

Distribution of Temperature and Hydrothermal Alteration Minerals in Aluto Langano Geothermal Wells

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ABSTRACT

In Aluto Langano geothermal field, the high-temperature is recorded in the central part of the field, where wells LA-3, LA-6, LA-9D, and LA-10D are located, the measured temperature is about 335°C. However, a decrease in underground temperature is observed towards the eastern and western parts of the field. The wells that are located in low temperatures, such as LA-4, LA-5, LA-7, and LA-8, show temperature inversion at depth. From the up-flow zone, the high-temperature geothermal fluid travels along the faults that strike NNE-SSW, which correspond to the alignment of Wonji Fault Belt. The faults that are aligned in NNE-SSW and NW-SE direction surrounding the main up-flow of the field act as a hydrological barrier. Hydrothermal alteration minerals in the wells are found as replacement of primary minerals and as fillings of microfractures, veins, and vesicles in the rock units. The sequence of the alteration mineral deposition within the wells ranges from low-temperature to high-temperature minerals. 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. Epidote is a key index mineral related to temperature and fluid composition in geothermal systems; it is found together with quartz, illite, and chlorite. Depending on the distribution of hydrothermal alteration minerals and formation temperature, four alteration zones have been identified. These are unaltered zones, smectite zone, illite/chlorite zone, and illite/chlorite/epidote zone.

1. INTRODUCTION

The Aluto Langano Geothermal Field is located about 200 km south of Addis Abeba, the capital city of Ethiopia. It is located within the Aluto volcanic complex (AVC) on the eastern margin of the Main Ethiopian Rift valley in the Lake District between Lake Ziway, to the north, and Lake Langano, to the south (Figure1). This is one of the geothermally active areas and the first geothermal field to be developed. From 1981 to 1986, eight exploration wells (LA- 1 to LA-8) were drilled with a maximum depth of 2,500 m, reaching a temperature of up to 335°C (Teklemariam & Beyene, 2002). By using four production wells (LA-3, LA-4, LA-6 and LA-8, and with one reinjection well, LA-7) the first 7.2 MW pilot power plant was installed by the Ethiopian Electric Power Corporation, and connected to the national power grid. In 2013, expansion work in Aluto Langano geothermal field started by drilling two exploration wells (LA-9D and LA-10D) to produce 70 MWe in two phases (Tasew, 2015).

The Aluto Langano Geothermal Field found within the Aluto volcanic complex (AVC). AVC situates on the eastern side of the Central Main Ethiopian Rift (CMER) floor, which covers an area of about 100 km². It reaches an elevation of 2328 m.s.l. and rises about 700 m above the rift floor (Teklemariam, 1996). AVC is dominated by a ~14 km-wide and 700 m-high edifices composed of a thick pile of rhyolitic lava flows and domes, pumice cones, and ignimbrite deposits (Hutchison et al., 2015). The Aluto caldera is extended in the WNW direction with a size of 6 km by 9 km (Kebede et al., 1984) and covered by alluvial sediments. According to Lloyd (1977), pyroclastics and rhyolites erupted through vents or centers, which are controlled by the Wonji fault belt (WFB) trending in the NNE direction. The initial Aluto volcanic activity is estimated to have taken place between 150 and 130 ka (Electroconsult, 2016). In the northwest of the complex, there is a significant number of smaller volcanic vents and domes located. The Aluto volcanic complex appears to be limited to the west by one of the numerous WFB faults and to the east by a series of step faults. These progressively rise above the rift floor to form the Eastern Escarpment (Hutchison et al., 2015).

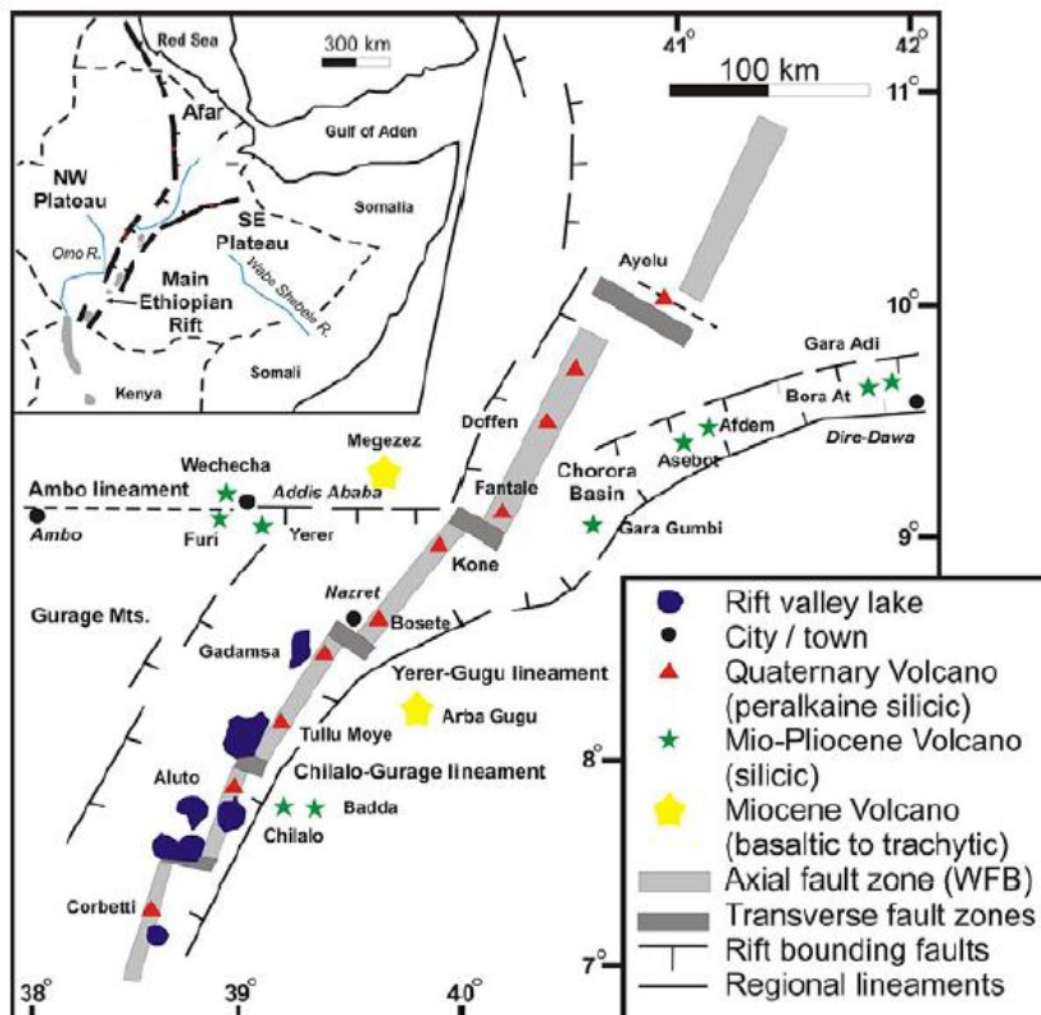


Figure 1: Location map of the Main Ethiopian Rift (MER) and Aluto Geothermal Field.

2. GEOLOGY

The surface geology of the Aluto-Langano geothermal field is mainly volcanic, along with some lacustrine sediments. The volcanic activity started around 150 ka ago with an explosive eruption of ignimbrite (Electroconsult, 2015) and with the build-up of a rhyolite flow dome, which was interrupted by explosive pyroclastic pumice eruptions and a major caldera-forming a pyroclastic eruption (Ernst & Nihon, 2010). Post-caldera collapse rhyolite flows, domes with minor pyroclastic products, formed along the NE-SE segment of the Aluto caldera rim on a basement of pumiceous ignimbrites and older rhyolite. The area is affected by the Wonji Fault Belt (WFB), which is trending NNE-SSW with several faults. A number of a complex set of intersecting structural lineation, discontinuities, and open fissures located and trending in NNE-SSW, NW-SE, N-S, NE-SW, and E-W direction. NE trending structural alignments intersects the eastern part of Aluto Langano, and the western part has NNE trending fracture lines. □

The subsurface lithological sequences encountered in all the wells are very similar, except for thickness variations of individual units between the wells. The common lithological units are ignimbrite, basalt, rhyolite, sediments, and pyroclastics (figure 2). According to Kebede et al. (2002), the oldest rock unit in Aluto Langano is the tertiary ignimbrite formation that is exposed in the eastern rift escarpment. It has a thickness of up to 700 m in most of the wells. The Tertiary ignimbrites are overlapped by alkali to transitional basalts. Lacustrine Sediment is observed in wells LA-2, LA-7, LA-8, LA-3, LA-6 and LA-10D, and covers a very wide portion of the Aluto Langano area. It is thinner towards the east, being absent in wells LA-4 and LA-5 and thicker in the western part (Teklemariam et al., 1996). The Aluto volcanic products are encountered in all wells. They are silicic in composition, and consist of a complex sequence of alternating pyroclastics, such as pumice falls, surge, pumice flows, tuff breccia with very viscous lava flows and domes (Electroconsult, 1986). The formation is found in the upper part of almost all deep wells. □

Hydrothermal manifestations on the AVC include hot springs, fumaroles, and hot and warm ground. According to Electroconsult (2015), all the fumaroles are located over 1,700 m.a.s.l. and the hot springs are sited below 1,700 m.a.s.l. Some of the boiling thermal springs are located south of the volcanic complex near the shore of Lake Langano and on an island in Oitu bay in Lake Langano, trending NW-SE. There are also abundant small low-pressure fumaroles clustered mostly in the eastern and southern parts of the volcanic complex, and a few of them scattered in the western part of the complex (Kebede et al., 1984) following the trend of E-W and N-S alignments. Some areas are covered by hot/warm grounds together with fumaroles.

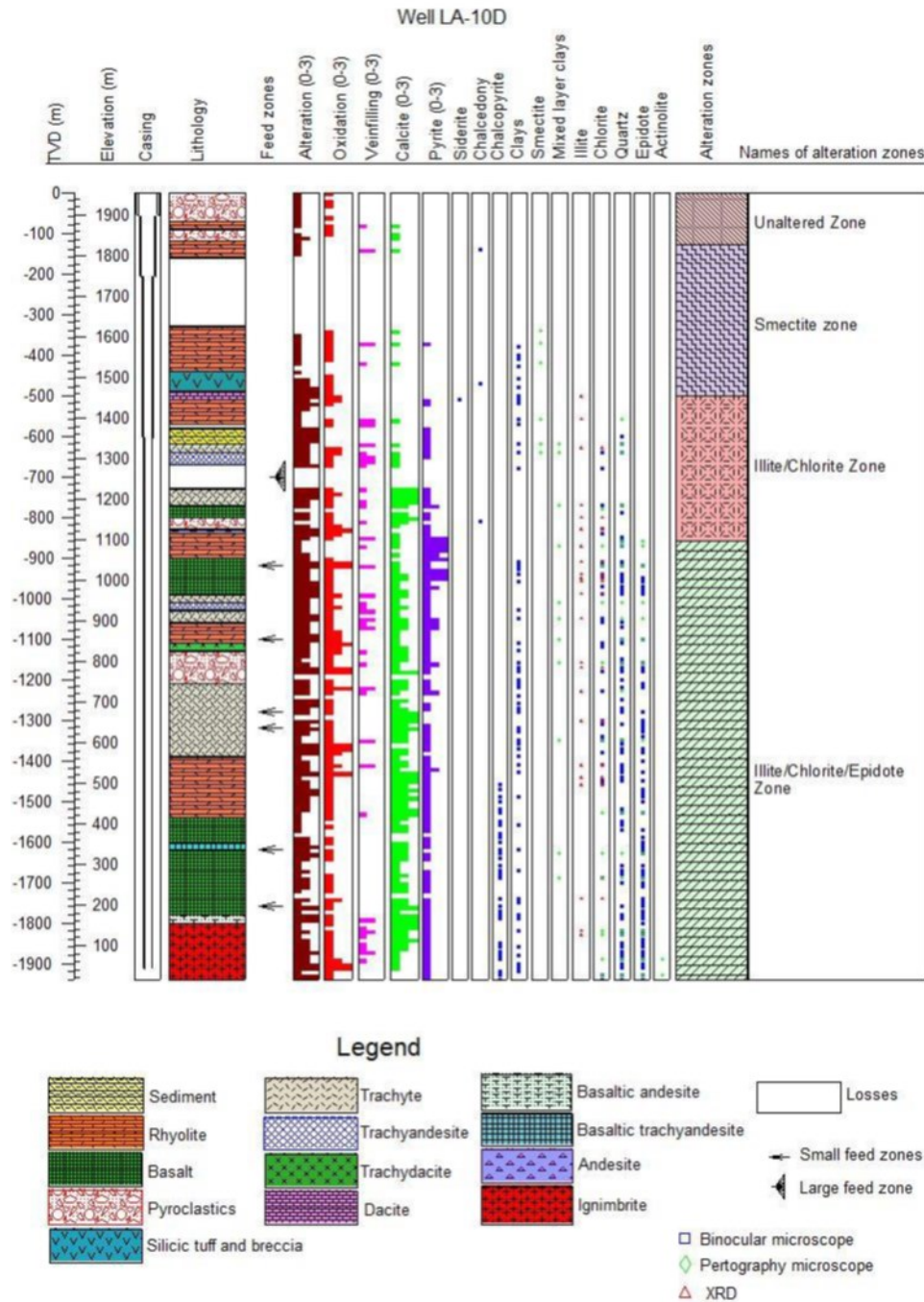


Figure 2: Subsurface lithological unit of well LA-10D □

3. TEMPERATURE DISTRIBUTION

In the 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 in LA-6 at an elevation of 500 m b.s.l. within the basalt formation (Ernst & Nihon, 2010). Wells LA-4, LA-5, LA-7 and LA-8 are located outside the up-flow zone, (Figure 3) shows temperature inversion at a depth of 1,600-2,014 m, 1,000-1,848 m, 1,600-1,900 m and 2,150-2,400 m, respectively. In well LA-7, temperature decreases to 140°C in the inversion zone at 1900 m depth, which indicates cold inflow (Electroconsult, 1986). In wells LA-9D and 10D, the temperature increases more than 300°C below 1,560 m depth. The temperature decreases towards the east. The south and the western part of the Aluto Langano area gives a mushroom-like shape to the thermal dome. From the up-flow zone, the high-temperature geothermal fluid travels along with it (the fault that cuts well LA-3 and LA-6) and the faults (Figure 3&5) that strike NNE-SSW. These faults are located to the west of the LA-3 and LA-6 wells. The NNE-SSW strike of the faults corresponds to the alignment of Wonji Fault Belt.

In the central part of the field, high temperature is recorded. A decrease in underground temperature is observed towards eastern and western parts. It seems to indicate that there may be lateral outflow along NNE trending faults of the Wonji Fault Belt 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.

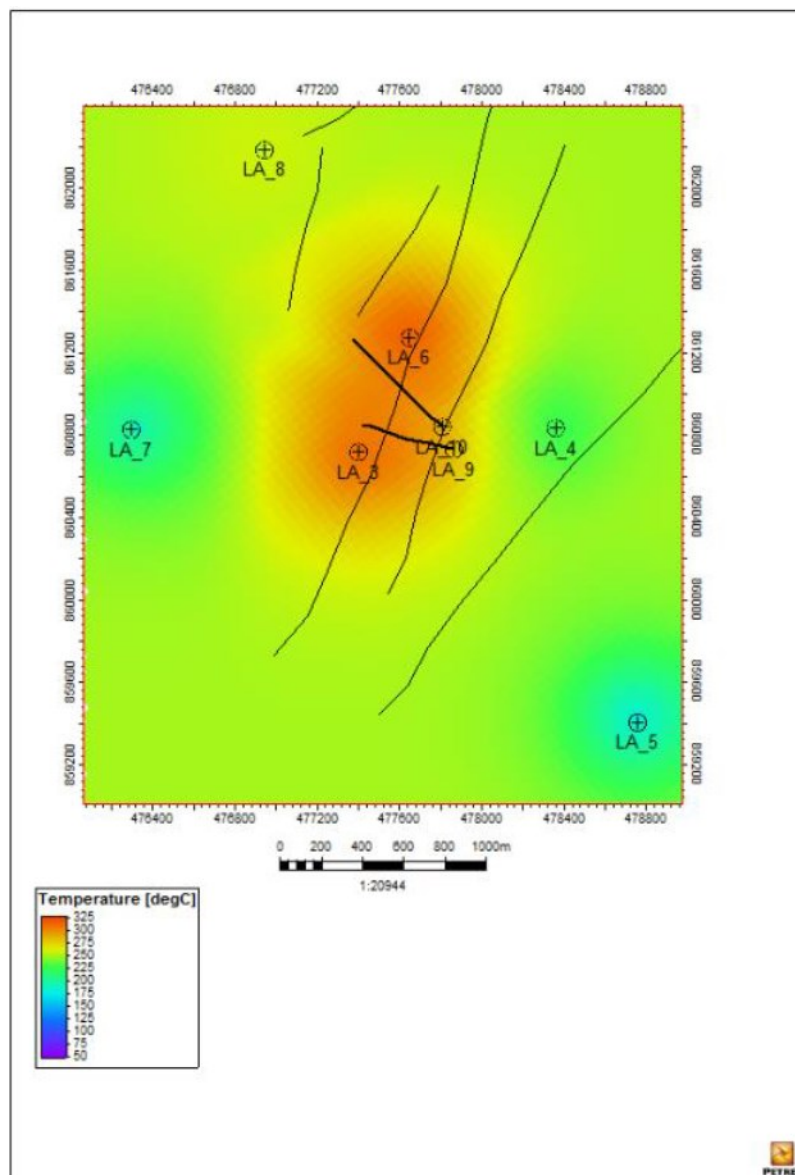


Figure 3: Distribution of temperature in the Aluto Langano geothermal field at 800 m.a.s.l.

4. HYDROTHERMAL ALTERATION

Hydrothermal alteration is a rock formation that is interacting with hot hydrothermal fluids. It is a change in mineralogy, texture, and chemistry of rocks due to thermal and environmental changes facilitated by geothermal fluids and gases.

The main hydrothermal alteration minerals in the Aluto Langano wells from low temperatures to high temperatures are calcite, pyrite, chalcopyrite, siderite, haematite, chalcedony, smectite, illite, mixed-layer clays (MLC), quartz, chlorite, epidote, and actinolite. The alteration minerals were found as replacement of primary minerals and as fillings of microfractures, veins, and vesicles in the rock units. □

According to the distribution of secondary alteration minerals, four alteration zones are identified in the wells. These alteration zones are unaltered zone (alteration temperature is below 50°C), smectite zone (alteration temperature is 75-150°C), illite/chlorite zone (alteration temperature is more than 200°C), and illite/chlorite/epidote zone (alteration temperature is above 240°C). (Figure 2 & Figure 4).

The formation temperature of Aluto Langano geothermal field has been measured during well logging. The distribution of formation temperature indicates that there is a narrow up-flow zone with high temperatures within the Aluto Langano geothermal reservoir. The up-flow zone of the Aluto Langano geothermal system is located beneath the LA-3, LA-6, LA-9D, and LA-10D wells (Figure 3 & Figure 5), within the Wonji Fault Belt.

The temperature recorded in the upper part of the wells from the surface to 2,000-1,840 m.a.s.l is <50°C and correlates with the unaltered zone. The highest temperature at this depth is observed in wells LA-3 and LA-6, which are located above the up-flow zone. At 1,840 -1,260 m.a.s.l., temperature is 75-150°C and the formation is characterized by slight to moderate alteration of minerals.

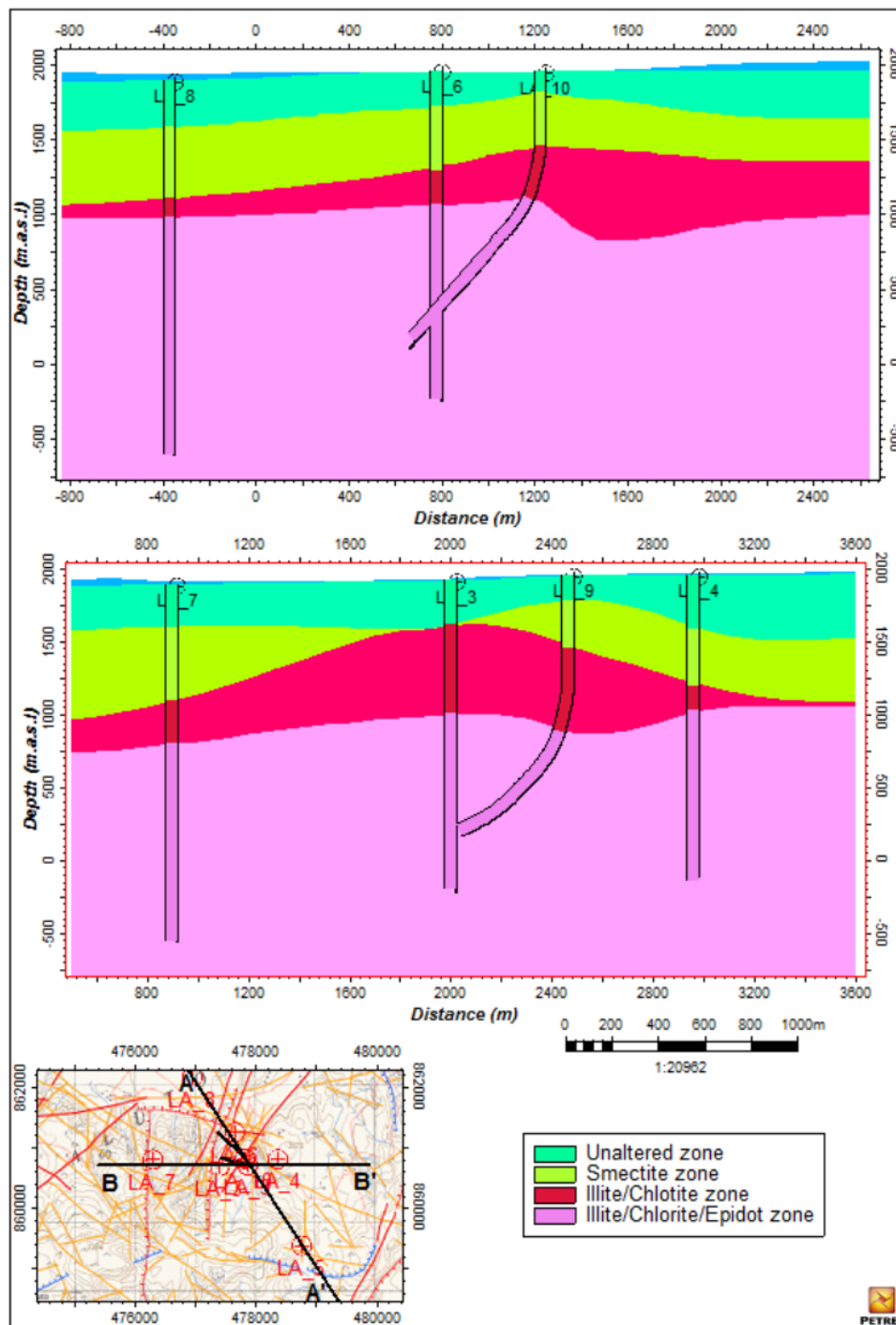


Figure 4: Cross-section of alteration zones in Aluto Langano geothermal wells

The smectite alteration zone is dominant at 120-500 m depth, which is consistent with the observed temperature. According to the information from the formation temperature, this zone represents the caprock of the geothermal system. Below the smectite zone, temperature increases from 180-250°C at a depth interval of approximately 1,200 to 960 m.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 5). High temperatures of >250°C are recorded in wells LA-3, LA-6, LA-8, LA-9D, and LA-10D within the illite/chlorite/epidote zone. □

The Aluto Langano geothermal field is water dominated. It is a gas-rich system with high reservoir temperatures ranging from 260 to >335°C. The heat source is associated with magmatism. Meteoric water is the reservoir fluid that has penetrated through the ground from the Eastern escarpment of the rift. Conductive processes heat the water from the magmatic heat source. □

Basalt and ignimbrite formations form reservoir rocks in the system. The cap rocks that overlie the reservoir are sediments and rhyolites, intercalated with pyroclastics. NNE-SSW trending faults of the WFB control the movement and up-flow of a deep hot

fluid. The up-flow zone is within a zone of NNW dipping faulted blocks with a total displacement of up to 400-600 m within the ignimbrite and basalt formations.

To the ENE and NW of the main up-flow temperature, reversal is observed. This could be related to the N-S trending faults in the NW part of the field, while the temperature reversal in the ENE part of the field may be associated with caldera faults. The main up-flow zone in the Aluto-Langano geothermal field is narrow and appears to be controlled by an NNE-SSW trending fault zone. This fault zone is characterised by NNW dipping faulted blocks. In the geothermal reservoir, a high-temperature gradient is an observed perpendicular to the trend of the WFB.

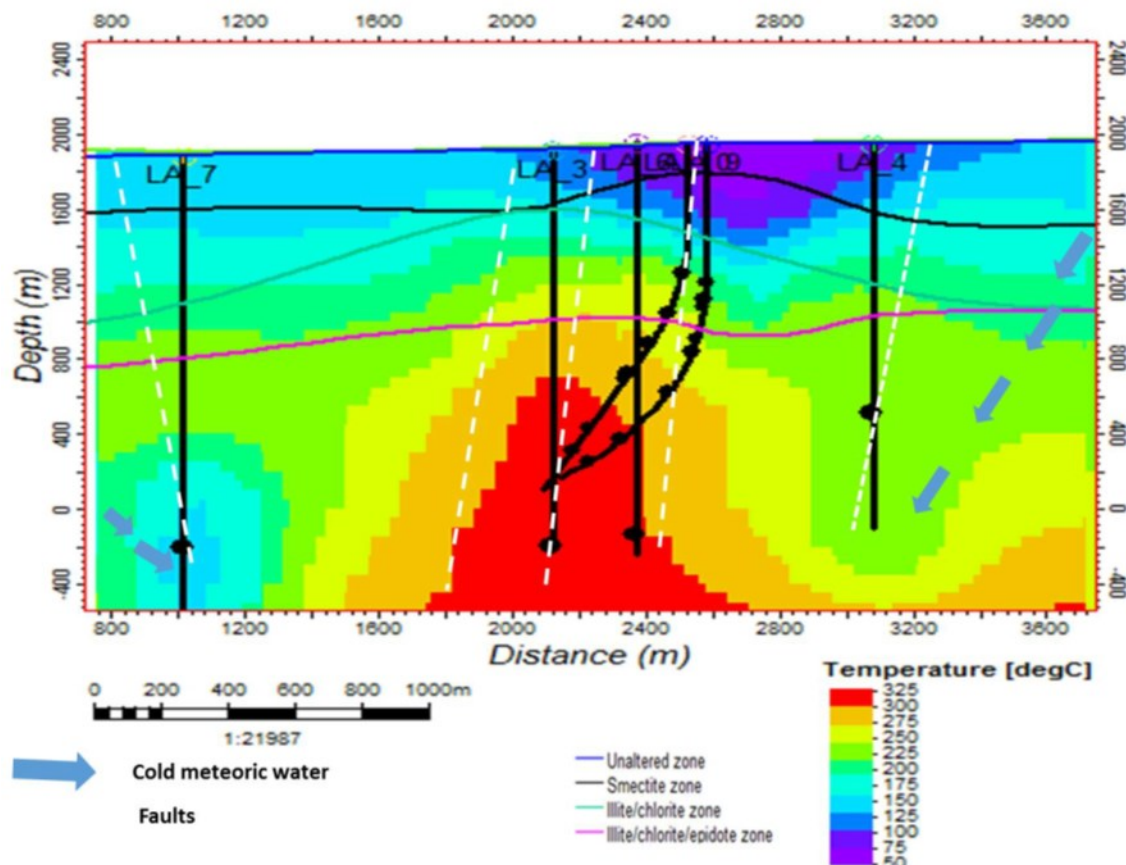


Figure 4: Conceptual model of the Aluto Langano field in relation to alteration mineral zones and formation temperatures.

5. CONCLUSION:

The major rock units identified in the wells are pyroclastics, silicic tuff and breccia, sediment, rhyolite, trachyte, basalt, and ignimbrite. □

Low to high-temperature hydrothermal alteration minerals are observed in the 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 in the upflow zone are heating up.

The reservoir rocks in the Aluto-Langano geothermal system are basalt and ignimbrite formations. The cap rocks that overlie the reservoir are sediments and rhyolites, intercalated with pyroclastics.

In the Aluto-Langano Geothermal Field, the upflow zone is narrow and structurally controlled by a NNE-SSW trending fault zone of the WFB, which is characterised by NNW dipping faulted blocks.

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