ALUTO-LANGANO GEOTHERMAL FIELD (ETHIOPIA), PROPOSAL OF A NEW GEO-VOLCANOLOGICAL MODEL BY COMBINING THE EXISTING DATA WITH MODERN STUDIES

T. Abebe [1], C. Pasqua [2], S. Kebede[3]
[1] ADHANA Geological Consultancy Services, via M.L.King, 9 Cascina (PI) Italy,
[2] ELC – Electoconsult SPA, Via Marostica 1, Milan, Italy,
[3]Geological Survey of Ethiopia, P.O. Box 2302 Addis Ababa, Ethiopia
e-mail: tsegaye.abebe28@gmail.com
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ABSTRACT

The Aluto Volcanic Complex (AVC) is situated in the central sector of the Main Ethiopian Rift (MER), close to its eastern margin in respect to the main axis. It is also located at the junction between two important hydrological basins, whose central portions are presently occupied by Lake Ziway in the north and by the three sister lakes of Langano, Abiyata and Shala in the south. The local geological setup of the AVC is quite complex. The oldest rocks are dated at about 150 Ka, while some of the post/syn caldera rocks are dated at about 55 Ka (ELC, 1986). The caldera collapse (8.5 x 5 km) elongated in E-W direction, might have taken place between 50 to 80 Ka ago. After the caldera collapse, volcanism continued from many small centers forming cones of pyroclastics and lava flows mainly following the caldera rim and the NE and the NNE regional fault systems. Although at present no volcanic center is active in the AVC, the complex itself is considered to be dormant, but not extinct. Biggs et al., 2011, using satellite based interferometric synthetic aperture radar observations, demonstrated the presence of uplifting and sinking of the surfaces of Aluto and other central volcanoes in the MER between 1993 and 2010.This indicates the presence of a hot magma chamber, which is continuously replenished, wherefore pressure build-up and collapse could be manifested on the ground surface. One of the youngest flow was dated at 2 Ka (ELC, 1986). Areal distribution of these very young products, together with the associated hydrothermal manifestations and the structural pattern, are important indicators of the favorable geological conditions of these sectors from the point of view of geothermal energy exploration. Other than along the **Jawe Fault Zone** (JFZ), most of the hydrothermal manifestations are concentrated in the eastern and western sides of the E-W elongated caldera rims, presumably due to the displacement of magma pockets in these sectors. Comparing the two sides of the caldera, it can be observed that the AVC products in the eastern part (**Bobessa Zone)** has an average thickness of 340 m and in the west (**Adonsha Zone)** about 600 m. Moreover, the lacustrine sediments and the remaining older volcanic successions are much thicker in the west, as a result of the rift-ward inclination of the layers and the presence of faults down-steping towards the rift axis. Due to the larger thickness of materials in the western rim of the caldera, hydrothermal manifestations and younger lava flows may appear in lower quantities as compared to the eastern rim. Nevertheless, a higher geothermal potential is expected to be in the western sector of the AVC, due to larger hydraulic recharge and thicker lacustrine sediments that may act as cap rock of the geothermal system.

1. INTRODUCTION

1.1. Location and acessability

The Aluto-Langano geothermal prospect is located in the floor of the Main Ethiopian Rift (MER), close to its eastern escarpment, some 200 km south of Addis Ababa. This prospect has been an important target, since 1969 a number of investigations were undertaken and in the eighties eight deep exploratory wells were drilled and it led to the discovery of a geothermal field of commercial interest and to the installation of a small geothermoelectric power plant. In view of the full development of the Aluto Langano geothermal resources, it was deemed opportune to extend the detailed exploration beyond the sector now under development, with the final object to increase the electric potential of the prospect from the present 35 MW to an additional 35 and possibly 70 MW (Aluto II and III). This implies the implementation of geological, geochemical and geophysical surveys over the whole Aluto Volcanic Complex (AVC), which is an area of about 200 km^2. This paper is an outcome of the last phase of investigation of Aluto, carried out by ELC in the summer of 2015.

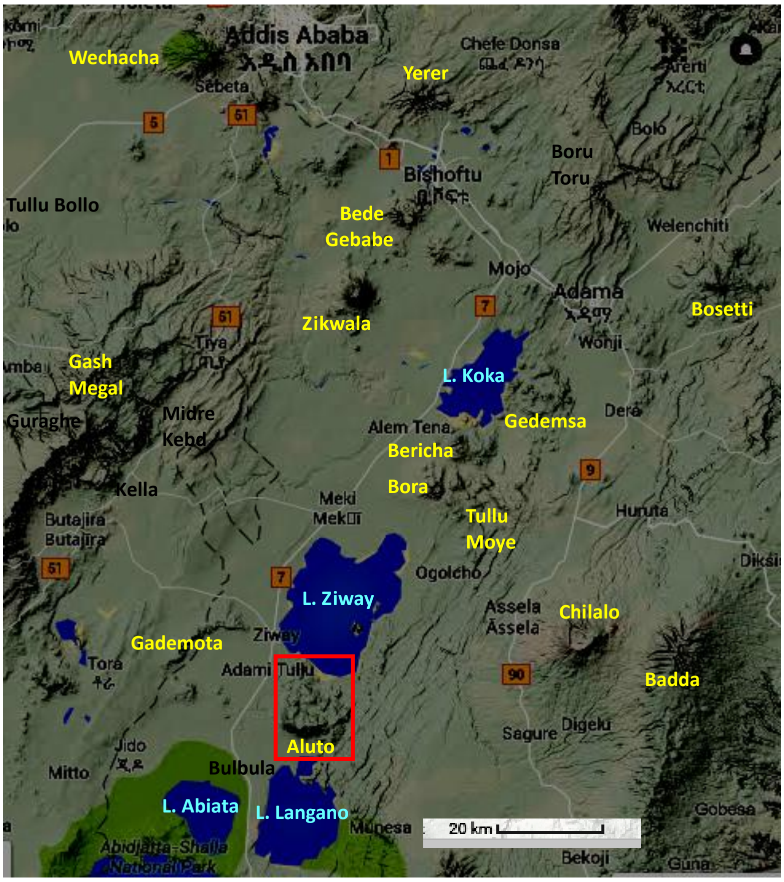


Figure 1: Location of the Aluto-Langano Geothermal Field (in red rectangle) in respect to the roads from Addis Ababa, important towns (black), lakes (blue) and volcanoes (yellow) in the northern central part of the Main Ethiopian Rift. Image from the Google terrain map.

The study area is situated within the Central Main Ethiopian Rift (CMER), in the Lakes District region, between Lake Ziway to the north and Lake Langano to the south (Figure 1). From Addis Ababa, Aluto can be reached in two ways: 1) via Bishoftu - Mojo – Ziway, and 2) via Alemgena (Sebeta) - Butajira- Ziway. The distances are similar, about 160km, but the Addis – Mojo road is a new highway. After the town of Ziway and a couple of km beyond the town of Adami Tulu the road proceeds in an all-weather gravel and it runs in SE direction for about 7 km reaching the power plant, located approximately at the center of the study area. From there the road extends further to the south and SW down to Lake Langano, passing through the deep well LA-1 site and the Geothermal base camp and it joins again the asphalted road at Bulbula.

1.2. Climate, vegetation and population

Aluto being one of the central volcanoes situated along axis of the rift, its prominent feature appears from the surrounding plane and the lake levels of Ziway (1635 m.a.s.l) and Langano (1585 m.a.s.l). The summit caldera floor has an average altitude of 2000 m and the topmost is 2328 m a.s.l. Ethiopia has five climatic zones, defined by altitude and temperature: 1) The hot, arid zone below 500 m; 2) The warm to hot, semi-arid zone, 500 –1,500 m a.s.l. ; 3) The warm to cool, semi-humid zone covers the temperate highlands between 1,500 and 2,500m a.s.l., with average annual temperatures of 16°C - 20°C, and annual rainfall about 1,200 mm; 4) The cool to cold humid zone includes the temperate highlands between 2,500 and 3,200 m a.s.l., 5) The cold, moist temperate zone between 3,200 and 3,500 m a.s.l. Accordingly, the area of Aluto lies in zone 3, where the annual rainfall is more than 1000mm and it is a semi-humid to arid zone. Vegetation in the floor of the rift is dominated by the spiny acacia trees and some short bushes. The massif of Aluto, in particular the young obsidian flows and domes, are covered by denser vegetation and a variety of trees and bushes.

Population settlement is dense in the important towns of Ziway (about 50,000), Adami Tullu (about 10,000), Bulbula (about 15,000), but there are also many villages along the southern cost of Lake Zeway, around the foots of Aluto and very small villages on top the volcano.

1.3. Regional geological setup

The Ethiopian rift system being Active rift type, up-doming was followed by volcanism and rifting. The earliest episodes took place in the Southern Ethiopia Rift (SER) and the Afar Rifts, before 25 Ma (e.g., Davidson and Rex,). Rift propagation proceeded both from the south and north directions towards the MER (e.g. Bonnini et al., 2005). Rifting in the MER did not start until about 8 Ma (Abebe et al., 2010), possibly due to the presence of transversal structures (GBL and YTVL to the south and to the north of MER, respectively), that stopped propagation of rifting for a long geological period (Figure 2).

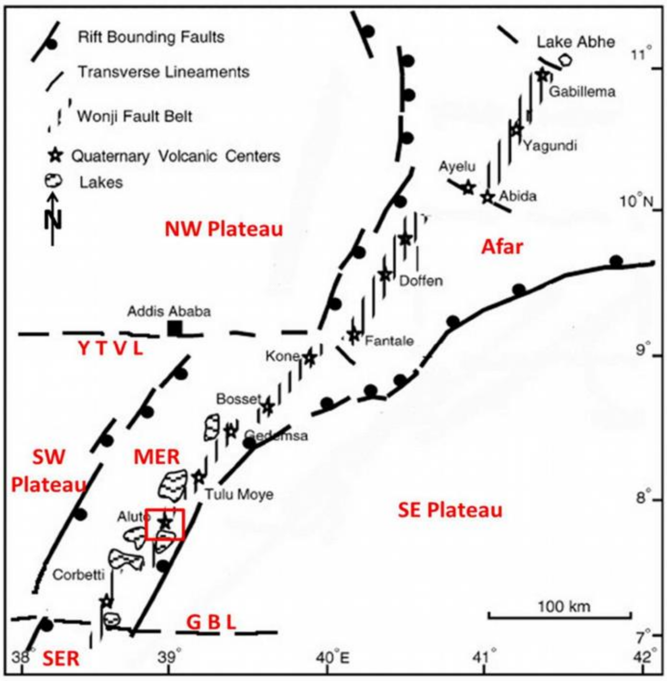


Figure 2. Regional structural configuration of the Main Ethiopian and Southern Afar Rifts. MER = Main Ethiopian Rift, SER = Southern Ethiopian Rift, GBL = Goba - Bonga Lineament, YTVL = Yerer – Tullu Wellel Volcano-tectonic Lineament

During the early stages of the MER, several central volcanoes erupted forming very thick pyroclastic deposits, thought to have been partially produced from fissures. These volcanic products have about 5 Ma and are known as the Nazret group (Kazmin and Berhe, 1978; WoldeGabriel et al.,1999; Boccaletti et al., 1999; Chernet et al., 1998; Abebe et al., 2005). Formation of the important rift margins of the Central MER took place about 3.5 Ma ago (e.g. WoldeGabriel et al., 1999), when the Munesa and Guraghe escarpments were formed. These escarpments are curved towards the rift and some authors considered them as the sources of the felsic pyroclastic deposits and large caldera collapses (e.g. WoldeGabriel et al.,1999). The important clue for such conclusion is that the curved escarpments of Munesa and Guraghe are related to the more than 700 m thick pyroclastic deposits that are found in both escarpments.

Lithologies with age younger than 1.6 Ma are related to the NE-SW trending fracture systems together with their transversal structures that are NW-SE and ENE-WSW oriented. After 1.6 Ma the Somalian plate drifting direction changed from SE towards nearly E (Boccaletti et al.,1999, Bonnini et al., 2005, Corti, 2008, 2009), causing the development of N-S/NNE-SSW trending fracture systems known as the Wonji Fault Belt (WFB). The AVC, being a Late Pleistocene to Holocene structure, is governed by the WFB, although the transversal structures (NW-SE and ENE-WSW) also played important roles.

2. GEOLOGY OF ALUTO AND ITS SURROUNDINGS

Since the AVC is situated very close to the eastern margin of the rift, its eastern portion directly overlies on the rift floor volcanics that are younger than 2 Ma. These volcanics are down faulted towards the rift axis, hence the AVC itself is tilted to the west with more than 1000 m thick products, whereas at the eastern caldera margin thickness of AVC products do not exceed 300 m. Volcanic products related to the AVC cover an area of about 120 km^2 forming a rhombic area elongated in a NW-SE direction.

2.1. Per-Aluto Volcanic Products

2.1.1. Bofa Basalt (Nqbb)

This unit is the oldest formation that outcrops only in the eastern part of the study area. The Bofa basalt in the study area appears on high ridges in two distinct lithotypes: 1) strongly porphyritic with plagioclase phenocrystals up to 3 cm long and max. thickness 200 m; 2) moderately porphyritic and very compacted of only few tens of meters thick. In the deep geothermal wells LA-3 and LA-6 a thickness of more than 700 m is reported (Kebede et al., 1985; ELC, 1986). In the deep geothermal wells, the Bofa basalt overlies a crystal rich ignimbrite exposed to more than 700 m at the Munesa fault (WoldeGabriel et al.,1999). This unit does not outcrop in the study area and was encountered in wells LA-3 and LA-6 at a depth of about 1,700 m below the ground level or elevation of 300 m a.s.l. (ELC, 1986; Kebele et al., 1985). Absolute age measurements of the Bofa basalt range between 3.5 and 1.5 Ma (Kazmin and Berhe, 1978; WoldeGabriel et al.,1999).

2.1.2. Dima Trachyte (Qdt)

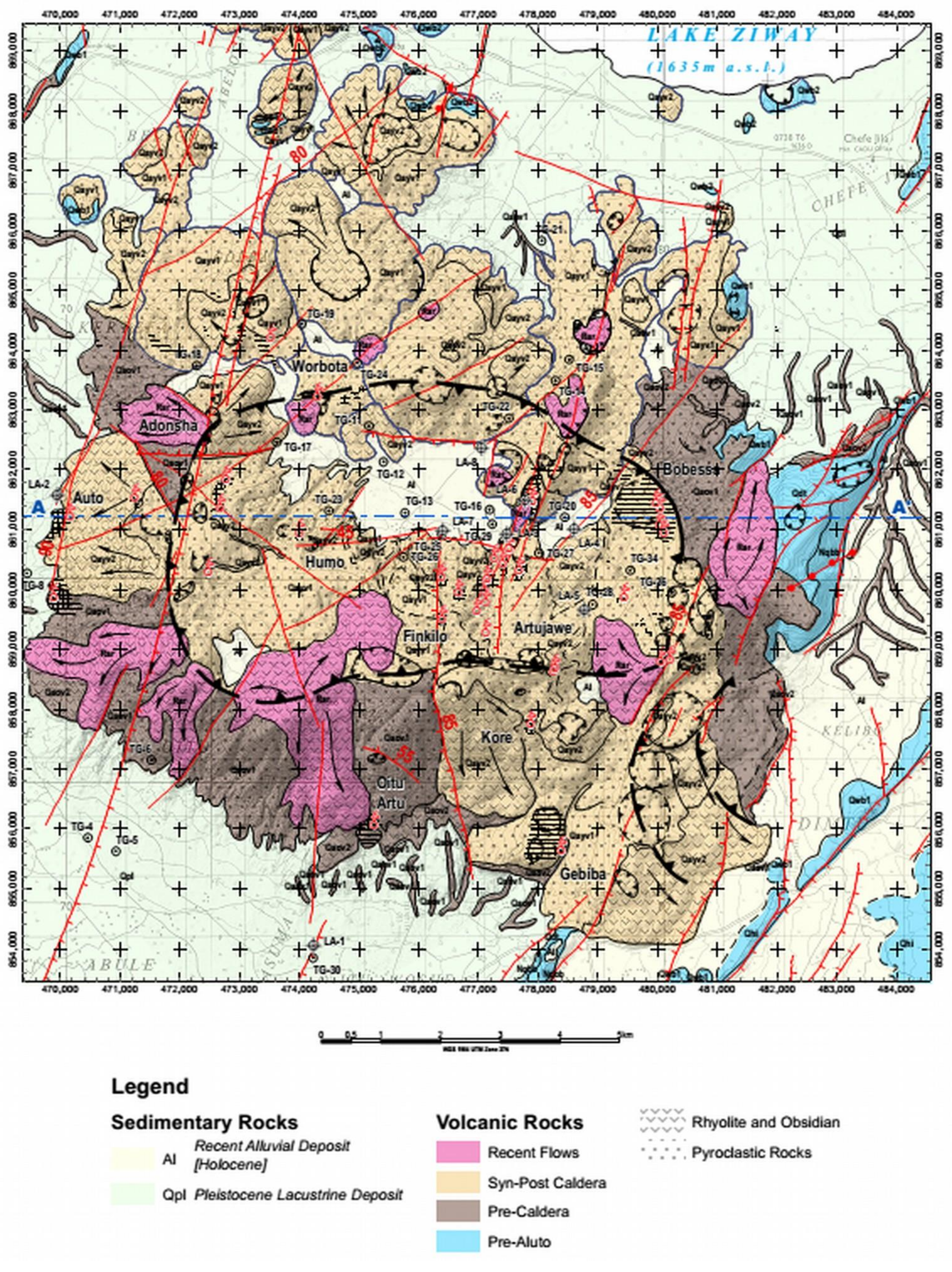
The Dima trachyte outcrops mainly in the southern and central parts of the study area (refer geological map of ELC 2015). In most cases the Dima trachyte is found on top of the Bofa basalt sometimes with clear unconformity, striking NE-SW,. The rock is variable from moderately alkali feldspars phyric to aphyric, but usually flow laminated. Its maximum extension is about 15 km and is believed to continue both to the east and west wards until the deep drilling area (Figure 3). However, the petrographic studies of the drilling cuttings and of the few core samples appear to have mistaken/missed these rocks, which were incorporated to the Bofa basalt. To the east of Bobessa it is about 70 m thick, but at the type locality (Dima) it does not exceed 25 m. In the cross-section (Figure 3) it is assumed to attain 100 m of thickness, since on the horst it is denuded. The westward extension of the Dima trachyte is not certain, since also in the log of well LA-2 the unit was identified as Bofa basalt. It is overlain by younger Quaternary rocks, with clear unconformity. Although no radiometric age determinations were carried out, by correlation with the surrounding units a Quaternary age was assigned (UNDP, 1973; Kebede et al., 1985; ELC, 1986). For detailed petrographic description, refer ELC report 2015.

2.1.3. Hula Senyo Ignimbrite (Qhi)

This rock unit outcrops in the south-eastern and north-western corners of the study area in the form of NE-SW trending patches. These pyroclastic flow deposits have filled the old grabens and step faults that cut the Bofa basalt. It extends to the SE of the study area covering a very wide and flat zone. In other parts of MER, these pyroclastic deposits are named as Quaternary Dino ignimbrite (Qdi), Kazmin an Berhe, 1981, Rift-floor ignimbrite or Chefe Donsa pyroclastics (Abebe et al., 1999, 2005). Radiometric and fission-track data indicate an age between 2.54 and 1.7 Ma (eg Morton et al., 1979; Boccaletti et al., 1999). In the vicinity of the AVC, older pyroclastics gave an age of 1.55 Ma (ELC, 1986). The Hula Senyo ignimbrite has a thickness of about 350 m at LA-3 and it gradually increases to the west. In fact, this rock unit does not appear on the horst that is located to the southeast of Bobessa. For detailed petrographic characteristics, refer ELC report 2015.

2.1.4. Kenchere Rhyolite (Qkr)

This rock unit is found exclusively in the southern part of the study area, in particular in the Edo Laki island, the eastern side of North Bay, Kenchere hill (the type locality) and the northern part of the Bole graben (south of Haroresa). The unit forms domes about 140 and 120 m high at the Bole graben and Kenchere, respectively, whereas at the Edo Laki Island it is less than 20 m thick. The Kenchere rhyolite is considered to be younger than the Hula Senyo ignimbrite, but older than most of the AVC products. There are no radiometric age measurements made on this unit, nor direct contact relationships with the Aluto volcanic products.


LAKE ZIWAY
(1635m a.s.l.)
Worbota
Adonsha
Auto
Humo
Finkilo
Artujawe
Bobessa
Kore
Oitu Artu
Gebiba
A
A'
Legend
Sedimentary Rocks
Al Recent Alluvial Deposit [Holocene]
Qpl Pleistocene Lacustrine Deposit
Volcanic Rocks
Recent Flows
Syn-Post Caldera
Pre-Caldera
Pre-Aluto
Rhyolite and Obsidian
Pyroclastic Rocks

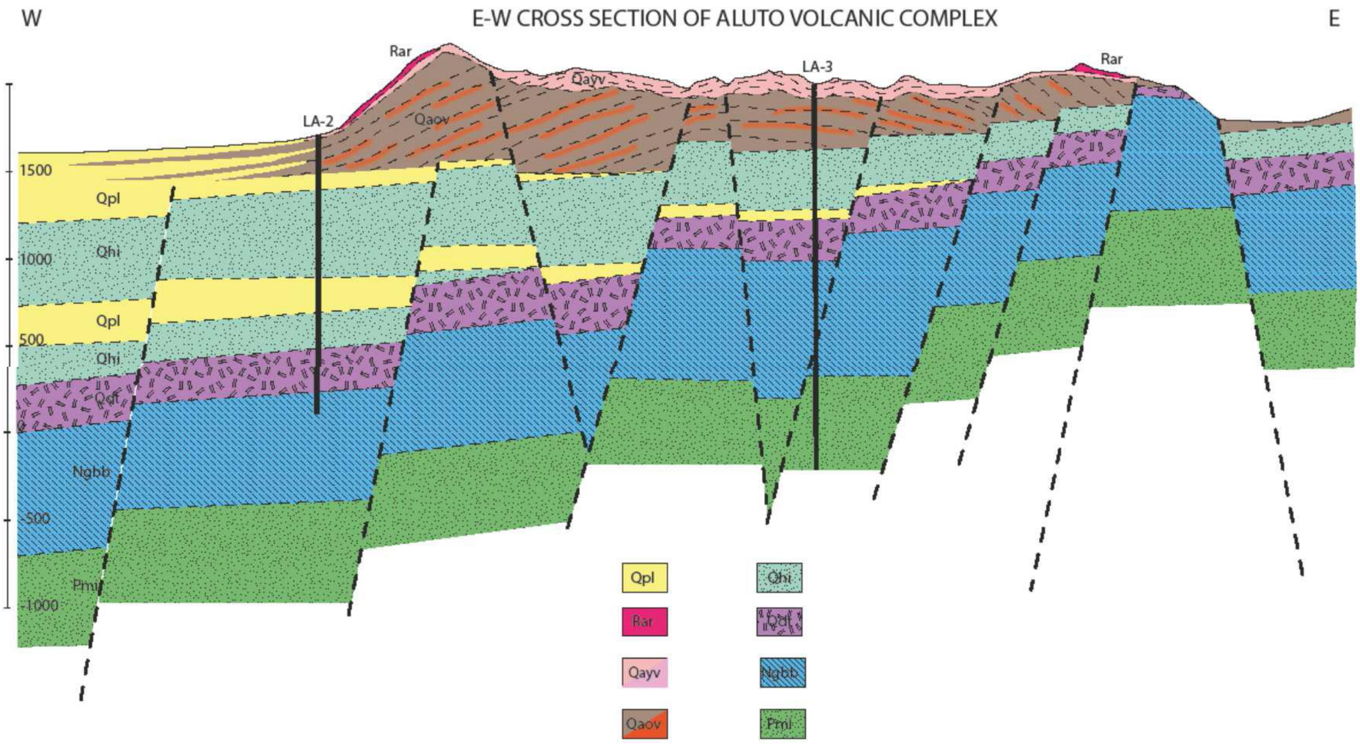


Figure 3. A simplified geological map of the Aluto Volcanic Complex (AVC), after ELC 2015 and an E-W geological cross section of the AVC (A-A' in the geological map), modified after ELC, 1986. Qpl = Quaternary – Pleistocene lacustrine sediments, Rar = Recent Aluto rhyolite (mainly obsidian lava flows), Qayv = Quaternary Aluto younger volcanics, upper pumiceous pyroclastics, lower rhyolite lava flows, Qaov = Quaternary Aluto olderer volcanics, upper pumiceous pyroclastics, lower rhyolite lava flows. Geological section shown by A-A' in Figure 2, not at the same scale.

2.1.5. Wenshe Danta Basalt (Qwb)

This volcanic unit represents the second and younger basaltic volcanic activity that took place in the study area after the older Bofa basalt and in the northern part of the MER is also called Wonji basalt and DebreZeyt basalt (Mohr, 1966, Morten et al., 1979; Abebe et al., 1999, 2005). Volcanic activity is mainly related to the Wonji fault belt that strikes NNE-SSW, wherefore the relevant products are aligned in a NNE direction in the eastern and north-western sectors of the study area. According to its location and the reaction with surface water, the Wenshe Danta basalt is subdivided into two sub-units: a) Scoria and basalt lava flows (Qwb1), b) Hydromagmatic deposits (Qwb2). Qwb1 includes the aligned scoria cones, < 100 m high, and associated basaltic lava flows. Most of the cones are breached along the strike of the fault that generated them. Similarly, the lava flows are elongated not more than a couple of km in the same NNE strike. The basalt lava flows are mildly porphyritic to fine grained with some visible plagioclase, olivine and pyroxene phenocrystals and are highly vesicular at their base and top.

Qwb2 is similar to Qwb1, but has reacted with the old Lake Ziway southern shore water. In fact, the hydromagmatic (hyaloclastites) deposits are limited to this shore, which is in the range of 3-4 km away from the present shore, except for Adami Tullu maar cone, which is situated at some 7 km to the southwest. Some of these hydromagmatic deposits might be completely buried by the younger products of Aluto, as observed in the geological map (ELC 2015 geological map), showing that Lekanshu and cones to the north are partially covered by the pumiceous pyroclastics of Aluto. Almost all the outcrops form a circular or semi-circular maar crater with very fine, highly fragmented and sandy pyroclastic layers, which are highly laminated and stratified.

2.2. Volcanic Products of the Aluto Volcanic Complex

2.2.1. Aluto Older Volcanics (Qaov), Pre caldera

These consist pyroclastics (Qaov1) and rhyolitic lava flows (Qaov2), from on big vent or many small coalescent centers that form a big strato-volcano, probably higher than the present Aluto edifice. These are now radially distributed, with inclination away from the center, in the external parts of the AVC and outcrop in the NE and SW areas where not covered by the younger products of the AVC itself. The best place where the older volcanic products can be observed is the north-eastern external slope of the Bobessa caldera rim (Figure 3). The earliest products could be contemporaneous to the fissural Hula Senyo ignimbrite dated by ELC, 1986 (ETI 53 = 155 Ka). Samples from Dodecha and Sedecha far to the north of Aluto gave an age of 129 Ka and 80 Ka, respectively (ELC, 1986). Therefore, volcanic activity in Aluto is supposed to have began between 150 and 130 Ka. Usually in the coalescent vents the gas rich pyroclastic materials erupt first and were followed by the degassed rhyolitic lava flows (Qaov2).

In some sections of the old pyroclastic deposits of Aluto, there are very fine grained and highly fragmented layers at the base of a single eruption and it appears as an inverse grading. A close examination of these outcrops (Figure 4) showed that these layers consist of hydromagmatic deposits of older craters/calderas that have been filled with water between distinct explosive episodes. These layers could be defined as hydroplinean deposits and witness a very common phenomenon of the AVC, indicating presence of lakes and higher precipitation during that time than the present.

Figure 4. Pre-caldera pyroclastic fall deposit in the southern flank of AVC, inclined outwards and different episodes are marked by the thin soil and yellow stain. Some of the episodes started with very fine and incoherent hydromagmatic type of deposits and show an inverted type of bedding, getting coarser when the eruption was dry again.

Considering the old stratovolcano, before the formation of the Aluto caldera, the maximum thickness of these pyroclastic deposits was probably over 600 m, but at present it does not exceed 450 m, as estimated considering its base at the elevation ~1,700 m a.s.l. near Oitu and its top, where the old pyroclastic deposits are not covered by the younger Aluto products, at an elevation ~2,150 m a.s.l. In LA-3 the whole succession of the Aluto products intersected by drilling is less than 400 m. This can be due to the elevated substratum of Aluto in the eastern part (Figure 3).

2.2.2. Aluto Younger Volcanics (syn and post caldera) (Qayv)

This rock unit refers to many central volcanoes that produced pumiceous pyroclastics (Qayv1) and rhyolite and/or obsidian lava flows (Qayv2). These include the syn and post Aluto caldera collapse products covering the caldera rim and others related. Qayv1 includes a very wide range of pumiceous pyroclastic deposits: fine grained ash, coarse grained rich in pumice and lithic fragments, hydromagmatic deposit outcropping close to the southern shore of Lake Ziway. It usually forms a cone (200 m on average) surrounding a vent and dipping away from it. The vents to the north of well LA-3 are aligned along a NNE trending fault and their products are also elongated in the same direction. The northern cones, close to the southern shore of Lake Ziway) should be relatively older in age judging from the morphology, superposition of layers and radiometric ages furnished by ELC, 1986. The volcanic centres on top of the main AVC should have an age younger than 55 Ka (age of sample # ETI 34 of ELC, 1986, collected from the upper parts of Aluto). Qayv2 has variable appearances, flow laminated or massive, porphyritic or fine grained and sometimes associated with obsidian and commonly consists of short lava flows forming small domes. Most of the vents are located either exactly on the caldera rim, flowing mostly outwards, or on the external flanks. Only a few flows moved into the caldera floor from the eastern and western margins of its rim. Almost all of the rhyolitic lava flows are the final degassed products of their respective volcanic center. A perfect example is the cone situated to the east of Golba and south of Lekanshu. The diameter of this cone is 2-3 km and its crater has a diameter of about 1 km, breached to the north-west. The rhyolitic lava has flowed for about 2 km forming a spectacular fan shape (Figure 3 geological map).

2.2.3. Aluto Rhyolite (Rar)

The youngest volcanic eruptions of AVC are represented by some 14 obsidian lava flows, whose vents are mainly situated at the junction of the caldera rim with the NNE and NE trending faults. Only three of them are situated out (to the north) of the caldera rim and two within the caldera, that is between wells LA-3 and LA-8. The recent obsidian lava flows form very distinct features, as observed from the satellite images, aerial photographs and in the field (Figure 5). Their highly blocky nature associated with sharp, very abrasive glass, made it almost impossible to be penetrated by animals and human beings. Therefore, these lava flows have developed a very dense vegetation, and this has created a distinct area which is visible even by inexpert eye. No overlaying unit was observed on these flows. A radiometric/fusion-track age measurement on the lava flow to the east of well LA-5, along the road side, gave a maximum age of 2,000 yrs, hence these flows can be all considered to be of Holocene/historical age. Most of these lava flows are porphyritic with abundant phenocrystals of alkali feldspar and few quartz. Thickness of the flows varies from a few meters up to tens of meters in the deeper paleo-valleys and depressions.

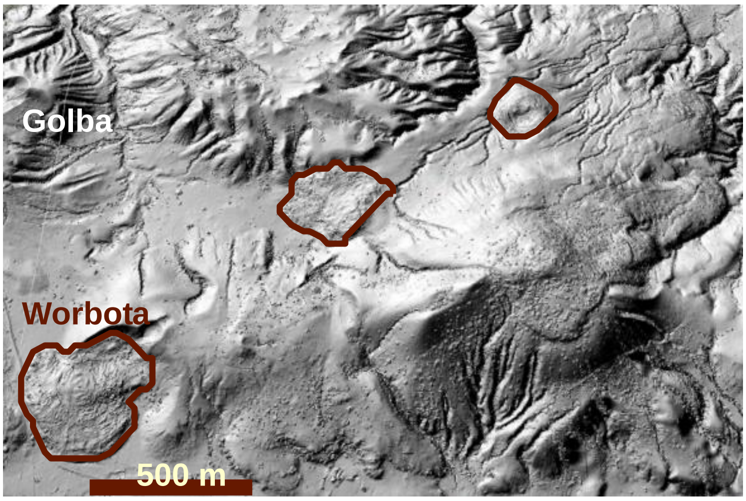


Figure 5. Digital Elevation Model showing the three youngest obsidian lava flows within the caldera.

2.3. Sedimentary Deposits

In the study area there are only lacustrine sediments and alluvial-colluvial cover, the latter found in areas of higher elevation as compared to the old lakes level. The highest level of lacustrine sediments registered in the study area is at about 1,750 m a.s.l.

2.3.1. Pleistocene Lacustrine Deposits (Qpl)

These lacustrine sediments occupy a very wide area and are found intercalated with the pumiceous pyroclastics and/or ash deposits of the AVC. Generally these deposits vary from sandy gravel to fine silt and clay size and are very rich in diatomites. Presence of lacustrine deposits at high elevation shows that the lakes level was higher in the past and some 10 Ka ago all the lakes between Ziway and Shalla were

connected and had formed one big lake ("Galla Lake": Laury and Alberitton, 1975; Le Turdu et al., 1999; Benvenuti et al., 2002, 2013).
According to Le Turdu et al., 1999, the lakes between Ziway-Shalla were formed in relation to the collapse of the Gademotta caldera, i.e. between 1.30 and 1.05 Ma ago. This event could be very important for the modification of the rift floor lake basins, but the rift was formed since about 8 Ma (Abebe et al., 2010). Formations of the eastern and western big margins of Munesa at and Guraghe at about 3.5 Ma (WoldeGabriel et al.,1999), significantly modified the rift structure with pronounced subsidences. This event could be the initial formation of the rift lakes. In wells LA-3 and LA-6 presence of lacustrine sediments at the base of the Bofa basalts is another direct proof of the formation of the lakes before 2 Ma.

2.3.2. Alluvial and Colluvial Deposits (Al)
This unit has a wide range of origin and composition. It consists mainly of soil that developed over the ignimbrite and the basaltic lava flows due to weathering and erosion of the substratum rock. The other s includ alluvial deposits of rivers and old river beds, slope scree and rock falls (particularly under big fault scarps), and other materials transported by wind, water or gravity.

3. STRUCTURAL SETTING

Four directions of tectonic setting are recognized in the area, namely: (1) NW-SE or Red Sea trend; (2) ENE-WSW or Gulf of Aden trend; (3) NE-SW or Ethiopian Rift trend and (4) NNE-SSW or Wonji Fault Belt trend (E.G., Mohr, 1962).

3.1. The NW-SE or Red Sea Trend

In the study area the NW fracture system is visible cross-cutting the NE major faults system, forming small rhombic terrains in the south-eastern parts of the AVC, in particular between Munesa and Aluto and to a minor extent in its south-central and northern parts. The south-central NW faults cross Aluto diagonally and connect several important hydrothermal manifestation, such as: Kore – Finkilo (near Jawe Artu), Oitu Artu – Adonsha (Figure 8). The NW system joins also more than seven craters and volcanic centers. It may be concluded that, based on the regional pattern, the intersection areas between the NNE and the NW fracture systems could be very interesting for geothermal energy exploration.

3.2. The ENE-WSW or Gulf of Aden Trend

In the MER, the ENE trend forms important lineaments such as the Ambo fault (Abbate and Sagri, 1980) and the Goba-Bonga lineament. Some volcanic centres on the rift margin and within the rift itself also follow the ENE trend, but are not as important as the NW-SE trend. Most of the calderas in the rift are elongated in nearly E-W direction (Acocella et al., 2009 and references therein). The Aluto caldera follows the same trend. Moreover, the southern rim of the caldera is made up of a chain of volcanic centres and craters that are elongated and aligned in an E-W direction. It is clear that the southern part of the AVC is much higher than its northern part, probably due to the fact that a northward breaching took place at Aluto before the caldera collapse.

3.3. The NE-SW or Ethiopian Rift Trend

In the study area the NE-SW trending faults and tectonic features are mainly expressed in the eastern and SE sectors and most of the tends deviate towards N, forming the NNE. Some of the volcanic centers, including the youngest three centers situated in the north-western part of the caldera (Worbota and two more to the NE, Figure 5), follow a NE-SW trend. This system has contributed significantly to the external and internal structural configuration of AVC. One of the important considerations refers to the fact that the older rock units, such as the Munesa crystal ignimbrite and the overlying Bofa basalt outcropping in the eastern side, are gradually lowered down to the west and in the central part of the AVC these units are found at a depth of several hundred meters.

3.4. The NNE-SSW or Wonji Fault Belt (WFB) Trend

This fracture system has a strike that varies between N10° to N30° and it was named as the Wonji Fault Belt (WFB) by Mohr, 1962. Many authors (E.g. Coti et al., 2013 and references therein) studied the system in terms of mechanism of opening, associated volcanic rocks and magmatic activities. In fact, almost all authors agree that these young axial (close to the eastern margin) and marginal (Butajira-Debre Zeyt) faults have a

NNE trend and are arranged in right en-echelon fashion. Some of them (e.g. Abebe et al., 1998) clearly showed that the transversal structures to the right en-echelon pattern are the NW-SE older fracture systems, which are continuously reactivated. The left lateral component of the WFB is also clearly stated by some researches (e.g. Abbate et al., 1995; Bonini et al., 2005). Emplacement of magma (central volcanoes) is almost always takes place at their intersection and in fact many young (Quaternary) silicic volcanic centres, including Aluto, are situated in correspondence of such intersections.
In the study area there are three important fracture (fault) zones that follow this trend: a) the Bobessa-Gebiba lineament that cross-cuts the eastern rim of the Aluto caldera; b) the Artu Jawe-Oitu Artu lineament that cross-cuts the central part of the Aluto caldera and c) the Worbota-Adonsha lineament that cross-cuts the western part of the Aluto caldera. For detailed description of these lineaments refer ELC 2015 and the discussion part of this paper.

3.5. Other Volcano-tectonic Structures
The AVC is situated between the Ziway basin to the north and the Langano-Abiyata-Shala basin to the south. The fact that the northern summit of the AVC is much lower than the southern one could be due to breaching towards the Ziway basin (Figure 6 and 8). The pre-caldera large deposits of pumiceous pyroclastics are lacking in the northern side, where syn and post caldera central cones and their final lava flows are commonly observed. Therefore, breaching of the AVC could have taken place after the formation of the main volcanic apparatus of Aluto, but before the caldera collapse. Age of the caldera collapse could be estimated between 150,000 and 55,000 years, based on the radiometric determinations by ELC, 1985 and the field relationship of the centers of the AVC.
The AVC comprises: one caldera collapse, some 65 craters associated with cones and more than 60 vents without craters but usually forming lava domes and flows. The large majority of these volcanic centers are controlled by the regional tectonic system and the caldera collapse.

3.6. Magmatologic Considerations
The caldera of AVC is elongated in E-W direction, as stated before. Plunging of the central summit of AVC into the central part of the caldera, might have displaced the magma chamber to the east and to the west sides (Hutchison et al., 2015). From the distribution of the youngest lava flows, the larger volume appears to have been displaced to the west. These volcanic products, in the course of the emission stage, had to overcome a large pile of the AVC and rift floor sequences, which are thicker towards the axis of the rift. The intermediate age (syn – post caldera) products are lacking in the eastern flank of Aluto (Bobessa, probably due to the strong inclination of the surface. There is no evidence of the youngest volcanic activity within the central part of the caldera except for two very small obsidian flows situated between wells LA-6 and LA-8. Most youngest volcanic eruptions are along the caldera rim. This may imply that the magma chamber has been squeezed laterally by the central caldera collapse, wherefore the heat source is not necessarily extended throughout all parts of the caldera, being more likely to occur along the rim and following important fractured zones.

4. HYDROLOGY AND HYDROGEOLOGY
4.1. Hydrological Setting
Since the study area is located within the rift and is close to its eastern margin, the terrain under the AVC is tilted westwards. Therefore, the regional dominant surface water flow is from east to west. Within the rift floor (near the axis) the drainage system is from north to south. A good example is Bulbula river that flows from Lake Ziway (1,636 m a.s.l.) to Lake Abiyata (1,576 m a.s.l.). At a regional scale (Figure 6); the drainage pattern can be subdivided into three major regions;
1) The eastern highland between Mt. Chilalo and Mt. Kubsa, where the basin of the Kefar River is located. Most tributaries of Kefar are oriented in a NE-SW direction, while the main river itself flows to the NW, almost perpendicular to its trubutaries. The Kefar River flows into the rift, unlike most of the Ethiopian highland rivers, which tend to flow away from the rift (Abebe, 2000).
2) The second region with distinct drainage pattern is the rift margin, dominated by the NNE (about N30°) system. Such system is cross-cut by the NW-SE trending and their combination formed a rhombic drainage pattern, similar to the tectonic fracture pattern. Under the AVC, this type of fracture pattern is expected, and this may constitute the main recharge of the geothermal system, that is linked to the east Langano highlands, north of Munesa (Figure 6).

3) The third region corresponds to the AVC drainage pattern, which is almost radial around the caldera collapse. A detailed analysis of this hydrological region indicates the following:
- most of the central drainage pattern starts from the inferred caldera rim and flows radially outwards away from the centre;
- the eastern part is dominated by the NE-SW drainage pattern with some minor variations and detours;
- the central part, where wells LA-3 and LA-6 are situated, is mostly controlled by the NNE pattern;
- the north-western part of the AVC is marked by the NW-SE trending drainage pattern and the relevant water courses partly extend up to the south-eastern foot of the complex. The fault system controlling the drainage pattern is not clearly seen on top of Aluto due to the youngest pyroclastics cover;

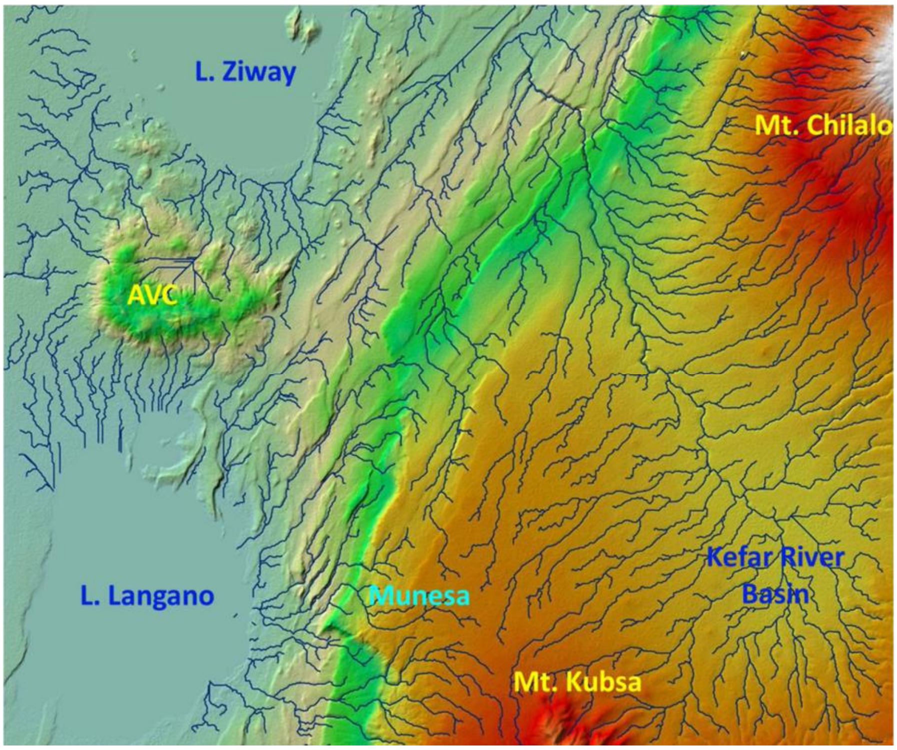


Figure 6. Digital Elevation Model (DEM) from radar data showing the regional hydrological pattern of the Aluto – Langano geothermal field and the surrounding area.

- At the western foot of the AVC, an E-W trending drainage pattern, that has also deviated the Bulbula river in an E-W direction, is clearly expressed, suggesting the presence of the nearly E-W trending fracture system. If there is a direct hydraulic connection between Lake Ziway (1636 m a.s.l.) and Lake Langano (1582 m a.s.l.), then under the AVC the ground water table is expected to occur at about 1600 m a.s.l., that is at a depth of about 400 m from the caldera floor.

4.2. Hydrogeological Setting

According to the regional geological map of Kazmin and Berhe, 1981, the bedrock of the Kefar River consists of ignimbrite of the Nazret Group, also called Munesa ignimbrite (e.g., WoldeGabriel et al., 1999). These rocks are highly porphyritic (alkali feldspars and quartz) and commonly vesicular. Therefore, their primary permeability should be high enough. Hence, as mentioned above, the major recharge of the geothermal reservoir comes from the Kefar River basin and from the Munesa highlands (Figure 6). At deeper levels the ground water is assumed to flow parallel to the rivers course, that is from north (Ziway) to south (Abiyata), except for the thick lacustrine sediments that may act as hydrogeological barriers. Although these sediments may let percolate some surface and/or subsurface water, in principle groundwater will follow the youngest fault system towards the axis of the rift, which is some tens of kilometers to the west of the AVC heat source, supposed to be under the AVC caldera. Along the young faults (Wonji Fault Belt), water circulation should be very easy.

Examining the E-W cross-section of the Aluto-Langano geothermal system (Figure 3), it can be observed that along the eastern margins of the AVC the trachytic and basaltic lava units (Qdt and Nqbb) are exposed on the surface. The Pliocene Munesa ignimbrite (Pmi) is also at a shallower level and outcrops further to the east. The faults form horst and graben in NE-SW direction, but with a regional inclination and lowering of all the layers to the west. Therefore, groundwater infiltrating either through primary porosity or, more commonly, through secondary permeability (mainly related to faults, fractures and caldera collapse) will flow like the surface water to the west. The scoriaceous basalts and trachytes and the uncompacted crystalline and vesicular ignimbrite could retain water as a reservoir for the geothermal system. Rainfall precipitation rate is much higher in the highlands as compared to the rift floor. In the case of the Aluto-Langano geothermal field, the rainfall in the eastern highlands, between Chilalo and Kubsa, that form the catchment area of River Kefar, is very important for the recharge of the ground water and of the geothermal fluid. The older rocks that are located under the AVC are exposed in the recharge area, therefore, percolation and recharge would be direct, if permeability of these rocks is not modified by hydrothermal alteration at depth under very high temperatures. Older fault systems might have created hydrogeological barriers restricting the flow of fluids. The western caldera wall together with some young fault systems could retain more fluid as compared to the eastern part. The caldera collapse may have determined favorable conditions for the formation of a reservoir, by lowering the whole succession by several hundreds of meters and intensifying fracturing in the internal part of the caldera, creating at the same time a barrier to the westward flow of groundwater. Under the western sector of the caldera the thick lacustrine sediments and the volcanic ash contained in the Hula Senyo ignimbrite may function as a cap rock. Hence, from the hydrogeological point of view the western caldera margin of the AVC appears to represent a priority target for further geothermal exploration.

5. HYDROTHERMAL MANIFESTATIONS

The hydrothermal manifestations of the study area; including hot springs (40 - 100°C), fumaroles (most close to 100 °C), hot and warm ground, can be subdivided into four major groups (Figure 7), namely:

1. The southern Edo Laki-Oitu-Bole group, composed mainly of hot springs with few fuming grounds (blue circle, Figure 7).
2. The eastern Bobessa-Gebiba group, dominated by fumaroles and hot grounds (red circle, Figure 7).
3. The central Artu Jawe-Oitu Artu group, composed of fumaroles and hot grounds, which extends parallel and very close to the Bobessa-Gebiba group (yellow circle, Figure 7).
4. The western Worbota-Humo-Hulo-Auto group, mainly composed of fumaroles and hot grounds (green circle, Figure 7).

The most striking aspect of the fumaroles distribution is the fact that, in the very central part of the AVC, there are no hydrothermal manifestations. In fact, with the exception of the Artu Jawe-Oitu Artu fumaroles, controlled by the NNE central Jawe fault system, the AVC manifestations are concentrated in the eastern and western extremes of the caldera rim. Over 20 groups and/or single manifestations have been numbered following the system adopted by the UNDP, 1973. Individual manifestations that could be measured and sampled are more than 65, plus some older manifestations (cold altered grounds), which are plotted on the map of ELC 2015, but are not included in this sketch.

6. DISCUSSION AND CONCLUSION

The AVC includes more than 125 volcanic centers, out of which 65 craters, from which lavas and pyroclastics were ejected. Most of these volcanic centres are situated along the caldera rim and following the NE and the NNE regional fault systems. Although at present no volcanic centre is active, the complex itself is considered to be active / dormant, but not extinct. Biggs et al., 2011, using satellite based interferometric synthetic aperture radar observations, demonstrated that at Aluto, Corbetti, Bora and Kone, between 1993 and 2010, there were inflations (uplifting) and deflations (sinking) of several centimetres of their surfaces. At Aluto the inflations took place in the periods December 17, 2003 - August 18, 2004 and May 14. 2008-December 1, 2008 and the deflations in the periods September 22, 2004-March 5, 2008 and January 12, 2009-July 28, 2010. These phenomena indicate the presence of a hot magma chamber, which is continuously replenished, wherefore pressure build-up and collapse could be manifested on the ground surface.

The youngest volcanic products of the AVC are mainly porphyritic obsidian lava flow or domes, which have been classified as “Recent Aluto rhyolite” (Rar) and are assumed to have an age lower than 10 Ka. Actually, the youngest flow was dated at 2 Ka (ELC, 1986). Areal distribution of these very young products, together with the associated hydrothermal manifestations and the structural pattern, are important indicators of the favorable geological conditions of these sectors from the point of view of geothermal energy exploration. In the case of the AVC, the hydrothermal manifestations are located preferentially around or very close to the caldera rim, in particular in the eastern and western extremes of the oval caldera sides. Moreover, there are intense manifestations along the Jawe fault zone, which crosses the central-eastern part of the caldera. It should be mentioned that the youngest obsidian lava flows are mainly concentrated in the eastern and western sides of the caldera, presumably due to the displacement of magma pockets in these sectors. Comparing the two sides of the caldera, it can be observed that volcanic products referable to the AVC in the eastern part have an average thickness of 340 m and in the western part about 600 m.

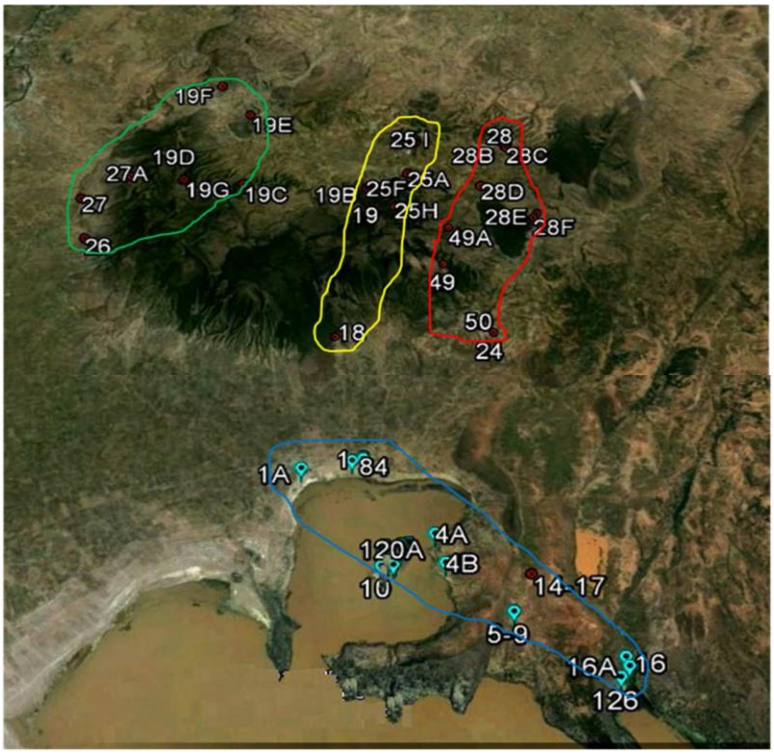


Figure 7. The four major groups of hydrothermal manifestations of the Aluto-Langano geothermal field. Red dot = fumaroles, magenta drop = hot spring. The four groups are 1) blue circle = southern Edo Laki – Oitu - Bole hot springs group, 2) red circle = eastern Bobessa-Gebiba fumaroles group, 3) yellow circle = central Artu Jawe - Oitu Artu fumaroles group, 4) green circle = western Worbota – Humo – Hulo - Auto fumaroles group. Manifestation numbers are according to UNDP, 1973 and ELC, 2015.

Moreover, the lacustrine sediments and the remaining older volcanic successions are much thicker in the west, as a result of the rift-ward inclination of the layers and the presence of faults down-throwing the geological sequence towards the rift axis. Due to the larger thickness of materials in the western rim of the caldera, hydrothermal manifestations and younger lava flows may appear in lower quantities as compared to the eastern rim. Nevertheless, a higher geothermal potential is expected to be in the western sector of the AVC, due to larger hydraulic recharge and thicker lacustrine sediments that may act as cap rock of the system.

Based on the surface and subsurface geological studies three principal priority zone are selected. These areas coincide with the three hydrothermal manifestation zones of AVC; a) the eastern caldera margin near the **Bobessa** hydrothermal manifestations zone ; b) the central part of the caldera along the **Artu Jawe fault** zone, where the deep wells proved the existence of a geothermal reservoir; c) the western portion of the caldera near the **Adonsha** hydrothermal manifestations (Figure 8).

A. Bobessa Zone (Red**)**

The Bobessa zone stands out as a sector of primary interest for two important reasons; 1) there are several hydrothermal manifestations, in particular fumaroles that gush under higher pressure as compared to the other regions. This suggests the existence of a geothermal reservoir underneath, rising to surface through the caldera rim and the associated NNE-SSW trending active faults system. 2) the presence of the youngest (about 2 Ka, ELC, 1986) obsidian lava flows is an indicator of an active heat source, which, based on the differentiated nature of the erupted products, is presumably located at fairly shallow depth. The fact that this area is situated at a higher level of the step faults system lowering the whole sequence to the west, together with the absence of lacustrine deposits and the relatively small thickness of the AVC pyroclastic deposits, casts some doubt on the existence of an effective cap-rock of the geothermal system, which may prevent a significant escape to the atmosphere of the geothermal fluids.

B. Artu Jawe Fault Zone (Yellow**)**

During the previous stage of exploration, following the unsuccessful drilling of two wells (LA-1 and LA-2) at the base of the AVC, the Artu Jawe Fault Zone (AJFZ) was identified as the most promising structure, directly investigated by 6 additional wells, out of which 2 (LA-3 and LA-6) resulted to be good producers and two more (LA-4 and LA-8) of possible commercial interest. LA-9 and LA-10 have a target to hit the AJFZ from the east by directional drilling. Like the other two preferential areas, along the AJFZ there are several hydrothermal manifestations, as well as the youngest obsidian lava flows that were ejected following the NNE-SSW fault system. As compared to the Bobessa zone, the AJFZ has more lacustrine sediments and thicker pyroclastic deposits, which may play a useful role to retain the steam present at depth. Models that have been proposed show that steam extraction in the AJFZ occurs from a secondary fault controlled system. A possible limitation of the AJFZ is the thickness of the shear sector associated with high permeability, which may be of only a few tens of meters, wherefore prolonged exploitation might cause a rapid reservoir depletion.

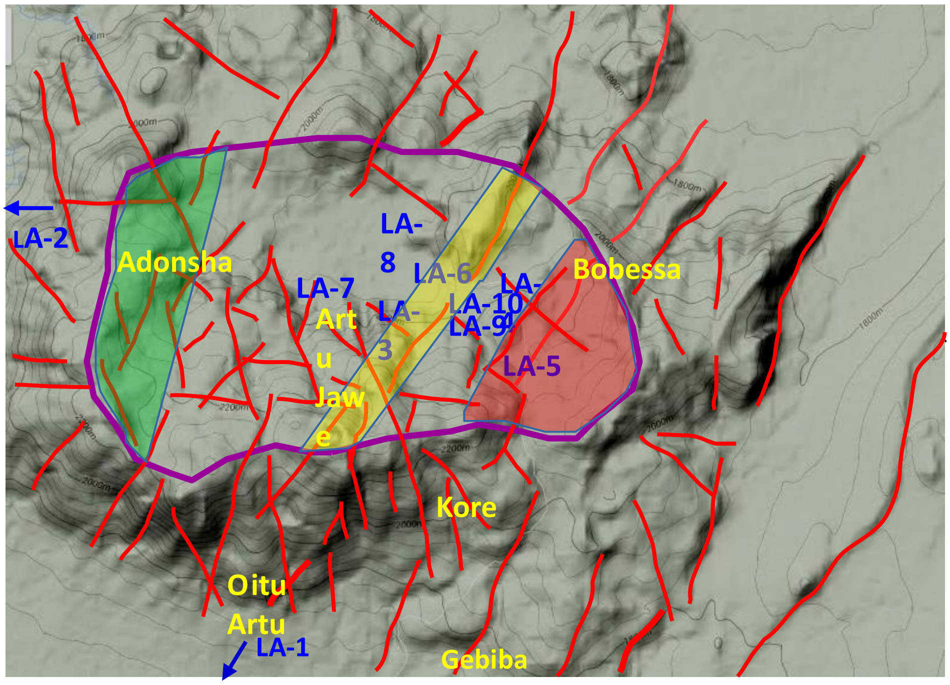


Figure 8. The priority zones of the AVC; Red = Bobessa Zone in the eastern internal part of the caldera, Yellow = the Artu Jawe Fault Zone, Green = the Adonsha Zone in the western internal part of the caldera.

C. Adonsha Zone (Green**)**

The Adonsha zone (Figure 8) is probably the most promising zone in the Aluto-Langano geothermal field. There are some important factors that point to this zone as of higher potential as compared to the above mentioned zones. 1) the Adonsha zone is located in the internal part of the caldera, where the AVC basement is particularly deep, the caldera rim might act as a hydrogeological barrier versus the groundwater flowing in that direction; 2) the lacustrine deposits and the fine pyroclastic deposits of the AVC are much thicker than in the other two zones, so the geothermal system might be less exposed to fluid escapes; 3) this zone is located

at the western side of the oval shaped caldera and it is deemed that, after the caldera collapse, the remnant magma shifted to the eastern and western extremes of the collapsed structure. Actually, the most voluminous youngest obsidian lava flows are found around this zone, suggesting a very favorable condition in terms of heat source. In the Adonsha zone three fracture systems, that is NNE-SSW, E-W, NW-SE, do meet. The last two are clearly expressed by the drainage system at the western foot of the AVC. Hydrothermal manifestations are not as vigorous as in the Bobessa and AJFZ zones, possibly due to the fact that the cap rock is here more effective: in fact, during this study large areas of fresh hot grounds were recognized.
In conclusion, from the manifestations, youngest obsidian lava flows areal distribution, other geological, hydrological and structural setup viewpoints, the Adonsha zone exhibits the most favorable indications for the existence of a higher potential geothermal system in the AVC.

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Recently the World Bank programmed to fund the developing countries to exploit their geothermal energy potential through the Icelandic International Development Agency (ICEIDA). Ethiopia was among these beneficiary countries and Aluto-Langano geothermal field is also one with high potential. The Geological Survey of Ethiopia launched a bid and ELC-Electroconsult won and this is part of the task. Geological mapping of Aluto was revised after 30 years, from the last comprehensive study. The field work was conducted between March 25 and April 11 2015. Geologists of the Geological Survey, Weinshet and Temesgen have participated during the whole period. Thin sections were made and studied in the CNR-IGG of Pisa. Drawings of the geological map, cross sections, and others were made by Francesco Baroni of ELC.

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