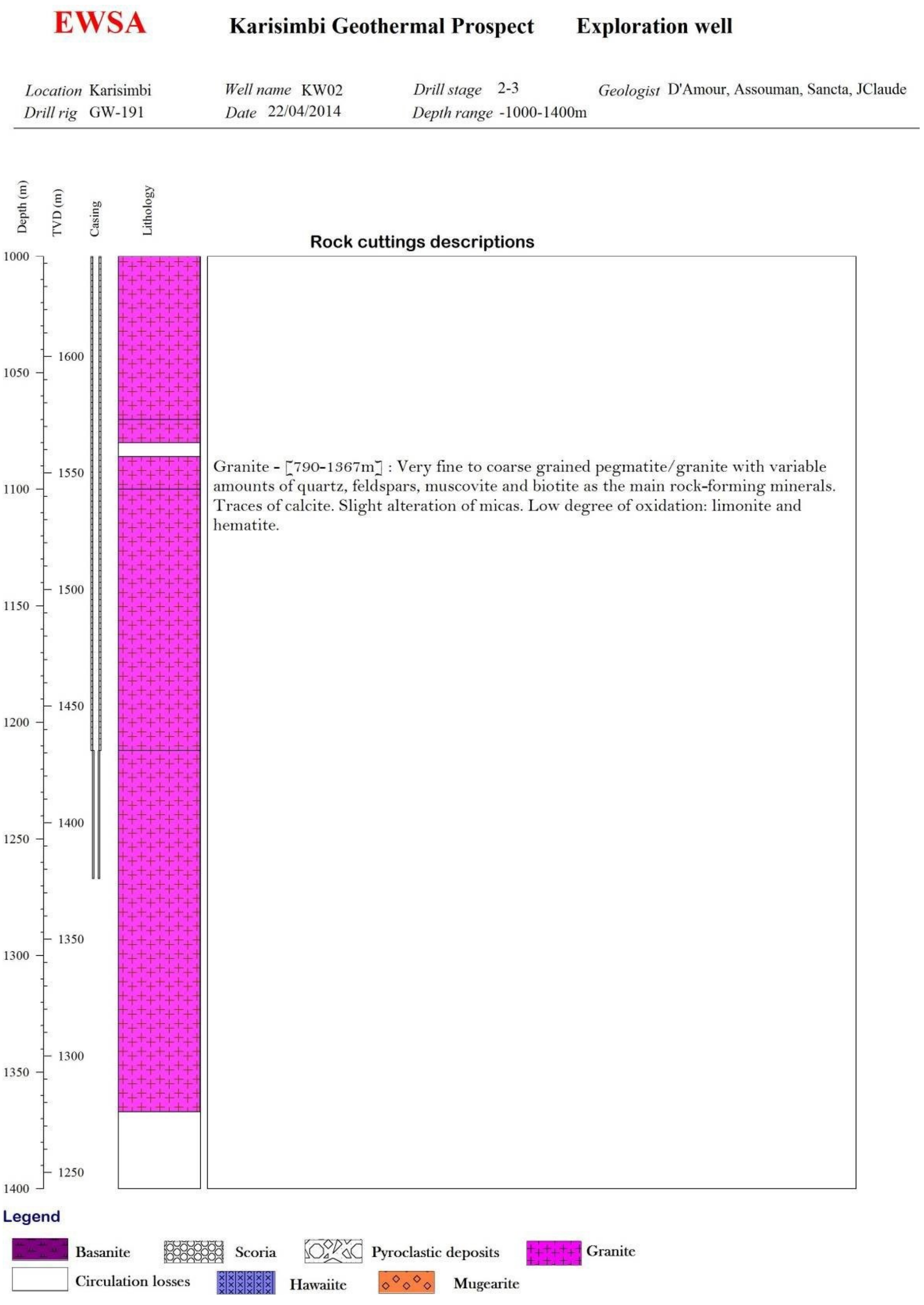

Figure 13: Stratigraphic log of well KW02 from 1000 to 1367m.

Figures 11, 12 and 13 illustrates the stratigraphy of well KW02.

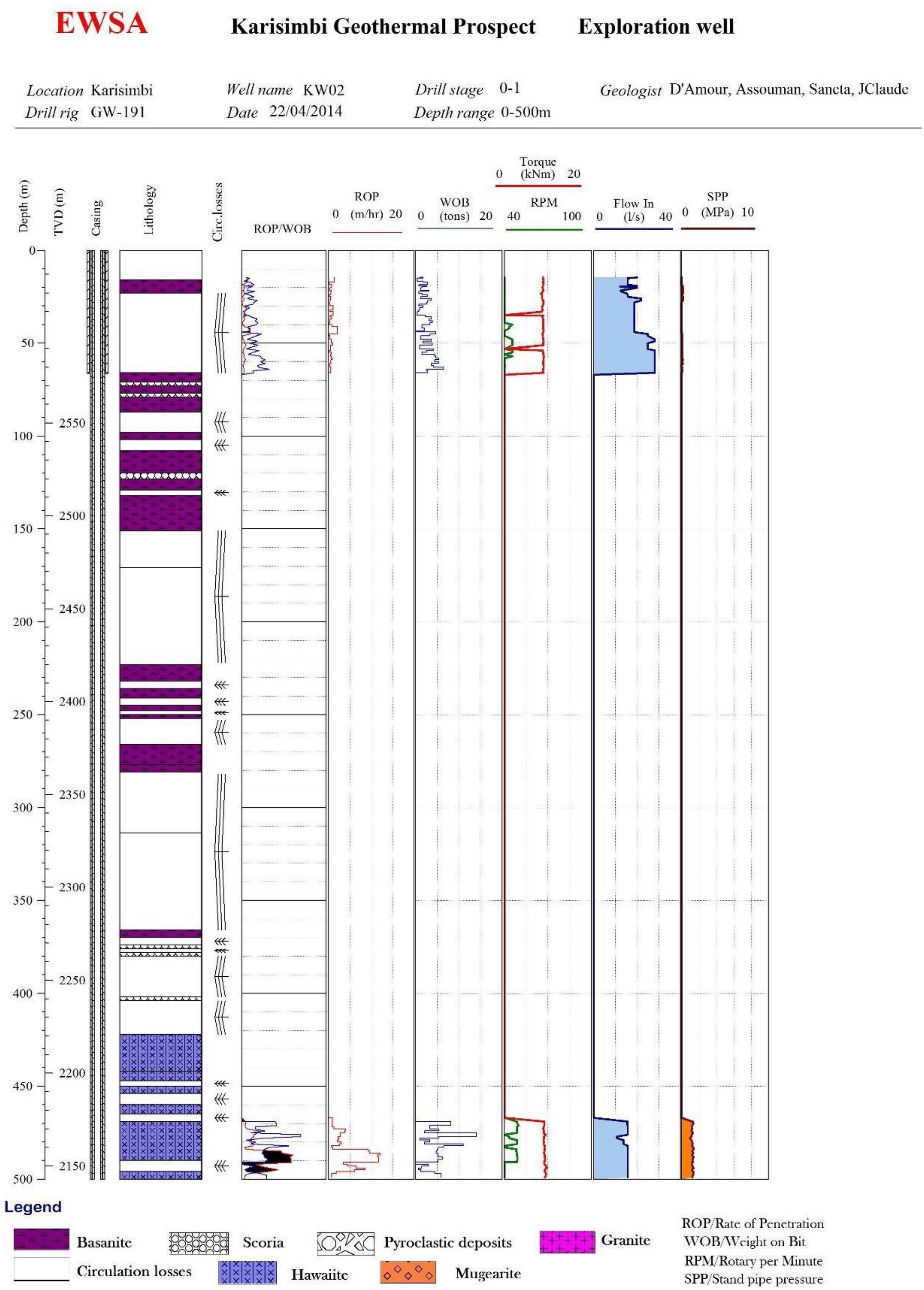

Figure 14: KW-02 logs: lithology and drilling parameters (0-500m).

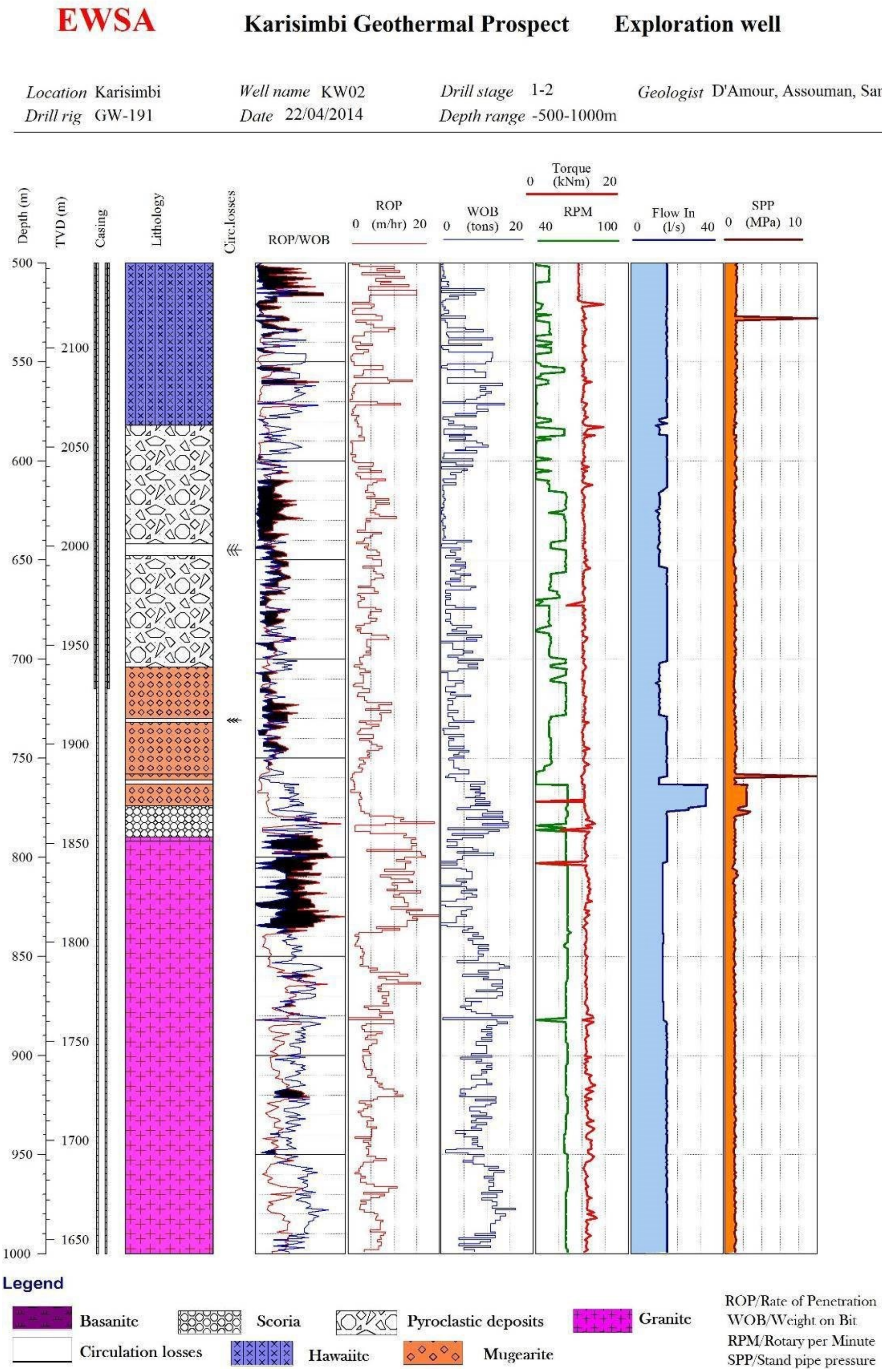

Figure 15: KW-02 logs: lithology and drilling parameters (500-1000m).

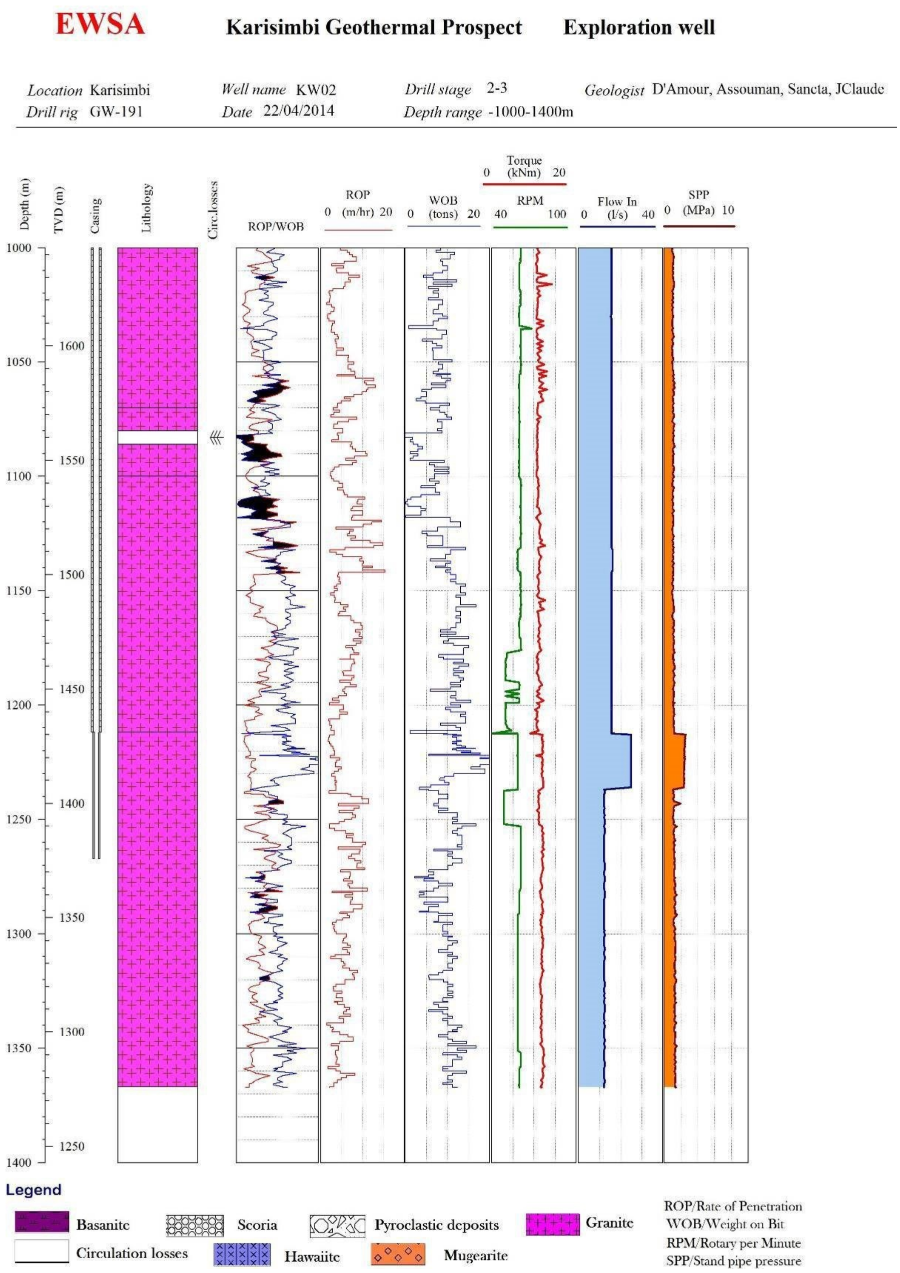

Figure 16: KW-02 logs: lithology and drilling parameters (1000-1367m).

5. HYDROTHERMAL ALTERATION: SECONDARY MINERALS, ALTERATION INTENSITY AND ALTERATION ZONING

Primary minerals observed in well KW-02 cuttings are pyroxene, olivine, plagioclases and biotite. The rocks are slightly oxidized and secondary minerals include yellowish limonite (16-102m interval), traces of zeolite dominated by cowlesite (16-71m, 442-642m and 758-774m intervals), various types and unidentified dirty clays (16-102m, 223-370m, 496-654m and 758-790m intervals), traces of Fe-oxides along the volcanic lava section and more pronounced between 72m and 102m, traces of calcite (98-129m, 496-582m, 654-790m), siderite (460-582m) and reddish hematite (450-454m).

Below 790m, the encountered rock type is a medium to coarse-grained pegmatitic granite in the upper section and a fine to medium-grained granite in the lower parts. The primary minerals are in various proportions quartz, feldspar, and micas. The rock is unaltered. Oxidation minerals, mostly limonite and hematite, were common along the 792-1367m section, showing yellowish to reddish colors.

Traces of calcite were seen sporadically from 792m to the bottom of hole. Pyrite and zeolite are absent. Clay minerals were also noted in the cuttings recovered from various depths, but especially in the lower part of the well from 792m to 1070 m depth.

Altered micas are recovered from 1100 m up to the bottom hole (1367m). The analysis of cuttings from well KW02 do not show any sign of hydrothermal alteration related to a high enthalpy geothermal system.

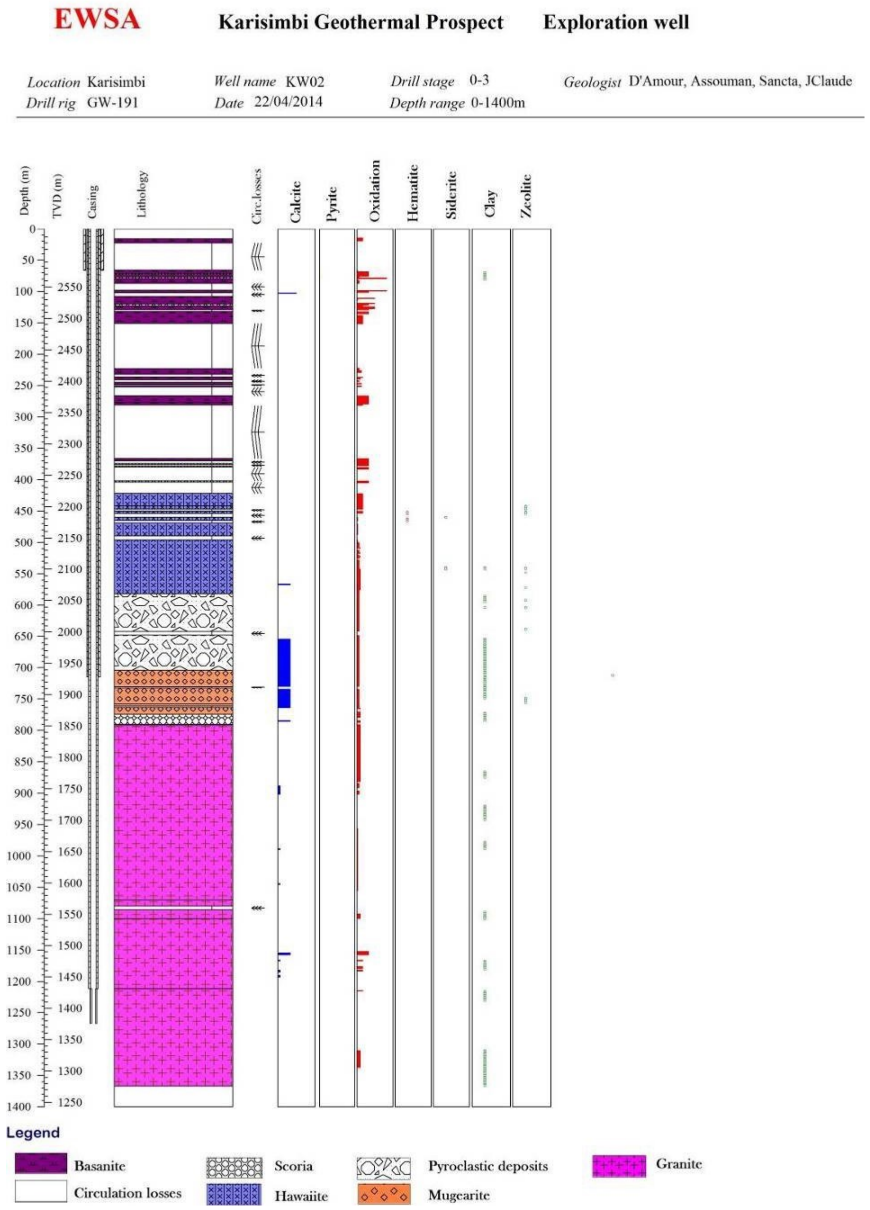

Figure 17: KW-02 Log: alteration minerals zoning.

6. DISCUSSION

6.1 Primary versus secondary minerals

Primary minerals in igneous rocks are minerals that form during the original solidification/crystallization of the rock. They are important for classification of the rock type drilled through. In contrast are secondary minerals which form at a later time after the host rock has gone through other processes which could change its chemical composition, processes such as metamorphism, weathering and hydrothermal alteration (Lapidus and Winstanley, 1987).

Due to high temperatures found in geothermal environment, high permeability and intense geothermal fluid activity, the primary rocks become unstable. Due to the interaction between hydrothermal fluids and the rocks through which they migrate, the rock's primary minerals undergo chemical reactions and readily alter into secondary minerals to become stable under the newly created natural conditions. The order of alteration depends on the Bowen reaction series.

Various methods and techniques are used in geothermal exploration to evaluate geothermal systems and understand geothermal reservoirs. Investigating hydrothermal alteration is one of the borehole geology methods that provides direct information about geothermal reservoirs due to geothermal fluids-host rocks interaction. This results in the formation of hydrothermal alteration minerals and some of which are known to form at specific and stable temperature regimes. Thus, they can provide a base for mapping the temperature regimes of a geothermal system. Identification and interpretation of these hydrothermal alteration minerals is an important part of geothermal exploration, as it gives insight into the present and past conditions of geothermal reservoirs.

The study of hydrothermal alteration on samples from rock formations drilled through well KW02 revealed a low temperature environment with a normal thermal gradient (30˚C/Km).

6.2 Secondary minerals

The properties of primary rocks control the speed, intensity and character of petro-physical alterations, therefore the chemical composition of the host rock determines the availability of components to form alteration minerals when subjected to factors that may cause disturbance in internal atomic properties.

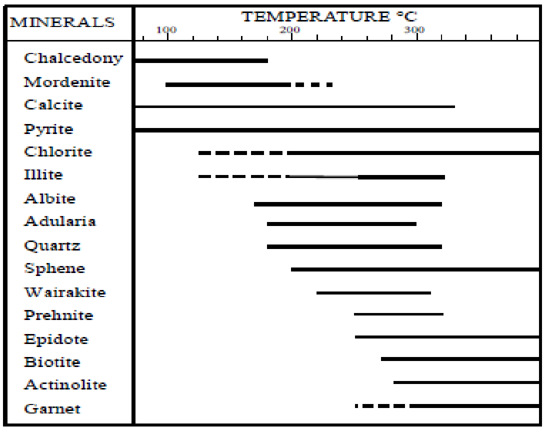

Figure 18: Common hydrothermal minerals used as geothermometers and their temperature stability ranges. Dotted sections indicate mineral outside their usual stability ranges (Reyes, 1990).

The first alteration in KW02 starts to occur smoothly in K-rich volcanic lavas and in granite where primary minerals are mainly quartz, feldspar, and sheet-silicates. The rock is rather slightly altered and highly oxidized as evidenced by the presence of limonite.

- Calcite was first noticed in small amounts at around 129 m. It increases considerably at around 1364 m. Some indications of vein fillings by Calcite can be seen, suggesting that there might be some fractures in the formation.
- Sporadic zeolites (cowlesite) may have been present at intervals from around 442m.
- Clay started to occur from 66m and become common around 790 m, sometimes with finely feathered appearance (perhaps suggesting some minor temperature increase).
- Oxidation minerals were noted in most of the samples, specifically limonite, hematite and siderite.

6.3 Alteration intensity

The presence of low temperature alteration minerals in well KW02 illustrates that the rock-forming minerals were slightly altered, mostly due to low density of fractures and therefore insufficient porosity.

The present minerals are either:

<u>Associated with cold water:</u>

Limonite is one of the minerals that form in cold groundwater systems above the geothermal system. It is a spherical mineral in shape and reddish in colour. It was found almost in all samples, from the surface down to the bottom of KW02.

Siderite is mainly found in fissures in basalts where hot water has flowed or at the margins of intrusions along with various ore minerals. It may be an important iron ore. It occurred here along with other minerals associated with oxidation. In the case of well KW02, it was found at two depth intervals, firstly above 260 m depth and secondly between 370 and 600 m depth.

<u>Or associated with temperature:</u>

Zeolite minerals formed by the chemical reactions between the different types of volcanic rocks and alkaline groundwater. The formation temperature of these minerals, with the exception of wairakite, ranges from about 30°C to about 200°C. Nevertheless, due to lack of advanced analysis equipment, it was impossible to identify the type of zeolite in well KW02.

Unidentified clay minerals are widely used as the best tool in geothermal exploration as temperature indicators. Clay minerals can be identified using a binocular microscope but, in some cases, it may be difficult to distinguish between them. Petrographically, these minerals can be distinguished as smectite, mixed-layer clays and chlorite based on their optical characteristics. X- ray diffraction (XRD) is, however, considered as the best method to distinguish between the three types of clay minerals. *Smectite* is the clay mineral with the lowest formation temperature which is likely present in KW02. It is generally formed from the alteration of glassy or primary minerals like olivine and also forms directly from water- host rock interaction, precipitating into voids and veins. It is an indicator of temperatures from 40 to 200ºC.

Calcite: Calcite formation is generally linked to boiling, dilution and condensation of carbon dioxide in geothermal systems. It can also form during the heating of cooler peripheral fluids (Simmons and Christenson, 1994). This mineral start to occur at around 790 m, increases considerably with the depth but remains in variable amounts down to the bottom. In binocular analysis calcite is identified using dilute hydrochloric acid. Furthermore, calcite crystals have obvious cleavage and can be distinguished from the plagioclase in this way. In thin section calcite occurs as radial, euhedral and platy. The mineral is aggressive as a replacement mineral, occurs mostly as vein and vesicle fillings.

6.4 Sequences of mineral deposition

The paragenetic sequence in mineral formation is an important concept in deciphering the detailed geological history of a geothermal system. In hydrothermal systems, mineral sequences are identified from crosscutting veins and amygdale infilling sequences through detailed microscopic studies of thin section as well as macroscopic field relations and, at times, fluid inclusions analyses (Lugaizi, 2011). Chemical composition analysis and petrographic characteristics of the minerals being deposited lead to an assessment of the chemical changes that have taken place. The mineral anomalies, where low- or medium temperature minerals appear with others which are stable at high temperatures are sometimes observed in mineral assemblages, possible transient or long term evidence of cooling in the geothermal reservoir. The time sequences in which fissures and voids are filled by mineral deposits permit us to evaluate changes in geothermal systems over time. In fractures, the generation of minerals was visible in thin section. An attempt to reconstruct the paragenetic scheme of hydrothermal alteration minerals using thin section analysis from various depths in a well shows that the hydrothermal system has evolved from low to high-temperature conditions. In well KW02, olivine and pyroxene appear first in the well and other primary minerals followed.

7. SUMMARY

Despite the presence of few traces of alteration minerals and dykes, there was no conclusive sign of the existence of an exploitable geothermal system in well KW02.

The relative scarcity of hydrothermally altered rocks did not allow the research work for any correlation with sub-surface conditions. This was attributed to the fact that the young mafic lavas covering the prospect are too permeable to allow any thermal waters that may exist in the sub-surface to reach the ground’s surface. However, the underlying pegmatitic granites and pegmatites, are permeable and fluids are able to move through joints and cracks in the rocks. Outcrops of granites and veins up to several centimeters wide are hosting secondary kaolinite, quartz and unknown black minerals, thus showing that they once suffered from magmatic and hydrothermal fluids (Browne, 2011).

Exploration drilling facilitates in identifying hydrothermal alteration minerals in the cuttings. Comprehension of the newly formed minerals may lead to understanding the characteristics of the thermal fluid. Furthermore, their genetic sequence elucidates on the changes taking place in the thermal system, thus relating geothermal alteration to the past and present conditions of the hydrothermal system. Applications of hydrothermal alteration in geothermal systems are mainly:

- Geothermometers and setting of the production casing;
- Permeability indicators;
- Chemical components of the geothermal fluid;
- Thermal history;
- Predicting scaling and corrosion tendencies of a well.

The study of hydrothermal alteration of the formations intercepted by drill hole KW02 involved three main techniques, namely:

Binocular microscope with which a number of hydrothermal alteration minerals were found, permitting the estimation of particular formation temperatures.

Petrographic microscope: Some minerals are too small to be seen in cuttings using a binocular microscope, either primary minerals or secondary minerals, thus leading to misunderstanding the types of rock-forming minerals. Thin section analyses give more refined results.

XRD. The efficient method of identification of alteration minerals is XRD. In geothermal analyses, it is mainly used for clay minerals and amphiboles. Geophysical borehole loggings, in addition to the analysis of cuttings, are quite useful in mapping geothermal aquifers and alteration zones.

The degree of hydrothermal alteration and amount of hydrothermal minerals formed in a geothermal reservoir depend largely on the following parameters:

- The type and permeability of the rock;
- The temperature and chemical composition of the fluid; and
- The duration of geothermal activity.

In all geothermal fields, proper understanding of hydrothermal alteration is important as it is this information that gives a general picture of the geothermal system, its history and possibly its future.

Hydrothermal minerals are useful geothermometers and, therefore, assist in determining the depth of the production casing while drilling. Additionally, these minerals are used in estimating fluid pH and other chemical parameters, as well as predicting scaling and corrosion tendencies of fluids, measuring permeability, possible cold-water influx and as a guide to the hydrology.

The minerals commonly used as geothermometers are zeolites, clays, epidote and amphiboles. Faults and fractures, are commonly the dominant physical controls on geothermal and mineral resources and are associated with hydrothermal alteration.

A microscopic study of cuttings is part of the geological and mineralogical research which aims towards a more thorough geological understanding of a geothermal reservoir but alone it could lead to more limited information. Additional measurements like temperature logging, resistivity logging etc., helps to confirm details of geothermal systems. One must appreciate that alteration portrays the long term condition of the geothermal system, while the present formation temperature shows only the last stage.

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