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Evaluation of Structural Permeability of the Northern Lake Abaya Geothermal Field, Southern Main Ethiopian Rift, Using CO_2 Flux Measurement

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ABSTRACT

The Northern Lake Abaya geothermal field is located on the axis of the Southern Main Ethiopian Rift (SMER), near the western margin where the plateau transitions into the rift floor. It is about 275 km south southwest of Addis Ababa. This research conducted to evaluate the structural permeability based on interpretation of geological field observations, structural data analysis and soil CO_2 flux survey. Geological observations in certain research area was done with the target to look for faults and collection of structural data measurements. The geological structures from field observation are transferred to structural map of scale 1:50,000. A number of 82 tectonic faults and joints were analyzed from field data. This is used to determine the locations and trends of geological structures and deduce the major structures controlling fluid movement. The soil CO_2 flux data were used to quantify the natural CO_2 emissions and establish the relationships between soil gas emissions and the geological structures which is then used for subsurface fault characterization of the research area.

The result of structural mapping and analysis shows that the research area is affected by extensional tectonics which is manifested by the occurrence of joints, fissures and extensive normal faulting, dominantly trending 005-010. The result of the soil CO_2 flux survey shows that the CO_2 flux anomalies are closely associated with the faults and surface manifestations. The elevated fluxes (>>100 $g\ m^{-2}\ d^{-1}$) is found along major faults and surface manifestations. The total CO_2 released from the Abaya fault has a total degassing amount of 282.274 ton d^{-1}. These anomalies CO_2 fluxes were interpreted as sections of greater permeability causing accelerated gas diffusion from geothermal or crustal magmatic sources.

The structurally controlled surface thermal manifestation and the anomalous soil CO_2 flux suggest that the Abaya geothermal system has favorable deep-seated permeable zones for the fluids to accumulate and continuously feed the surface thermal emissions.

1. INTRODUCTION

The Northern Lake Abaya geothermal field is located on the axis of the Southern Main Ethiopian Rift (SMER), near the western margin where the plateau transitions into the rift floor. It is about 275 km south southwest of Addis Ababa. The geothermal exploration license in the area is owned by Reykjavik Geothermal Ltd, an Icelander geothermal development company.

The principal sources of energy in Ethiopia are represented by traditional (biomass) energy sources. This is because more than 80% of the country's population is engaged in the small-scale agricultural sector and lives in rural areas (Kebede, 2016). The continuous economic growth has brought about a significant growth of energy demand including electricity. Currently, all the energy to be produced in the country are focus in renewable energy resources centered on hydropower, with complementary geothermal energy (Kebede, 2016).

Geothermal resource exploration and study in Ethiopia started in 1969 with a collaboration work of the Ethiopian Geological Survey and the United Nations Development Program (UNDP). Over the years, an inventory of the possible resource areas within the Ethiopian sector of the East African Rift system (EARS), as reflected in surface hydrothermal manifestations has been built up. A regional reconnaissance work was conducted in the whole rift, including Geological, geochemical and hydrological surveys (UNDP, 1973). Lake Abaya geothermal prospect was one of the selected areas as the most promising geothermal fields.

Resource exploration and assessment activities in the Northern Lake Abaya geothermal field consist of detailed geological mapping, analysis of remote sensing data, such as; digital elevation models, aerial photography and thermal imagery, soil temperature and soil gas flux measurement, fluid and gas sampling, resistivity survey. The results are combined into a geothermal conceptual model. This paper will explain the evaluation of structural permeability and their control on the thermal manifestations tested by using CO_2 flux survey. Surface structural mapping and field point measurement of the structural trend is also presented.

2. REGIONAL GEOLOGY

The volcanic activity in and around the Lake Abaya geothermal field is typically marked by bimodal activities (Minissale et al., 2017). The first stage of volcanic activity is constituted by rhyolitic centers characterized by the emission of large volumes of peralkaline lava flows, domes and pyroclastic deposits. Very recent obsidian and pitchstone flows are located near the southern edge of the Hobitcha caldera, at Salewa-Dore and Hako volcanic centers. These latter centers probably represent the youngest rhyolitic activity in the area and are characterized by ongoing steam vents and steaming ground activity (Chernet, 2011). The youngest rhyolitic centers are thought to host a shallow magma chamber that serve as the heat source for geothermal resource existing in the area.

The second stage of volcanic activity is characterized by basaltic lava flows, scoria cones and phreatomagmatic deposits. The basalts are associated with the recent faults. These faults are documented by NNE-SSW alignments of numerous scoria cones marking the main fault swarms (Corti et al., 2014).

The outcropping rocks in and around the Lake Abaya geothermal field are mainly volcanic and volcano-sedimentary formations, mostly associated with the main rifting events (Corti et al., 2014). The oldest volcanic products are represented by Oligocene (30–36 MA years old), pre-rift basalts of the Trap Series (Mohr and Zanettin, 1988). These units are overlain by Pliocene peralkaline pantelleritic Nazret ignimbrites and trachytic lava flows. These units are in turn overlain by sequences made of alluvial and rare lacustrine sediments, with interbedded pyroclastics and basalt flows of Pleistocene-Holocene age (Corti et al., 2014).

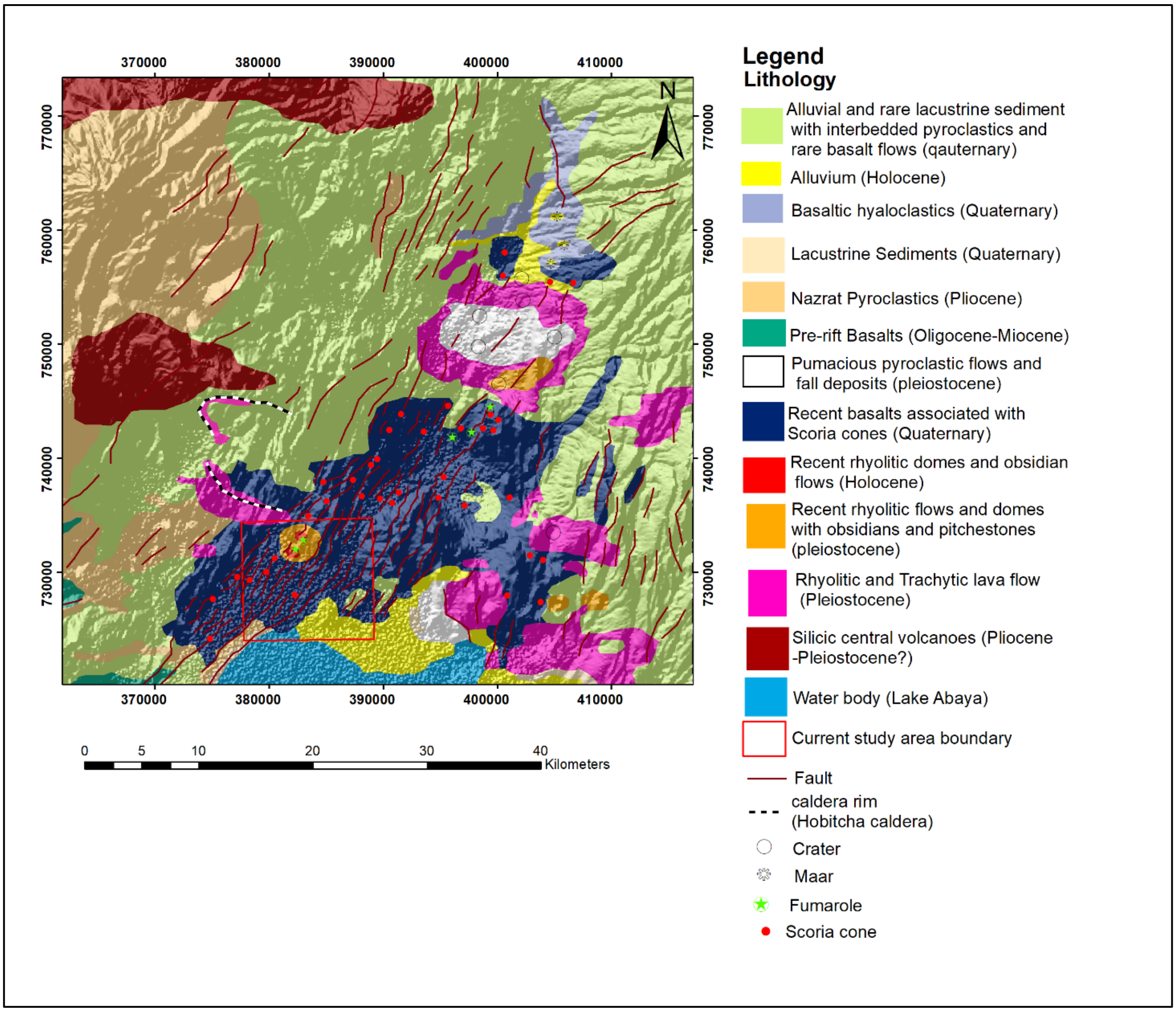

Figure 1: Simplified geological map of the Wolaita Soddo area shows the rock formations in the study area are in the red box located on Quaternary volcanic rocks consisting of young rhyolitic products and basaltic lava flows (Corti et al., 2014)

3. MATERIAL AND METHOD

The data used in this study is the result of field observations and soil CO_2 flux survey.

3.1 Field Observation

The field work was carried out to collect primary data include structural mapping and soil CO_2 flux data collection. At this stage, the geological observations in certain research area was done with the target to look for faults and collection of structural data measurements.

The geological structures from field observation are transferred to structural map of scale 1:50,000. This is used to determine the locations and trends of geological structures and deduce the major structures controlling fluid movement. Field structural data consists of over 82 fault measurement points and more then 10 for fractures and joints. Selected structural data are presented in Table 1.

Table 1: Selected field structural (fault) data

ID	Orientation		Location			Down throw	Lithological Unit
	Strike	Dip	Easting	Northing	Elevation		
F001	32	85SE	373468	736095	1393m	15m	Basalt
F002	10	80SE	375379	738719	1417m	35m	basalt
F003	15	85SE	379414	733645	1208m	180m	Ignimbrite
F004	005	65SE	378414	733159	1263m	25m	Basalt
F005	10	75SE	377069	732432	1296m	45m	Basalt
F006	30	85SE	374742	732686	1294m	20m	Basalt
F007	15	70SE	374676	732816	1303m	20m	Basalt
F008	25	75NW	372562	735099	1354m	20m	Basalt
F009	345	65NE	378535	731185	1457m	150m	Ignimbrite
F010	10	85SE	377116	742292	1452m	40m	Basalt
F011	005	80SE	376197	742239	1439m	10m	Basalt
F012	345	75SW	380202	743697	1428m	40m	Basalt
F013	340	65SW	380318	743710	1414m	30m	Basalt
F014	30	85SE	381368	744683	1387m	5m	Basalt
F015	005	70NW	382180	745033	1415m	18m	Basalt
F016	10	85NW	382082	744264	1393m	30m	Basalt
F017	30	85NW	381951	744151	1377m	50m	Basalt
F018	340	75NE	377910	730967	1261m	15m	Ignimbrite
F019	20	65NW	382594	732306	1209m	85m	Ignimbrite
F020	005	35SE	382980	732269	1221m	35m	Ignimbrite

3.2 Soil CO_2 flux measurements

The soil gas flux survey consist of 756 direct measurement points. This was conducted in a selected research area at predefined profiles and fixed intervals, perpendicular to the fault structure and systematic sampling method. The CO_2 flux through the soil was measured over a rectangular grid with intervals of 50 m E-W and 200 m N-S with some exclusion in areas not suitable for measurement.

The target areas for the soil CO_2 flux survey was based on the surface studies result (remote sensing analysis, structural mapping) conducted earlier than the survey and previous literatures done on the same geological environment (e.g. Hutchison et al., 2015). The soil CO_2 flux data were used to quantify the natural CO_2 emissions and establish the relationships between soil gas emissions and the geological structures which is then used to evaluate the structural permeability (subsurface fault characterization) of the research area.

4. RESULT AND DISCUSSION

Integration between field structural observation and soil CO_2 flux data interpretation were done to determine the major geological structures controlling the geothermal fluid flow by providing channels of high permeability.

4.1 Geological structures and permeability

Field structural observation in this study shows the presence of series of intense normal faulting, volcanism and active geothermal activities in the area. Here, detailed structural mapping and structural analysis (the trend of the structures) of field data using the stereographic projection technique in GeoRose software is conducted and presented.

Normal fault is the predominant structure mapped during the field activity (Figure 2). Faults are characterized in general by the occurrence of steep slopes, separating rocky ridges with steep sides usually covered by basalt and ignimbrite blocks from flat, narrow plains underlain by volcano-sedimentary deposits. The throw of the faults within the basaltic and ignimbrite portion can be estimated to be in the order of 10-180 m. It is noted that the faults change its attitude both along strike and dip. Faults observed and measured are high-angle normal faults where their dips are ranging from 75° to 85° to the northwest and the southeast. Fault strikes vary from N-S, NNE-SSW, NE-SW but most of the study area has a high density of 005-010 trending faults as it is depicted in structural analysis (Figure 3). Joints and cracks were also the other structures mapped during the field campaign. The structural analysis of the measured joints and cracks shows three general trends: NW-SE, NE-SW and NNW-SSE (Figure 3).

Geothermal fluid flow along the Ethiopian rift system is greatly influenced by the system of normal faulting, en echelon rift shoulder faulting and the rift floor basin (Hutchison et al., 2015). The faults may facilitate geothermal fluid flow by providing channels of high permeability or they may create barriers to flow by offsetting areas of high permeability. Previous studies to evaluate geothermal resources within the MER have indicated that Quaternary extensional tectonic movements along the axis of the rift have evidently created wide spread secondary permeability and faulted the cap rock thereby a supply of hydrothermal fluid to surface manifestations (e.g., Corti, 2014).

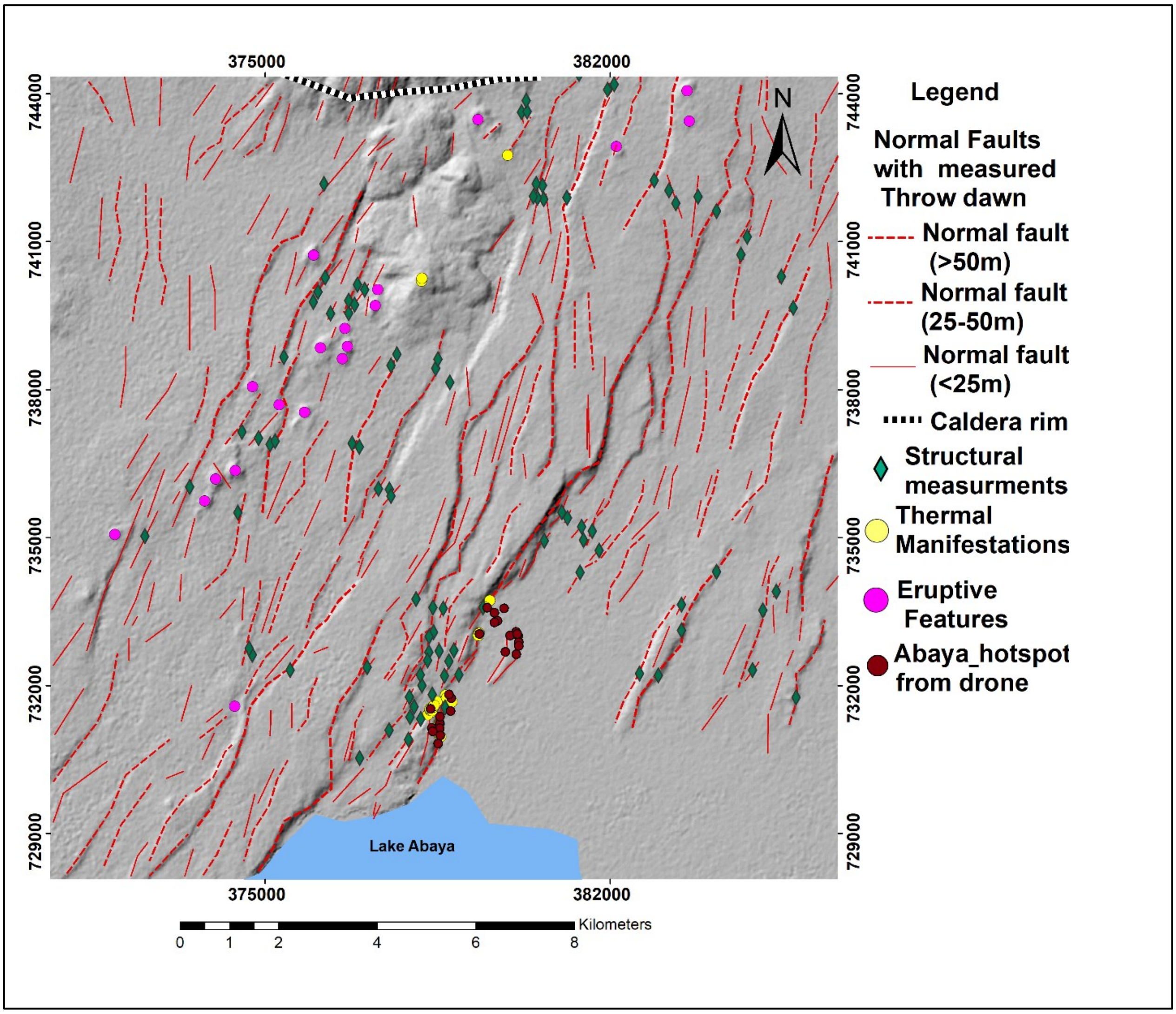

Figure 2: Structural map of the study area with sites of structural measurements overlain on hill shade as a background; mainly interpreted from Google earth, SRTM DEM, Landsat 8 and field mapping.

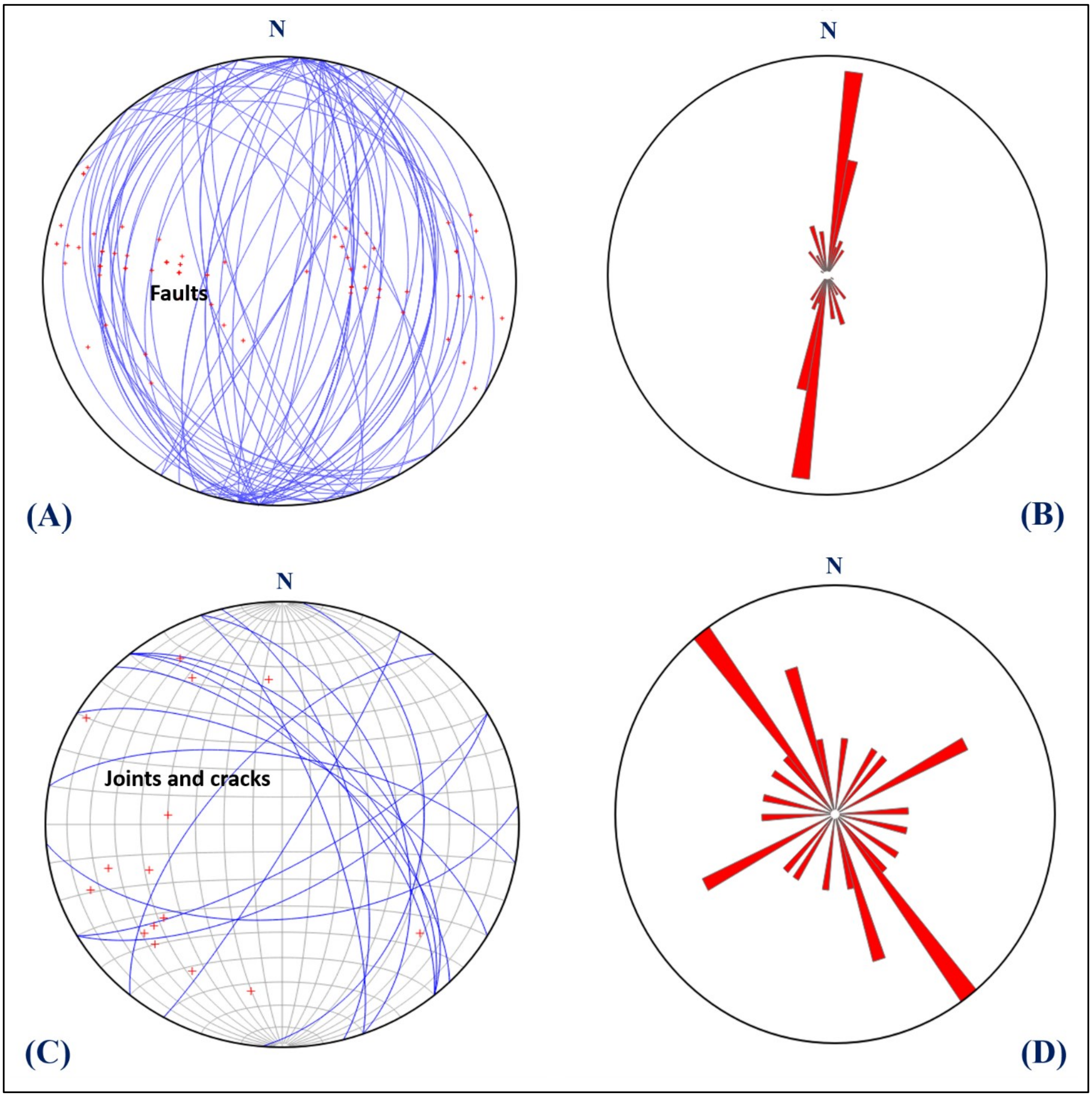

Figure 3: Schmidt net lower hemisphere plot of structures measured in the field A. stereo plot of faults B. Rose plots comprising fault trends C. stereo plot of systematic joints and cracks D. Rose diagram of joints and cracks

The structural mapping and analysis shows that most part of the research area is intensely fractured by tectonic activity. The series of dense normal fault system with dominantly trending in 005-010 is important as a passage way for geothermal aquifer. The high density and length of faults and joints causes high degree of fracturing of rock formations. The presence of highly displaced fault system (180 m) is an implication of the effect of the faults to the crustal depth. This tectonic fracturing creates high degree of enhanced (secondary) permeability of geothermal reservoir.

4.2 Soil CO_2 flux measurement and distribution

The study of the soil CO_2 gas flux distribution has proven to be an important methods to identify vertical zones of high permeability. This is based on the theoretical assumption that areas which are highly affected by brittle structure will have high CO_2 flux result because those structures act as a conduit and make the lithology and the soil more permeable. It finally enable us to get high value of diffuse degassing structures (Hutchison et al. 2015).

The CO_2 flux survey area is partitioned in to four sites for the purpose of easy analysis of data (Figure 4). Site-1 is the measurement stations north of the Salewa Dore volcanic complex; Site-2 is measurement points at the south of Hako volcanic complex; Site-3 is found at the southwest part of the study area and Site-4 is the CO_2 flux measurement stations at the Abaya fault around the main thermal manifestations (Abaya spring area).

Field soil CO_2 flux measurement shows that the value ranges between 0.223 - 2000 (g m^{-2} d^{-1}), with one value 6020 (g m^{-2} d^{-1}) and here considered an outlier and excluded from the analysis. The CO_2 flux distribution of the collected data is depicted in cumulative percentage in Figure 4. The flux values below 16.1 g m^{-2} d^{-1} (the 75% lowest values) are considered a background value. The measurement values between 16.1 g m^{-2} d^{-1} to 47.4 g m^{-2} d^{-1} (75% - 90%) are considered as a transitional value and the flux values greater than 47.4 g m^{-2} d^{-1} (the 90% greater values) as geothermal anomaly.

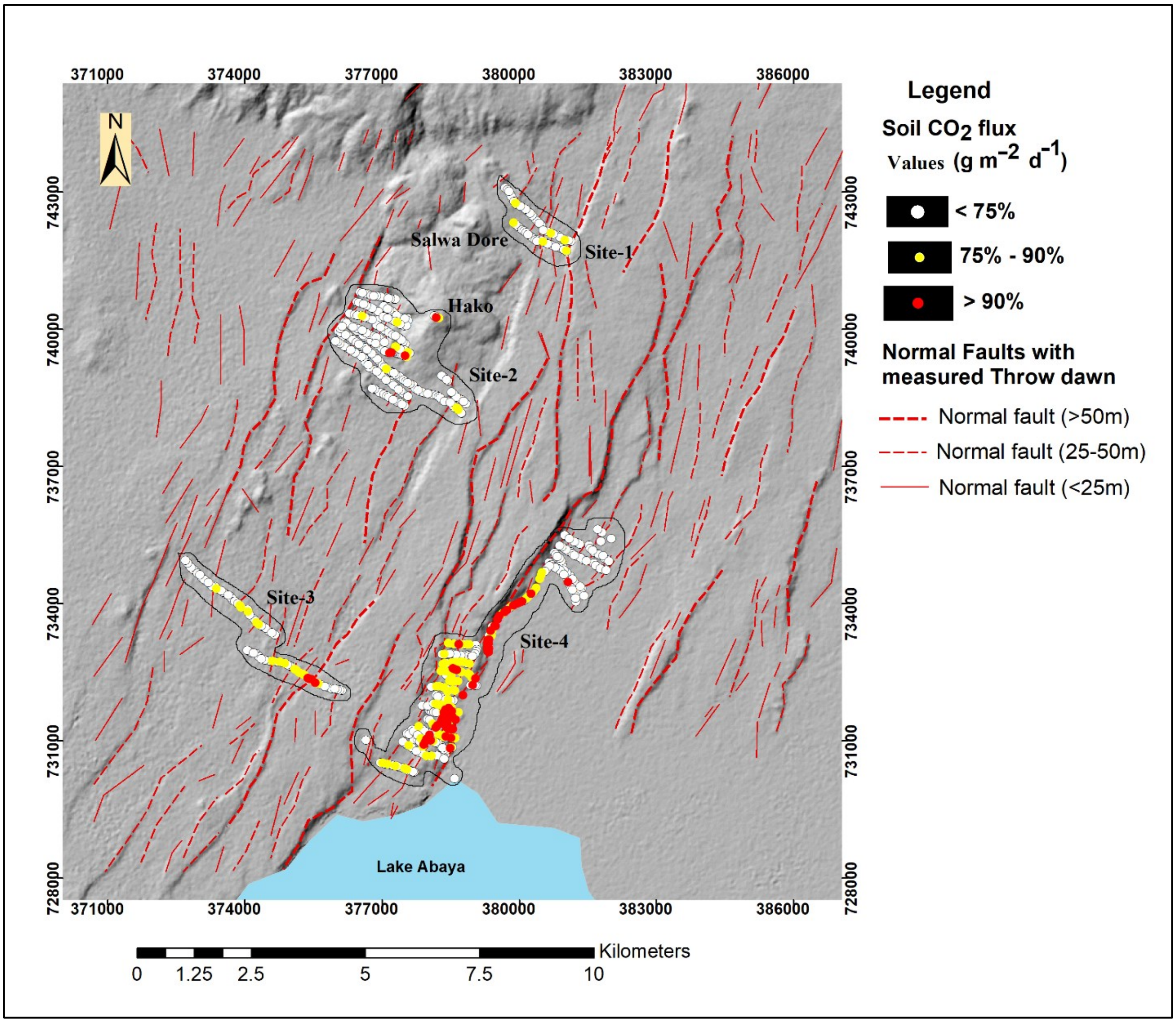

Figure 4: Location and spatial distribution of soil CO_2 flux. The measurement stations are in the area around Salewa Dore-Hako rhyolitic complex, a profile crossing the SD-H graben and in the Abaya springs. Spatial distribution of soil CO_2 flux is reported in cumulative percentage, with white circles representing a background value, yellow representing a transitional value and red representing a geothermal anomaly

Mathematical analyses of the soil CO_2 flux data make it possible to calculate the total CO_2 emission in the study area. Accordingly, the highest CO_2 emission is from an active geothermal area (Site-4) adjacent to the Abaya fault scarp that is amounted to ~ 282 t d^{-1} (Table 2).

Table 2: Calculation of the total gas emission for site- 4 from each CO_2 flux population

Populations	Cumulative (%)	Mean CO_2 flux [g m^{-2} d^{-1}]	Area covered (m^2)	Total gas emission (ton d^{-1})
Background	75	6.738	3,672,359	24.745
Transitional	15	25.877	3,672,359	95.031
Geothermal Anomaly	10	44.244	3,672,359	162.481
Total				282.274

The soil CO_2 flux data at site-4 was gridded for contour maps and interpolation between data points is made to yield spatial distribution and finally degassing structural pattern was identified. A dashed line linking the CO_2 flux anomalies is used to depict interpolated fault in the areas of thermal manifestation around the Abaya hot springs (Figure 5).

The result of the soil CO_2 flux survey shows that the CO_2 flux anomalies are closely associated with the faults around the surface manifestations. It shows elevated fluxes (>>100 g m^{-2} d^{-1}) along major faults Abaya hot springs and fumaroles suggesting that the CO_2 in that area travels mostly with rising hydrothermal steam. The high CO_2 flux can be interpreted as sections of greater permeability causing accelerated gas diffusion from geothermal or crustal magmatic sources. The anomaly may be attributed to presence of fault intersections which may have been reactivated to allow partial permeability. Alternatively, the anomaly may be in close proximity to an up flow zone.

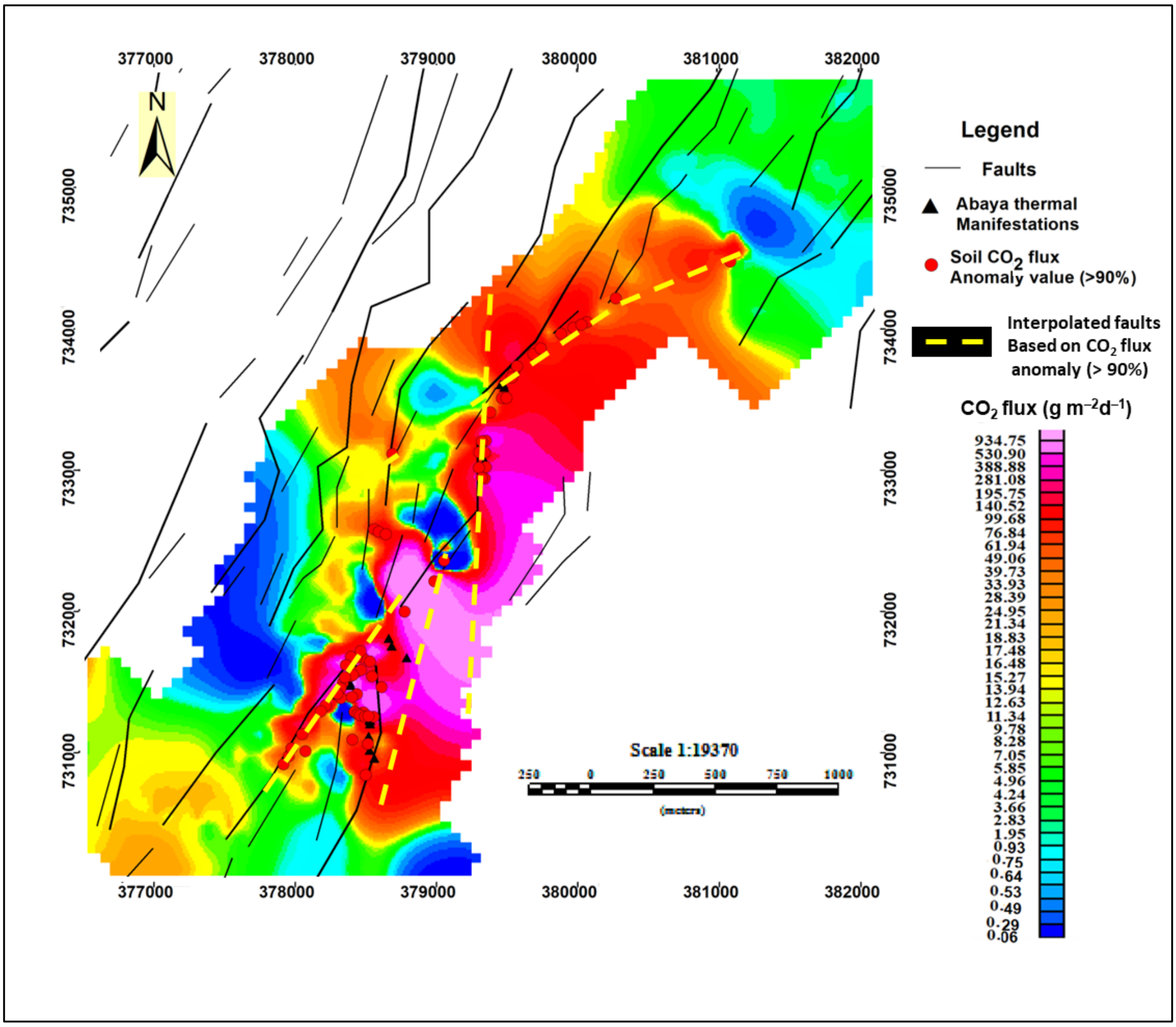

Figure 5: Grid map showing soil CO_2 flux distributions for the south eastern part of the study area (site -4 which is Abaya fault around the main thermal manifestations)

5. CONCLUSION

A combination of field structural mapping, structural analysis and soil CO_2 flux measurement were employed to evaluate the structural permeability in the Northern Lake Abaya Geothermal Field. The main outcomes of this study are listed in points below.

1. The structural map produced from integrated field work and remote sensing indicate different geological structures and active geothermal activities. The geological structures observed include cracking, joints and normal fault system with dominantly trending in NNE-SSW that imitate the regional tectonic structure of the WFB in the Main Ethiopian Rift. The geothermal activities are in clear connection with these NNE-SSW-trending structures, suggesting the geothermal fluid flow and degassing are controlled by faults.

2. The soil CO_2 flux survey showed that soil gas anomalies can be correlated to the permeability characteristics of structures. The distribution of soil CO_2 flux has been established in accordance to standard practice. A normal background value for the CO_2 flux and measured temperature was established and geothermal anomalies were mapped. The result shows elevated fluxes (>>100 g m^{-2} d^{-1}) along the major faults and surface manifestations. The total CO_2 emission from the Abaya fault has a total degassing amount of

282.274 ton d^{-1}. It is evident that the CO_2 soil flux anomalies are well defined and the shapes of the anomalies coincide with local structural directions. The structural lineament and geothermal manifestations are parallel with the interpolated fault patterns from the soil CO_2 anomaly. This advocate's the presence of hidden structure associated with the general NNE-SSW direction of the flat lain Abaya area.

The combination of structural mapping, structural analysis and Soil CO_2 flux survey all suggested that the area has permeable zones for the fluids and gases expulsion therefore the present of potential geothermal resources.

6. ACKNOWLEDGEMENT

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