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The Quest for Fluid Pathways at Meru Volcanic Area, Tanzania, Using Remote Sensing and Soil Gas Analysis

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ABSTRACT

Meru volcanic area, situated in the Northern Tanzania Divergence, an extension of the East Africa rift system is characterized by Pleistocene to recent tectonic and volcanic activities. The last volcanic activity in the area was recorded a century ago by the emergence of ash cone at the floor of the Meru crater. Fumarolic activities within a Meru crater was recorded half a century ago.

Structural delineation from shuttle radar topography mission (SRTM) data and soil gas survey has been applied to trace the permeable pathway of geothermal related fluid. CO_2 flux and radon concentration data are applied to delineate possible permeable zones that act as fluid pathways. The relatively high flux of CO_2 and radon gas may signify permeable structures which form a potential target for further geothermal exploration.

The lineaments extracted from SRTM and anomalous emanation of soil gas shows three trends; SW-NE, NNE-SSW and NW-SE trend that correlate well with the general structural trend of the Meru volcanic area. However, CO_2 flux and radon concentration has revealed the major permeable zones trends NE-SW. From the findings presented in this study, it is suggested that these soil gas anomalies are structural controlled.

1. INTRODUCTION

Meru Volcano is located in Tanzania, within northern Tanzania Divergence, a tectono-volcanic structure (**Fig. 1**), an extension of the East Africa Rift System e.g. Dawson (2008). This Neogene volcanic area of northern Tanzania e.g Wilkinson et al., (1986) is characterized by relatively young volcanic and tectonic activities. Dating of rocks at Meru Volcanic area suggests that the alkaline volcanic activity occurred in two main phases, the earliest being between 2 to 1.5 Ma and the later main phase began around 0.3 Ma and intensified between 0.15 to 0.06 Ma e.g. Wilkinson et al. (1986). Minor tectonic and volcanic events continued after the major two episodes; 7800BP Lahar deposit from Meru Crater collapse and the ash cone eruption in the last century at the floor of the Meru Volcano. Wilkinson et al (1986) argued that Meru volcano is highly explosive characterized by episodes of Plinian eruptions. Major features of the Meru area are a 3.5 km diameter Meru crater which extends eastwards to a sector graben and Ngurdoto crater located southeast of Meru volcano **(Fig. 2**).

In this study, carbon dioxide surveying was applied to map permeable structures related to geothermal activity. This method has been widely used in monitoring volcanoes and their activities; and in geothermal exploration, specifically to map permeable pathways of geothermal fluid, estimation of heat flow and locating the approximate boundary of a geothermal reservoir by linking the degassing structures with their sources e.g. Chiodini et al. (1998); Harvey and Harvey (2015). There could be two main possible sources of CO_2 in a volcanic area such as Meru volcano; biogenic source from buried flora and fauna or magmatic source, a deep, related to magmatic activities permeating through fractures connected to the source- magma.

2. METHODOLOGY

The digital elevation model derived from SRTM (Shuttle Radar Topography Mission) aboard the space shuttle Endeavour and Band 8 of Landsat 8 imagery derived from OLI/TIRS sensor, path 168/Row 62 acquired on 23rd September 2017, were applied in this study. The spatial resolutions of the data sets are 3-arc seconds (approximately 90m) and 15m pixel resolution (https://lpdaac.usgs.gov/products/ measures_ products_table) These two data sets were used to extract geologic lineaments and tectonic landforms. Band 8 of Landsat 8 imagery was applied to enhance visual inspection due to its higher resolution i.e.15m pixel.

Chenrai (2012) argued that geologic structures are represented as a linear or curvilinear feature in a remote sensed data, that being the case, using relief shading technique, manual extraction criteria for lineaments and visual interpretation were based on image characteristics (tone and texture), lithological boundaries (rock units) and the geomorphological features e.g. Ehsan (2012). The relief shading method has to depict the form of a terrain in a descriptive and easily sizeable manner. Different azimuths of the sun and vertical exaggeration technique were applied to enhance and improve the image for visual interpretation. Sun angle used was 60º while sun azimuth varied from 45º to 315º to accommodate lineaments in different orientations.

Measurements of CO_2 flux and radon gas were carried out in two surveys between August 2017 and July 2018. The CO_2 flux was measured directly using the Accumulation Chamber Method e.g. Chiodini et al. (1998) by West Systems portable soil gas flux meter equipped with a LICOR LI-8100 automated soil CO_2 infrared gas analyzer. CO_2 concentration was measured by placing a 200mm diameter accumulation chamber on the soil surface, then the flux was calculated based on the rate of increase of concentration in a duration of measurement i.e. 60 seconds.

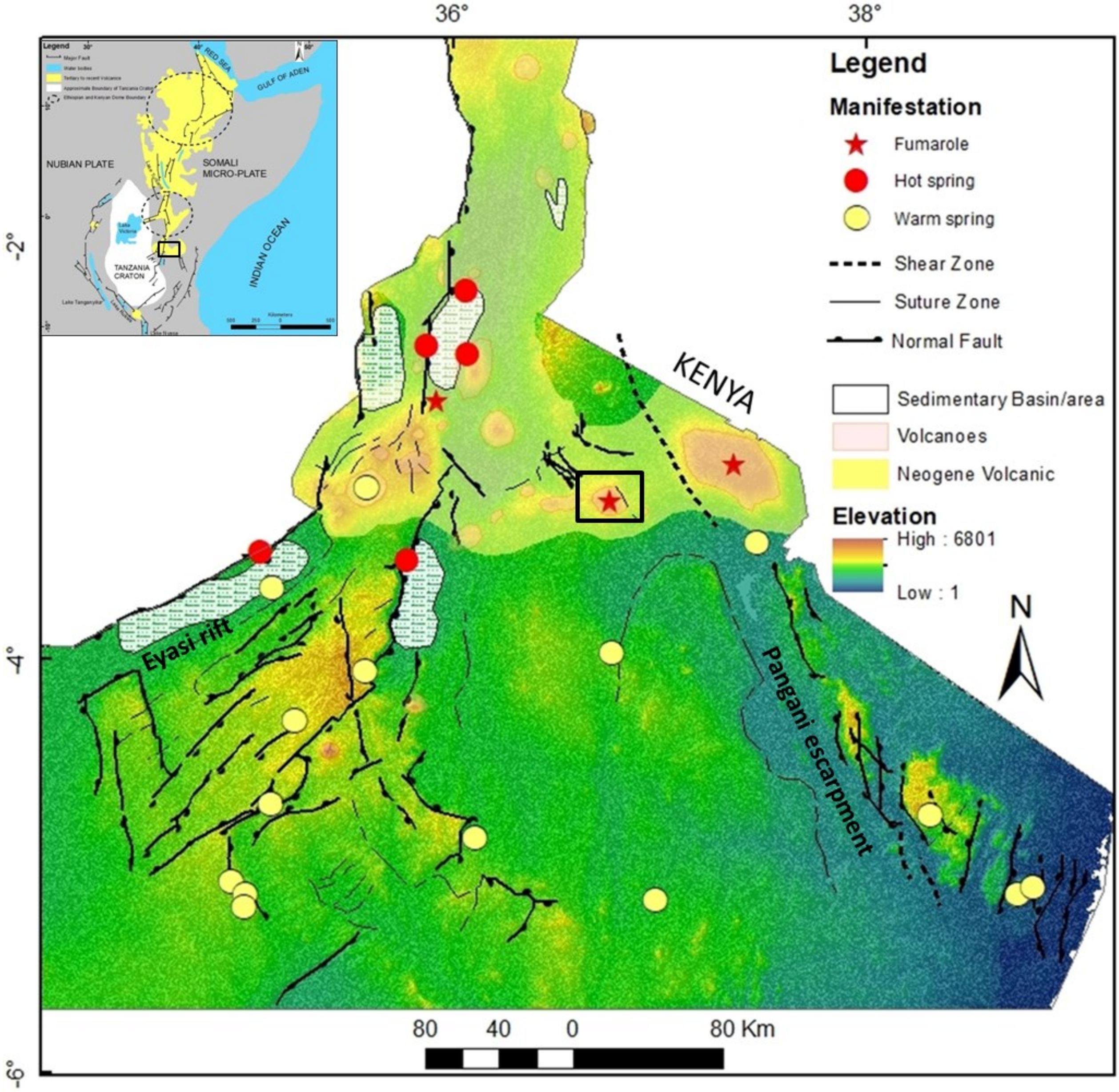

Figure1: The map showing the Northern Tanzania Divergence (NTD), structure setting and major geothermal manifestastion, a black box shows a study area. Map edited from Dawson (2008).

Radon concentration was recorded using RAD 7 radon meter. Measurement was done by connecting a tube from radon meter to a hollow metal rod of ~100cm length and 2.5cm diameter which was hammered to the ground to an average depth of 70cm. Three readings of background values were recorded before connecting the tube, each for the period of 2 minutes, thereafter three set of readings of gas concentration are read and recorded each for period of 2 minutes. The background values are subtracted from the actual reading to get the true reading.

3. LINEAMENT DELINEATION

Delineation of lineaments from SRTM data successfully extracted geological lineaments which were used as a base for soil gas survey plan. The extracted lineaments coupled with previously known structure shows two major dominant trends in the area; the NW – SE trend which is in line with the regional structural trend and orientation of a crater sector collapse and the NE – SW structural trend. The lower eastern flank of the Meru volcano is blanketed by lahars attributed to crater collapse. To extract the continuation of the structure and assess the permeability of fluid through the identified and pre-existed structures, CO_2 and radon gas survey was conducted.

4. SOIL GAS ANALYSIS

Radon gas concentration and Carbon dioxide flux was applied to identify permeable structure at Meru volcanic area and asses their relationship with geothermal and/or magmatic activity. This method is proven in delineating the permeable structures and is widely applied in different geothermal prospects during exploration phase e.g. Chiodini et al. (1998); Harvey and Harvey (2015); Jolie (2014).

4.1 Statistical analysis

General descriptive statistics of the soil gas data are presented in **Table 1**. Quantile-Quantile plot and Cumulative probability plots were applied to statistically analyze the data and understand the type of distribution to better classify and identify anomalous values. The Goodness-of-Fit tests were estimated using a software, ProUCL 5.1. Determination of threshold values or classification of concentration was decided depending on the type of data distribution.

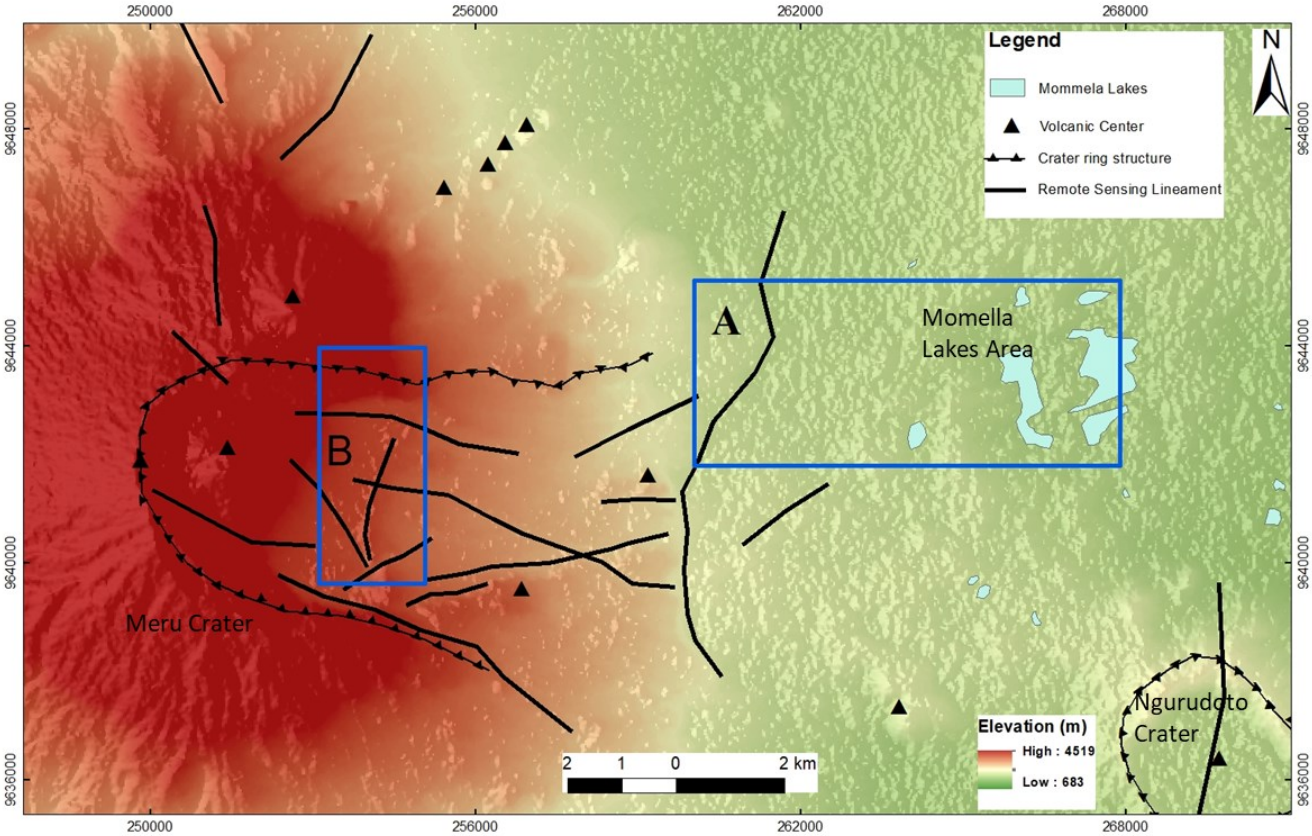

Figure 2: A map of Meru volcanic area showing lineaments extracted from SRTM and soil gas surveyed area, blue boxes (A: Mommela Lakes area, B: Meru crater area).

Table 1: Descriptive statistics of the soil gas data of Meru area

Item	Rn-222 (cpm)	CO_2 Flux ($gm^{-2}d^{-1}$)
Mean	21.82	28.06
Median	14.00	18.49
Standard Deviation	22.84	27.38
Sample Variance	521.68	749.77
Skewness	2.02	2.56
Range	119.34	182.36
Minimum	0.15	1.84
Maximum	119.34	184.20
Count	78	179

4.2 Carbon dioxide flux and delineation

Carbon dioxide flux survey was applied to map permeable structures related to geothermal activity in Meru geothermal prospect. A total of 122 points were sampled around this area and 57 points were sampled at the Meru crater area. From descriptive statistics (**Table 1**), the high positive value of skewness suggest that the data is either log-normally or exponentially distributed. The log-cumulative probability plot shows polymodal distribution and was then partitioned into five populations namely A, B, C, D and E (**Fig. 3**) from the highest to lowest values adopting the procedure done by Cardellini et al. (2003).

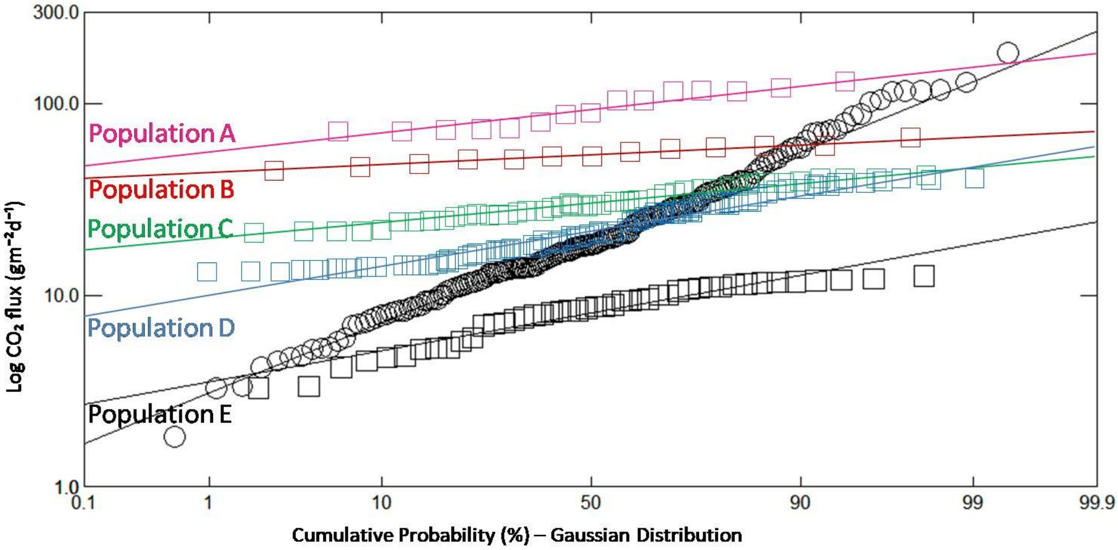

Figure 3: A log cumulative probability plot of CO_2 flux with five populations partitioned e.g. Cardellini et al. (2003), individual populations are represented by squares of different colors.

Two outliers were identified from log plot, the highest value being 184.3 $gm^{-2}d^{-1}$ and lowest value being 1.84$gm^{-2}d^{-1}$. The two outliers were not considered in the partitioning of the data.

Table 1: The statistical parameters of the individual population of the CO_2 flux

Population	N	Minimum	Maximum	Mean	Geometric Mean	SD	SEM
		g/m²/day					
A	15	70.2	129.2	94.47	92.27	21.16	5.464
B	13	43.41	64.44	53.18	52.84	6.229	1.728
C	48	21.01	40.32	29.84	29.33	5.716	0.825
D	102	13.03	39.86	22.5	21.25	7.818	0.774

Carbon dioxide flux map shows that the dominant structural trend in the Meru crater area is NE-SW while the dominant trend depicted by remote sensing in the same area is WNW-ESE. In the Mommella lakes area dominant trend from CO2 flux map is also NE-SW while les dominant trend is NW-SE. Dominant trend of lineaments extracted from remote sensing also display the dominant trend of NE-SW in complete agreement with structures inferred from soil gas survey.

4.2 Radon concentration and delineation

A radon isotope ^{222}Rn was surveyed at Meru volcanic area to delineated shallow permeable structure. Based on descriptive statistics (**Table 1**), radon data are either log-normally or exponentially distributed. Probability plot of radon (**Fig. 5**) was used to classify the data, based on deviation or break of data continuation in a line from one cluster to another. A cluster will represent same or similar characteristics of data population e.g. Varekamp and Buseck (1983). The spatial interpolation identified three anomalous areas; NW, SW and immediate W and NE of Momella lakes (**Fig. 6**). The anomalies show preferential orientations, which may suggest that, the mentioned anomalies are structural controlled. The dominant lineation trends are NNE-SSW and NE-SW.

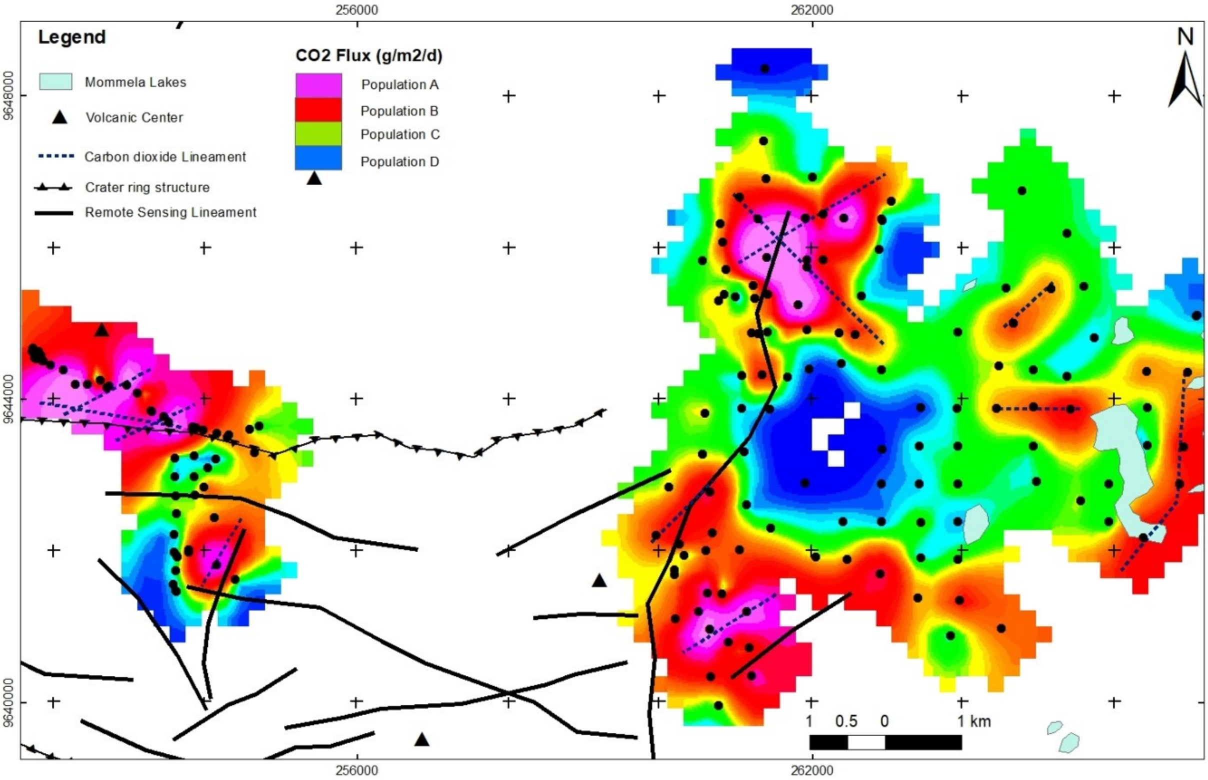

Figure 4: The CO_2 flux map of Meru crater to the west and Momella lakes area to the east. Lineaments inferred from CO_2 flux anomaly overlaid by lineaments extracted from SRTM.

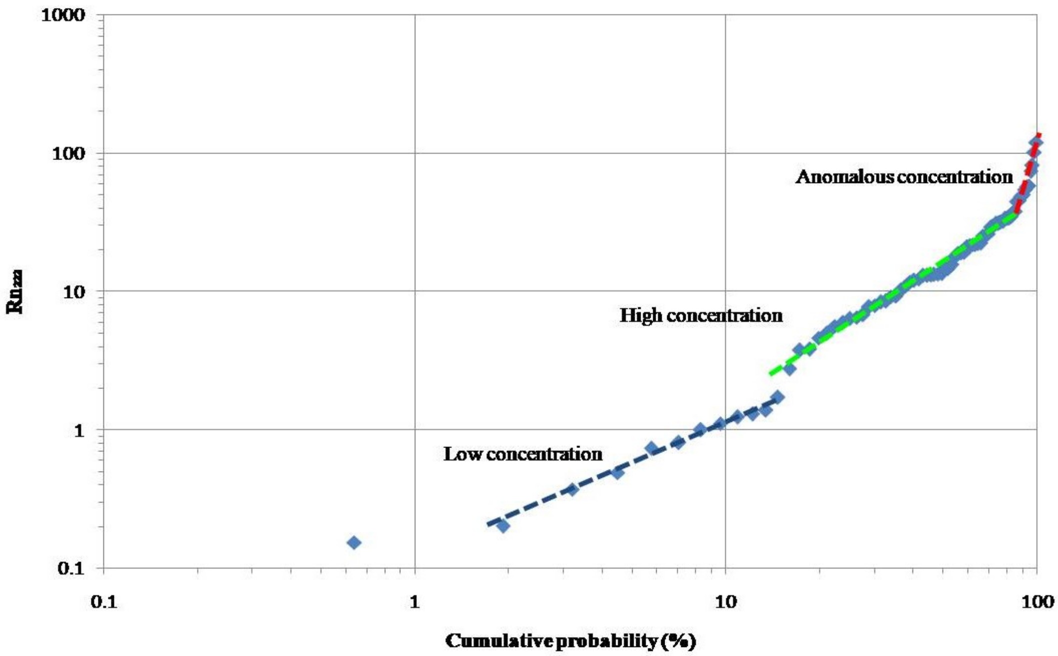

Figure 5: A log cumulative probability plot for Rn_{222}

Structures inferred from ^{222}Rn anomaly map forms a general trend of NE-SW and correlate with lineaments extracted from remote sensing. **Fig. 7** shows the combined structures inferred from soil gas survey (carbon dioxide flux and ^{222}Rn counts) and lineaments extracted from remote sensing. The structures generally show good correlation except for some areas which are discussed in the next section of this paper.

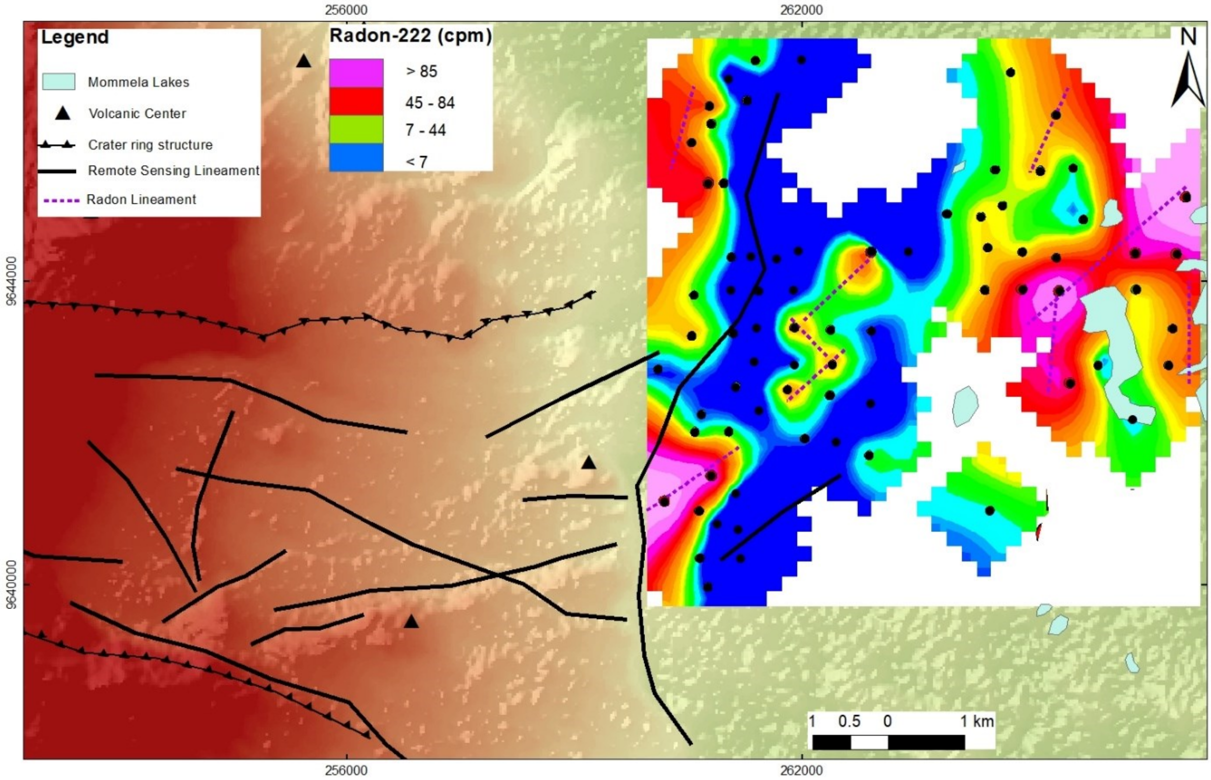

Figure 6: Radon (^{222}Rn) distribution map (right of the map) with structures inferred from radon anomalous emanation which are correlated by lineaments extracted from remote sensing. ^{222}Rn map and structures are overlaid on the Digital Elevation Model.

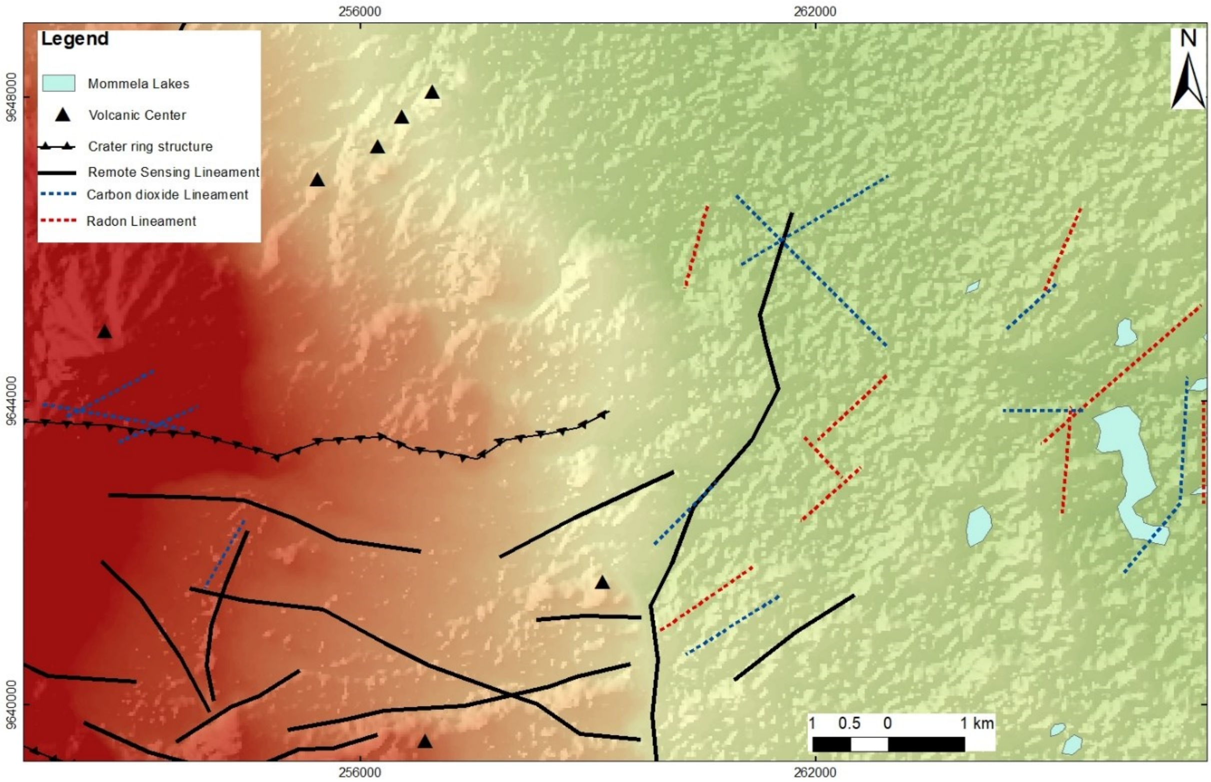

Figure 7. Digital Elevation Model showing structures inferred from soil gas survey and lineaments extracted from remote sensing for the Meru volcanic area.

5. DISCUSSION

Principally, the structural trends in the research area seems to be influenced by the regional structural setting. The dominant NW-SE trend at Meru volcanic area follows the Pangani escarpment structural trend (**Fig. 1**) which makes part of the Northern Tanzania Divergence. The lineaments delineated from remote sensing formed a base for the soil gas survey plan to identify extension of permeable zones from Meru crater where hydrothermal altered zones were observed (**Fig. 8**)

Figure 8: The altered zones observed in a volcanic cone on the floor of the Meru crater. Evidence of historical hydrothermal fluid activity in the area.

From soil gas perspective, Harvey et al. (2014) argued that the average biogenic CO_2 flux ranges from 9.3 to 20.5 g m^{-2} d^{-1}, depending on the method of estimation and climate. However, suggested that average biogenic CO_2 flux is largest for tropical soils. Assessment of the statistics of population presented in **Fig. 3**, suggests that population E are background values which are not related to subsurface degassing hence not considered for further analysis. Population D is a representation of biogenic values of the CO_2 caused by biological processes occurring in soils. The population C is a result of possible mix of biogenic CO_2 and magmatic/geothermal related fluxes. Population A and B are considered to be the anomalous values in this case and relate to geothermal activity in the area. Population A has an average value that correlate with other reported CO_2 values in active geothermal areas e.g. USA; Jolie (2014). Population B has lower average values compared to other geothermal areas but it is considered anomalous considering the huge cover of lahars deposit in the studied area, which may limit the fluid flow to the surface. Arguably this suggest that the flux is related the deep source. The spatial interpolation of CO_2 flux (**Fig. 4**) shows three anomalous areas in Momella area and two anomalous areas in the Meru crater area, which suggests that the CO_2 flux is related to deep magmatic degassing.

Meanwhile, Radon has 36 radioactive isotopes (^{193}Rn to ^{228}Rn) and is considered the heaviest of all noble gases. Only three of the isotopes occur naturally which are ^{222}Rn (radon), ^{219}Rn (action) and ^{220}Rn (Thoron) from ^{238}U, ^{235}U and ^{232}Th decay series, respectively (Baskaran, 2016). Variation in radon activity on earth surface was applied as a tracer for geochemical exploration to provide a clue to the occurrence of geothermal resources, uranium ore, hydrocarbon deposits, and impending earthquakes and/or volcanic eruptions Baskaran (2016). According to Cox and Thomas (1980) radon can migrate by diffusion and convection in the subsurface. Applications of Radon gases in geosciences are limited to shallow depth processes due to its low mobility and short half-life for instance ^{222}Rn which has half-life of 3.82 days (Baskaran, 2016). Radon gas emanation rates from rock and minerals vary significantly. Radon emission rates have been described to be higher from subsurface active faults, because they provide major conduit path for radon and other gases like carbon dioxide, methane, helium and fluorine to emanate.

The structures inferred from anomalous emanation of soil gas shows persistence of SW-NE and NW-SE trend (**Fig. 7**). In some areas such aa the Momella lakes area structures from soil gas survey correspond with lineaments extracted from remote sensing. However, in the Meru crater area, structures from soil gas survey do not correspond with the regional structures extracted from remote sensing data. This has been interpreted that, the gas permeable structures are younger formed probably due to reactivation caused by later eruption of the Meru volcano. The structural analysis in the study area the area is characterized with permeable structures that pave the way for fluids movement.

6. CONCLUSION

The application of remote sensing and soil gas survey proved to be effective method during early phase of geothermal exploration. The dominant structures at Meru Volcanic area trends NW-SE and NE-SW, from remote sensing lineament delineation. Soil gas survey has revealed the major permeable structures trending in the NE-SW direction. It is suggested that, the crater floor structures are extending towards eastern lower slope and covered with lahars. These permeable zones form a potential target for further geothermal exploration in Meru area.

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