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Use of Radon and Carbon Dioxide in Geochemical Exploration of Menengai and Silali Geothermal Prospects, Kenya

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ABSTRACT

Anomolous concentrations of indicator gas components in subsurface air are related to the geological structures and geochemical environments of the regions under consideration. Intensity of gas flow, its composition and isotope ratio of some of its components radically change in periods of seismic activity. Gas surveying in combination with other geochemical, geophysical and geological methods can be applied to fulfilling a number of needs in geological prospecting. High values of Radon//CO_2 ratios were detected in the Menengai caldera and towards the north and north western parts out of the caldera, coinciding with high ^{222}Rn (cpm) and somewhat elevated CO_2 values (% v/v), indicating good permeability. In the Silali geothermal prospect, high carbon dioxide concentrations in the soil gas were observed around the south, south east, north and north-eastern flanks of the caldera, areas that coincide with the deep seated faults where the source may be a magmatic body. A NE-SW and N-S trend emerges in areas of high radon distribution. Soil gas survey values are consistent with surface manifestations showing a permeable area with somewhat elevated soil gas concentrations on the south eastern side of the Silali caldera.

1. INTRODUCTION

The soil-gas method used to infer the nature of subsurface geology/geochemistry is based on the concept that gases which are released from active geothermal systems, can freely rise through overlying cover to be detected in the near-surface. Volcanoes release gases not only from the central crater and through openings such as fumaroles, but also on their flanks by diffuse degassing of gaseous species such as carbon dioxide (CO_2), helium (He) and radon (Rn). Whereas the high-temperature gases in craters tend to be highly acidic and reactive (e.g. SO_2, HCl), some species like CO_2 and Rn do not react with country rocks. The distributions and quantities of these gases provide information on the overall permeability of a volcanic edifice, the potential for lateral degassing from areas other than the active crater and the ability of a volcano to diffusely release large quantities of CO_2 and the other gases.

Geothermal gases form during thermal breakdown of volatile-rich components in reservoir rocks, by reaction of circulating fluids with reservoir rocks and by contributions from degassing magma bodies. The proportions of non-condensable gases emitted from geothermal manifestations (fumaroles, steam vents, hotsprings, mudpots) generally resemble those in underlying reservoirs, and for volcanic systems, CO_2 is highly emitted as compared to other gases (Goff & Janik, 2000). The high mobility of some gases makes them the best pathfinders for concealed natural resources. Indeed, the gases produced and/or accumulated in geothermal reservoirs can escape towards the surface by diffusion, through transportation by rising hot fluids and by migration along fractures and faults. Faults and fractures favor gas leaks because they usually increase rock and soil permeability, and thus the presence of linear soil-gas anomalies longer than several meters are often taken as strong evidence of tectonic features (Fridman, 1990).

Radon is one of the naturally occurring radioactive elements in the environment produced from the radioactive decay of radium isotopes, which are the decay products of U^{238}, Th^{232} and U^{235}. The concentrations of uranium and thorium in the bedrock and soil materials hence determine the amount of radon produced in the soil. The radon produced in the soil migrates through the mechanism of diffusion and convection through pore spaces in the soil, fractures in the rocks and along with weak zones such as shear, faults, thrust, etc. For some geological situations, radon migrates long distances from its place of origin and can be detected by alpha-particle recorders at the earth's surface. The concentration of radon in an area is governed by the radium content in the minerals, radon emanating power in the materials, permeability of the soil and the underlying rock, and moisture content of the soil. Radon (Rn^{222}) and thoron (Rn^{220}) are produced in approximately equal amounts, but the latter is often ignored because its contribution to the overall dose of radiation is relatively small. Estimation of radon in the soil-gas has been suggested as a tool for many investigations, such as exploration of uranium, earthquake prediction, groundwater transport and assessment of geothermal resources.

CO_2 is the most common gas in geothermal fluids and is known as one of the volatiles emanating from magmatic processes. The concentration of this gas in steam vents in geothermal fields ranges from a few tenths of a percent to several percents, although condensation near the surface can result in even higher concentrations. Measuring the diffuse flow of CO_2 through soil in geothermal fields for the purposes of geothermal exploration has been used in recent years (Chiodini et al., 1998; Fridriksson et al., 2006; Magaña et al., 2004; Opondo 2010 and Voltattorni et al., 2010).

One of the major tasks of geothermal resource assessment department of the Geothermal Development Company (GDC) is evaluation of the numerous geothermal prospects within the Kenya rift. Detailed surface investigations using various scientific methods are carried out before a field is committed for exploration drilling. In some of the prospects (e.g. Menengai and Silali) in the Kenyan rift, strong and numerous surface manifestations and water discharges are limited or lacking thus the need for soil gas (radon and CO_2) surveys that can be used to detect buried structures in the volcanic settings.

Soil-gas flux studies have been applied successfully to a number of fields from hydrocarbon to uranium exploration, and from geothermal processing to volcanic and seismic forecasting. It is however, important to identify other mechanisms which may influence the gas distributions, like climatic effects (rain, humidity, and barometric pressure) that can significantly influence the amount of diffuse degassing, before interpreting spatial or temporal trends of diffuse gases (Stix and Gaonac’h 2000).

1.1 Objective

The main objective of the soil gas surveys was to locate potentially attractive heat source, which could be economically exploited for geothermal power generation through inter-disciplinary geo-scientific disciplines (geology, geochemistry, geophysics and heat loss surveys). Radon and soil CO_2 gas surveys were used to demarcate areas of permeability since surface features are absent in the greater part of the Menengai and Silali prospects.

2. LOCATION AND GEOLOGICAL SETTING

Menengai and Silali geothermal prospects are located in the eastern arm of the Great Rift Valley in Kenya, East Africa and are two of the fourteen geothermal prospects that have been identified along the rift valley (Figure 1).

2.1 Menengai Geothermal Prospect

The Menengai caldera is a shield volcano with a summit elevation of 2278m (7,474 ft) located at 0°12'0"S and 36°4'0"E. The massive Menengai shield volcano occupies the floor of the East African Rift. Construction of a $30km^3$ shield volcano beginning about 200,000 years ago was followed by the eruption of two voluminous ash-flow tuffs, each preceded by major pumice falls. The first took place about 29,000 years ago and produced a large caldera. The second major eruption, producing about $30km^3$ of compositionally zoned per-alkaline trachytic magma took place about 8000 years ago, was associated with formation of the present-day elliptical 12 x 8 km summit caldera.

More than 70 post-caldera lava flows cover the caldera floor, the youngest of which may be only a few hundred years old. The caldera floor covers an area of about $88km^2$, and is partially covered by young rugged lava flows that are post caldera in age (Lagat et al, 2010). No historical eruptions are known from Menengai. Fumarolic activity is restricted to the caldera with a few fumaroles located to the north western part out of the caldera (at Ol’rongai area, Figure 2). The chronology of syn- and post-caldera events is based on correlation with dated fluctuations in the levels of nearby lakes, suggesting that the two ash-flows may have been erupted at about 29 000 and before 12 850 years ago. Lake sediments inside the caldera provide evidence for a late intra-caldera lake from about 10 300 to 8300 years B.P. (Leat, 1984 and Leat, et al., 1984)

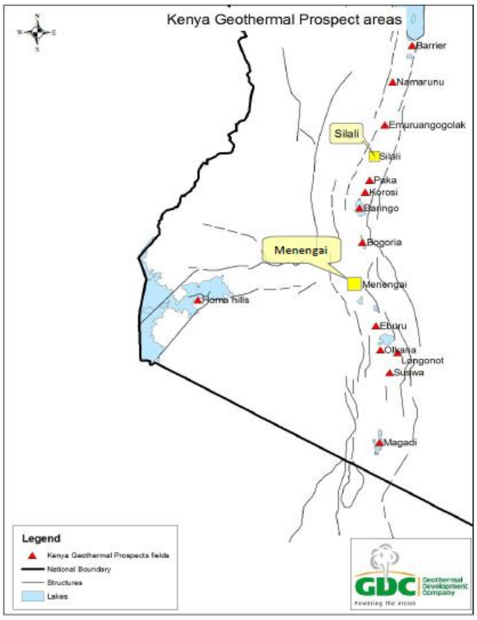

Figure1: Map of the Kenyan Rift showing the geothermal prospects and projects.

The Menengai geothermal prospect is located within an area characterized by a complex tectonic activity associated with a rift triple junction. This is at the zone where the Nyanza rift joins the main Kenya rift. A large area around the caldera is covered by mainly pyroclastics erupted from centers associated with Menengai volcano. The major structural systems in the area are the Menengai caldera, Molo tecto-volcanic axis (Molo TVA) and the Solai graben. The ring structure has been disturbed by the Solai graben faults on the NE end and one fracture at the SSW of the caldera wall extending southwards. The Molo TVA/Ol’rongai fracture system intersect the Menengai caldera on the NNW part. Most of the caldera infill lavas are from fissure eruptions that flowed out of the fracture openings.

2.2 Silali Geothermal Prospect

Silali geothermal prospect is located in the East African Rift (Kenya), to the east of Kapedo Town, part of Turkana District and marks the political boundary between Baringo and Turkana Districts and the informal divide between local Pokot and Turkana pastoralists. Silali volcano is situated on the border of Baringo and Turkana Districts, 50km north of Lake Baringo at 1^{0}10’N, 36^{0}12’E.

Silali is one of the largest and spectacular volcanoes of the Kenyan Rift, being a broad shield volcano that rises 760m from the rift floor. The prospect is situated within a semi-arid region with typical daytime air temperatures of 35-40^{0}C. Rainfall peaks in April and August, with annual potential evaporation rates exceeding 445mm of rainfall per year. There are few discharging fumarolic areas in the prospect in addition to the Kapedo and Lorusio hot springs.

3. PREVIOUS STUDIES

3.1 Previous exploration studies

3.1.1 Menengai prospect

Previous geochemical investigations of the Menengai area were carried out by Geotermica Italiana Srl, (1987) and Ministry of Energy in the period 1985-1986 under the auspices of the United Nations Department for Technical Development (DTCD), from the Menengai caldera to Lake Bogoria and further north. It involved sampling water points and a few soil gas surveys targeting mainly carbon dioxide. The few soil gas samples were picked mainly along the major access roads in Ol'banita and Ol'rongai areas. Soil gas survey was carried out in areas adjacent to the Solai graben and the Ol'banita and Ol'rongai areas. Carbon dioxide contents of the soil gas showed higher contents around the Ol'banita and Ol'rongai areas than around the Solai graben. Some of the sampled boreholes had temperature measurements above ambient.

The need for a detailed survey in the area inspired Kenya Electricity Generating Company (KenGen) in the year 2004 to embark on a more comprehensive study now targeting areas not covered by preceding researchers (KenGen, 2004). As a result, KenGen found high CO_2 values (>2.5%) at a narrow belt running in a NW-SE trend with other areas exhibiting low values of <1%. The absolute values of Rn^{222} showed the northern and northwestern parts of the surveyed area as having the highest concentrations i.e. the area around Kampi ya Moto.

3.1.2 Silali prospect

Brief reviews of the geochemistry of Silali, based on the work of McCall have been presented by Williams et al., (1984) and Key (1987). Other than a brief mention by McCall of fumaroles on the eastern flanks, no details of the geothermal manifestations on Silali have been published prior to the survey by Dunkley et al. (1993). In addition to the fumaroles mentioned by Williams et al. (1984), hotsprings at Kapedo and Lorusio areas but no other manifestations can be located in or around the caldera. Surface exploration work in Silali, carried out by Dunkley et al. (1993) under the auspices of UNDP, British Geological Survey and the Government of Kenya (MOE) which included geological and geophysical surveys indicated that a hot magmatic body does exist under the Silali volcano that could sustain a large geothermal system. In their report, Dunkley et al. (1993) recommended further detailed geo-scientific studies to define the availability and extent of the resource. Gas geothermometry gave temperatures of 238-287^{0}C using hydrogen (Allen and Darling, 1992). No soil gas surveys were conducted hence necessitating this study.

3.2 Geothermal manifestations

3.2.1 Menengai manifestations

In the Menengai geothermal prospect (now proved to be a geothermal field and a sustainable resource due to the successful drilling and discharge of high temperature wells), the thermally active areas are centered within the caldera with a few weak ones located at Ol'rongai. There are scattered fumaroles within the caldera floor but most of the thermal areas are hidden by the vast lava flows (Figure 2). Three groups of active fumaroles found in the caldera have a real extent ranging from a few m^2 to less than a km^2. The two groups in the central and western portion of the caldera floor are located within fresh lava flow and close to their eruption centres. The steam emission from the fumaroles has a mild H_2S smell. The other group of fumaroles located in the central eastern part of the caldera floor is found at the young lava/pumice contact and has extensively altered the pumiceous formation. The structural controls for these groups of fumaroles appear to be the eruption craters that may be the source of the pyroclastics deposit. The caldera floor is however almost covered by young lava flows. Another group of fumaroles is located out of the caldera to the north western part at Ol'rongai.

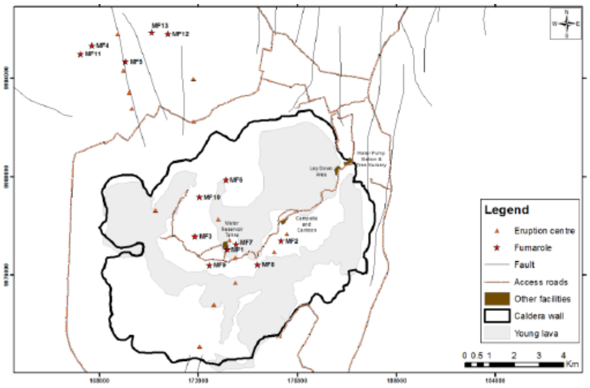

Figure 2: Geothermal manifestations in and around the Menengai caldera.

3.2.2 Silali manifestations

Altered grounds with fumaroles occur in the lower eastern half of the Silali caldera and on the upper eastern flanks of the caldera (Figure 3). The most extensive and hot geothermal activity in the prospect occurs in the eastern half of the caldera floor, where it is largely concealed by pumice thus the need for a detailed soil gas survey to indicate the hidden structures. Hot altered ground and fumaroles also occur on the walls of the eastern half of the caldera.

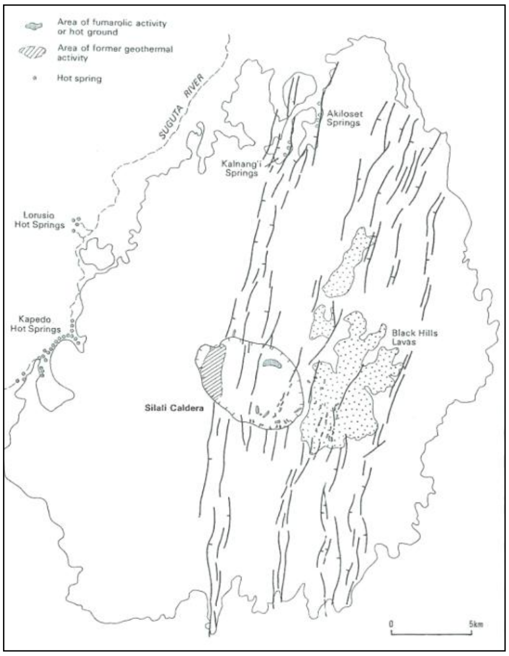

Figure 3: Summary of geothermal activity on Silali volcano (Dunkley et al, 1993).

The western half of the caldera appears to be geothermally inactive, although hydrothermally altered areas with ambient temperatures on the walls testify to former activity. In total, the geothermal activity in the caldera and upper eastern flanks fall within an area of about 20km^2. Surface manifestations within these areas are controlled by NNE to NE-trending faults, fissures and the caldera ring fracture. Some steam vents were also located close to Naudo. At the base of the western flanks around Kapedo there is an extensive hot spring system, and a separate spring system occurs 9km further north at Lorusio. Warm alkaline springs also occur along several fault lines at the periphery of the northern flanks.

4. METHODOLOGY

4.1 Radon- 220/222 Measurements

Measurements of radon-222 and radon-220 were done from a depth of 0.7m below the ground surface using the spike as used in CO_2 sampling. A stopper attached to a flexible tube was fixed on to the mouth of the outer jacket and the soil gas was sniffed into a radon emanometer (radon detector) by using the inbuilt meter pump. Three radon counts read out from the LED display were recorded at two-minute intervals.

The soil gas sample containing radon was drawn into the decay chamber of the emanometer consisting of a cylindrical copper can, whose walls are coated with zinc sulphide where the radon decays into other radio-nuclides by emitting alpha particles. The alpha emissions are detected by a photomultiplier tube attached to the detector and a rate meter displays the signals. Three background counts were recorded at two-minute intervals prior to introduction of the sample into the emanometer. After introduction of the sample, three readings were taken at two-minute intervals to give the total radon counts. Both $Rn^{222}$and Rn^{220} are detected by the emanometer but since they have different half-lives, it is possible to differentiate between the two.

4.2 Carbon Dioxide Measurements

In areas like Menengai and Silali geothermal prospects with few surface features, carbon dioxide in the soil gas is a very useful tool in the search of buried sources of heat and the determination of structures. Other sources of CO_2, if not magmatic, could easily be from biological decay of organic material. This could also determine the concentration of the soil gas in the samples, although the effect of biological CO_2 is removed by using the Rn/CO_2 ratio to interpret the emissions in a geothermally active area.

Carbon dioxide (CO_2) gas was measured using an Orsat apparatus. Soil gas samples were obtained using a spike, equipped with a steel outer jacket to penetrate the ground to a depth of 0.7m. The spike was then removed and the outer jacket left inside the hole to allow for the sampling. A stopper and a hosepipe were fixed onto the mouth of the jacket and by using a hand operated vacuum pump, the soil gas was driven into the analytical apparatus (Orsat), after evacuating the jacket and pipe connection to prevent any atmospheric CO_2 contamination. The Orsat apparatus consists of absorption vessels, which measure 100cm^3 of gas and contain 40% KOH solution for absorbing the acidic CO_2. The corresponding volume changes in the absorption vessel represent the corresponding amounts of the CO_2 gas as % v/v of the total gas.

5.0 DISCUSSION

5.1 Radon RadioActivity in the Soil Gas

Radon, adopted from mineral exploration techniques, has been used in the exploration for geothermal areas, with little or no surface expressions. Uranium-238 (U^{238}), the parent source of Rn^{222} is highly mobile and tends to be concentrated in the late phases during crystallization. Radon is a naturally occurring radioactive noble gas produced from the radioactive decay of radium isotopes, which are the decay products of U^{238}, Th^{232} and U^{235}. There are two isotopes of radon, Rn^{222} derived from U^{238} decay series and Rn^{220} (Thoron) from Thorium-232 decay series that are of interest in the geothermal exploration (Figure4). The two isotopes are easily distinguished by their different half-lives (3.82 days for Rn^{222} and 55.6 seconds for Rn^{220}) but the latter is often ignored because its contribution to the overall dose of radiation is relatively small. Uranium and thorium in the bedrock and soil materials determine the amount of radon produced in the soil.

The radon produced in the soil migrates through the mechanism of diffusion and convection via pore spaces in the soil, fractures in the rocks and along with weak zones such as shears, faults, and thrusts. Since it is a noble gas and is soluble in water, Rn^{222} can be used to infer areas of high permeability and of high heat flow from water and gas samples. High values of the total radon counts at the surface are taken to indicate fractures or fissure zones where both isotopes can migrate to the surface rather quickly. High temperature fluids carry the radon by convection to the surface through fissures and crashed rock zones along faults but in geothermal fluids is a function of porosity and fracture distribution in the geothermal reservoir. An area where radon reaches the surface quickly is an indication of a highly permeable zone.

Other factors that affect radon counts are distance travelled between the source and the detection point, temperature and the mineralogy of the reservoir rocks. The short half-life of radon and physical characteristics of the host rock limit the mobility of radon.

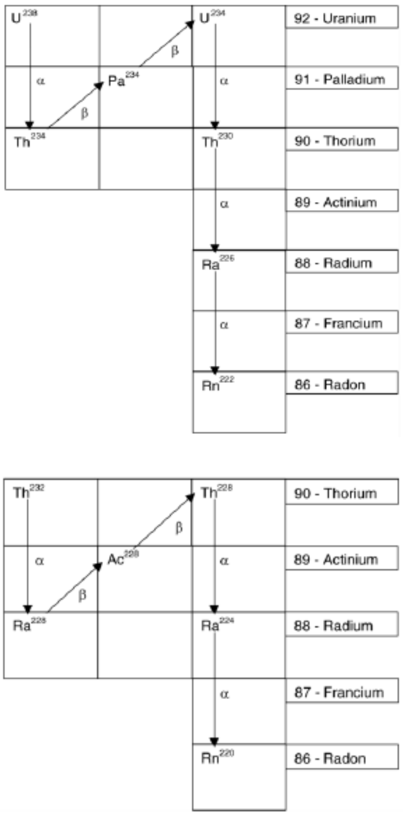

Figure 4: Uranium and Thorium decay series to Rn222 and Rn220 (Vanloon & Duffy, 2011).

The areas with high concentration of Rn^{222} are indicative of areas of high permeability and high heat flow and in most cases coincide with the manifestations, as shown by the distribution maps, Figures 5 and 6 for Menengai and Silali prospects respectively.

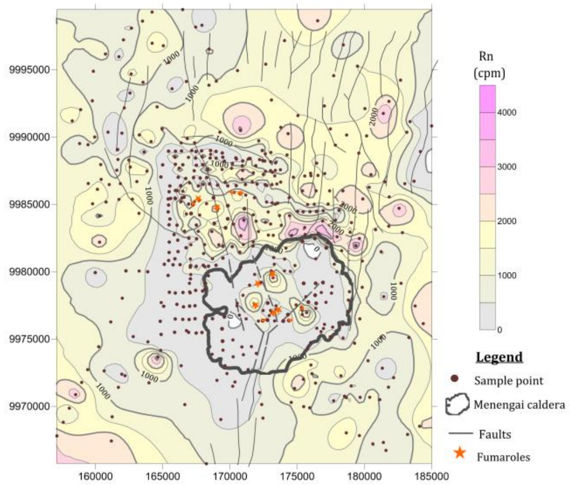

Figure 5: Menengai prospect radon distribution.

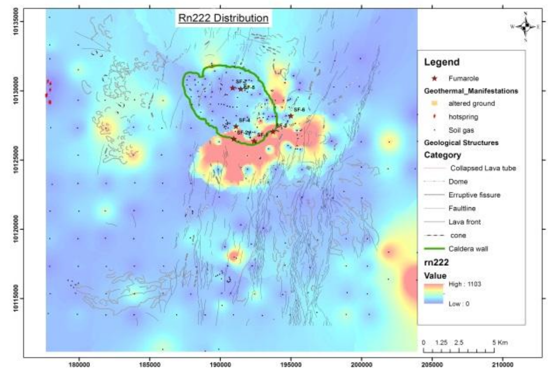

Figure 6: Silali prospect radon distribution

5.2 Carbon Dioxide Distribution in the Soil Gas

In an area with few surface expressions, carbon dioxide in the soil gas is useful in the search for buried fumarolic activity, determination of geological structures indicating permeability or to confirm presence of potential geothermal areas where other evidence is lacking. The porosity of the formation and other biogenic sources also determine the concentration of carbon dioxide measured in the soil gas. High carbon dioxide concentration in the soil gas, Figures 7 and 8 was observed around hot/altered grounds and fumaroles. For the Menengai prospect, high CO_2 concentrations were found around the fumarolic areas outside the caldera north western side and around the fumaroles in the caldera,while in the case of the Silali prospect, this was found in the north eastern and south eastern areas in and outside the caldera and the eastern parts outside the caldera. The areas noted above coincide with deep-seated faults or fractures indicating that the source may be of magmatic origin.

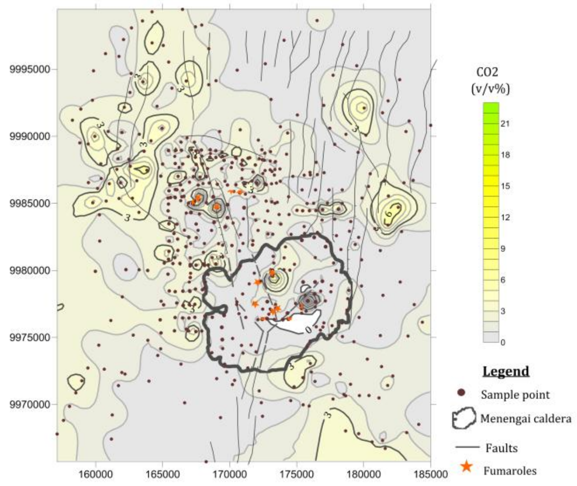

Figure 7: Menengai prospect CO2 distribution

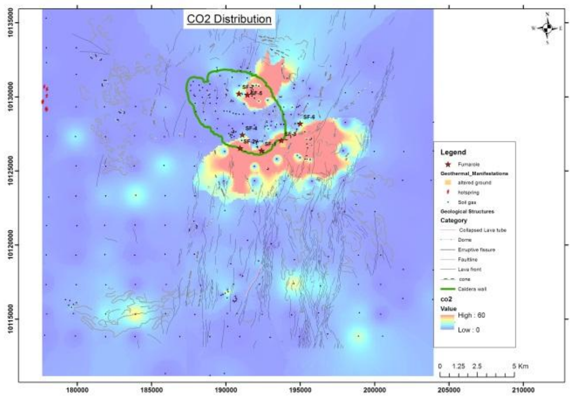

Figure 8: Silali prospect CO2 distribution

5.3 Radon-222/CO_2 Ratio

Rn^{222} (t½ = 3.82 days), implies that it has to travel long distances within a short period of time to be detected at the surface. For the detection of high concentration of CO_2 at the surface, CO_2 has to travel through a relatively permeable zone to avoid dispersion and subsequent dilution. Interferences due to different sources of Rn^{222} and carbon dioxide can be reduced or eliminated by evaluating the Rn^{222}/CO_2 (Figures 9 and 10) ratio in the soil gas. The areas previously highlighted as having high concentration of Rn^{222} and carbon dioxide, are reaffirmed by the ratio.

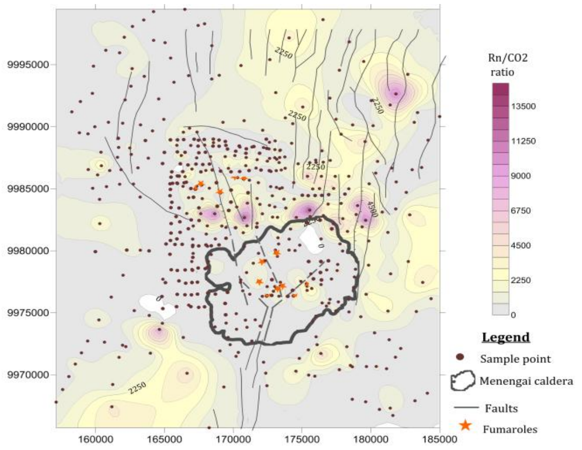

Figure 9: Menengai prospect's radon-222/CO2 ratio

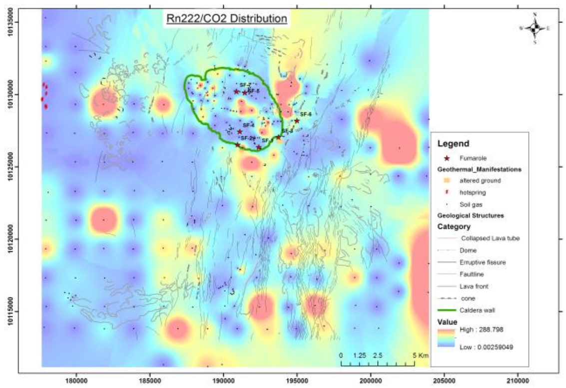

Figure 10: Silali prospect's radon-222/CO2 ratio

6. CONCLUSION

Soil gas survey values are consistent with surface manifestations showing an active area in both prospects with somewhat elevated soil gas concentrations in and around the calderas. The high radon counts could be closely associated with the highly fractured area and a high heat flux. The spatial pattern of the CO_2 flux anomalies as well as Rn soil-gas anomalies suggest a structural control on degassing; in particular, the convergence of different gas species (Rn^{222}/CO_2 ratio) anomalies indicate zones where better permeability can occur at depth.

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