

## **SURFACE GEOLOGICAL MAPPING AT TENDAHO GEOTHERMAL FIELD, ETHIOPIA**

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### **ABSTRACT**

Key words: Tendaho graben, crisscrossing faults, permeability

The Tendaho Geothermal Prospect is located in the north eastern part of Ethiopia within Tendaho Rift, Afar depression. The area is bounded between 11°30'-12° (N) latitude and 41°00'-41°30' (E) longitude. The Afar area is characterized by active volcanism and extensional tectonics. It is a junction of three rifts, namely the Main Ethiopian Rift (MER), Red Sea rift and the Gulf of Aden that forms the Afar triple junction. Tendaho Geothermal prospect is one of the promising prospects in the Afar region. It has been geoscientifically well studied. 3 deep and 3 shallow wells were drilled. Follow up geochemical, well testing and reservoir engineering studies proved a high temperature (200-270°C), liquid dominated shallow reservoir.

The present study has focused to conduct local structural geological study in and around Tendaho area in view of the regional structure and the volcano-tectonic history of the region.

Interpretation of SPOT satellite and DEM images were used to define the location and pattern of major lineaments. In the field lineaments were checked and compass and GPS readings were taken. Both satellite imagery and field observations show that the main lineament is NW-SE, indicating the prevalence of the Red sea trend. At the western graben margin, NW-SE and NE-SS trending lineaments crisscross each other forming grid faults. Within the graben east-west and north-west trending structures are observed, though they are not prominent.

Joint interpretation of the results of the study with geophysical results shows that the NE-SW trending structures of MER are continuous in the subsurface within the graben and extend further to the eastern margin to about 10-15 km from Tendaho graben border. These continue, even further in a NE trend away from the graben itself. Since Tendaho is an active site of the present day extension, such fracturing and faulting counteract the sealing effect of hydrothermal activity. The existence of crisscrossing fault structures of MER (NE) and Red Sea (NNW) indicate potential increase in permeability to allow the circulation of fluid in the graben.

## **1.0 Introduction**

The Tendaho geothermal prospect area has been studied jointly by the then Ethiopian Institute of Geological Surveys (EIGS) and Aquater (1979) after the works of UNDP (1973) for the exploration of geothermal resources. The work included pre-feasibility and technical-economic studies to confirm the possibility of geothermal resource for electricity generation.

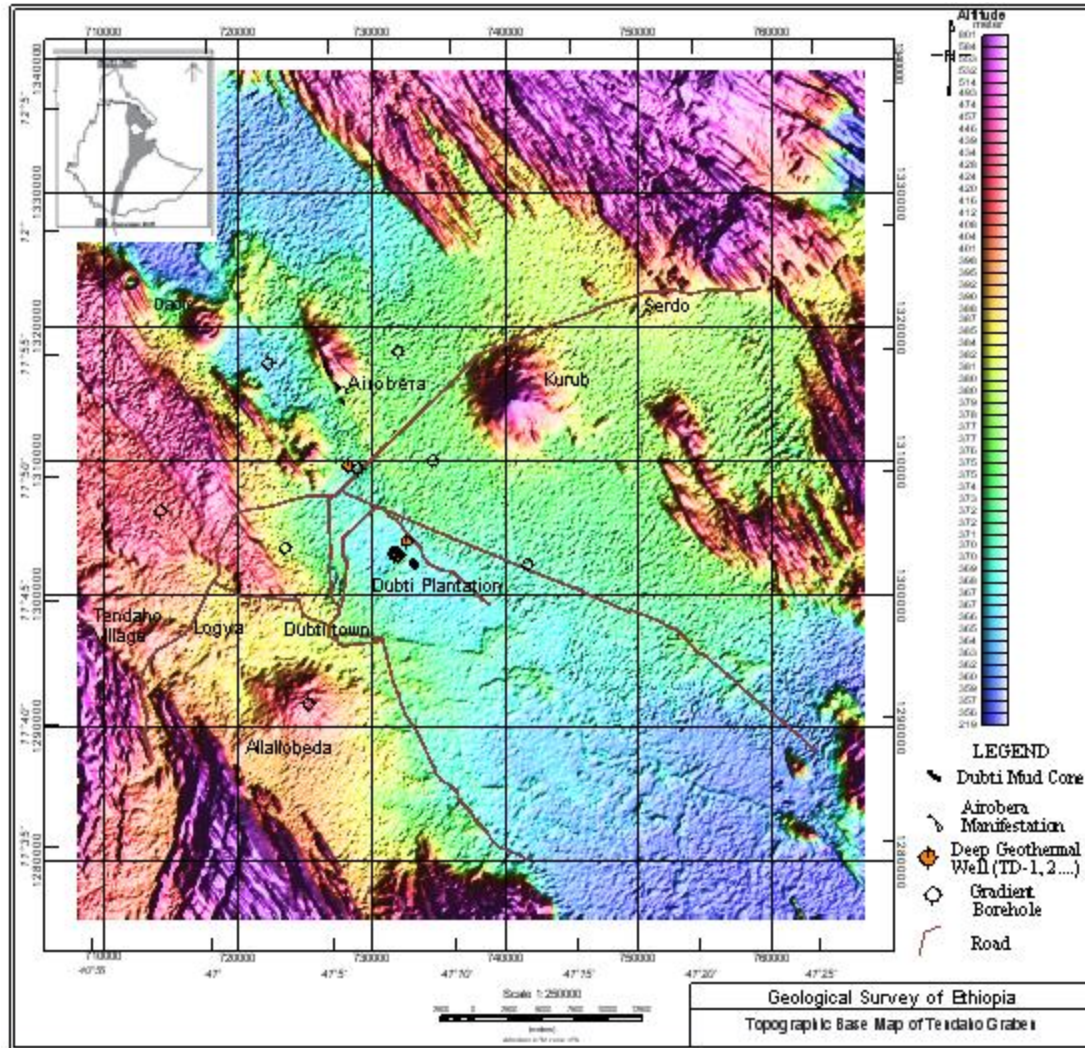
By the financial assistance of the Italian Ministry of Foreign Affairs in 1990, a drilling company, Aquater was hired to organize and implement the drilling activities; four wells (TD 1-4) were drilled; logging & in hole measurements were carried out; and field operations were completed by 1995.

Furthermore, between 1997 and 1998 Geological Survey of Ethiopia (GSE) carried out further drilling of two wells (TD-5 & 6) using its own resources. Subsequently, GSE conducted well testing and reservoir engineering studies. The results of these series of activities confirmed the existence of a shallow geothermal reservoir at Tendaho with reservoir temperatures ranging from 220-250 °C, with a relatively high permeability and having low salinity and non-condensable gas content. It was estimated that 2-5 MW of electric power could be generated from the existing wells.

Present structural study is a continuation of the previous studies and may provide additional information to understand more about the prospect area.

### **1.1 Location**

The Tendaho Geothermal Prospect is located in the Afar Regional State, north eastern part of Ethiopia, about 600 km of Addis Ababa, in Tendaho graben. The area is bounded between 11°30'-12° (N) latitude and 41°00'-41°30' (E) longitude (Fig.1).



**Figure 1: Location of Tendaho Geothermal Field**

## 1.2 Objectives

The purpose of the field work is to conduct structural geological study in and around Tendaho area to indicate possible areas of high permeability.

## 1.3 Previous Work

The Afar area is characterized by active volcanism and extensional tectonics. It is a junction of three rifts, namely the Main Ethiopian Rift (MER), Red Sea Rift and the Gulf of Aden Rift which forms the Afar triple junction. This unique nature has attracted several local and international researcher to investigate the tectonic, volcanic and geology of the area. Previous works include UNDP (1971-1973), geological map of North Afar and Lake Afrera areas at a scale of 1:100,000, CNRS and CNR (1972), Craig (1970) and others.

Tendaho Geothermal Prospect has been geoscientifically well studied by Aquater in 1979, in early 1980s and later. The outcome of the study gave good understanding of the heating and the circulation system and the siting of exploration wells to intersect the geothermal reservoir. Further geoscientific studies continued till 1993 and jointly by the financial and technical assistance of the Italian and Ethiopian governments. 3 deep and 3 shallow wells were drilled between 1993 and 1998. Follow up geochemical, well testing and reservoir engineering studies proved a high temperature (200-270°C), liquid dominated shallow reservoir. Geophysical surveys including MT and TEM, DC resistivity methods, gravity and magnetics were employed to study the subsurface structure. The MT survey was a reconnaissance type, which gave an insight into deeper part of the upper crust, but failed to delineate the reservoir. Therefore, high resolution MT is underway in order to discover an exploitable geothermal resource.

The results from re-analyses and interpretation of geophysical data enabled to map the subsurface geophysical structure and also assist in the understanding of the regional structures. The results of the present structural study (analyses) in addition with other studies conducted by different groups will be reviewed and help to analyze and determine the local structures in view of the regional mega structures.

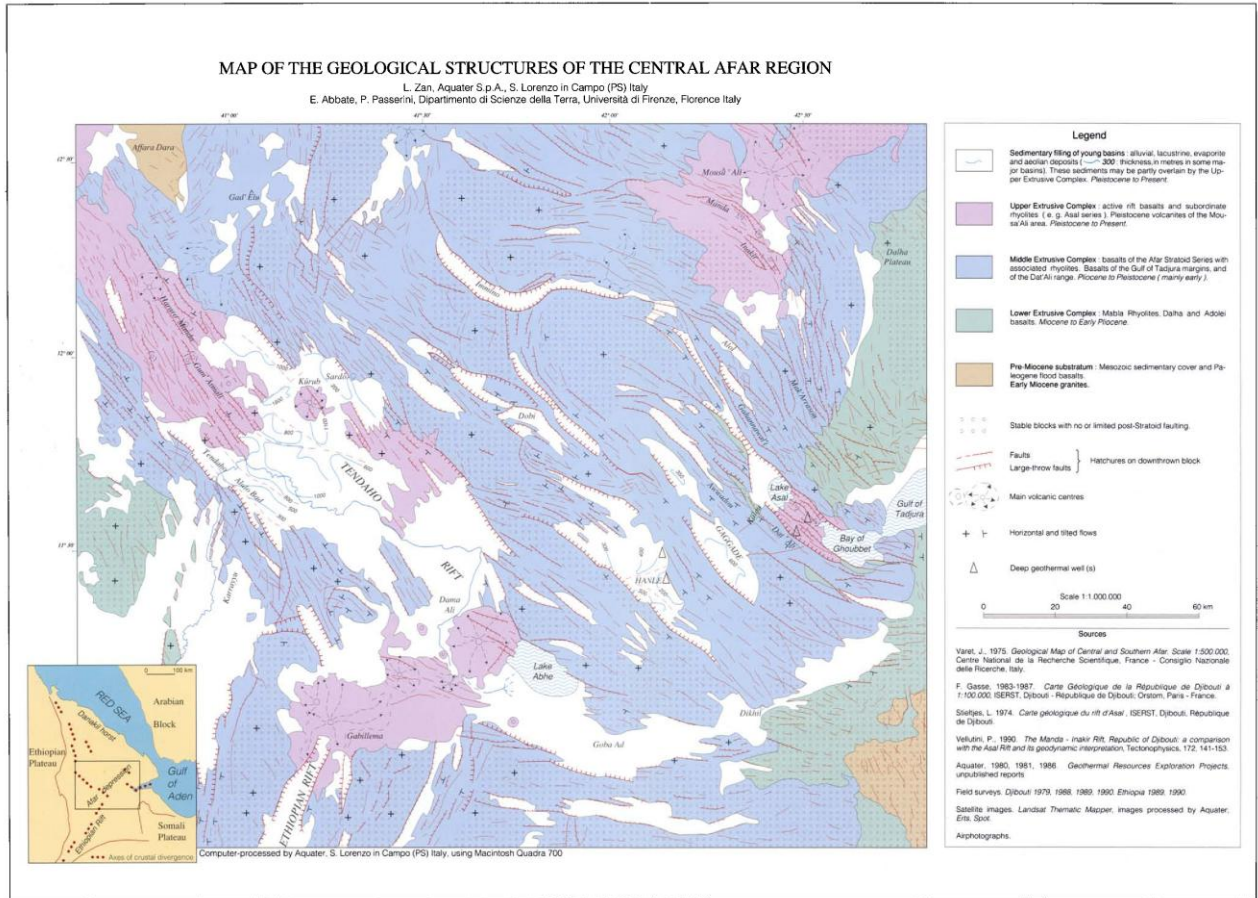
## **2.0 Regional Geology**

The Afar region is an area of active extensional tectonism and volcanism where the Red Sea, East African Rift system and The Gulf of Aden rift meet. Rifting in Afar began during lower Miocene on a continental arch where important basaltic activity was probably in progress. The Afar Depression is believed to have reached to its present geological setting during the Pleistocene period, with the formation of axial ridge. Intense tensional tectonics affects the entire depression, thus, forming a complex mosaic of horsts and grabens that are still active and contain localized sedimentary basins. From west to east, these are the Tendaho Graben, the Dobi Graben, the Gaggade Graben and the Assal Graben (Megersa et al., 2006).

Pre-Stratoid formations outcrop mainly at the margins of the Triangle. Directly beneath the Afar Stratoid Series lies the Miocene to Pliocene Dalha basalts (8.9-3.8Ma) formation (Varet, 1975) and Gasse et al., 1987), which is the main component of the Lower Extrusive Complex (Abbate et al., 1995) (figure 2). This unit consists of a series of basaltic flows. It is common toward the borders of the Triangle, and locally occurs at its interior (west and south of Lake Asal).

Earlier products of rifting include Miocene Mabla rhyolites. This unit, according to Barberi et al. (1975), has an age ranging from 15 to 10 Ma, and consists of thick flows, domes and ignimbrites of weakly peralkaline rhyolites (comendites).



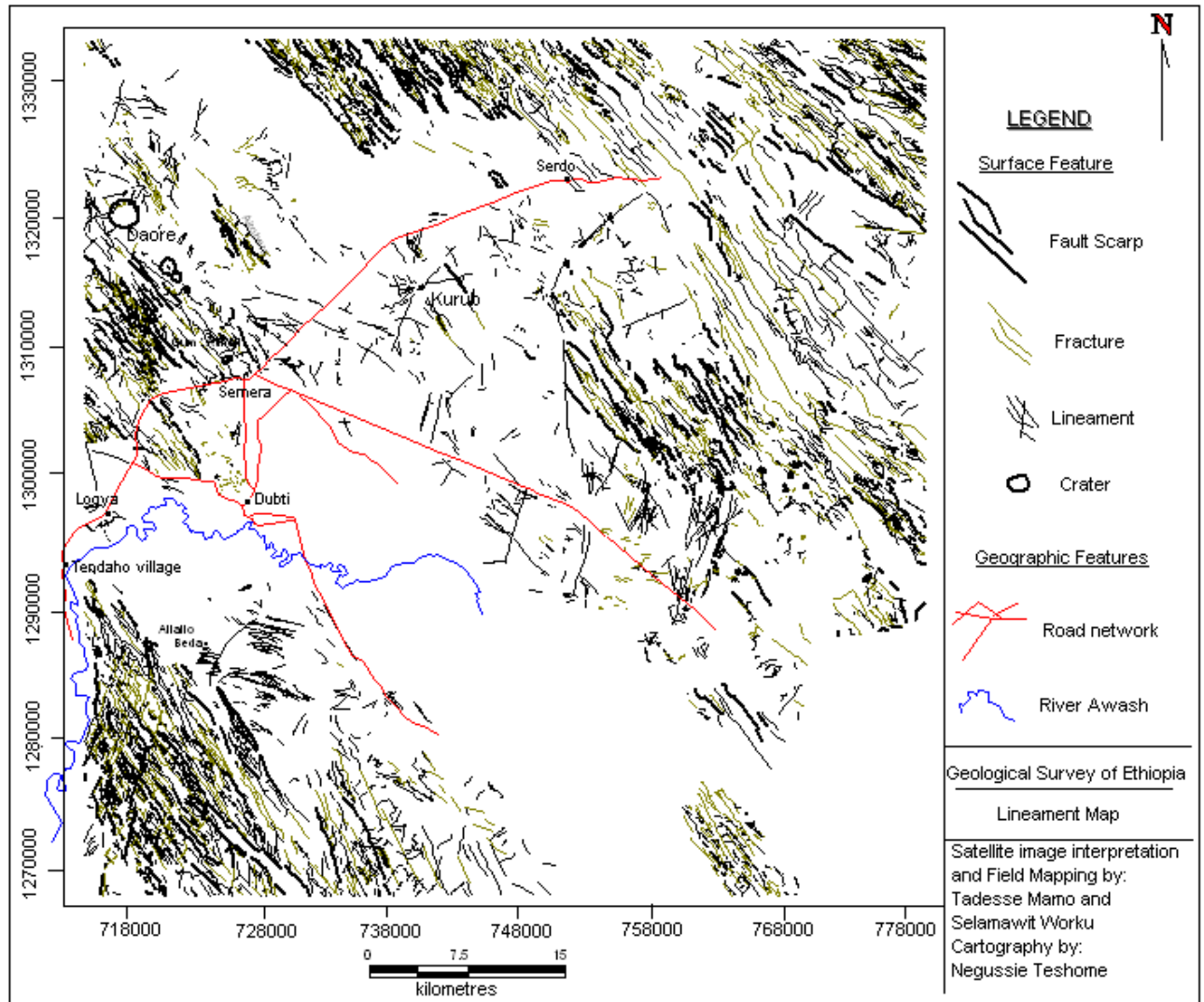


**Fig 2 Geological Map of Tendaho Area (after Abbate et al., 1995; Aquater, 1996)**

### 3.0 Local Geology

Tendaho graben trends in NW-SE direction, which is the southern portion of the regional Erta'ale-Manda Hararo Rift Systems. It has a width of about 50 km. Figure 2 portrays the geology and structures of the explored part of Tendaho. The Graben is covered by Pliocene – Early Pleistocene (4-1Ma) basaltic formation of the Afar Stratoid Series (Varet, 1975). This unit is constituted by monotonous sequence of basaltic flows and rare associated rhyolitic volcanic centers. Sedimentary and pyroclastics are observed being associated with the series. It outcrops on the graben margins. The Afar Stratoid Series is emplaced through fissures with a main NW-SE direction. The series is affected by tensional tectonics as observed by the numerous faults and fractures. The graben is characterizes by faults and block tilting during the emplacement of the series (Aquater, 1980). Later the margins of the graben were affected by tectonics and volcanism. There are younger and recent basaltic flows and subordinate rhyolites (Upper Extrusive Complex of Abbate et al. (1995), produced along rifts and at volcanic centers, and young sediments filling the inner tectonic basins (Aquater, 1996).

The borders of the Tendaho Rift are constituted by the Afar Stratoid series, the graben is filled with lacustrine and alluvial deposits and with post-Stratoid recent basalt flows. This filling is topped by recent volcanoes, including the historically active Kurub (younger volcanic products formed between 4,000 – 10,000 years ago). Afar Stratoid Series basalt form the Allalobeda escarpment on the south-western side of the graben (Abbate et al., 1995, Aquater,1996) (figure 1).



**Fig. 3 Structural Map of Tendaho Area**

## 4.0 Result and Discussions

The Tendaho Rift shows open fissures and active faults which define a pattern of NW-SE elongated blocks as observed from dem most of the faults trend in NW direction. At the

rift floor, these fault blocks may be either slightly tilted with homoclinal setting or sub-horizontal with a small-scale horst and graben array. At the rift margins, the blocks are mildly tilted toward the rift in the form of more or less continuous flexures broken by synthetic faults. Most of the faults show steep inclinations, having intersections with the topographic surface; in fact most of them are nearly vertical. The structures show strike-slip movements at the rift margins.

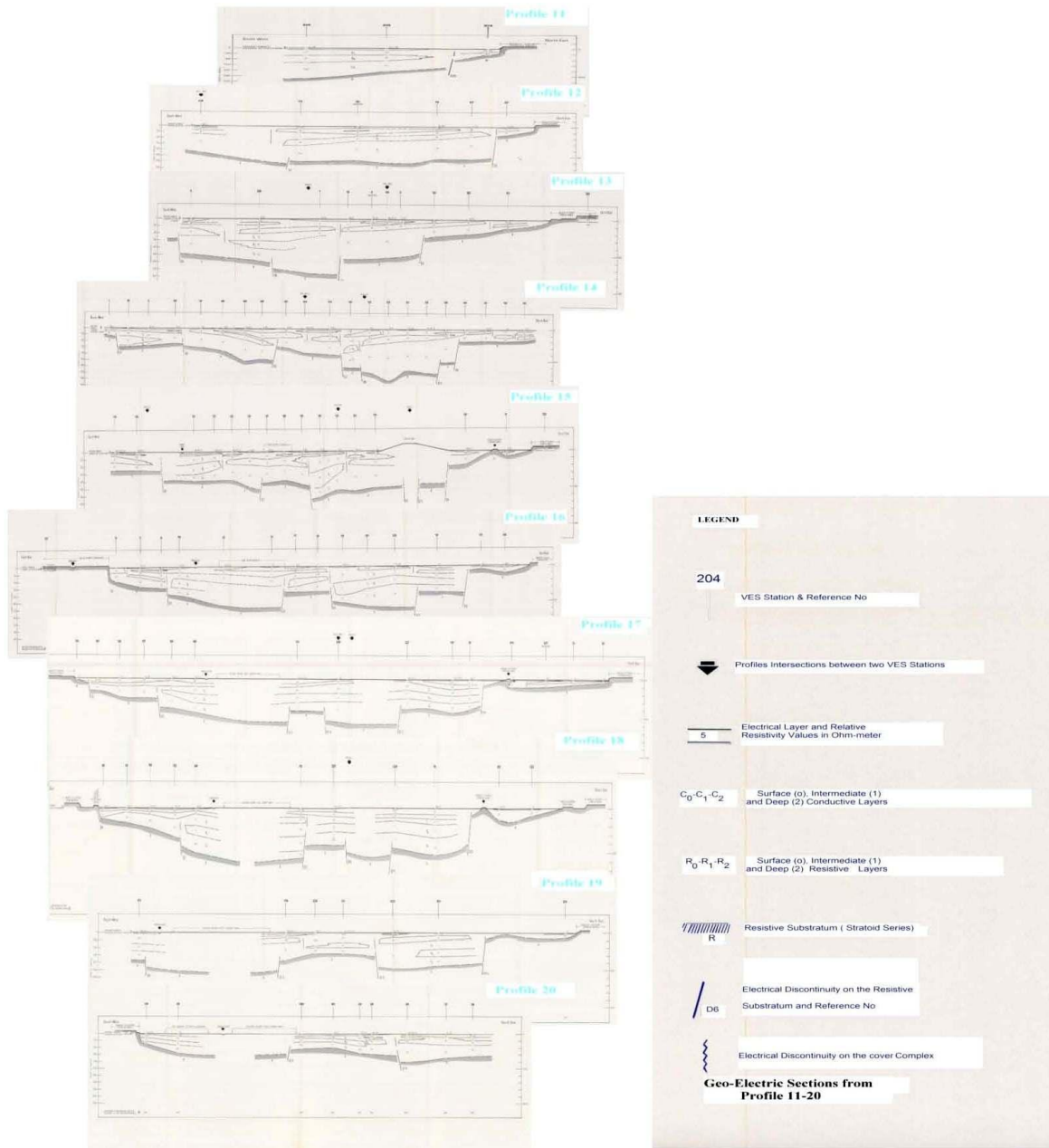
On its south-western margin abundant hydrothermal activity can be observed, both present and fossil, in particular along the major border fault at Allalobeda and to the north and south of this discontinuity, are not similar to that of Maganta Ali ridge (figure 3). The fossil manifestations occurring northwards, is represented by siliceous veins produced by hydrothermal circulation along NW-SE trending sub vertical fractures cutting the fluvio-lacustrine deposits Aquater (1996). These rocks emerge from the relatively flat topographic surface as sharp as “walls” denudated by selective erosion. In these veins hydrothermal acted until  $12 \pm 6$  ka (U/Th dating of hydrothermal calcite in chalcedony). Some exposed slicken sides indicated a mainly NNW strike. Movements along them consist of a well marked principal dip-slip, and a subordinate strike-slip shown by more delicate and less frequent striate.

Inside the Tendaho Rift lacustrine and alluvial plains alternate with zones where basalts crop out as NW-oriented elongated fault blocks. Evidence for active NW-striking faults is present also in the sediments within Dubti Plantation; these consist of aligned steaming grounds, fumaroles and hydrothermal deposits.

In the Gum’Atmali area the basalts are dissected by NNW-trending extensional fractures. According to the results of a micro-seismic study carried out by Aquater (1995), the area appears affected by tectonic activity produced by dip-slip and sinistral strike-slip movements which is also visible in the surface fractures.

As observed in the structural map (figure 3) the NE-SW trending structure of the MER is discontinuous on the surface in the graben then it continues further from the eastern margin to about 10-15 km from Tendaho graben border, further continuing in NE manner to the northeast. At the western portion of the graben margin NW-SE and NE-SW trending lineaments crisscross each other forming grid faults. Within the graben east-west and northwest trending structures are observed, though they are not prominent. This mega structure is also revealed in the reinterpreted subsurface geophysical data. Some of the major lineaments SW facing escarp of the Tendaho Rift and of the main branch of the East African Rift define an arcuate connection, indicating some kind of continuity. The throw is more than 1000 m. The central part of the rift, probably the axial zone, is a buried horst formation as both the geo-electric section and contour map of depth to the resistivity substratum indicate (figure 4). This is confirmed by gravity ridge of the axial region and magnetic maps. It is bounded by buried graben structures on its west and east sides (figure 5). In the central part, the horst is displaced by a right lateral fault and its intersections with the horst bounding normal faults may give rise to an excellent permeability (Bekele, 2012). It is also shown on the map an east-west trending fault which was also observed in the logs of TD-1 and TD-2 stratigraphy.

The Stratoid basalt is a corrugated feature formed by graben, horst and stepping structure as interrupted by a major resistivity discontinuity (figure 4). At the northern part of the structures, a stepping resistivity structure, forming a half graben can be observed. Depths to top of the Afar stratoid vary along the resistivity profiles which cross the Tendaho rift. As a result, thicknesses of sediments deposited over the graben and horst, on the averages, are 1300 to Afar Stratoid in the grabens and 800 meters to recent basalt or the horst structure, respectively (Bekele, 2012).



**Figure 4: Stacked geoelectric sections, showing the subsurface rift configuration (digitized & reproduced from Aquater (1980) by Bekele(2012)).**



Gravity and magnetic data were reinterpreted to map the subsurface structure mainly using residual gravity and magnetic fields and their filtered components. Euler 3-D deconvolution was applied using fault model with structural index of 0.5 to estimate source positions. Figure 5 below portrays the final results of interpretations.

Fault depths vary from 450 to 2500 meters with mean depth of 970 m. These faults bound the graben and horst structures. They are coincident with the resistivity structures shown above in figure 4.

Three alignment directions, namely northwest, northeast, and east-west trending features interpreted as faults can be easily distinguished in figure 5 below. In the geothermal bore hole area the alignment of mud cones enabled to infer a northwest trending Dubti faults.

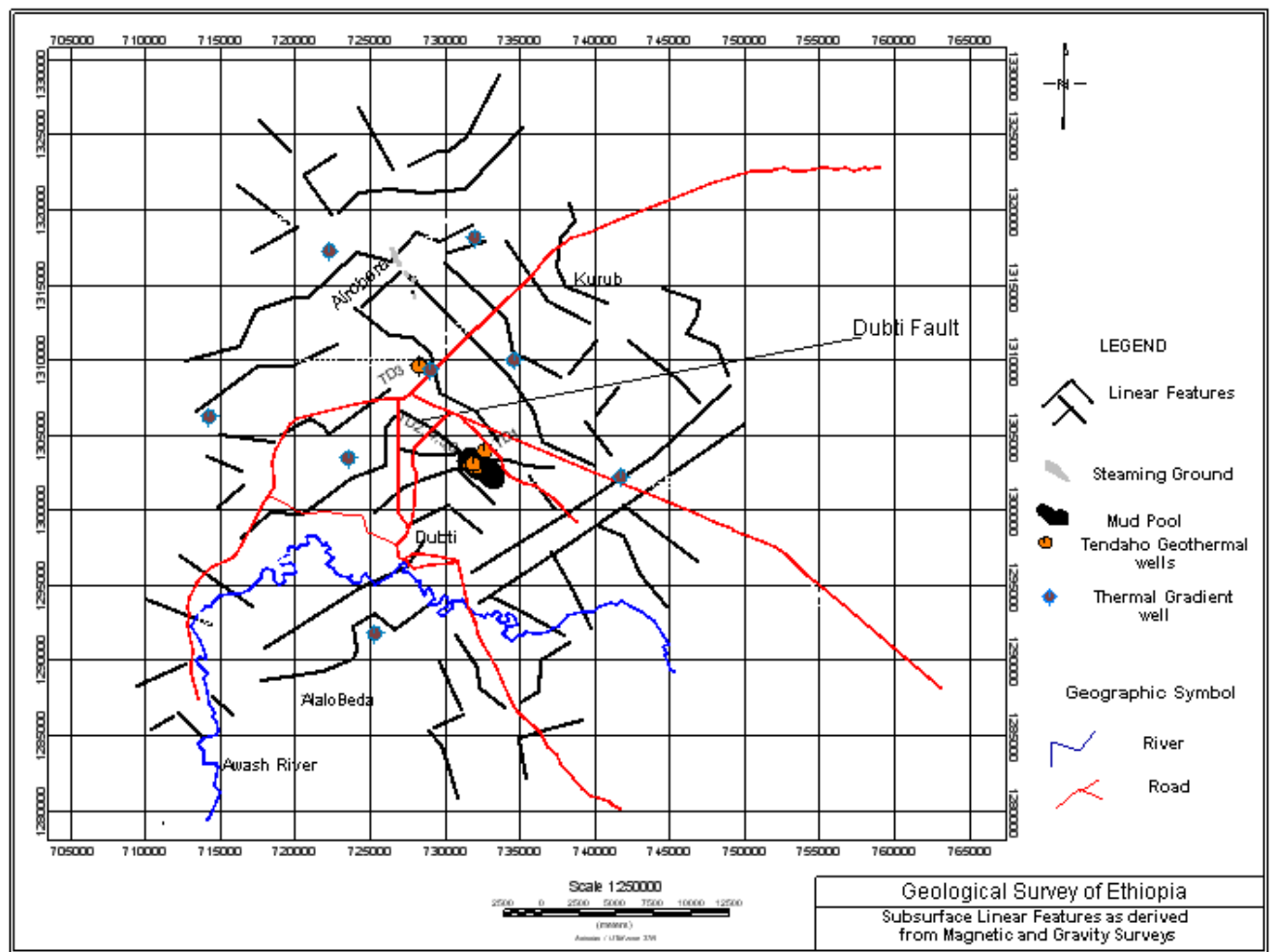


Figure 5: Interpreted subsurface structures derived from magnetic and gravity data (after Bekele B., 2012).

In this same area the east-west fault has been detected by wells TD-1 and TD-2. In the subsurface the east west fault interacts with the other two faults striking northwest and northeast. At Ayrobera, where weak fumaroles and hot steaming ground exist there is a crisscross between the northwest and northeast trending faults. At the south of the explored area a prominent northeast trending fault traverse the Tendaho graben. At south and southeast of the bore area it offsets the principal northwest trending faults. However, at the southwest, south of Dubti town it is displaced by the northwest faults. This shows that the two fault systems are active as evidenced by their interactions at borders of Tendaho rift.

Along the western boundary fault regionally trending NNW (Maganti Ale) near Awash River, the area is covered by chalcedony deposits crossed by a fissure trending 30°NNE. The ridge is mainly composed of Afar Stratoid basalt trending 330°NNW. Further going south towards Allalobad, there is an area of warm/hot ground having temperature of 40°C aligned in N-S direction (grid ref. UTM 0717280mE and 1290573mN). The sediment at the base of the fault is altered to whitish, yellowish grayish and reddish soft clay like material. Following the same trend there is a fumarolic area having temperature of 80°C and covering an area having 50 m radius and the sediment is altered to reddish clay (grid ref. UTM 0717247mE and 1290397mN). During the field study, it was observed that the fumarolic activity has increased along the major fault. At Allalobad the flow rate of the individual springs has increased but the geyseric activity has decreased. In the vicinity of the springs there is a NNE 60° trending fault intersecting the major NNW structure (Maganti Ale fault) (grid ref. UTM 0719371mE and 1287670mN) .

There is an artificial dam constructed by damming Awash River for Sugar Cane Plantation. The axis of the dam is parallel to the Maganta Ali fault. The activities which have increased and the area being affected became wider this might be due to seepages from the reservoir of the dam along the major structures. In addition in the vicinity of the reservoir the NNE trending MER and the NNW trending Red Sea Rift crisscross. These structures also might have allowed the infiltration of the reservoir water.

## **5.0 Conclusion**

The Tendaho Graben has a huge potential for geothermal resource as indicated by different stages of studies. Such studies also include the drilling of three deep and three shallow geothermal wells. The outcome of the study indicated Recent to Pliocene-Pleistocene volcano-tectonic activities characterize the area.

The active and the fossil thermal manifestations in Dubti plantation area are concentrated along the Dubti fault which runs in NNW manner following the major graben axis. It can be concluded that its interaction with the other fault systems create passages for the ascending geothermal fluid.

Similarly the active manifestations at Ayrobera projected to the surface due to the crisscross of the NW and NE trending structures. The Allalobad areas are aligned along the main NNW trending structure since this fault serve as a conduit for the ascending hot

fluid (steam and hot water). Therefore, the presences of these active and fossil hydrothermal manifestations indicate the presence of geothermal reservoir at depth.

The existence of crisscrossing fault structures of the MER and Red Sea in the southwest of the graben which was observed by the geological mapping on the surface and the continuation to the subsurface from geophysical interpretation, indicate presence of possible reservoir at depth. Therefore, the delineation of the reservoir is highly necessary to know the size and the volume. Furthermore, the presence of lacustrine sequence, as obtained from the drill holes serves as a cap rock to the geothermal reservoir.

Finally, the recent phenomenon around Allalobad and Maganti Ale ridge tells us that, there is an increase in the activity after the damming of Awash River for irrigation. Therefore, it is recommended to conduct further geo-scientific study to understand the interference with the shallow circulation fluid.

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