ACTIVE FAULT DELINEATION STUDIES USING SOIL GAS SURVEY IN THE NORTH-GHOUBBET GEOTHERMAL PROSPECT.

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ABSTRACT

Soil gas surveying (carbon dioxide, Radon and mercury soil sample) are important assets for geothermal resource exploration. Several surface manifestations, in particular, fumaroles occur in the North-Ghoubbet geothermal field and have not yet been examined by those techniques. Therefore, this study aims to determine the flow of geothermal fluids by examining the soil CO_2 flux, radon and mercury distribution to detect buried structures that may infer permeability for the Nord-Ghoubbet geothermal area as a preliminary investigation. Anomalous distribution of the following soil gas (Radon (Rn), dioxide carbon (CO_2), mercury (Hg) etc…) should be the "halos" of underground geothermal system and frequently used for the first phase of geothermal. Soil gas samples were obtained by hammering steel pipes in the ground to penetrate the ground to a depth of 0.6~1.0 meter. In total, 86 points were measured by CO_2 (using a Kitakawa Gas detector), and mercury (The samples were analysed by a mercury analyser, NIC, MA 3000 at Kyushu University) at the same points. And 76 points for radon (using radon detector "RD-200"). In this study area, they are no background values measured for radon and CO_2 concentration, for that statistic analysis were applied to determine the threshold value (the anomalous concentration). According to the calculated descriptive statistics , the skewness must be close to zero and doesn't exceed 0.1 but in the data, the skewness is very high which means the data are not a normal distribution, the data is either log-normally or exponentially distributed. Quantile plot (The quantile-quantile (q-q)) plot were used to analyse the data and data appear as a lognormal distributed. The cumulative probability plots were used also to perform statistical analyses and classify the anomalies distribution.

The anomaly distribution highlighted the lowest value is located in the Moudououd horst with a significantly lower concentration, 0.01% of CO_2, 1.3071 ppb of mercury and a relatively low-value anomaly of 1 cpm for the radon gas survey. The highest CO_2 and mercury anomalous concentrations were located at the Afay, Anale and Qeridaba areas with 2.5% CO_2 and 1000 ppb of mercury, and the anomalous concentration of radon (for the thorium ^{220}Rn with more than 100 cpm, and the radon ^{222}Rn more than 10 cpm) concentrate to the Afay area. In the central part of the study area, the fumaroles and altered ground were distributed, and also the soil gas sampling was concentrated in this area. The NNW and NW structures are dominant and coincide with structures already exist in the study are by soil gas analysis. The buried structures can be estimated as active faults, which may be a conduit path of gas emanations.

1. INTRODUCTION

The North-Ghoubbet area is in the western part of the Gulf the Tadjourah and the central part of the Republic of Djibouti, on the northern side of the bay of Ghoubbet Al Kharab, between Lake Asal and the Gulf of Tadjourah. The issue of geothermal prospects in Djibouti are permeability and salinity, but according to previous research (BRGM 1982; CERD 2011)(JICA et al. 2015)**,** the North-Ghoubbet area is characterized as one of the major geothermal potential areas in Djibouti by structure well developed and good reservoir fluid condition (low salinity). Soil gas measurement was applied to identify the permeable structure and also to assess the geothermal activity or magmatic activity (for the magmatic CO_2 is the best marker to link magmatic activity with the CO_2 gas concentration). The gas is transported from the subsurface to the surface by advection of fluids mostly through the structures (faults and fractures) zones. Anomalous distribution of the following soil gas (Radon (Rn), dioxide carbon (CO_2), mercury (Hg) etc…) should be the "halos" of underground geothermal system and frequently used for the first phase of geothermal exploration. The concentration of mercury in soils is the result of the accumulation and losses processes, therefore it may not always give information on the present geothermal activity. Thus, soil air mercury is a more reliable indicator of the geothermal fluid at depth. Data was collected in October-November 2021 in Nord-Ghoubbet geothermal field. The interpolation method used is the Kriging method for spatially interpolating.

In a geothermal investigation, soil gas analysis has been an important tool for the identification of buried faults and structure may infer the permeability. Several authors have applied the soil gas analysis in the pre-feasibility stage of geothermal exploration, such as (Cox 1980), who applied the measurement of radon gas at a shallow depth to explore geothermal in Hawaii; (Inés Magaña, De Henríquez, and López 2003) compile alteration mineralogy and soil gas (^{222}Rn, ^{220}Rn, CO_2). The

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soil gas survey, the main target will be to determine whether there is some flow of geothermal fluids by examining the soil CO_2 flux, Radon and Mercury distribution and to detect buried structures that may infer permeability.

2. GEOLOGICAL STUDY

The study area is located at the triple junction among the Nubian plate (Northeast), the Somali plate (Southeast) and the Arabian plate. This triple junction forms the convergence area of the three rifts, called the Afar Depression. The Red Sea (oceanic rift) defines the Arabian plate of Africa, the Gulf of Aden (oceanic rift) extends from the Indian Ocean to the Red Sea, and the East African rift (rift) is the frontier between Nubian and Somalia rifts and extends up to Tanzania. The recent geological history of this region is the result of the spread of the Gulf of Aden ridge (the Gulf of Aden is a young oceanic crust) resulting in the formation of a series of disjointed rift segments in which tectonic deformation and magmatic activity are still active. This ridge seems to end abruptly to the west on the coast of Africa. However, a narrow Gulf extends landward, the Gulf of Tadjourah is enclosed within the Republic of Djibouti recognized as a portion of the oceanic rift in the prolongation of the Gulf of Aden (Gaulier and Huchon 1991). The western part of this oceanic axis is the famous Asal rift (Francheteau et al. 1976). The rift of Asal-Ghoubbet is one of the youngest and most western segments of this ridge. It constitutes the onshore extension of the Tadjourah Rift (Manighetti et al. 1998 and Daoud et al. 2011). Nord-Ghoubbet area is one of the major geothermal potential areas in Djibouti and is located near the NW-SE trending axial volcanic range of the Asal-Ghoubbet rift which has a high enthalpy geothermal prospect (Mohamed Houmed, Omar Haga, and Varet 2012). This site was characterized by different tectonic patterns affected by several fault systems, noted normal faults with NW-SE direction (Asal rift)(Courtillot, Tapponnier, and Varet 1974), N-S (transform faults) (Courtillot, Tapponnier, and Varet 1974), and NNW-SSE (the opening of Tadjourah Gulf direction (Figure 1) (O. Richard and J.Varet 1981). The surface manifestation, in particular, fumaroles are clear phenomena to show the fairly active tectonics in the study area. The older formation hosting a geothermal reservoir is characterized by Dalha basalt (4 to 8 Ma) and overlaying recent gulf basalt (formed during the early stage of penetration of Aden ridge, through the Gulf of Tadjourah at 4 to 2 Ma). The Nord-Ghoubbet area acts as a block and stops the extension of Tadjourah Gulf to the landward and change the direction to NW-SE in 0.9 Ma (Asal rift) (Mohamed Houmed, Omar Haga, and Varet 2012). This tectonic evolution and variations indicate that the active faults are resulting from the transform system linking Ghoubbet with the Gulf of Tadjourah ridge but it also results from the fast rotation of this brittle block (Manighetti et al. 2001). Numerous fumaroles affecting the whole block, testify to the leakage of the geothermal reservoir due to the active tectonics of the site. The fracture network in Nord-Ghoubbet was well developed

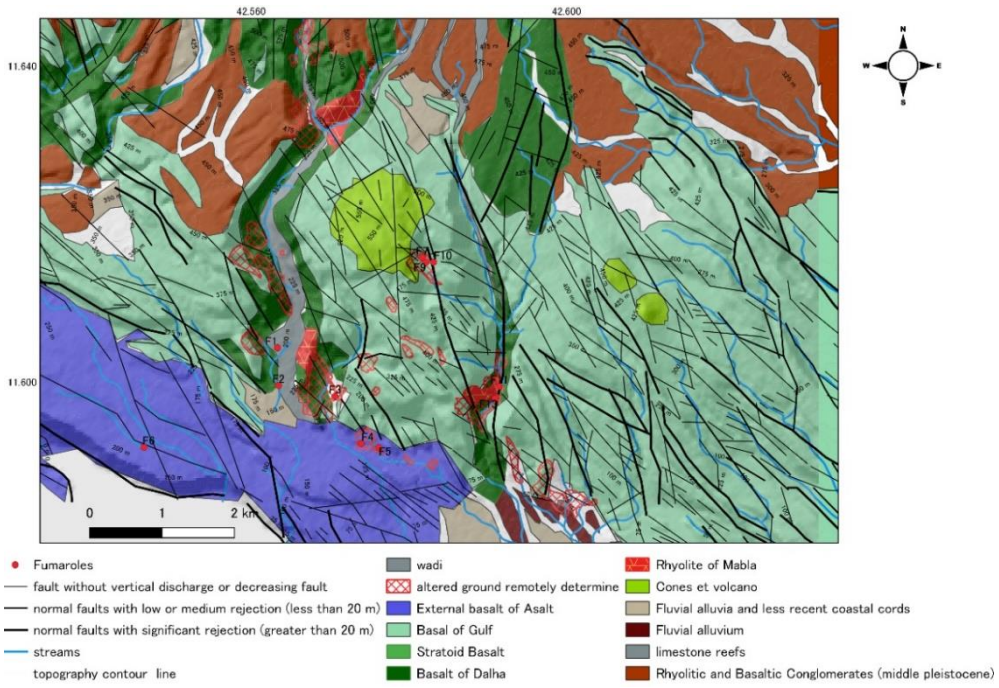


Figure 1: Geological map in Nord-Ghoubbet (modified of Carte Geologique de la Republique de Djibouti « Tadjourah », (Gasse, Richard, and Ruegg 1985) with fumaroles (ODDEG 2019, reconnaissance field)

3. METHODOLOGY

3.1. Soil gas measurements

Soil gas samples were obtained by hammering steel pipes in the ground to penetrate the ground to a depth of 0.6m. The steel was then removed and the outer jacket was left inside the hole to allow for the sampling. Related to carbon dioxide (CO_2) gas was measured using a Kitakawa Gas detector. A probe penetrated the hole and this probe was attached to the Kitakawa Gas

detector to measure the CO_2 concentration. In total 86 points were measured in this study. Measurements of radon (^{222}Rn) and thorium (^{220}Rn) were done from a depth of 0.6m below the ground surface by hammering steel pipes in the ground as used in CO2 sampling. A stopper attached to a flexible tube was fixed onto the mouth of the outer jacket and the soil gas was sniffed into a radon emanometer (radon detector "RD-200") by using the inbuilt meter pump. Three radon counts read out from the LED display were recorded at one-minute intervals at three counts. In total 76 points were measured in this study. ^{222}Rn and ^{220}Rn were calculated by the following equations.

$$^{222}\text{Rn} = (87*C3) + (32*C2) - (34*C1).$$

$$^{220}\text{Rn (Tn)} = \sum X\ net - Calculated\ 222\text{Rn}$$

$$\text{Where } \sum X\ net = (C1 + C2 + C3)/3$$

Mercury samples were collected in the same points at 0.6 meters and dried two weeks before being analysed. The samples were analysed by a mercury analyzer, NIC, MA 3000 at Kyushu University. The weight variation depends on the mercury concentration in the sample. If the mercury value is high above the limit of standard (10 ng), the weight was reduced but if the value is low the weight is increased. The results were measured by parts per billion (ppb). In total 84 samples were collected. Data was collected in October-November 2021 in North-Ghoubbet geothermal prospect. The interpolation method used is the Kriging method for spatially interpolating for further interpretation of soil gas results.

3.2. Statistical analysis

In this study area, they are no background values measured for radon and CO_2 concentration. Statistical analysis was applied to determine the threshold value (the anomalous concentration). According to the calculated descriptive statistics (Table 1), the skewness must be close to zero and does not exceed 0.1 but in the data, the skewness is very high which means the data are not a normal distribution, the data is either log-normally or exponentially distributed. Quantile plot (The quantile-quantile (q-q) plot is a statistics (graphing) technique for determining whether there is a common distribution of two sets of data coming from populations) were used to analyse the data and data appear as a lognormal distributed (Fig. 3). The cumulative probability plots were used also to perform statistical analyses and classify the anomalies distribution.

Table 1: Descriptive statistics of Soil gas data

	Rn_{222} (cpm)	**Rn_{220} (cpm)**	**CO_2 (%)**	**Mercury (ppb)**
Mean	2.25	45.35	0.23	172.44
Median	1.26	1.80	0.09	5.52
Standard Deviation	3.13	127.65	0.40	861.65
Sample Variance	9.78	16294.82	0.16	742440.2
Kurtosis	8.52	15.80	11.15	49.92
Skewness	2.77	3.80	3.25	6.86
Range	16.36	742.20	2.2	6478.70
Minimum	0	0	0	1.3071
Maximum	16.36	742.20	2,2	6480
Sum	150.66	3038.83	19.95	10519.38
Count	67	67	85	61

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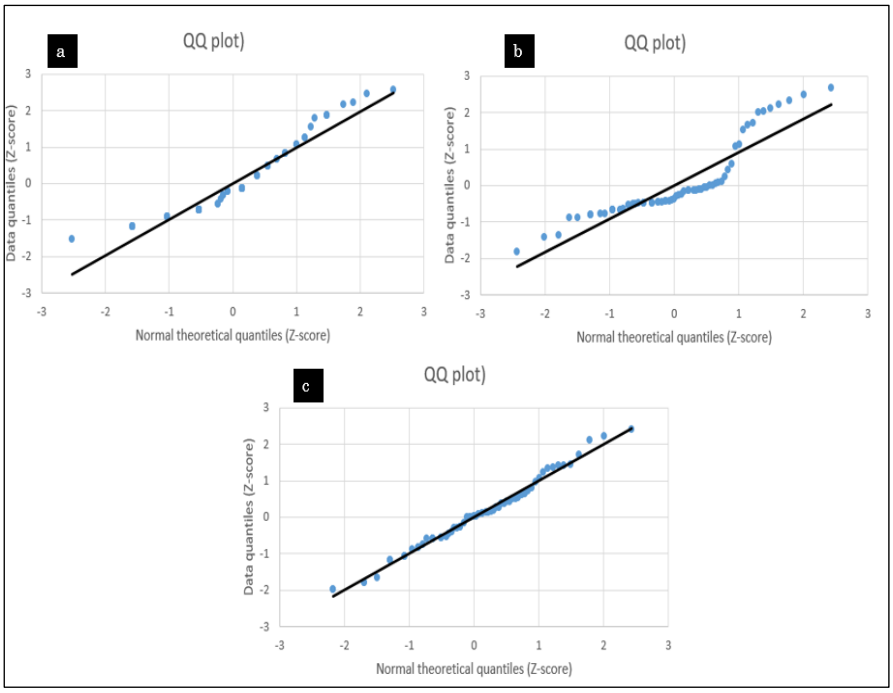


Figure 3: The lognormal Q-Q plot of soil gas data for a) CO_2, b) Rn^{220} and c) Rn^{222}.

4. RESULTS AND DISCUSSION

Radon gas, carbon dioxide gas in soil air and mercury were used in this study and is considered to concentrate in fracture zones. Therefore, their results of them are used for estimating locations of open fractures near the surface. Soil gas measurement was applied to identify the permeable structure and also to assess the geothermal activity or magmatic. The gas is transported from the subsurface to the surface by advection of fluids mostly through the structures (faults and fractures) zones. Anomalous distribution of the following soil gas (Radon (Rn), dioxide carbon (CO_2), mercury (Hg) etc…) should be the "halos" of underground geothermal system and are frequently used for the first phase of geothermal exploration.

4.1. Carbon dioxide distribution

CO_2 in soil gas survey was carried out during this study in Nord-Ghoubbet geothermal field. In general, CO_2 was used to delineate permeable structures related to geothermal activity. High concentrations can be interpreted as a greater permeability causing accelerated gas diffusion from crustal magmatic sources. In geothermal exploration, this method allows mapping the permeable pathway of geothermal fluid, an estimate of heat flow (Chiodini et al. 1998). The anomalous point is distributed widely to the southwest and southeast of Moudououd Horst (Fig. 5). The low concentration of CO_2 in Moudououd Horst can be explained probably due to thick basalt formed the Horst burial of their sources.

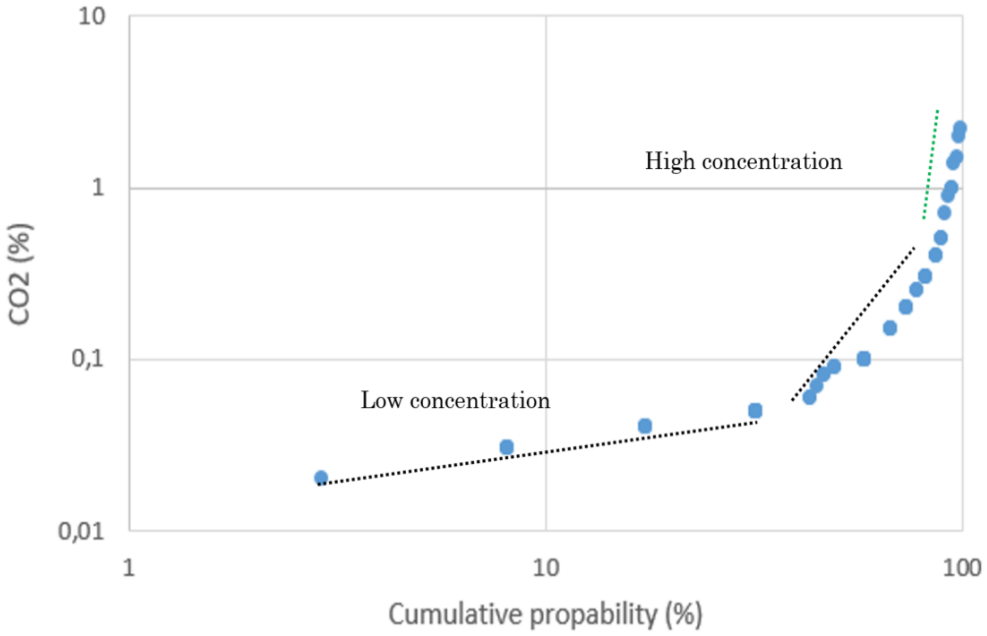


Figure 4: A log cumulative probability plot for carbon dioxide

The gas in the reservoir can be produced by thermal alteration of carbonate rocks and minerals, a magmatic and mantle origin, where it is transported by deep crustal fractures (Nicholson, 1993). Gas values range from 0.01 to 2.5% volume of the total gas phase. The anomalous point is distributed widely to the southwest and southeast of Moudououd Horst. The highest CO2 concentration was located in the Afay Anale area. Gas values range from 0.01 to 2.5% volume of the total gas phase. In the Moudououd horst, not anomaly distribution. As the spatial anomalous point map highlight, the lowest value is located in the Moudououd horst with a significantly lower concentration of 0.01%. The low concentration of CO_2 in Moudououd Horst can be explained probably due to the thick basalt formed the Horst burial of their sources. There is an NW and NNW trend of high gas concentrations marked by the red line.

The origin of this degassing along the lineament determine based the CO_2 degassing of the soil may be either been sourced from deep volcanic origin or from shallow organic sources. The anomaly may be attributed to the presence of a fault intersections that may have been reactivated the NW and NNW faults to allow partial permeability. According to the (CERD 2011) estimation (the fumaroles in Afay wadis are aligned in NNW direction, this fault maybe be an active fault), this assumption is emphasized more. This shows the high level of permeability to the surface with a localized high concentration of CO_2.

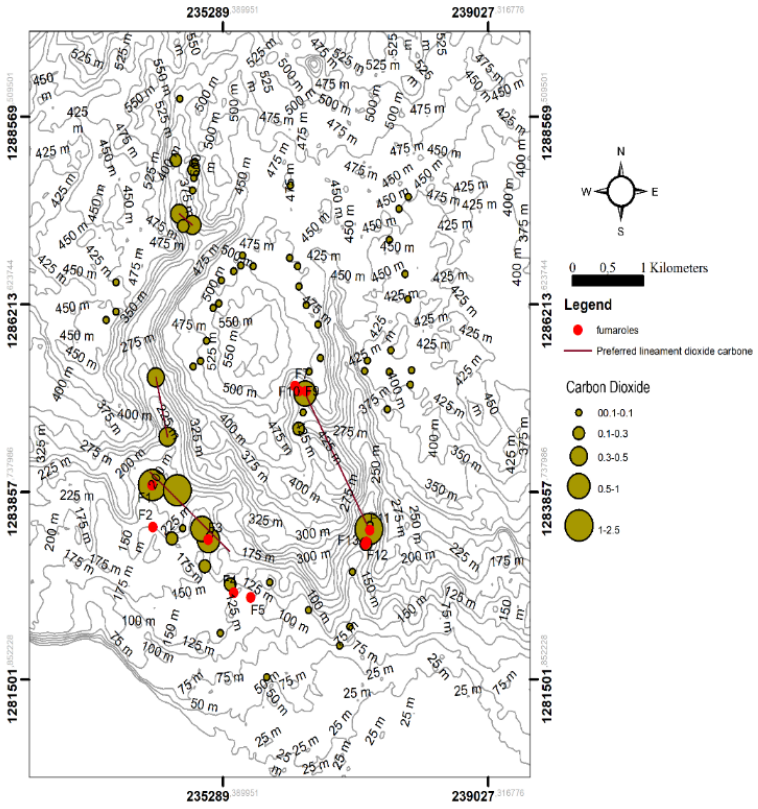


Figure 5: Spatial distribution of CO_2 in soil gas in the study area, red lines represent the lineament delineated based on anomalous concentration orientation

3.3. Radon gas anomaly concentration

Radon has 36 radioactive isotopes (^{193}Rn to ^{228}Rn) and is the heaviest noble gas. Of the 36 radioactive isotopes, Twenty seven unstable isotopes of radon exist (^{200}Rn to ^{226}Rn). Radon is a decay product of Uranium-238 (^{238}U), which originates from deep magmatic sources. Only three radon (^{222}Rn), actinon (^{219}Rn) and thoron (^{220}Rn) occur in the natural environment according to their half-lives of 3.825 days, 3.92 seconds and 54.5 seconds because most of them have extremely short half-lives (Cox 1980) which from the decay of radioactive chains ^{238}U, ^{235}U and ^{232}Th respectively. After the radioactive decay of uranium and thorium, radon migrates through the soil by diffusion and convection. It moves along areas of weaknesses such as pore spaces, shear zones, faults and fractures. Due to its effective solubility in water, it is mainly used to infer areas of high permeability as well as upflow zones.

According to statistic descriptive, the radon is distributed log-normally or exponentially distribution. The cumulative probability plot of radon (Figs. 6 and 7) was applied to classify the data for different clusters according to the deviation or break of data continuation line a cluster to another.

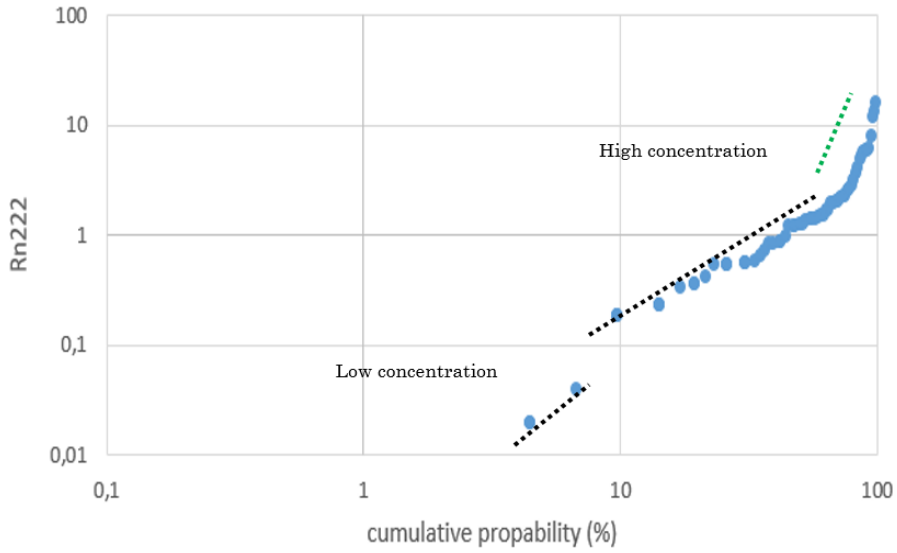


Figure 6: A log cumulative probability plot for ^{222}Rn

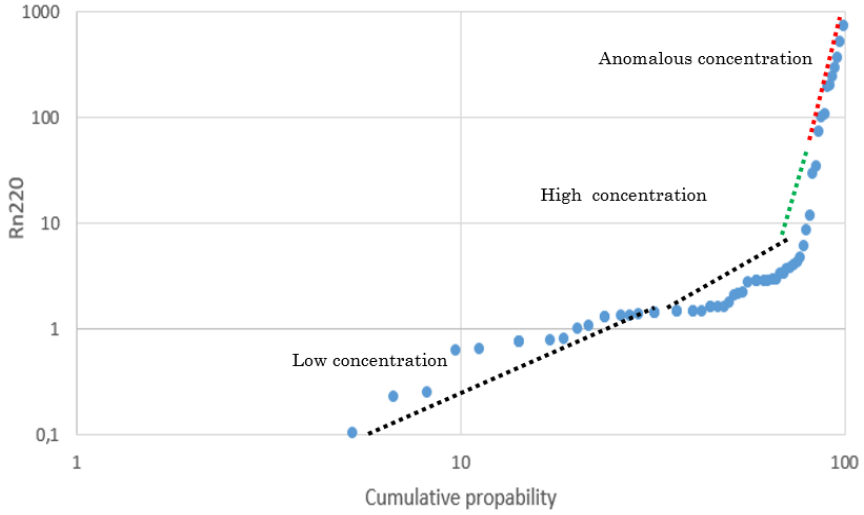


Figure 7: A log cumulative probability plot for ^{220}Rn

The determination of different clusters was also considered in the previous study (varekamp and Bussek, 1980). According to these statistics plots, low, high and anomalous concentration was defined. The anomalous concentration was determined the thorium ^{220}Rn with more than 100 cpm (count per minute) and sometimes area arrives 742 cpm. The spatially anomalous data point of Radon (^{222}Rn and ^{220}Rn) are distributed widely to the southwest and southeast of Moudououd Horst as CO_2 anomalous point distribution and the lowest point are located in the Moudououd Horst as the CO_2 distribution (Figs. 8 and 9).

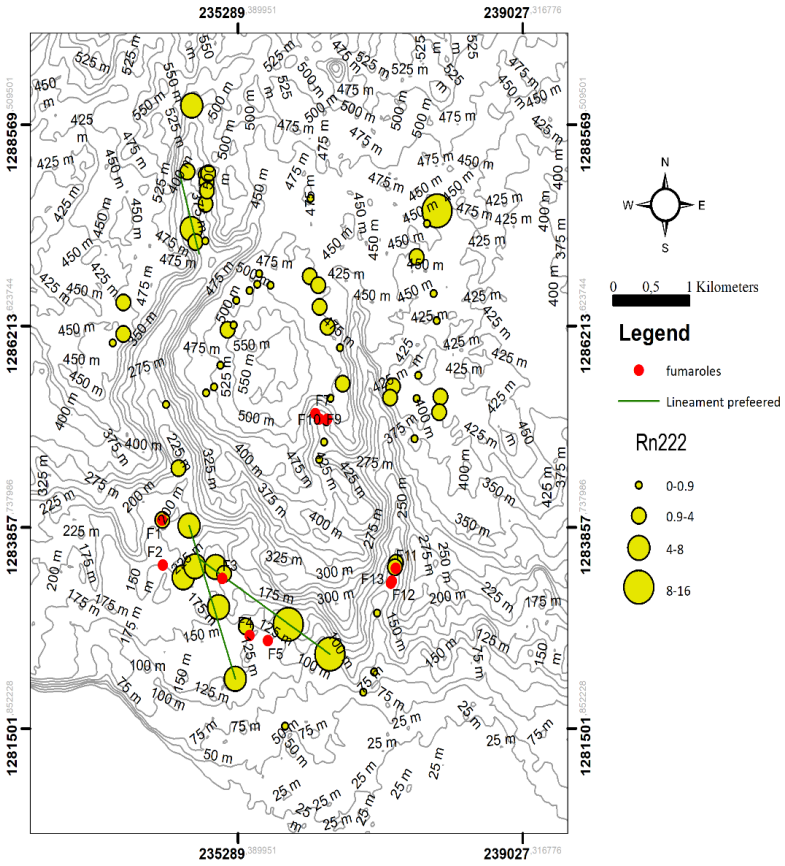


Figure 8: Spatial distribution of anomalous ^{222}Rn sampling point in the study area, green lines represent the lineament delineated based on anomalous concentration orientation

Radon gas survey results show relatively low-value anomalies in the Moudououd Horst going 1 cpm. ^{222}Rn and ^{220}Rn anomalous concentrate to the southeast and south-west of Moudououd also show a preferred NW, NNW orientation (marked with a green line) similar to the high CO_2 soil concentrations which might be indicative of a similar source (magmatic or reservoir???). This distribution similarity of soil gas is an indication of a faster travel rate of radon gas to the surface it is still difficult to assume the pathway of the gas are fracture systems or is transported in solution by upwelling geothermal fluids. However, the anomalies certainly indicate high permeability.

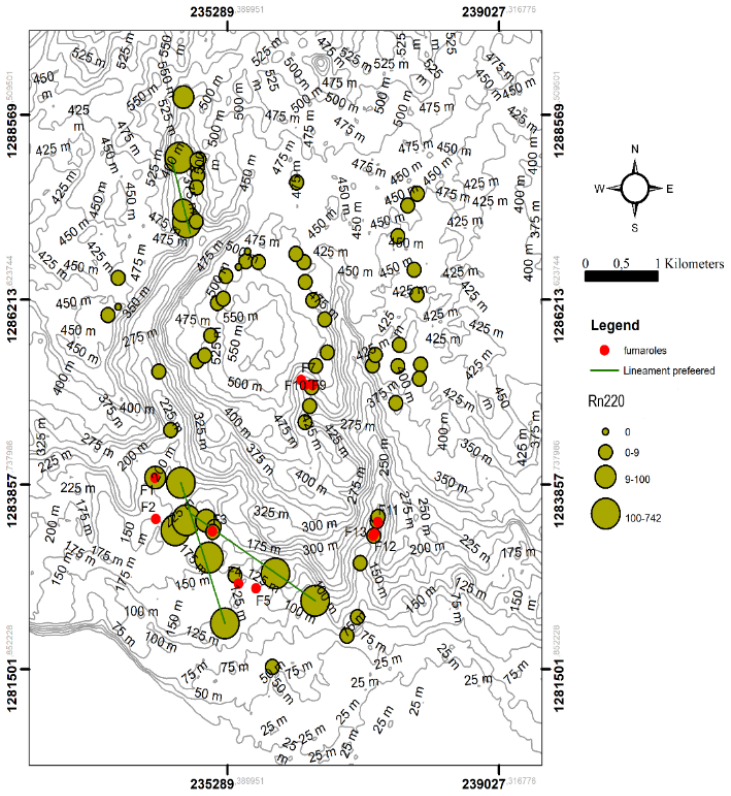


Figure 9: Spatial distribution of anomalous ^{220}Rn sampling point in the study area, green lines represent the lineament delineated based on anomalous concentration orientation

3.4. Mercury survey

Mercury is most widely used as an indicator for the distribution of underground geothermal systems in the early stages of exploration in Japan (Shigeno 1992). In general, Mercury (Hg) in soil survey is one of the key methods applied to delineate the shallow structure and convection-related geothermal activity (Varekamp and Buseck 1983). In vapor-dominated systems, soil Hg anomalies can be used to delineate accurately the areas of major steam upwelling and thus can provide valuable information for drill site exploration (Phelps and Buseck 1980). The concentration of mercury in soils is the result of the accumulation and losses processes, therefore it may not always give information on the present geothermal activity. Mercury in soil survey was carried out during this study in Nord-Ghoubbet geothermal field. The determination of different clusters was also considered in the previous study (varekamp and Bussek, 1983). The mercury volatile gas is propagated vertically and it is a good indicator of geothermal upwelling. Low, high and anomalous concentration was defined based on the cumulative probability plot. The lowest value is 1.3071 ppb and locates in Moudououd Horst as the carbon dioxide and radon low values distribution. The Highest concentration is 6480 ppb and is located in Anale fumaroles. The Anomalous concentration is located in the eastern part (Anale and Moudououd fumarole) (Fig. 11), maybe this important upwelling geothermal activity occur.

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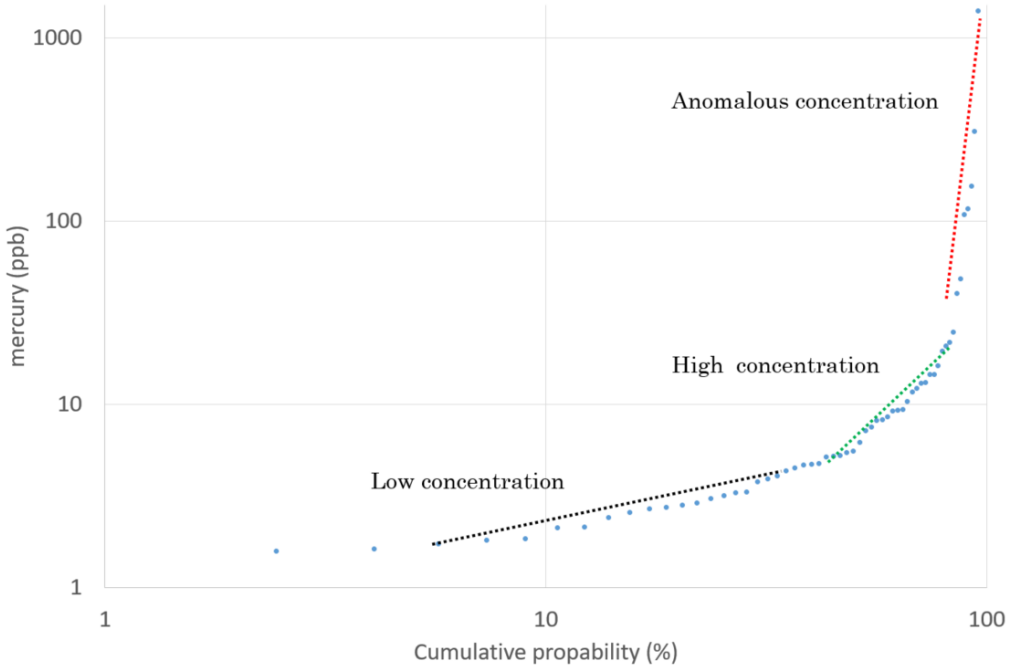


Figure 10: A log cumulative probability plot for mercury soil samples

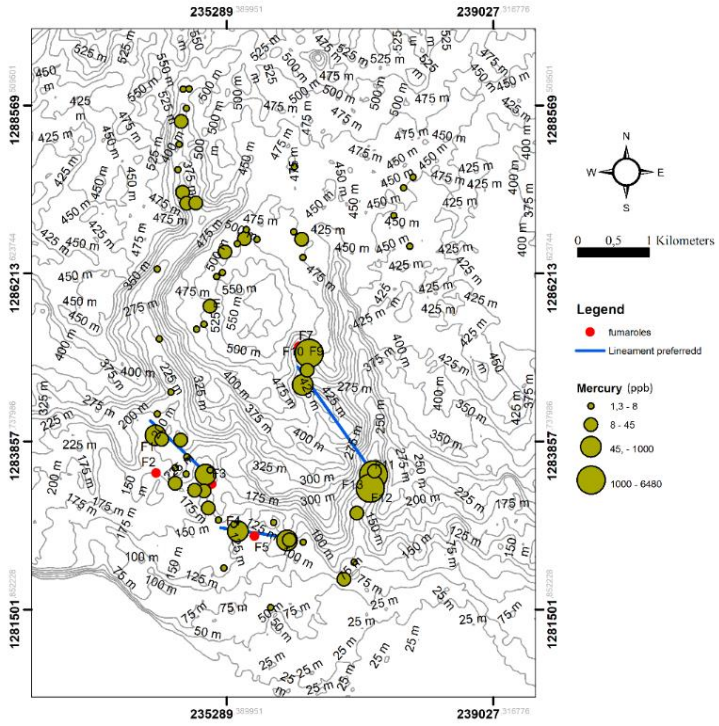


Figure 11: Spatial distribution of anomalous mercury soil sampling point in the study area, blue lines represent the lineament delineated based on anomalous concentration orientation

The radon propagation properties assume that if the gas meets a groundwater (reservoir) the quantities of gas particles who travel into the surface decrease. In Anale area, the carbone dioxide and mercury emanation are important and less of radon that can be explained as a hypothesis that area have a groundwater that can be interpreted as a preliminary interpretation like a reservoir.

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CONCLUSION

The soil gas survey (radon, mercury and carbon dioxide emanation) are significant in some areas of the study area, especially to the SW and SE of the study area (Afay and Anale area). That emission rate can be described to be higher from subsurface active faults. The active faults were possible to be a conduit path of those gas emanations. The mercury indicates convection geothermal activity that can suggest the Anale area have an important geothermal activity beneath. This hypothesis has been reinforced by the lack of radon anomaly in the same area. The presence of a deep or shallow aquifer stops radon propagation through the structure. These two assumptions can become on maybe the geothermal reservoir is located in the Anale area.

REFERENCES

BRGM. 1982. "Géol-NordGhoubbet-BRGM1982.Pdf."

CERD. 2011. "PROSPECT GEOTHERMIQUE DU ' NORD GOUIHET."

Courtillot, Vincent, Paul Tapponnier, and Jacques Varet. 1974. "Surface Features Associated with Transform Faults: A Comparison between Observed Examples and an Experimental Model." *Tectonophysics* 24 (4): 317–29. https://doi.org/10.1016/0040-1951(74)90015-8.

Cox, Malcolm E. 1980. "Ground Radon Survey of a Geothermal Area in Hawaii." *Geophysical Research Letters* 7 (4): 283–86. https://doi.org/10.1029/GL007I004P00283.

Daoud, Mohamed A., Bernard Le Gall, René C. Maury, Joël Rolet, Philippe Huchon, and Hervé Guillou. 2011. "Young Rift Kinematics in the Tadjoura Rift, Western Gulf of Aden, Republic of Djibouti." *Tectonics* 30 (1): 1–20. https://doi.org/10.1029/2009TC002614.

Francheteau, J., P. Choukroune, R. Hekinian, X. Le Pichon, and H. D. Needham. 1976. "OCEANIC FRACTURE ZONES DO NOT PROVIDE DEEP SECTIONS IN THE CRUST." *Can J Earth Sci* 13 (9): 1223–35. https://doi.org/10.1139/e76-124.

Gasse, Françoise, Olivier Richard, and Jean Claude Ruegg. 1985. *Carte Géologique de La République de Djibouti à 1:100 000. Tadjoura. Notice Explicative. Orstom*.

Gaulier, J. M., and P. Huchon. 1991. "Tectonic Evolution of Afar Triple Junction." *Bulletin - Societe Geologique de France*. https://doi.org/10.2113/gssgfbull.162.3.451.

Guild, Philip W. 1974. "Distribution of Metallogenic Provinces in Relation to Major Earth Features." In *Metallogenetische Und Geochemische Provinzen / Metallogenetic and Geochemical Provinces*, 10–24. Vienna: Springer Vienna. https://doi.org/10.1007/978-3-7091-4065-9_1.

Inés Magaña, Ma, Elizabeth De Henríquez, and Dina López. 2003. "Study on Diffuse Degassing and Alteration Mineralogy in the Berlín Geothermal Field." *International Geothermal Conference*.

JICA, Japan International Cooperation Agency, LTD. Nippon Koei Co., LTD. Sumiko ressource exploration and developpment Co., and LTD JMC Geothermal engineering Co. 2015. "Data Collection Survey for Geothermal Developpment in the Republic of Djibouti (Geophysical Survey). Final Report," 1–88.

Manighetti, I., P. Tapponnier, V. Courtillot, Y. Gallet, E. Jacques, and P. Y. Gillot. 2001. "Strain Transfer between Disconnected, Propagating Rifts in Afar." *Journal of Geophysical Research: Solid Earth* 106 (B7): 13613–65. https://doi.org/10.1029/2000jb900454.

Manighetti, I., P. Tapponnier, P. Y. Gillot, E. Jacques, V. Courtillot, R. Armijo, J. C. Ruegg, and G. King. 1998. "Propagation of Rifting along the Arabia-Somalia Plate Boundary: Into Afar." *Journal of Geophysical Research: Solid Earth* 103 (3): 4947–74. https://doi.org/10.1029/97jb02758.

Mohamed Houmed, Abdou, Abrourahman Omar Haga, and Jacques Varet. 2012. "Nord-Ghoubbet Geothermal Site, Djibouti Republic," 21–23.

Nicholson, Keith. 1993. "Geothermal Fluids." *Geothermal Fluids*. https://doi.org/10.1007/978-3-642-77844-5.

O. Richard and J.Varet. 1981. "Study of the Transition from Deep Oceanic to Emerged Rift Zone: Gulf of Tadjura (Republic of Djibuti)."

Phelps, D., and P. R. Buseck. 1980. "Distribution of Soil Mercury and the Development of Soil Mercury Anomalies in the Yellowstone Geothermal Area, Wyoming." *Unknown Journal* 75 (5): 730–41. https://doi.org/10.2113/GSECONGEO.75.5.730.

ISSN 2703-4275

Shigeno. 1992. “Applications of Geochemistry in Geothermal-Field Development of Japan.” Application of Geochemistry in Geothermal Reservoir Development. 1992. https://gbank.gsj.jp/geolis/geolis_link/199206660/en.

Varekamp, J. C., and P. R. Buseck. 1983. “Hg Anomalies in Soils: A Geochemical Exploration Method for Geothermal Areas.” *Geothermics* 12 (1): 29–47. https://doi.org/10.1016/0375-6505(83)90039-1.

ISSN 2703-4275