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SUB-SURFACE GEOLOGY AND HYDROTHERMAL ALTERATION OF WELLS LA-9D AND LA-10D OF ALUTO LANGANO GEOTHERMAL FIELD, ETHIOPIA

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ABSTRACT

Aluto Langano geothermal field is one of geothermally active area located in Aluto volcanic complex (AVC). To study the subsurface geology and mineralogy of wells LA-9D and LA-10D, various analyses have been conducted including: binocular microscope analysis, petrography microscope analysis, X-ray diffractometer analysis and Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES) analysis. Lithologies that are found in the study wells, identified with the aid of binocular microscopy and petrographic microscopy, are pyroclastics, silicic tuff and breccia, sediments, rhyolite, trachyte, basalt and ignimbrite, while ICP-OES analyses also led to the identification of very scarce and thin layers of trachyandesite, basaltic trachyandesite, trachydacite, basaltic andesite and andesite units. Hydrothermal alteration minerals are found as replacement of primary minerals and as fillings of veins and vesicles. Four alteration zones are recognized in both study wells, and include an unaltered zone, smectite zone, illite/chlorite zone and illite/chlorite/epidote zone. Eight feed zones (with one major and seven minor) were identified in well LA-9D and seven (one major with six minor) feed zones in LA-10D are observed. Most of the feed zones are located in fractured basaltic units. The highest temperature recorded was more than 300°C in well LA-9D below 1560m depth, and below 1600m in LA-10D, the recorded temperature indicated more than 300°C. Both wells appear to be in the upflow zone of the system.

1. INTRODUCTION

Aluto Langano geothermal field is one of geothermally active areas and the first geothermal field to be developed in Ethiopia. It is located within the Aluto volcanic complex (AVC) on the eastern margin of the Main Ethiopian Rift valley (Figure 1).In Aluto Langano geothermal field, eight exploration wells (LA- 1 to LA-8) were drilled in 1981 to 1986 with a maximum depth of 2500m, reaching temperature of up to 335°C (Teklemariam & Beyene, 2002).The first 7.2MW pilot power plant was installed by the Ethiopian Electric Power Corporation, and connected to the national power grid. It was started by four production wells (LA-3, LA-4, LA-6 and LA-8, and with one reinjection well, LA-7).

In 2013, expansion work in Aluto Langano geothermal field was started. The project is a collaboration of and financed by the Ethiopian government, the World Bank and the government of Japan (Tasew, 2015). The expansion is expected to produce 70MWe in two phases. Two exploration wells have been drilled, LA-9D and LA-10D, with the use of a rig owned by the Geological Survey of Ethiopia.

LA-9D and LA-10D are the first directional wells in Ethiopia with a depth of 1920m and 1940m, respectively, and were drilled within the Aluto volcanic complex. LA-9D was drilled directionally from 700m to N70°W and 51° inclinations; and LA-10D from 450m with a direction of N43°W and 25.75° inclination.

In this paper, the subsurface rock units were identified from directionally drilled wells such as LA-9D and LA-10D. The wells are located in the Aluto Volcanic Complex (AVC) together with six vertically drilled wells. Aluto Volcanic Complex (AVC) is a silicic peralkaline system and dominated by rhyolitic lava flows and domes, pumice cones and ignimbrite deposits (Electroconsult, 2016).

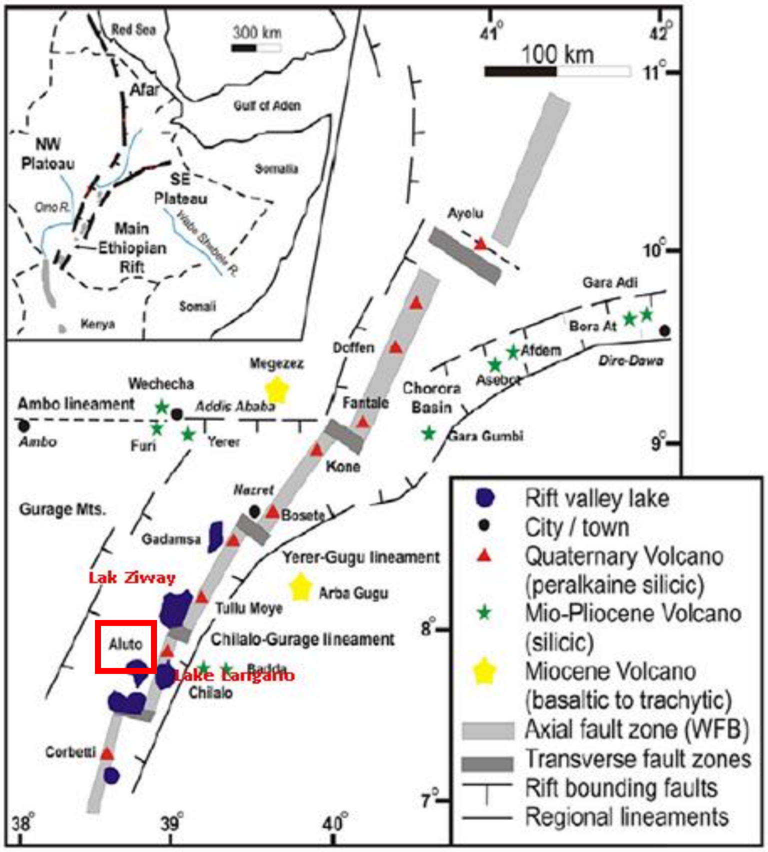

Figure 1: Location map of the Main Ethiopian Rift (MER) and Aluto Geothermal Field.

2. LITHOLOGY

The main lithology in wells LA-9D and LA-10D were identified by analyzing of drill cuttings which are pyroclastics, silicic tuff and breccia, sediment, rhyolite, trachyte, basalt and ignimbrite. These rocks are identified and confirmed by binocular and petrography microscope. Additionally, by ICP-OES analysis, rare transitional rock units were identified, such as trachyandesite, basaltic trachyandesite, trachydacite, basaltic andesite and andesite units. Most of the transition units show a range of medium to high alteration intensity, and theintermediate compositions could be the result of mixing end-members, in particular at deeper levels in the wells. Intermediate rocks are found as thin layers with intercalations of basalt and trachyte units. Ignimbrite is observed only in LA-10D wells. This might be due to the shallower depth of well LA-9D compared to the LA-10D well (Figures 2 and 3).

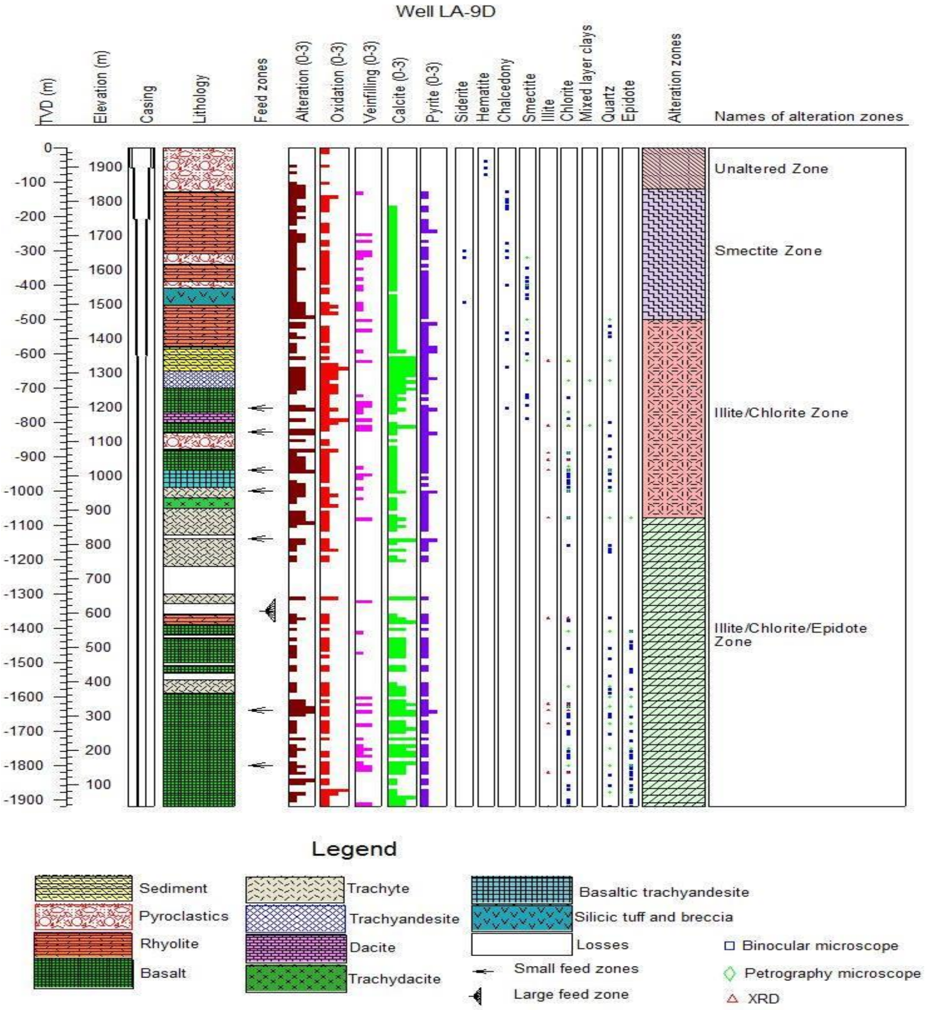

Figure 2: Lithology, alteration minerals and alteration zones of well LA-9D

3. HYDROTHERMAL ALTERATION MINERALOGY

Hydrothermal alteration is seen as change in mineralogy, texture and chemistry of rocks due to thermal and environmental changes facilitated by geothermal fluids and gases. The intensity of the changes also depends on texture and time. The factors that control alteration in geothermal systems are temperature, rock type, permeability, fluid composition and the duration of fluid-rock interactions (Reyes, 2000).

Various hydrothermal alteration minerals are observed in both LA-9D and LA-10D wells. The sequence of the alteration mineral deposition within the wells ranges from low-temperature to high-temperature minerals. The alteration minerals were found as replacement of primary minerals and as fillings of micro fractures, veins and vesicles in the rock units. The common primary minerals that are found in the study wells are volcanic glass (mostly found in pyroclastics, silicic tuff and breccia, to a lesser extent in rhyolite); scarce olivine is noted in the wells; pyroxene (mostly seen in basaltic rock units); sanidine (in trachytic units); plagioclase is the dominant primary mineral in most of the basaltic rock units, found as phenocrysts and in groundmass; and oxide minerals found together with alkali feldspar in groundmass.

Secondary hydrothermal alteration minerals were identified in the study wells. The minerals in the wells range from low-temperature minerals, such as chalcedony, siderite, haematite and smectite, to moderately high-temperature alteration minerals, such as mixed layer clay (MLC), illite, quartz, chlorite, epidote and actinolite. An abundance of calcite and pyrite is observed throughout the wells. It indicates that calcite and pyrite form at widely varying temperature and pressure. The large quantity of calcite, pyrite and quartz found in the bottom parts of the wells indicates the presence of permeable zones in this part of the system. Epidote is a key index mineral related to temperature and fluid composition in geothermal systems. It is found together with quartz, illite and chlorite. Low-temperature minerals are in the upper 500m of the wells, while the high-temperature minerals were observed below 500m depth in both the study wells (Figure 2 and 3).

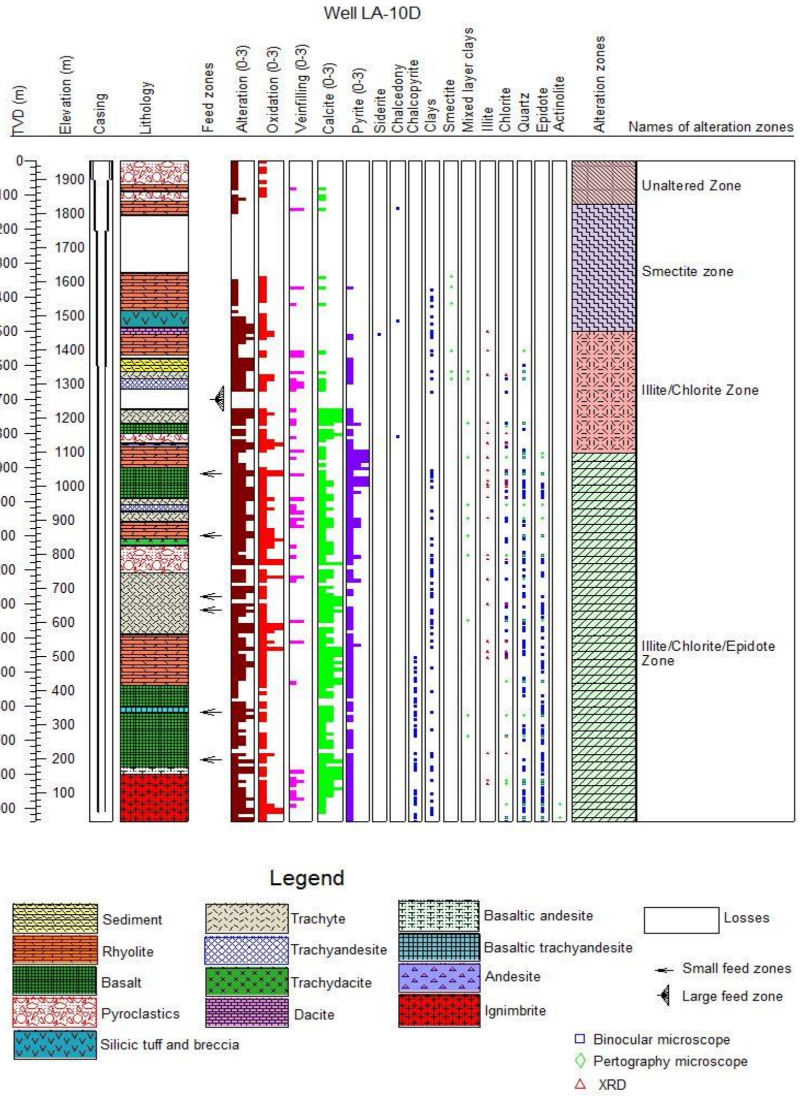

Figure 3: Lithology, alteration minerals and alteration zones of well LA-10D

According to the abundance of secondary alteration minerals, the wells are divided in to four alteration zones. Unaltered zone (>50°C) is situated in well LA-9D and LA-10D at a depth of 0-120m and 0-130m, respectively. Smectite zone (75-150°C) is at 120-500m in LA-9D and 130-500m in LA-10D. Illite/chlorite zone (<200°C) is located 500-1020m in LA-9D and 500-860m in LA-10D. The last alteration zone is the illite/chlorite/epidote zone (<240°C), which is observed at 1080-1920m in LA-9D and 860-1940m in LA-10D. This division into alteration zones is defined by the first appearance of hydrothermal alteration minerals (Figure 2 and 3). The sequence of mineral deposition within wells shows that the hydrothermal system evolved from low to high temperature.

4. FEED ZONES

Feed zones are located in the water-saturated regions in the subsurface. The movement of the subsurface water is controlled by permeability, porosity, temperature, types of rock formations and the nature of recharge. According to Reyes (2000), feed zones are associated with structural formations such as faults, fractures, joints, lithological contacts and paleosoils in geothermal systems. Abundance of calcite and pyrite can be indicators of feed zones. Additionally, increased intensity of alteration can be an indicator of a feed zone as local increase in alteration may imply more water-rock interaction. Alteration intensity and permeability are directly proportional. When alteration intensity increases, permeability also increases. The feed zones in these wells are identified on the basis of temperature recovery profiles and the intensity of alteration, abundance of calcite and pyrite, lithological contacts and circulation losses.

In well LA-9D seven small feed zones were located at a depth of 760m, 830m, 940m, 1000m, 1140m, 1640m, 1800m, while large feed zone is encountered at depth of 1350m.

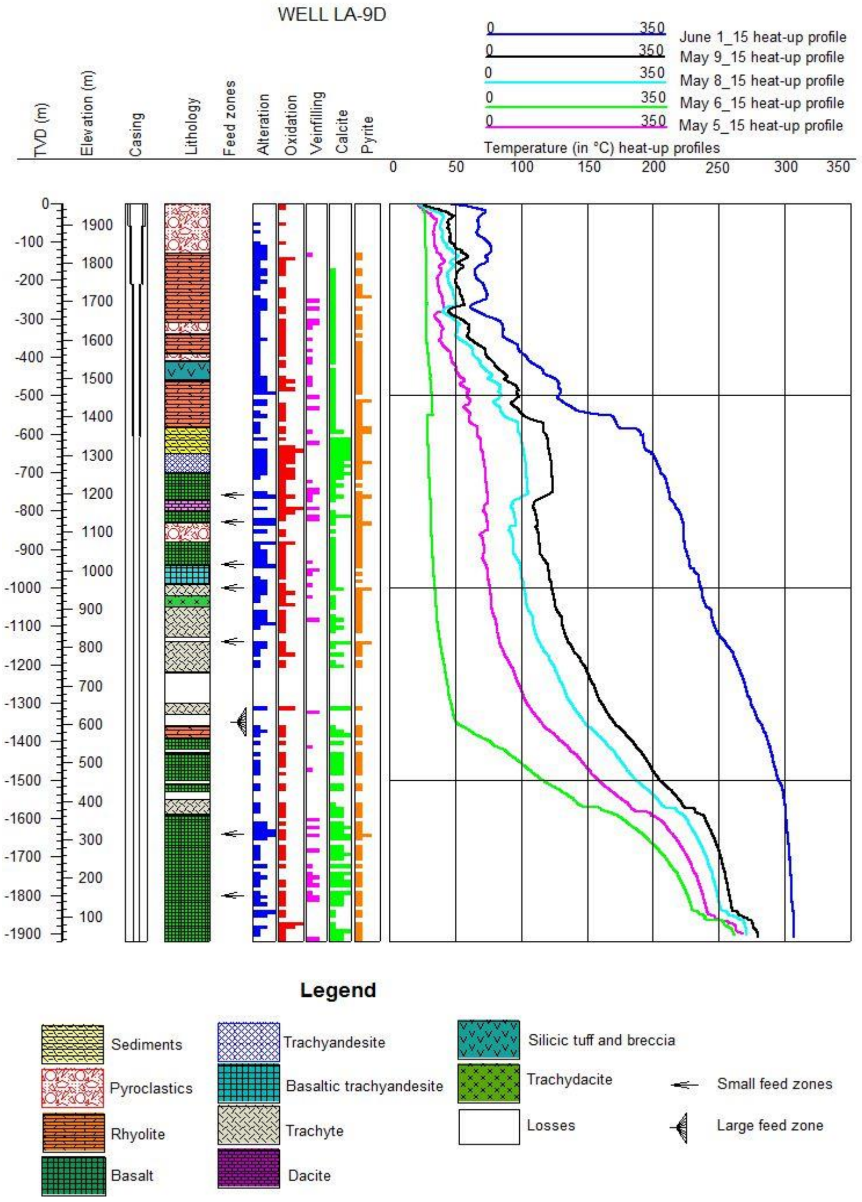

Figure 4: Feed zones in well LA-9D inferred from loss of circulation, temperature logs, alteration intensity and abundance of alteration minerals.

The feed zones were identified through temperature recovery measurements which were taken in May 5, 6, 8, 9, 10 and June 1, 2015 (Figure 4). The first three small feed zones (760m, 830m, and 940m) and the last two small feed zones (1640m, 1800m) were located in units of basalt. The alteration intensity was high, while a medium to low abundance of calcite and pyrite were observed. The feed zone at 1000m was located at boundary contact between basalt and basaltic trachyandesite where the alteration intensity was moderate and the abundance of calcite and pyrite was low. At 1140m and 1350m feed zones were encountered with circulation losses.

In well LA-10D, six small feed zones were located at 920m, 1160m, 1280m, 1320m, 1620m, 1760m and one large feed zone at 700m (circulation loss zone) (Figure 5). The small feed zones at 920m, 1100m, 1280m, and 1320m were located in trachyte units, while the feed zone at 1620m depth is the contact between a unit of basaltic trachyandesite and basalt. The feed zone at 1760m depth is located in a basaltic unit. All feed zones are associated with high alteration intensity and medium to high abundance of calcite and medium to low abundance of pyrite. The feed zones were identified through temperature recovery measurements that were taken on October 5, 6, 24 and November 18, 19, 28, 2015 (Figure 5).

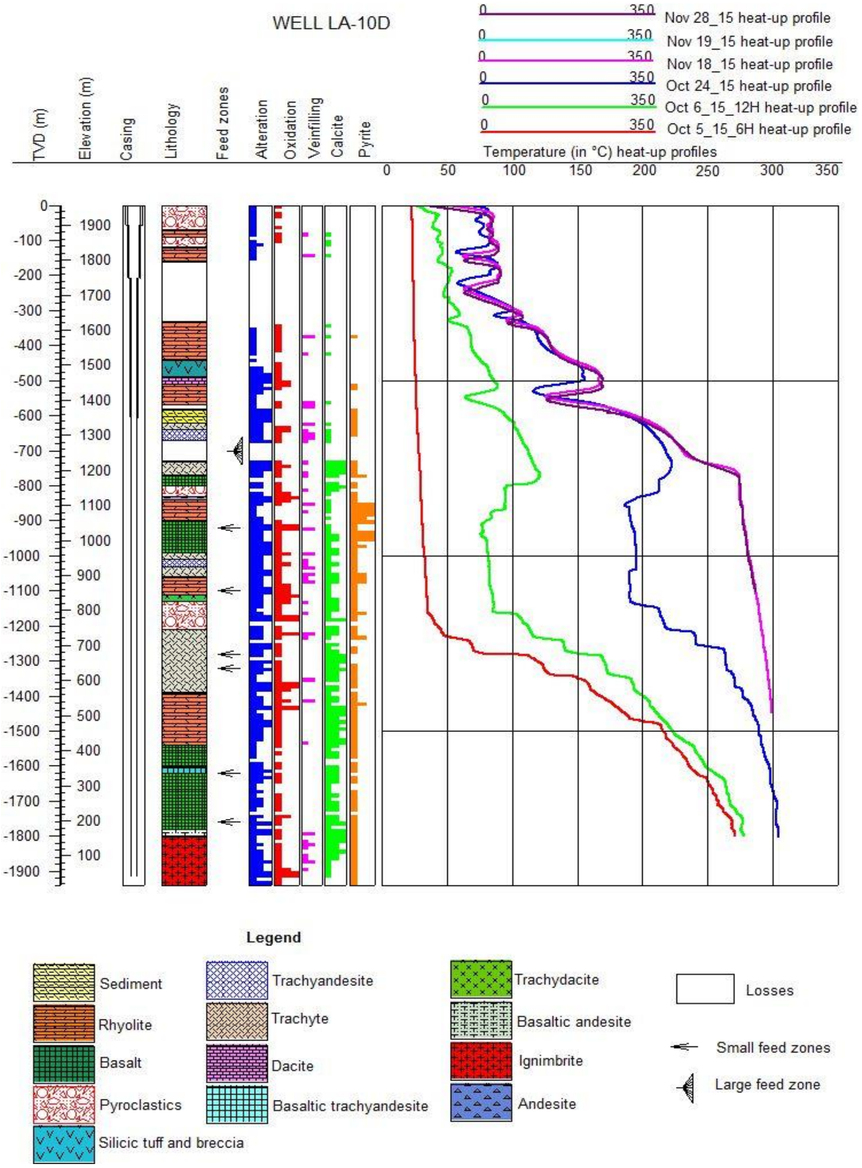

Figure 5: Feed zones in well LA-10D inferred from loss of circulation, temperature logs, alteration intensity and abundance of alteration minerals.

5. TEMPERATURE DISTRIBUTION AT ALUTO LANGANO GEOTHERMAL FILED

In Aluto Langano geothermal field, a high-temperature anomaly is located in the central part of the field, where wells LA-3, LA-6, LA-9D and LA-10D are located. The highest recorded temperature is about 335°C at the bottom of LA-3 and LA-6 at an elevation of 500m.b.s.l. (Ernst & Nihon, 2010). The zone with the highest temperature in the wells is located within the basalt formation.

The wells that are located outside the up-flow zone, such as LA-4, LA-5, LA-7 and LA-8, (Figure 6) show temperature inversion at a depth of 1600-2014m, 1000-1848m, 1600-1900m and 2150-2400m, respectively. In well LA-7, temperature decreases to 140°C in the inversion zone at 1900m depth, which indicates cold inflow (Electroconsult, 1986). No temperature inversion is recorded in wells LA-3, LA-6, LA-9D and LA-10D, which are located at the main up-flow zone of the geothermal field.

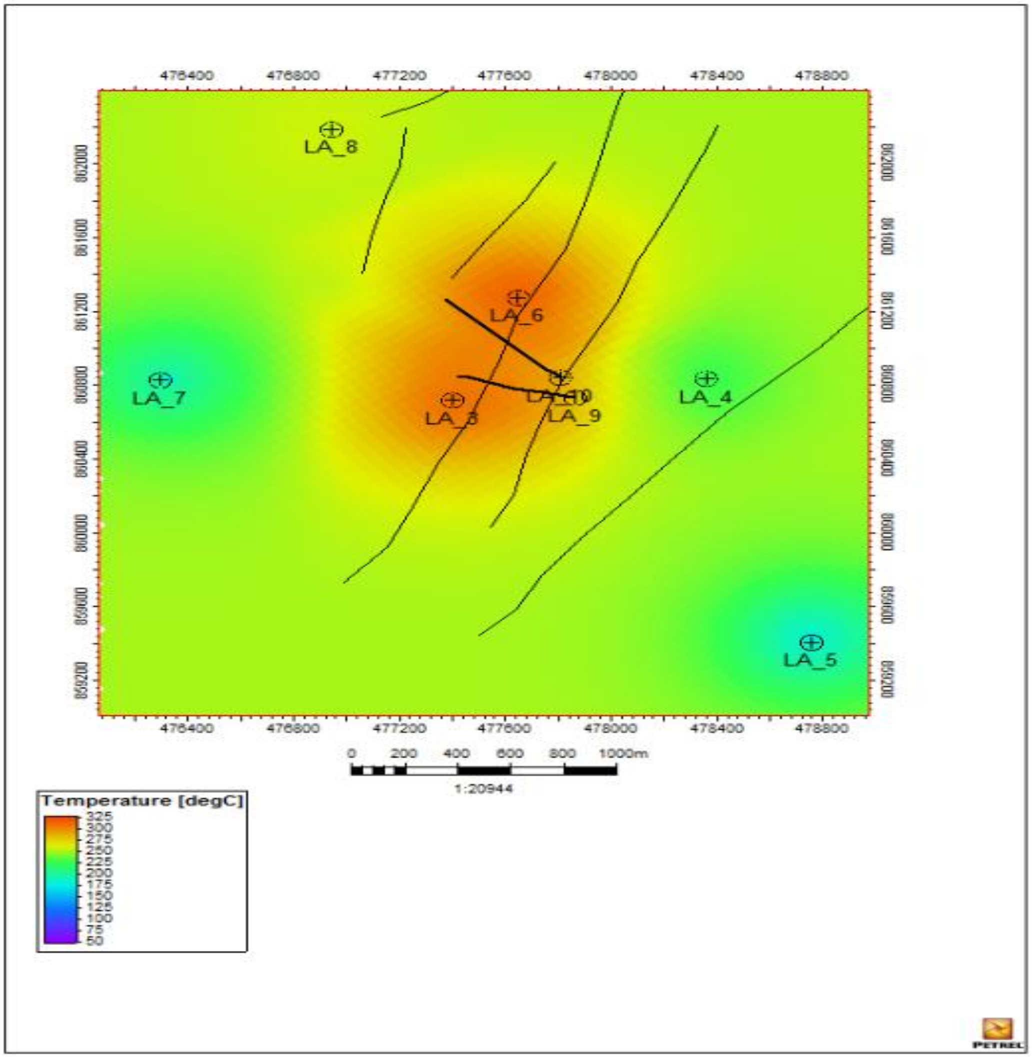

Figure 6: Temperature distribution in Aluto Langano geothermal field at 800m.a.s.l. (black lines represent faults)

The temperature decrease towards the east, the south and the western part of the Aluto Langano area gives a mushroom-like shape to the thermal dome. In the upper part of LA-9D and LA-10D wells from surface to 550m to 450m, respectively, the temperature is below 150°C. The temperature increases with depth in well LA-9D and at 1120-1560m depth temperature increases from 250°C to 300°C, while temperature is higher than 300°C below 1560m depth. The highest temperature recorded in well LA-9D is 307°C at 1909 m. In well LA-10D, temperature increases from 250°C to 300°C between 740 to 1600m. Below 1600 m depth, temperature is higher than 300°C, but the highest temperature measured in the well is 305 °C at 1801 m depth.

In general, the highest temperature is recorded in the central part of the Aluto Langano field, while a decrease of underground temperature is observed towards eastern and western parts of the field. It seems to indicate that there may be lateral outflow along NNE trending faults and also that the faults that are aligned in NNE-SSW and NW-SE direction surrounding the main up-flow of the field acts as a hydrological barrier.

6. FORMATION TEMPERATURE VS HYDROTHERMAL ALTERATION MINERAL ZONATIONS

In geothermal system, temperature increases with depth in the up-flow zone of the geothermal system. However, in the periphery and in out-flow zones of geothermal reservoirs, temperature inversion can be observed, but cold recharge can cause temperature inversion.

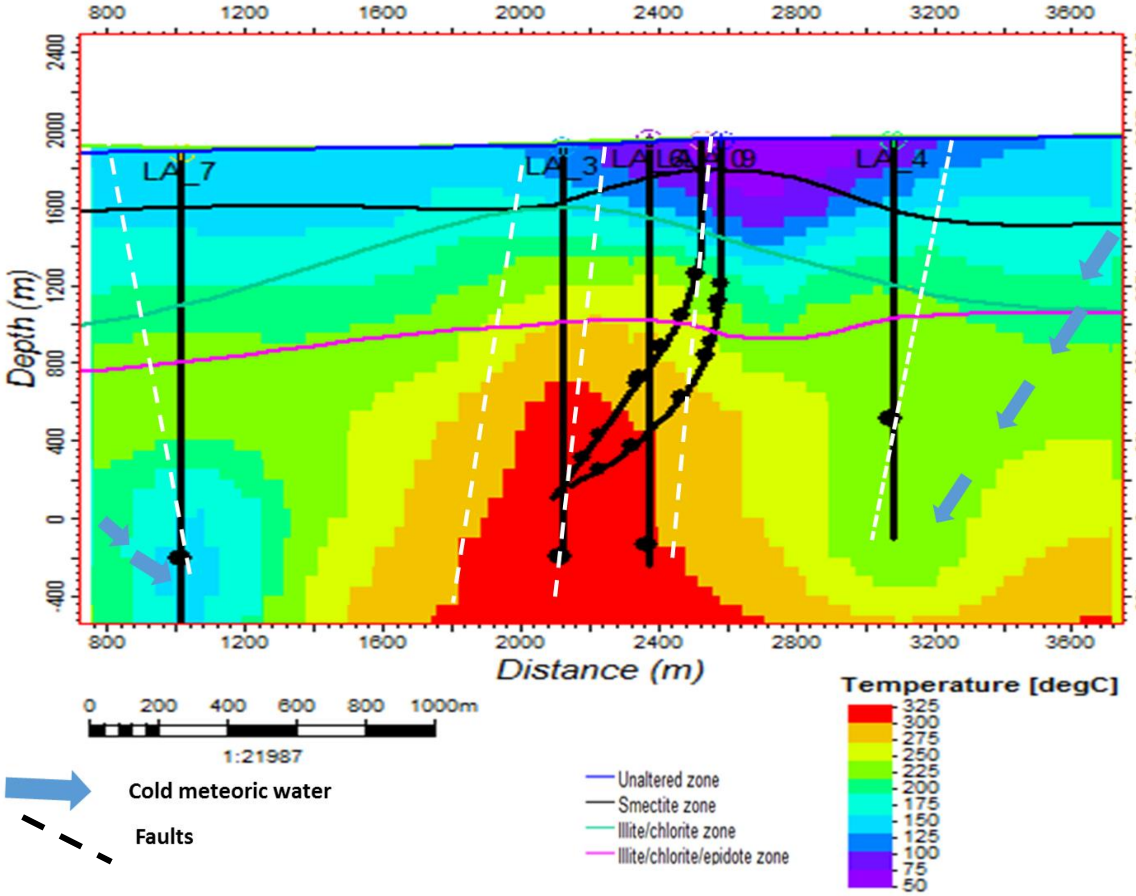

Figure 7: Conceptual model of Aluto Langano field in relation to alteration mineral zones and formation temperatures (black dote represent feed zones).

The temperature recorded in the upper part of the wells from surface to 2000-1840m.a.s.l is <50°C and correlates with the unaltered zone. Temperature is slowly increasing below the unaltered zone, but the temperature change varies from well to well (Figure 7). The highest temperature at this depth is observed in wells LA-3 and LA-6, which are located above the up-flow zone. At 1840 -1260m.a.s.l. temperature is 75-150°C and the formation is characterized by slight to moderate alteration of minerals.

The smectite alteration zone is dominant at 120-500m depth, which is consistent with the observed temperature. According to the information from formation temperature this zone represents the cap rock of the geothermal system. Below the smectite zone, temperature increases from 180-250°C at a depth interval of approximately 1200 to 960m.a.s.l in the wells. In this temperature and depth interval, illite and chlorite are the dominant hydrothermal alteration minerals. The top of the illite/chlorite zone is marked with a green line zone (Figure 7). High temperature of >250°C are recorded in wells LA-3, LA-6, LA-9D and LA-10D within the illite/chlorite/epidote zone.

The illite/chlorite/epidote zone is found at similar depth in wells LA-3 to LA-10, but it appears below 960m.a.s.l to the bottom of these wells. The illite/chlorite/epidote zone is marked by the first appearance of epidote. Temperature in wells LA-4, LA-5 and LA-7 is <250°C. In these wells, the high-temperature alteration minerals (illite/chlorite/epidote) were observed, which implies that higher temperature has existed in the past in this area of the geothermal reservoir.

7. CONCLUSION

- The major rock units identified in the study wells LA-9D and LA-10D are pyroclastics, silicic tuff and breccia, sediment, rhyolite, trachyte, basalt and ignimbrite.
- The petrochemistry analysis shows that the rock composition in LA-9D and LA-10D ranges from basalt through intermediate rocks to trachyte or rhyolite compositions. Scarcities of transitional rock units are noted. Intermediate compositions should be noted with caution as they may possibly be caused by mixing of drill cuttings in the wells.
- Low to high temperature hydrothermal alteration minerals are observed in the study wells. The common alteration minerals are siderite, haematite, chalcedony, smectite, quartz, mixed layer clays, illite, chlorite and epidote.
- Four alteration zones are identified by the abundance and first appearance of alteration minerals, namely an unaltered zone, smectite zone, illite/chlorite zone and illite/chlorite/epidote zone.
- Alteration minerals, depositional sequences and formation temperature indicated that the wells (LA-9D and LA-10D) are heating up.
- The abundance of calcite and pyrite is observed throughout the wells, indicates the presence of permeable zones in the well.
- Eight feed zones were identified in well LA-9D and seven in LA-10D, which are related to lithological boundaries within the basalt formation and between the basalt and ignimbrite formation, as well as faults related to the NNE trending WFB.
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8. RECOMMENDATIONS

Detailed fluid inclusion studies need to be carried out, specifically in wells LA-9D and LA-10D to supplement information about alteration and measured formation temperatures, to understand the evolution of the geothermal system.

Detailed surface and borehole petrochemical studies in Aluto Langano geothermal field are highly recommended to understand the geochemical evolution of the rocks.

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