A thesis submitted in partial fulfillment of the requirements for the award of degree of Master of Science in the School of Pure and Applied Sciences of Kenyatta University

APRIL, 2015
DECLARATION

This Thesis is my original work and has not been presented for the award of a degree or any other award in any University.

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Signature Date

We confirm that work reported in this thesis was carried out by the candidate under our supervision.

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signature Date
DEDICATION
This thesis is dedicated to God, my dear wife Maurine Akinyi and our sons Teddy Herrizon Ouko and Ryan Rodriguez Jairo.
ACKNOWLEDGEMENT

Firstly, I would like to thank Almighty God who granted me good health, opportunity and spiritual fulfillment that enabled me to overcome challenges during the research period.

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## ABBREVIATIONS, SYMBOLS AND ACRONYMS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>ADC</td>
<td>Analogue to Digital Converter</td>
</tr>
<tr>
<td>ALARA</td>
<td>As Low As Reasonable Achievable</td>
</tr>
<tr>
<td>BaF₂</td>
<td>Barium Fluoride</td>
</tr>
<tr>
<td>BOG</td>
<td>Bismuth Germanate</td>
</tr>
<tr>
<td>CaF₂(Eu)</td>
<td>Europium Doped Calcium Fluoride</td>
</tr>
<tr>
<td>Cs F</td>
<td>Cesium Fluoride</td>
</tr>
<tr>
<td>CsI(Tl)</td>
<td>Thallium Activated Cesium Iodide Detector</td>
</tr>
<tr>
<td>CsI(Na)</td>
<td>Sodium Activated Cesium Iodide Detector</td>
</tr>
<tr>
<td>DRCF</td>
<td>Dose- to- Risk Conversion Factor</td>
</tr>
<tr>
<td>EC</td>
<td>European Commission</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency (USA)</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width at Half Maximum</td>
</tr>
<tr>
<td>HBRA</td>
<td>High Background Radiation Area</td>
</tr>
<tr>
<td>IAEA</td>
<td>International Atomic Energy Agency</td>
</tr>
<tr>
<td>ICRP</td>
<td>International Commission on Radiological protection</td>
</tr>
<tr>
<td>LiI(Eu)</td>
<td>Lithium Iodide Europium Doped Detector</td>
</tr>
<tr>
<td>MCA</td>
<td>Multichannel Analyzer</td>
</tr>
<tr>
<td>NaI(Tl)</td>
<td>Thallium Activated Sodium Iodide Scintillator</td>
</tr>
<tr>
<td>NEA</td>
<td>Nuclear Energy Agency (USA)</td>
</tr>
<tr>
<td>NCRP</td>
<td>National Council on Radiation Protection (Maryland)</td>
</tr>
<tr>
<td>NORM</td>
<td>Natural Occurring Radionuclides Materials</td>
</tr>
<tr>
<td>PMT</td>
<td>Photomultiplier Tube</td>
</tr>
<tr>
<td>TAP</td>
<td>Total Absorbed Peak</td>
</tr>
<tr>
<td>UNATSDR</td>
<td>United States Agency for Toxic Substance and Disease Registry</td>
</tr>
<tr>
<td>UNSCEAR</td>
<td>United Nations Scientific committee on Effects of Atomic Radiation</td>
</tr>
<tr>
<td>β</td>
<td>Beta particles</td>
</tr>
<tr>
<td>α</td>
<td>Alpha particles</td>
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ABSTRACT

Natural radiation is the major source of external doses in our environment. Human exposure to high dose rates poses a health risk. In this research work, radiometric survey and dose rate assessment was carried out on Archean rocks within the gold belt mining complex of Migori, Kenya. The objective was therefore to find out the contribution of different Archean rocks to the ambient gamma-ray dose in the mining complex. The high-resolution gamma-ray spectroscopy NaI (TI) provided a sensitive experimental tool in this study. The gamma –ray radiation hazards due to the specified radionuclides $^{226}$Ra, $^{232}$Th and $^{40}$K was assessed by representative radiation hazard index ($I_g$) and Radium equivalent activity ($R_{eq}$). Standard IAEA certified samples were used for energy calibration and efficiency calculation of the spectrum. Radiological investigations carried out revealed that there is relatively normal level of natural radiation in the area. An arithmetic mean average activity concentration for all the rock samples was found to be 1012.20±22.81 Bqkg$^{-1}$ for $^{40}$K; 70.57±18.77 Bqkg$^{-1}$ for $^{232}$Th and 69.19±11.29 Bqkg$^{-1}$ for $^{238}$U. It was evident from the result that potassium contributes most specific activity concentration compared to thorium and uranium. All different rock types analyzed in this work produced activity concentration that exceeded the world average values. Granite rock which is an igneous rock registered high content of potassium. The total dose rates and external hazard index of the rocks samples under consideration were calculated. The results showed that granite rocks contain a high proportion of natural radioactive elements concentration compared with other types of rocks. The annual effective dose of between of 0.30 mSv$y^{-1}$ for rocks and 0.22 mSv$y^{-1}$ for soil was registered. The average value of radium equivalent was below the recommended maximum values of 370 Bqkg$^{-1}$. 
1 INTRODUCTION

1.1 Background of gold mineralization in the area.

The rocks in Migori are Archean in age, about 2.8 billion years old (Shackleton, 1946). Migori is considered to have relatively continuous volcano- sedimentary greenstone sequences and granite. Shackleton (1946) made the first comprehensive set of geological mapping and coined the term “Migori gold belt” The earlier researchers identified different areas of Migori to contain different rock types (Shackleton, 1946; Sanders, 1964; Ogola and Omenda, 1991).

The Archean greenstone rocks of Migori are known to contain gold. Gold was first discovered in the county as early as 1904 but not in workable quantities (Shackleton, 1946). A government geologist Mr. Coates visited the area in 1909 and reported wide spread occurrence of gold in the streams and rivers but was unable to locate payable ore-bodies (Shackleton, 1946). Wayland E. J, then director of geological survey of Uganda in 1931, at the request of Kenyan government made a geological reconnaissance and reported favorably on the geological setting and economic prospects of the gold bearing veins which were being prospected, and recommended detailed geological mapping of the area. Shackleton (1946), mapped the gold belt topographically and geologically to serve as a basis for the further prospecting and development of the area. He was able to identify different rock types that exist in the gold belt. Ichang’i (1990) carried out a study in the complex to establish a lithostratigraphic frame work for geochemistry, geology and economic mineral potential figure 1.2. Ogola (2001) carried out a study to appraise the environmental impacts and ascertain the concentration levels of Hg, Pb and As. He found
that the levels of these heavy metals were above acceptable limits. Macalder stream recorded 11075 mgKg\(^{-1}\) for Pb, Mikey tailings recorded 1920 mgKg\(^{-1}\) for Hg and As had 76 mgKg\(^{-1}\). In this region, gold occurs in quartz veins within the mafic volcanic of the Nyanza group with the host rocks such as; metabasalt, banded iron stone, greywacke, tuff, conglomerates, shale and andesite.

This study is therefore meant to do radiometric survey to ascertain the level of natural radioactivity in the gold mining belt. Migori in western Kenya has been considered an ideal location for the study since it is a major gold mining area where trace element concentrations, chemical and normative compositions of granite rocks containing gold and radioactive metals are found (Shackleton, 1946; Sanders, 1964; Ogola and Omenda, 1991).

Several hypotheses are advanced for gold-sulphide mineralization in the region. Shackleton (1946) considered the presence of apophyses and veined ore bodies within the host rocks at Macalder to be indicative of hydrothermal- met somatic origin. However, Sanders (1964) suggested that gold-sulphide mineralization in this deposit took place in a pre-existing thrust structure. In contrast, Hutchinson (1981) concluded that these rocks are a deformed volcanogenic massive sulphide deposit of primitive type, which was formed over a sea floor hydrothermal vent. Ogola et al. (1987) concluded that in Migori deposits, the emplacement of gold within the host rocks was due to epigenetic vein-type mineralization and the mode of formation is volcanogenic hydrothermal. Keays (1982)
reckons that most vein-type Archean gold deposits probably formed after the deformation and metamorphism of the rocks, apparently due to late-stage metamorphic fluids.

Figure 1.1: Simplified stratigraphic section across the Migori greenstone complex, (Ichang’i 1990)

Artisan mining is an important economic sector in many developing countries. However, limited resources and training, and the availability of cheap, but potentially hazardous methods of extraction and processing of minerals can cause significant threats to both miners and the local environment. The natural radioactivity and the suspected high dose rates in these mining areas could probably complicate health problems and act as carcinogen. Ogola (1987) notes that, the relationship between mining and environment is
particularly complex and not yet fully understood especially in developing countries. In Kenya, he notes that this complexity is due partly to level of research and lack of adequate and analytical capabilities as well as foolproof diagnostic ability for environmentally related health conditions. It is on this ground that this research work was carried out to determine the contributions of rocks from the mining belt to the natural radioactivity concentration in the area.

1.2 Naturally occurring radionuclides

The earth has always been bombarded by high energy particle showers in the lower atmosphere. Additionally, the earth’s crust contains radionuclides. For most individuals, exposure to natural background radiation is the most significant part of their total exposure to radiation. Radon is usually the largest natural source of radiation contributing to the exposure of members of the public, sometimes accounting for half the total exposure from all sources. Besides the shielding provided by the earth’s magnetic field, life is shielded against cosmic radiations by an air layer of approximately 10,000kg/m², which is comparable to a 10m thick water layer. As a result at sea level the cosmic radiation contributes about 10% of the total dose rate from natural radiation to which human beings have always been exposed (UNSCEAR, 2008).

The natural radionuclides can be placed in three general categories: Primordial, Cosmogenic and Human produced (UNSCEAR, 2000; Tzortzis et al., 2004). Cosmogenic radionuclides and primordial radionuclides, such as $^{40}$K and the nuclides from the $^{232}$Th and $^{238}$U series and their decay products, occur at trace levels in all ground formations (UNSCEAR, 2000). The distribution of these naturally occurring radionuclides depends
on the distribution of rocks from which they originate and the process which concentrates
them (Mohanty et al., 2004). They are ubiquitous in the environment hence they are the
main sources of radiation exposure to the general population (Radiation information
network, 2004). Figure 1.1 shows the percentage contribution of various radiation sources
to human exposure.

![Figure 1.1](image)

**Figure 1.1**: Percentage contribution of various radiation sources to human exposure.

**Figure 1.2: Various sources of background radiation in nature.** (Clark et al., 1997)

### 1.2.1 Primordial radionuclides

Primordial radionuclides are left over from when the world and the universe were
created. They are typically long lived, with half-lives often on the order of hundreds of
millions of years. Some of the basic information on common primordial radionuclides is
shown in appendix V (Radiation Information Network, 2004).

### 1.2.2 Cosmogenic

Cosmic radiation permeates all over space, the source being primarily outside of our solar
system. The radiation is in many forms, from high speed heavy particles to high energy
photons and muons. The upper atmosphere interacts with many of the cosmic radiations,
and produces radioactive nuclides. They can have long half-lives, but the majority
has shorter half-lives than the primordial nuclides. Appendix V shows some common cosmogenic nuclides: (Radiation Information Network, 2004).

1.2.3 Anthropogenic

Humans have used radioactivity for one hundred years, and through its use, added to the natural inventories. The amounts are small compared to the natural amounts and due to the shorter half-lives, many of the nuclides, have seen a marked decrease since the halting of above ground testing of nuclear weapons. Appendix V shows some common human produced or enhanced nuclides: (Radiation Information Network, 2004)

1.3 Statement of the research problem

Natural environmental radioactivity and the associated external exposure due to gamma radiation depend primarily on the geological and geographical conditions, and appear at different levels in the rocks and soils of each region in the world (UNSCER, 2000). The geological conditions and postorogenic granite rocks in Migori provide a source of natural radioactivity. Migori is considered to have relatively continuous volcano-sedimentary greenstone sequences and granite that contains radioactive substances (Shackleton, 1946; Sanders, 1964). This has led to several environmental and health consequences from the artisanal mining. Depreciation of the component of the ecosystem is being witnessed in the region could be due to suspected high natural radioactivity and high doses from the rocks that contain gold. There are few surveys and pertinent data to corroborate all these speculations. For instance, whereas the mining environment is known to be polluted, details of the fugitive elements such as lead, mercury, arsenic and
Thorium in terms of the nature of radiations, the impact on the environment and the extent of damage to health are not properly known (Ogola, 1982; Ichang’i, 1990). This project will therefore seek to find out whether radiation from the rocks within the volcano-sedimentary greenstone belt of Migori has contributed to the suspected health problems ranging from leukemia, different strands of cancer and respiratory problems.

1.4 Hypothesis

The hypothesis of this study is that the presence of natural radioactivity and high dose rates from the Archean rocks of the Migori greenstone complex mining sites may be higher than the acceptable values.

1.5 Objectives of the research project

1.5.1 Main objective

To determine the human exposure to natural sources of radiation from various rock types and soil from the Migori gold belt complex.

1.5.2 Specific objectives

The specific objectives of this research are as follows;

(i) Measure the levels of activity concentrations of natural radionuclides in different rocks within the Migori gold belt complex.

(ii) To calculate the radiological parameters (hazard indices, absorbed dose rates and annual effective dose rate) due to each rock type.

(iii) To estimate the radiological hazards of exposure to both the miners and the general public from sampled rocks.
1.6 Rationale

Releases of radionuclides from radioactive rocks and mining wastes to the environment during mining and processing operations and subsequent waste management activities may result in high radiation exposure to the public which could pose a health hazard. Adequate information on natural radioactivity in our environment and dose rates is very important for risk awareness and can be used as basis for planning management strategy to achieve better environmental quality and provide general public information. Migori gold belt complex has mineral deposits and therefore is likely to contain high level radiation and doses from the Archean rocks. This project intends to carry out a radiometric survey using gamma-ray spectrometry so as to provide data and baseline map of radioactivity background level in the surrounding environment and will be used as reference information to assess any changes in the radioactive background level due to geological process.
2 LITERATURE REVIEW

2.1 Introduction

In this chapter, the relevant literature of the biological effects of radioactivity and types of radionuclides that were considered in this study are discussed. Various environmental radioactivity studies done in Kenya and outside are discussed and the findings presented.

2.1 Biological effects of radioactivity

The knowledge of radionuclides distribution and radiation levels in the environment is important for assessing the effects of radiation exposure due to both terrestrial and extraterrestrial sources (El-Arabi. 2007). Focus has been laid on the areas which are suspected to be high background radiation areas (HBRA). The knowledge of radionuclides distribution and radiation levels in the environment from rocks, water and soil is important due to the health hazard they pose to the human population.

Radioactive materials decay spontaneously and produce ionizing radiation, which may have sufficient energy to strip away electrons from atoms creating two charged ions or to break some chemical bonds. Therefore, any living tissue in the human body can be damaged by ionizing radiation in a unique manner. There is therefore, a great interest in the study of natural environmental radiation and radioactivity in rocks and or soil from mining areas because the population is exposed to natural radioactivity at different levels depending on minerals in the region (Radhakrishna et al., 1993).
All ionizing radiation causes similar damage at cellular level. Because $\textit{beta}$ ($\beta$) and $\textit{alpha}$ ($\alpha$) are relatively non penetrative, external exposure does not cause a lot of damage however, they become more dangerous when swallowed. The penetrative power of gamma radiation makes it be absorbed in the body and thus can easily cause radiation effects (Zamanet $et$ $al.$, 1993). It is worthwhile to note that exposure to the radiation doses should be kept as low as reasonably achievable (ALARA). This project is therefore intended to do radiometric survey and dose rates assessment in rocks from the mining areas so as to understand the extent of the problem of toxicity, by linking the technical knowledge on the subject with mining activities going on in the area.

2.3 Radionuclides considered

The three most common primordial radionuclides that were investigated in the study area are potassium-40 ($^{40}$K), Radium-226 ($^{226}$Ra) and Thorium-232 ($^{232}$Th).

2.3.1 Radium ($^{226}$Ra)

$^{226}$Ra is considered as the most radiotoxic natural radionuclide in $^{238}$U decay series. The $^{226}$Ra decays to Radon (Rn) which consists of 3 isotopes; $^{219}$Rn, $^{220}$Rn and $^{222}$Rn. Radon normally emanates from materials carrying Uranium (soil, sand, rocks, gravels etc.). Despite the short half-life of $^{222}$Rn (3.84 days), it presents a long term hazard, since the decay of $^{226}$Ra (half-life of 1,600 years) constantly produces new radon. In addition, the tailings also contain the predecessor of $^{226}$Ra in the decay chain including $^{230}$Th, which decays with half-life of 75,400 years, again constantly producing $^{226}$Ra. When $^{222}$Rn gas is inhaled it gets to the lungs and deposits large amounts of energy to the surrounding
tissue which may bring severe biological damage that might cause lung cancer (Fleischer et al., 1978).

2.3.2 Potassium (\(^{40}\text{K}\))

Natural potassium has 3 isotopes: \(^{39}\text{K}, {^{40}\text{K}}\) and \(^{41}\text{K}\). Among them, the only isotope of interest is the unstable \(^{40}\text{K}\) with a half-life of \(1.26 \times 10^9\) years. It possesses natural gamma radioactivity and its abundance in nature is 0.0118 % of all potassium present in the earth crust (Engelkemeiret al., 1962). During decay \(^{40}\text{K}\) produces two daughter isotopes; decay to give \(^{40}\text{Ca}\) and or electron capture to \(^{40}\text{Ar}\).

2.3.3 Thorium (\(^{232}\text{Th}\))

In nature almost all thorium is \(^{232}\text{Th}\). There is about 1.35 \times 10^{-8} \% of \(^{228}\text{Th}\) and extremely small amount of \(^{234}\text{Th}, {^{230}\text{Th}, {^{231}\text{Th}}\) and \(^{227}\text{Th}\). \(^{232}\text{Th}\) has a half-life of 14 billion year with specific activity of \(1.1 \times 10^{-7}\ \text{Ci g}^{-1}\) (UNSCEAR, 2005).

2.4 Environmental radioactivity studies in Kenya

Studies carried out in Kenya have shown that natural radioactivity is due to the primordial radionuclide \(^{238}\text{U}, {^{232}\text{Th}}\), and \(^{40}\text{K}\). \(^{222}\text{Rn}\) is the greatest contributor of indoor radioactivity (Chege, 2007). Elevated level of indoor radon in homes and workplaces in Kenyatta University has been reported with a mean and maximum concentration of \(^{222}\text{Rn}\) in indoor air of 100 and 1160 Bq m\(^{-3}\) respectively (Mustapha, 1999; Chege, 2007). The radon concentration in some areas has been found to be above the EPA recommended level of 148Bq m\(^{-3}\) (Chege, 2007). It was established that indoor dose rate depend on the
type, model and construction material used in building a house (Chege, 2007). Buildings
constructed by materials with high $^{226}\text{Ra}$ concentration influence the indoor concentration
and hence the dose rate. Also the ventilation of the building affects the build-up of radon
inside the building.

A measurement of radiation of geological samples from Mrima hill area has been done
Prior measurements showed that the area has high background radiation with an annual
effective dose rate as high as 106mSv$^{-1}$ and the later study indicates that the area has an
absorbed dose of rate of 440nGy$^{-1}$ which is far above the world average of 60nGy$^{-1}$
(Mustapha, 1997; Kebwaro, 2009).

Study on levels of radionuclides along the Kenyan coast has also been conducted. The
average levels of the radionuclides $^{238}\text{U}$, $^{232}\text{Th}$ and $^{40}\text{K}$ were $22.8 + 1.8$ Bq$\text{Kg}^{-1}$, $26.2 +
1.7$ Bq$\text{Kg}^{-1}$ and $479.8+24.3$ Bq$\text{Kg}^{-1}$ respectively (Hashim, 2001). The annual effective
dose rate from gamma radiation as a result of naturally occurring radionuclides was in the
range 0.03-0.2 mSv$\text{h}^{-1}$. This was below the global limit of 1mSv$^{-1}$, however, traces of
$^{137}\text{Cs}$ were detected in some samples (Hashim et al., 2004). The population-bias average
effective dose rate from natural sources of radiation in Kenya has been estimated to be
0.41 mSv$^{-1}$ (Mustapha, 1999).

2.5 Environmental radioactivity studies outside Kenya

The assessment of the radionuclide and trace-element pollutants in the general
environment has been done in different parts of the world.
Ibrahim et al. (1993) measured the radioactivity levels in the soils of Nile delta and middle Egypt. It was found that the highest radionuclide activity occurs in clay soils and the lowest occur in sand soils. The highest activity in $^{137}$Cs was found in the region with dark clay and muddy clay soils.

Radiological investigations carried out recently in the eastern coast of Orissa, India to measure the radiation dose rates have revealed that there is enhanced level of natural radiation in the area. The activity concentration of $^{232}$Th was found to be 2825 Bqkg$^{-1}$ while $^{238}$U was 350 Bqkg$^{-1}$ (Mohanty et al., 2004).

Shaban et al. (2011) investigated natural radioactivity and their radiological effects for different types of rock samples from Egypt. Twenty one rock samples were analyzed by gamma-ray spectrometry using NaI(Tl) detector with specially designed shield. The concentration of three natural radionuclides namely $^{226}$Ra, $^{232}$Th and $^{40}$K was determined. Concentration ranged from (3.4–99, 7.5–134 and 93–3382 Bq kg$^{-1}$), (54.9–211.6, 20.71–170.5 and 2068–2344 Bq kg$^{-1}$) and (13–106, 29.25–106.1 and 682–755 Bq kg$^{-1}$) for gneiss, granite and basalt rocks, respectively, while the values were (7.5, 12.5 and 263.9 Bq kg$^{-1}$) and (113, 148.5 and 1672 Bq kg$^{-1}$) for $^{226}$Ra, $^{232}$Th and $^{40}$K in sandstone and siltstone rocks, respectively. Also radium equivalent activity, total dose rates and external hazard index of the rock samples under consideration were calculated. The results showed that granite rocks contain a high proportion of natural radioactive elements, while sandstone rocks had lower radioactivity concentration compared with other types of rocks.
Senthilkumar et al. (2005) assessed the level of terrestrial gamma radiation using \( \gamma \)-ray spectrometry and associated dose rates from the naturally occurring radionuclides \(^{232}\text{Th}\), \(^{238}\text{U}\) and \(^{40}\text{K}\) in 10 soil samples collected from Thanjavur (Tamil Nadu, India). The activity profile of radionuclides has clearly showed the existence of low level activity in Thanjavur. The geometric mean activity concentrations of \(^{232}\text{Th}\), \(^{238}\text{U}\) and \(^{40}\text{K}\) is \(42.9 \pm 9.4\) Bqkg\(^{-1}\), \(14.7 \pm 1.7\) Bqkg\(^{-1}\) and \(149.5 \pm 3.1\) Bqkg\(^{-1}\) respectively are derived from all the soil samples studied. The activity concentration of \(^{232}\text{Th}\), \(^{238}\text{U}\) and \(^{40}\text{K}\) in soil is due to the presence of metamorphic rocks like shale, hornblende-biotite gneiss and quartzofeldspathic gneiss in these areas (Senthilkumar et al., 2005). Gamma absorbed dose rates in air outdoors were calculated to be in the range between 32 nGy\(^{-1}\) and 59.1 nGy\(^{-1}\) with an arithmetic mean of 43.3 \(\pm\) 9 nGy\(^{-1}\). This value is lower than the population weighted world-averaged of 60 nGy\(^{-1}\). Inhabitants of Thanjavur are subjected to external gamma radiation exposure (effective dose) ranging between 39.2 and 72.6 \(\mu\)Svy\(^{-1}\) with an arithmetic mean of 53.1\(\pm\)11 \(\mu\)Svy\(^{-1}\). The values of the external hazard index determined from the soil radioactivity of the study area were found to belower than the recommended safe levels.

Radionuclides in rock samples collected from Southern Nigeria have been measured using gamma ray scintillation spectrometry (Joshua et al., 2009). The dose rate and annual effective dose rate calculated ranged from 0.012 to 0.042\(\mu\)Gyh\(^{-1}\) and 0.06 to 0.21mSvy\(^{-1}\) respectively. Implying the radiation from rocks is below the world average background. The activity concentration was found to depend on the rock type, granite rocks had the highest \((882 \pm 298\) Bgkg\(^{-1}\)) activity concentration of \(^{40}\text{K}\) because of more
silica content and fairly high (131±43Bqkg$^{-1}$ and 129±38 Bqkg$^{-1}$) activity concentration for $^{232}$Th and $^{238}$U respectively. The least activity concentration for all radionuclides was found in ferrogeneisis shale rock types because of iron content in which $^{232}$Th and $^{238}$U are minimal. Despite the variation of the activity concentration with rock type, they were not found to pose any significant radiation hazard when used as building material (Joshua et al., 2009).

Oktay et al. (2010) assessed natural radioactivity and radiological hazards in construction materials used in Elazig Turkey by use of gamma ray spectrometry method. From the measurements done, the lowest (36.5 Bqkg$^{-1}$) radium equivalent activity was noted in bricks while highest (405.2 Bqkg$^{-1}$) value was noted in concrete. The specific activity ranged from 1.6 Bqkg$^{-1}$ to 4928 Bqkg$^{-1}$. The average indoor radon concentration in the newly constructed floor was 364.3Bqm$^{-3}$ which is higher than the global mean value.

Turhan et al. (2007) assessed natural radioactivity and radiological hazards for cements and its raw materials in Turkey using gamma – ray spectrometry. The assessment showed differences in radioactivity depending on the materials used in the cement manufacturing process. The activity concentration of 147.8 Bqkg$^{-1}$, 110.1 BqKg$^{-1}$ and 2447.7 BqKg$^{-1}$ for $^{238}$U, $^{232}$Th and $^{40}$K respectively were the highest recorded in the assessed samples. This can be attributed to high radioactivity of the blast furnace slag raw material. The mean indoor absorbed dose rate was found to be 87.3nGyh$^{-1}$ which is slightly higher than the population weighted average of 84nGyh$^{-1}$. The result means that the cement does not pose any hazard when used as building material.
Ahmed et al. (2006) did comparative study of the natural activity of some selected rocks from Egypt and Germany. The aim of the study was to compare the natural activity level of the common rocks used for building in the two countries. A variation of activity concentration of the collected rocks was noted. Even though the radionuclides from the rocks were widely distributed, their concentration depends of the local geological conditions. The concentration of $^{40}\text{K}$ in igneous rocks varied roughly with an abundance of silica in the rock. In sedimentary rocks, the concentration of $^{40}\text{K}$ was found to depend on the relative amount of feldspar, mica and clay minerals that make up the mineral aggregate. Activity concentration is higher in acidic igneous rocks (with abundance of silica content) than in ultra-basic rocks.

Santos et al. (2010) assessed radium equivalent and annual effective dose from geological samples from Pedra-Pernambuco-Brazil using high resolution (hyper pure germanium) gamma ray spectrometry. The study observed values of activity concentration lower than the maximum recommended limit of 370BqKg$^{-1}$. The greatest contribution found in U was observed in calcium-silicate samples and this is due to uranium anomaly found in calcium-silicate. The greatest contribution from $^{40}\text{K}$ was observed in granite which means high concentration of potassium in the rocks.

From the above studies it is evident that there are two factors that determine the level of activity in rocks: the rock type which depends on mineral composition based on the forming process and the geochemical composition based on the interactions with either the rock themselves or with other substances within the earth crust during the rock
forming process. Therefore, different rocks have different level of radioactivity. The aim of this work is to investigate the contribution of different types of rocks found in Migori gold belt complex to radiation exposure based on the activity concentration of the naturally occurring radionuclides in the rocks and to assess whether they pose any risk to human beings.
3 THEORETICAL BACKGROUND OF NaI (TI) SPECTROMETER

3.1 Introduction
In this chapter the theory of the Gamma-ray spectrometry used in this project work is discussed. The gamma ray spectrometry involves the detection and measurement of the energies and intensities of the γ-ray radiation emitted. In gamma spectroscopy, thallium activated sodium iodide detector NaI (T1) is one of the commonly used detector to measure radiation levels in the soil and rock samples.

3.2 Radioactive decay equilibrium
The condition, when the activity of the higher atomic number nuclide, the “parent,” is equal to the activity in the next step, the “daughter”, is known as radioactive equilibrium. Thus, secular equilibrium between a parent and a daughter implies the activity ratio is 1 (Gordon, 2008). When the half-life of the original radionuclide is much longer than the half-life of the decay product, the decay product generates radiation more quickly. Within about 7 half-lives of the decay product, their activities are equal, and the amount of radiation (activity) is doubled. Beyond this point, the decay product decays at the same rate and is said to have reached a state called "secular equilibrium". For example, as $^{238}\text{U}$ begins to decay to $^{234}\text{Th}$, the amount of thorium and its activity increase. Eventually the rate of thorium decay equals its production; its concentration then remains constant. As thorium decays to proactinium-234, the concentration of proactinium-234 and its activity rise until its production and decay rates are equal. The graphs below illustrate the progress of ingrowth, and its effect on overall activity, and the potential for radioactive equilibrium in three general cases.
Disequilibrium sometimes occurs when one or more decay products in a decay series are completely or partially removed or added to the system. Thorium ($^{232}\text{Th}$) rarely occurs out of equilibrium in nature and there are no disequilibrium problems with potassium ($^{40}\text{K}$). However in Uranium decay series disequilibrium is common and can occur at several positions in the $^{238}\text{U}$ decay series (Stuckless *et al.*, 1983). For instance, $^{226}\text{Ra}$ can be selectively removed from the decay chain and $^{222}\text{Rn}$ is a mobile gas and can escape from soils and rocks into the atmosphere. This disequilibrium in $^{238}\text{U}$ is common source of error in gamma ray spectrometry (Stuckless *et al.*, 1983). $^{238}\text{U}$ concentration estimates are therefore based on the measurements of $^{214}\text{Bi}$ and $^{214}\text{Pb}$ isotope abundances. These normally occur far down in the decay chain and may not be in equilibrium. Estimates of U are usually reported as “equivalent Uranium (eU)” as these estimates are based on the assumption of equilibrium conditions.
3.4 Background of gamma ray radiation

Radioactive materials decay spontaneously and produce ionizing radiation, which may have sufficient energy to strip away electrons from atoms creating two charged ions or to break some chemical bonds. Gamma ray is often produced alongside other forms of radiations such as $\alpha$ and $\beta^+$ or $\beta^-$. When unstable atomic nucleus decays to stable nucleus, the daughter nucleus is sometimes produced in an excited state. The subsequent decay of the excited state results in the emission of gamma rays (figure 3.2). For instance the transition of the excited $^{60}_{28}\text{Ni}^\ast$ resulting from the $\beta^-$ decay of $^{60}\text{Co}$ into stable $^{60}_{28}\text{Ni}$, through an emission of two $\gamma$ rays of energies 1173keV and 1332 keV.

![Figure 3.2: Decay scheme of $^{60}\text{Co}$.

Another process through which gamma rays are produced is annihilation of positrons in matter. As a positron comes to rest, it combines with one of the many free electrons in the surrounding, producing two annihilation gamma rays. Due to conservation of momentum, the free electron is of the same energy and recoil in the opposite directions. Each gamma ray is of 0.511 MeV energy as a result, the two energies add up to the energy equivalent to $2M_0C^2$ of the disappearing electron and positron which then become gamma ray.
3.5 Gamma ray spectroscopy

Gamma – ray spectroscopy is used for analysis of radionuclide concentrations of the samples. The principles of the structure of the atom and the process of γ-ray interactions with matter are presented here. The respective photon energies are used to identify which particular radionuclide is present in the sample material. Quantitative and qualitative analyses of a gamma ray spectrum enable one to identify unknown radioactive elements in the sample. The gamma-ray spectrum is characteristic of the gamma-emitting radionuclides contained in the source. The detection of gamma rays is critically dependent on causing a gamma ray photon to undergo an interaction that transfers all or part of the photon energy to an electron in the absorbing material (Debe rtinet al., 1988).

For a detector to serve as a gamma ray spectrometer, it must act as a conversion medium in which incident gamma rays have a reasonable probability of interacting to yield one or more electrons and must function as a conventional detector for these secondary electrons (Delaney et al., 1992). The interaction mechanisms of gamma rays include photoelectric absorption (predominantly at low energy gamma-rays and high atomic number materials), pair production (predominantly at high energy gamma-rays and high $Z$ material), and Compton scattering (most probable process over the range between the pair production and photo-electric absorption).

To make an excellent γ-ray detector, therefore one must use a material in which the photoelectric and pair production cross-sections are large compared to the Compton scattering cross-section. The total probability of gamma–ray interaction is the sum of all the individual probabilities given as;
\[ \sigma = \sigma_{pe} + \sigma_c + \sigma_p \]  

3.1

Where; \(\sigma_{pe}\), \(\sigma_c\) and \(\sigma_p\) are the cross-sections for photoelectric, compton and pair production effects respectively. The production of the \(\gamma\)-ray photo involves the interaction of the incidence photon or moving charged particles with the inner shell electrons of the atom and the subsequent transitions by the outer shell electrons to the ionized level.

3.6 Interaction of gamma rays with matter

The photon interactions may be with a tightly bound electron i.e. with an atom as a whole (photoelectric effect), with the field of the nucleus (pair production) or with an essentially free orbital electron (compton effect, triplet production). During the interaction the photon may completely disappear or it may be scattered coherently or incoherently. There are three major types of photon interaction with matter.

3.6.1 Photoelectric effect

In the photoelectric effect the photon interacts with a tightly bound orbital electron of an attenuator and disappears, while an energetic orbital electron is ejected from the atom as a photoelectron. The interaction takes place with the atom as a whole and cannot take place with free electron since conservation law would be violated. For gamma rays of sufficient energy, the most probable origin of the photoelectrons is the most tightly bound or K shell of the atom (Leo, 1994). The photon appears with a kinetic energy \(E_K\) given by equation 3.10.

\[ E_K = h\nu - E_b \]  

3.2
Where; $E_K$ - kinetic energy of ejected electron; $hv$ - Incident photon energy and $E_b$ - binding energy. The interaction leaves an ionized absorber atom with a vacancy in one of its bound shells. This vacancy is quickly filled through the capture of free electron from the medium and or rearrangement of electrons from other shells of the atom (Nicholas, 1995).

Figure 3.3: Illustrations of the incoming photon ejecting photoelectron, followed by the movement of an outer orbital into the vacancy left.

No photoelectric effect occurs when the binding energy is greater than the incident photon energy $E_b > hv$. However, when $hv > E_b$ or $E_b = hv$ photoelectric may occur.

Figure 3.4: Illustration of how the incoming photon may or may not eject photoelectrons depending on it energy.
The atomic attenuation coefficient for the photoelectric effect $\tau_a$ is proportional to $\frac{Z^4}{(hv)^3}$ while the mass attenuation coefficient for the photoelectric effect $\tau_m$ is proportional to $\left(\frac{Z}{hv}\right)^3$ where $Z$ is the atomic number of the attenuator and $hv$ is the photon energy. The significance of all these equations is that heavier atoms absorb gamma radiation as far as photoelectric effect is concerned, more effectively than lighter atoms. Therefore an ideal detector would be made of a high $Z$ material, given their charge collection characteristic are satisfactory. The strong dependence on the photon energy on interaction cross section is the reason why the effect is the dominant mode of interaction at low energies but negligible at high energies (Gordon, 2008).

### 3.6.2 Compton Effect (incoherent scattering)

The Compton effect involves a photon interaction with an essentially ‘free and stationary’ orbital electron. The incident photon energy $hv$ is much larger than the binding energy of the orbital electron, electron is therefore considered to be free i.e. $hv \gg E_b$. The photon loses part of its energy to the recoil (Compton) electron and is scattered as photon $hv'$ through a given scattering angle with respect to its original direction (equation 3.2) becomes;

$$hv' = hv - E_k \quad 3.3$$

The scattered electron may or may not interact again inside the detector. The probability of the second interaction depends on the size of the medium of interaction, the position of the first interaction, the energy of the scattered photon and on the material of which the detector is made (Nicholas, 1995). Because all angles of scattering are possible, the
energy transferred can vary from zero to a large fraction of the gamma ray energy. For higher gamma energies the binding energy of the electron to the atom becomes increasingly irrelevant, the Compton interaction, which is directly between the gamma quantum and an essentially free electron, becomes important. The gamma ray only transfers part of its energy to a recoil electron. Figure 3.4 show Compton scattering process.

![Compton scattering diagram]

**Figure 3.5: Schematic illustration of Compton scattering interaction of gamma photon.**

In his explanation of the Compton scattering experiment, Arthur Compton treated the x-ray photons as particles and applied conservation of energy and conservation of momentum to the collision of a photon with a stationary electron. Using the Planck relationship and the relativistic energy expression, conservation of energy takes the form;

\[ h\nu_i + m_e c^2 = h\nu_f + \sqrt{p_f^2 c^2 + m_e^2 c^4} \]  

3.4

conservation of momentum requires that,

\[ \vec{p}_i = \vec{p}_f + \vec{p}_e \]  

3.5
Where $p = \frac{E}{c}$ is used for the photon momentum. Squaring this equation using the scalar product gives

$$p_e^2 = (\vec{p}_i - \vec{p}_f) \cdot (\vec{p}_i - \vec{p}_f) = p_i^2 + p_f^2 - 2p_i p_f \cos \theta$$

3.6. Again using the Planck relationship and the relativistic energy expression; multiplying by $c^2$ and substituting $pc = h\nu$;

$$(p_e c)^2 = (h\nu_i)^2 + (h\nu_f)^2 - 2v_i v_f h^2 \cos \theta$$

3.7. The energy conservation expression above can be squared to give;

$$(p_e c)^2 = (h\nu_i)^2 + (h\nu_f)^2 - 2v_i v_f h^2 + 2m_e c^2 (h\nu_i - h\nu_f)$$

3.8. These two forms can be equated to give;

$$-2v_i v_f h^2 \cos \theta (h\nu_i - h\nu_f) = -2v_i v_f h^2 + 2m_e c^2 (h\nu_i - h\nu_f)$$

3.9. which can be rearranged to give;

$$\frac{1}{h\nu_f} - \frac{1}{h\nu_i} = \frac{1}{m_e c^2} (1 - \cos \theta)$$

3.10. finally to the standard Compton formula;

$$\lambda_f + \lambda_i = \Delta \lambda = \frac{h}{m_0 c} (1 - \cos \theta)$$

3.11. 3.6.3 Pair production

It involves the transformation of a photon into an electron-positron pair. i.e. the photon disappears and an electron–positron pair with a combined kinetic energy equal to $h\nu - 2m_0 c^2$ is produced in the nuclear Coulomb field. It occurs in the nucleus in order to conserve momentum (Leo, 1994).

Thus the state of the nucleus before and after interaction is the same, except for a very small change in its kinetic energy and momentum. There is no excitation of the nucleus.
The two electrons produced \( e^- \) and \( e^+ \) are not scattered orbital electrons but are created, de novo, in the energy or mass conversion of the disappearing photon.

\[ T_{e^-} + T_{e^+} = T = h\nu - 1.02\text{MeV} \quad 3.12 \]

When pair production occurs in the field of an orbital electron, the effect is referred to as triplet production, and three particles; an electron–positron pair and the orbital electron share the available energy. The threshold for this effect is \( 4m_e c^2 \). The pair production does not occur for photon energies below the threshold energy and increases rapidly with photon energy above the threshold. The atomic attenuation coefficient for pair production \( \mu \) and the mass attenuation coefficient for pair production \( k/\rho \) vary approximately with \( Z^2 \) and \( Z \), respectively.
3.6.4 Coherent (Rayleigh) scattering

In coherent (Rayleigh) scattering the photon interacts with a bound orbital electron (i.e. with the combined action of the whole atom). Photon loses essentially none of its energy and is scattered through only a small angle. Since no energy transfer occurs from the photon to charged particles. Rayleigh scattering plays no role in the energy transfer coefficient; however, it contributes to the attenuation coefficient. The atomic cross-section for Rayleigh scattering $\sigma_R$ is proportional to $\left(\frac{Z}{hv}\right)^2$ and the mass attenuation coefficient $\sigma_{R/\rho}$ is proportional to $\frac{Z^4}{(hv)^2}$.

3.6.5 Relative predominance of individual effects

The probability for a photon to undergo any one of the various interaction phenomena with an attenuator depends on the; energy $(h\nu)$ of the photon and the atomic number $Z$ of the attenuating material. In general, the photoelectric effect predominates at low photon energies, the Compton effect at intermediate energies and pair production at high photon energies (figure 3.7).

![Figure 3.7: The regions of relative predominance of the three most important individual effects with $h\nu$ and $Z$ as parameters.](image)

The left curve represents the region where the atomic coefficients for the photoelectric effect and Compton effect are equal \((a_r = a_c\sigma)\) thus delineate the regions of photoelectric effect predominance at low photon energies, Compton effect predominance at intermediate energies and pair production predominance at high photon energies. The right curve is for the region where the atomic Compton coefficient equals the atomic pair production coefficient \((a_c\sigma = a_K)\).

As an x-ray beam or gamma radiation passes through an object, it can penetrate the section of matter without interacting, can interact with the matter and be completely absorbed by depositing its energy and can interact and be scattered or deflected from its original direction and deposit part of its energy.

Behavior of photon in matter is different from that of charged particles. Photon lacks an electric charge hence makes it impossible for the inelastic collision with atomic electrons. The reaction of photons explains two principal qualitative features of x-ray and gamma-rays: X-rays are more penetrating in matter than charged particles due to smaller cross section and beam of electron is not degraded in energy as it passes through matter but only attenuated in intensity. The attenuation suffered by a photon beam is exponential with respect to the thickness, i.e.

\[ I = I_0 e^{-\mu x} \]

Where; \(I_0\): incident beam intensity; \(x\): Thickness of absorber and \(\mu\): Absorption coefficient. (Probability or cross section of photon interaction depends on; energy of the photon (hv) and Atomic number Z of the attenuator).
3.7 Scintillation Detectors

The most widely used detector of gamma radiation for geologic mapping is one or more crystals of thallium-activated sodium iodide. When a gamma ray enters the crystal and strikes an electron, the electron gains energy which is then emitted as a tiny flash of light when the electron returns to its original energy state. The number of flashes is proportional to the gamma ray energy, so that the total light intensity is a measure of the energy of the incoming gamma ray. An array of photomultiplier tubes converts the light into an electrical signal. Sodium iodide crystals are preferred to other detector types for three principle reasons: they have good resolution of the energies in the 0.3 to 3 MeV range, have a high transparency and thus, even weak flashes of light can be detected and is relatively easy to grow large crystals of NaI, and therefore they are a relatively economical detector (Delaney et al., 1992).

Solid state semiconducting detectors, like lithium-drifted germanium crystals, have superior resolving power to that of NaI (50 to 80 times). However they are difficult to grow and in order to operate effectively they must be maintained at liquid nitrogen temperatures thus presenting handling and weight problems. Scintillation detectors are in two categories; organic or inorganic. Examples of inorganic scintillators are BOG, BaF₂, NaI(Tl), CsI(Tl), CaI(Na), LiI (Eu), and CaF(Eu) and CsF. NaI(Tl) has an excellent light yield and linearity but relatively slow response time (Tsouflanidis, 1995). It is hygroscopic and will deteriorate due to water absorption if exposed to the atmosphere for a long time. To prevent this, it must be canned in an air tight container. ZnS(Ag) has high efficiency compared to NaI(Tl) but is available as polycrystalline powder. Its use is
therefore limited to thin screen used primarily for alpha particles and other heavy ion detection. Cesium fluoride has a faster decay time but its light yield is low. The effect of temperature on scintillators varies significantly from one detector to another over a temperature range of \(-100^\circ C\) to \(140^\circ C\) (Nicholas, 1995). However, the temperature effect on NaI(TI) is less significant for radionuclides measured at room temperature, because this detector displays a rather stable light output response at and CaF\(_2\)(Eu) to dark matter particles has indicated that relative scintillation efficiency of NaI(TI) remains constant at lower energies while that of CaF\(_2\)(Eu) shows arise in lower energies (Tovey\textit{et al.}, 1998)

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
Material & Wavelength of max. emission (nm) & Scintillation efficiency (%) & Decay time (micro-seconds) & Density (Kg/m\(^3\)) \\
\hline
Bi\(_4\)Ge\(_3\)O\(_{12}\) & 480 & 8 & 0.30 & 7.18 \\
NaI(TI) & 410 & 100 & 0.23 & 3.67 \\
LiI(Eu) & 470 & 30 & 0.94 & 3.49 \\
CsI(Na) & 420 & 80 & 0.63 & 4.51 \\
CdWO\(_4\) & 530 & 20 & 0.90 & 7.90 \\
CaF\(_2\)(Eu) & 435 & 50 & 0.94 & 3.18 \\
CsI(TI) & 565 & 45 & 1.00 & 4.51 \\
\hline
\end{tabular}
\caption{Properties of certain Inorganic Scintillators}
\end{table}

3.8 NaI (TI) scintillation detector

This detector makes use of the principle of emission of light by special materials upon interacting with radiation. Thallium activated sodium iodide –NaI(TI) spectroscopic system was used for the measurement of the energy spectrum of the emitted gamma rays in the energy. A fraction of energy absorbed by the material is converted into scintillation
photons. The number of electrons liberated by the scintillation photon on the photocathode of the photomultiplier is linearly proportional to the number of primary electrons, and thus to the energy absorbed by the scintillating material (Leo, 1994). Hence the total charge produced on the output of the photomultiplier (PM) can be used to measure energy deposited by the nuclear radiation in the detector. The pulses of electrons are fed into a multichannel analyzer (MCA) which sorts them according to size, with bigger pulses going into higher numbered channels. Thus channel number is related to gamma – ray energy. The scintillation mechanism depends on the energy states determined by the crystal lattice. The charged particles passing through the medium will form a large number of electron – hole pair created by the elevation of electrons from the valence band to the conduction band. The resulting spectrum will contain one or more photo peaks at the energies of the gamma rays emitted from the source (Chozzi et al., 2000). The efficiency of photoelectric conversion in the photocathode depends on the frequency of incident photon and structure of the material. The efficiency is equivalent to the radiant cathode sensitivity defined by the equation 3.19 (Leo, 1994);

\[ S(\lambda) = \frac{I_k}{P(\lambda)} \]  

\[ 3.14 \]

Where \( I_k \) and \( P(\lambda) \) are photoelectric emission current from cathode and incident radiant power respectively. Figure 3.8 shows the band structure in an activated crystal.
3.9 Mechanism of NaI(Tl) gamma ray spectrometry

The scintillation counter is coupled with a suitable scintillation phosphor to a sensitive photo multiplier tube (PMT). The detector comprises of a single crystal of sodium iodide activated with thallium. The working of the detector is based on the scintillation mechanism; As radiation interacts in the scintillation crystal, energy is transferred to bound electrons of the crystal’s atoms. If the energy that is transferred is greater than the ionization energy, the electron enters the conduction band and is free from the binding forces of the apparent atom. This leaves a vacancy in the valence band (hole). If the energy transferred is less than the binding energy, the electron remains attached, but exists in an excited energy state. Once again, a hole is created in the valence band. By adding impurities during the growth of the scintillation crystal, activator centres are produced with energy levels located within the forbidden energy gap.

The activator centre traps mobile electron, which raises the activator centre from its ground state, G, to an excited state, E. When the centre de-excites, a photon is emitted.
The electrons emitted are by a voltage drop of about 50 volts to the nearest dynode in the PMT. The photoelectrons strike the first dynode with sufficient energy to liberate several new electrons for each photoelectron. The second generation –electrons are in turn, attracted to the second dynode where a larger third – generation group of electrons is emitted. This amplification continues through 10 to 12 stages. At the last dynode; sufficient electrons are available to form a current pulse suitable for further amplification by transistor circuits (Delaney et al., 1992; Chozzi et al., 2000). The quality of a given scintillation counting system is often characterized by the magnitude of its energy resolution.

![Diagram of NaI (TI) scintillator]

**Figure 3.9: A block diagram of NaI (TI) scintillator**

The use of linear attenuation coefficient is limited by the fact that it varies with the density of the absorber material, therefore the mass absorption coefficient is more widely used, which is defined as;

\[
\text{Mass absorption coefficient} = \frac{\mu}{\rho}
\]

3.15
Where \( \rho \) represents the mass density of the material for a given photon of energy the mass attenuation coefficient does not change with the physical state of the material.

### 3.10 NaI (TI) Spectrometer Calibration and Data Corrections

To convert the observed counting rates that are measured in the three or more spectral windows of the differential spectrometer into numbers of incoming gamma rays per unit of time from Bi\(^{214}\), Tl\(^{208}\), and K\(^{40}\), NaI(TI) must first be calibrated and corrected for background effects, atmospheric noise, and compton scattering (Grasty, 1977).

#### 3.10.1 Calibration

Calibration is basically the process of adjusting the output of the detector to agree with standard IAEA radionuclides. This is done because of the changes in the weather, vibrations and heating up of the detector.

The systems count rate is related to the gamma ray intensity through various instrumental parameters, the most important being the sensitivity of the detector. Because this sensitivity varies with the temperature of both the crystal and the photomultiplier tubes, the temperature of the detector should be carefully controlled during operation (Grasty, R.L. 1979). Energy calibration is generally done to derive the relationship between peak position in the spectrum and the corresponding gamma ray photon energy. For this research work the system calibration was done using three standard materials, obtained from International Atomic Energy Agency. The standards are RGU-1 and RGTH-1 RGK-1, for \(^{238}\)U, \(^{232}\)Th and \(^{40}\)K respectively (IAEA, 1987). The activities of the standard are
4900 Bqkg\(^{-1}\) for RGU-1, 3280 Bqkg\(^{-1}\) for RGTH-1 and 13400 Bqkg\(^{-1}\) for RGK-1. In addition to these standard materials, RGMIX-1 was used which has the following activity concentration for each radionuclide, 1150 BqKg\(^{-1}\) for \(^{238}\)U, 1250 BqKg\(^{-1}\) for \(^{232}\)Th and 5400 BqKg\(^{-1}\) for \(^{40}\)K. The following energy peaks were used \(^{214}\)Bi (609 keV) and \(^{214}\)Bi (1765 keV) for \(^{238}\)U, \(^{208}\)Ac (583 keV) and \(^{208}\)Ti (2615 keV) for \(^{232}\)Th and \(^{40}\)K (1460 keV).

Figure 3.10: shows a typical gamma ray spectrum of the standard samples.

The photon energy was represented as a function of channel number using a second order polynomial whose quadratic calibration function was used to convert other channel numbers to photon energy (equation 3.21) (Debertinet al., 1988).

\[
E = K_0 + Ax + Bx^2
\]

3.16

Where; \(E\) is the photon energy; \(x\) is the channel number; \((A, B\) and \(K_0)\) are fit parameters.

Table 3.2: Fit parameters are used for calibration in this research work \(R^2 = 0.99894\)

<table>
<thead>
<tr>
<th>parameter</th>
<th>Fitted value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3.5008</td>
</tr>
<tr>
<td>(K_0)</td>
<td>-50.75265</td>
</tr>
<tr>
<td>B</td>
<td>1.12666 x10(^{-4})</td>
</tr>
</tbody>
</table>
Figure 3.11: Graphical representation of the energy calibration of NaI(Tl) detector for this work. (The line represents the second order polynomial fit to the data).

Figure 3.12: Gamma ray spectrum of the samples analyzed.

3.10.2 Background determination and Correction

The "background" refers to the general background count rate that prevails in each channel, or spectral window, that is due to non-geologic sources, primarily atmospheric radon, cosmic rays and natural radionuclides in the neighboring materials. For this work,
the background count was determined by counting distilled (de-ionized) water in the same geometry as was for the sample (for a total time of 36000 seconds in the same 500ml plastic beaker) (Martin, 2011; Righi et al., 2009). The net count is then given by equation 3.22 and illustrated in figure 3.13.

\[ Y_g - Y_b = Y_n \]  

Where; \( Y_g \) is the total spectrum count; \( Y_b \) is the background count; \( Y_n \) is the net spectra count of the sample.

Figure 3.13: Typical gamma ray spectrum before and after subtracting background radiations.
4MATERIALS AND METHODS

4.1 Sampling and sample preparation

Twenty six rock samples from different geological mining sites in the Migori gold belt complex of western Kenya and twenty soil samples were collected. The rocks were chipped off from the weathered rocks or picked randomly from the surface after being excavated by miners. The Global Positioning System (GPS) was used to determine the coordinates of the sampling points. Sampling was done from the following major mining sites within the gold belt; Macalder, Nyatworo, Osiri, Masara, Kamwango, Kitere, Mikey, Nyamume and Migori (Figure 4.1). Apart from being mining points, these areas were also considered because of their sensitivity to biological life. The major rock samples collected from these sites included; granites, tuff, greywacke, shale, diorite, conglomerate, talc, phylite, rhyolite, quartz, laterite, covellite and basalt. Sizable quantities of rocks were collected. It’s important to note that multiple sampling was done at each site in order to achieve the statistical sensitivity of sampling (Stuckless et al., 1983). The rocks were then put in separate polythene bags to avoid contamination and properly marked for easy identification. They were then transported to Kenyatta University physics research laboratory.
The identification and geological classification was done to the rock samples collected. This was done through proper study of the region where the rock was collected, physical examination of the rocks and assessment of features like; texture, color, foliation, mineral composition, size of the grains, porosity and existence or absence of layers. Each rock type was then marked uniquely for easy identification.

Rocks and soil samples were then crushed and pulverized, sieved through 1 mm by 1 mm sieve and dried in an oven at a temperature of 110 °C for 24 hours to remove all the moisture content. 500g of each sample was then sealed in air tight standard 500ml plastic
beakers for at least one month. This was done to allow the in-growth of uranium and thorium decay products and prevent the escape of radiogenic gases $^{222}$Rn and $^{220}$Rn so as to allow secular equilibrium between $^{238}$U, $^{232}$Th and their decay products. For instance, $^{222}$Rn from $^{238}$U can easily escape by diffusion during sample preparation. As the half-life of $^{222}$Rn is 3.84 days, once the $^{222}$Rn escape from the sample it needs at least 7 half-lives to attain secular equilibrium. Shielded NaI(TI) gamma ray spectrometry was used to measure the activity concentration of radionuclides. This was done for accumulative time of 36000 seconds to increase the precision of the radiometric measurements ((Stuckless et al., 1983; Tzortzis et al., 2003).

4.2 Gamma ray spectrometer-NaI(TI)

Thallium Activated Sodium Iodide (NaI(TI)) spectroscopic system of 76 mm by 76 mm was used for the measurement of the energy spectrum of the emitted gamma rays in the energy. The spectroscopy system is linked with an Oxford PCAP-P Multi-Channel Analyzer (MCA) which is a PC-based plug-in PCI card consisting of an 80MHz Wilkinson Analogue-to-Digital Converter (ADC), Advanced Multi-Channel Analyzer (MCA) emulation software (MAESTRO-32) which enabled data acquisition, storage, display and analysis of the acquired gamma spectra.

4.2.1 NaI(TI) energy resolution

Energy Resolution can be defined as the ability of a detector to differentiate the photon energy of the two or more closely lying radionuclides. For this work, energy resolution was calculated using equation 4.1 and was found to be 7.3 %. This was obtained by
measuring the gamma-ray energy peak at 663.3 keV as shown in figure 4.2. The Gaussian fitting was done on $^{137}$Cs peak and the fit parameters were used to calculate the resolution of the NaI (TI) used. The width of the photo peak in keV at half- maximum height was expressed in percentage of the photon energy (peak centre - % FWHM) (Figure 4.2). The smaller the value of FWHM, the higher the energy resolution i.e. the narrower the peak the greater the resolution of the detector.

![Energy spectrum and Gaussian fit](Figure 4.2: A typical energy spectrum and the Gaussian fit used in energy resolution for this work)

**Table 4.1: Gaussian fit parameters used in energy resolution calculations for this work (The Chi-squared was 0.15095)**

<table>
<thead>
<tr>
<th>Fit parameter</th>
<th>Value with error margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y_0$</td>
<td>1.52366±0.18286</td>
</tr>
<tr>
<td>$X_c$</td>
<td>663.32008±0.12045</td>
</tr>
<tr>
<td>$W$</td>
<td>48.43941±0.42835</td>
</tr>
<tr>
<td>$A$</td>
<td>1975.91733±24.37382</td>
</tr>
</tbody>
</table>
Energy resolution \( R \) = \( \frac{W}{X_c} \times 100 \% \) \hspace{1cm} 4.1

Where; \( R \) is the resolution; \( X_c \) is the energy at photo peak; \( W \) is the FWHM.

\[
R = \frac{48.439}{663.320}\times 100 = 7.30\%
\]

The Gaussian model equation used to generate Figure 4.2 is:

\[
y = y^0 + \frac{A}{\sqrt{\pi}W} e^{\left(-\frac{2(x-x_0)^2}{W^2}\right)^2}
\] \hspace{1cm} 4.2

Where; \( y^0 \) is the baseline offset; \( A \) is the area under the curve; \( x_0 \) is the centre of the peak; \( W \) is the width of the curve at half height.

**4.2.2 Counting efficiency of the NaI(Tl) detector**

This was obtained using the standard International Atomic Energy Agency (IAEA) certified sample (RGMIX). The gamma line 1765 keV of \(^{214}\text{Bi}\), 2615keV of \(^{208}\text{TI}\) and 1460keV of \(^{40}\text{K}\) were used in equation 4.3 to obtain counting efficiency of NaI(Tl) in counts sec\(^{-1}\) per Bqkg\(^{-1}\) (Mustapha, 1999);

\[
\varepsilon_i = \frac{n_s-n_b}{E C m_s}
\] \hspace{1cm} 4.3

Where; \( \varepsilon_i \) is the counting efficiency of the detector photo peak of the radionuclide \( i \);

\( n_s \)is the counting rate recorded in the energy window when the standard material (RGMIX) was used;

\( n_b \) is the counting rate in the same window when de-ionized water is used;

\( E \) is the photo emission probability;

\( m_s \)is the mass of the RGMIX standard used;

\( C \) is the activity concentration of a given radionuclide in RGMIX. (Bq/kg)
Table 4.2: Counting efficiency of NaI(TI) detector for this work

<table>
<thead>
<tr>
<th>Reference Material</th>
<th>Gamma ray energy (keV)</th>
<th>Source Nuclide</th>
<th>Counting Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>RGMIX 2</td>
<td>1460</td>
<td>$^{40}$K</td>
<td>0.00547138± 0.00013</td>
</tr>
<tr>
<td></td>
<td>1765</td>
<td>$^{214}$Bi</td>
<td>0.002459627±0.00041</td>
</tr>
<tr>
<td></td>
<td>2615</td>
<td>$^{208}$Ti</td>
<td>0.00147343±0.00082</td>
</tr>
</tbody>
</table>

4.2.3 Detection limit for the NaI(TI) detector:

The detection limit of the detector was computed using the following relation in equation 4.4 (Mustapha, 1999);

$$L_D = \frac{1}{m_s \varepsilon_i E} \left[ \frac{2.71}{T} + 4.65 \sqrt{\frac{C_B}{T}} \right]$$

Where; $C_B$ is background count rate in the channels of interest;

$T =$ counting time; $E$ is the photo emission probability; $m_s$ is the mass of the RGMIX standard used; $\varepsilon_i$ is the counting efficiency of the detector photo peak of the radionuclide $i$;

4.3 Measured spectra decomposition and striping

The quality of a given scintillation counting system is often characterized by its energy resolution. The NaI (TI) detector has low energy resolution typically of 9.6% at photo peak energy of 662kev of $^{137}$Cs. For this work energy resolution was found to be 7.3 % at energy peak of 663.3 keV for $^{137}$Cs. To solve the problem of low resolution, the measured spectrum was decomposed into parts that appear in the decay chain of $^{238}$U, $^{226}$Ra and $^{232}$Th and the spectrum of $^{40}$K. The spectrum of a sample is normally presented as a sum of composing spectra of the radiation $\gamma_i$ of separate i radionuclides, there decay products
and the background radiation as in equation 4.5 (Muminov et al., 2005).

\[ \gamma_{\Sigma_0} = \gamma_b + \gamma_{Th} + \gamma_U + \gamma_K \]  

4.5

If the background counts are subtracted, equation 4.4 becomes;

\[ \gamma_n = \gamma_{Th} + \gamma_U + \gamma_K \]  

4.6

Where; \( \gamma_n \) is the sum of the composing spectra of the radiation after the component of background radiation has been subtracted (Figure 3.13).

The extraction of the interfering components from the spectrum was done using striping off method. In this method, the total absorbed peak (TAP) of the radiation of a radionuclide \( i_1 \) which weakly interferes with radionuclides was picked. For this work \(^{214}\)Bi of peak energy 1765 keV; \(^{208}\)Ti of peak energy 1460 keV and \(^{40}\)K of peak energy 2615 keV which interferes with other peaks were chosen. A ratio \( c_1 \) between its intensity and the corresponding intensity of the standard source \( E_{i_1} \) was determined. This ratio was used to normalize the spectrum of the standard source to the spectrum of the radionuclides in the sample under investigation. The spectrum of the radionuclides \( i_1 \) contained in the sample was calculated using equation 4.7 (Muminov et al., 2005).

\[ \gamma_{i_1} = c_1 E_{i_1} \]  

4.7

Where; \( \gamma_{i_1} \) is the spectrum of the radionuclide \( i_1 \);

\( c_1 \), is the normalizing factor; \( E_{i_1} \) is the spectrum of the corresponding standard radionuclide. Subtracting \( \gamma_{i_1} \) from the spectrum that has been corrected for background (equation 4.6) we obtain;

\[ \gamma_{n_1} = \gamma_n - \gamma_{i_1} \]  

4.8
This was done to all the other spectra, which weakly interfere with the other radionuclides in the sample. The decomposed spectrum was fitted with a Gaussian fitting and the fit area used for activity calculation.

4.4 Radionuclides activity concentration

Naturally occurring radionuclides of $^{238}$U, $^{232}$Th and $^{40}$K were detected in all the rock and soil samples analyzed. The activity concentrations in Bq Kg$^{-1}$ was computed using the method of comparison UNSCEAR (1988, 2000); Abbady et al. (2005)

$$\frac{A_s M_s}{I_s} = \frac{A_R M_R}{I_R} \tag{4.9}$$

Where; $A_s$ is the activity concentration of a radionuclide in the sample; $M_s$ is the mass of the sample; $I_s$ is the peak intensity of the radionuclide in the sample; $A_R$ is the activity concentration of a radionuclide in the standard reference sample; $M_R$ is the mass of the reference sample; $I_R$ is the peak intensity of the radionuclide in the standard reference sample;

4.5 Calculations of the outdoor absorbed dose rate

Calculations of count rates for each detected photo peak and radiological concentrations of the detected radionuclides depends on the secular equilibrium in the sample. Using the calculated specific activity of the samples, the absorbed dose rate for naturally occurring radioactive elements such as $^{238}$U, $^{232}$Th and $^{40}$K in the sample, was obtained in nGy h$^{-1}$ units using the formula proposed by UNSCEAR (1988, 2000) and Abbady et al. (2005)

$$D = \alpha A_{Ra} + \beta A_{Th} + \gamma A_K \tag{4.10}$$

Where; $\alpha$, $\beta$ and $\gamma$ are conversion factors for $^{238}$U, $^{232}$Th and $^{40}$K
\[ D = \sum_x A_x C_x \]  
4.11

Where \( A_x \) (Bq kg\(^{-1}\)) are the mean activity concentrations of \(^{238}\)U, \(^{232}\)Th and \(^{40}\)K, \( C_x \) nGy h\(^{-1}\) per Bq kg\(^{-1}\) is their corresponding dose conversion factors. With the assumption that \(^{232}\)Th and \(^{226}\)Ra were at radioactive equilibrium with their precursors, dose conversion factors reported by UNSCEAR (1988) was used; (0.462 nGy h\(^{-1}\) per Bq kg\(^{-1}\) for \(^{238}\)U, 0.621 nGy h\(^{-1}\) per Bq kg\(^{-1}\) for \(^{232}\)Th and 0.0414 nGy h\(^{-1}\) per Bq kg\(^{-1}\) for \(^{40}\)K.

### 4.6 Calculations of the indoor absorbed dose rate

This was calculated using the formula proposed by EC (1999):

\[ D = 0.67A_{Ra} + 0.78A_{Th} + 0.057A_{K} \]  
4.12

Where; 0.67, 0.78 and 0.057 are the dose conversion factors in nGy h\(^{-1}\) per Bq kg\(^{-1}\). These conversion factors are chosen based on the model house typical to the building constructed using rocks from Migori gold belt complex. This is a house in which the floor and the walls are made of radioactive materials while the roof ceiling is made of wood. Using the world average value 60 nGy h\(^{-1}\) (UNSCEAR, 2008) for the background, the excess dose rate in a room was calculated by subtracting this background from the calculated value of the indoor rate.

### 4.7 Calculation of radium equivalent activity

The gamma –ray radiation hazards due to the specified radionuclides \(^{238}\)U, \(^{232}\)Th and \(^{40}\)K was assessed by radiation hazard index Ra\(_{eq}\) (Equation 4.13). The Radium equivalent activity is the weighted sum of activities of the three radionuclides based on the
estimation that 370 Bq/kg of $^{226}$Ra, 259 Bq/kg of $^{232}$Th and 4810 Bq/kg of $^{40}$K produce the same gamma ray dose rates (Beretka et al., 1985; Abbady et al., 2004):

\[
\text{Ra}_{eq} = 370 \text{BqKg}^{-1} \left( \frac{A_{Ra}}{370 \text{Bqkg}^{-1}} + \frac{A_{Th}}{259 \text{Bqkg}^{-1}} + \frac{A_{K}}{4180 \text{Bqkg}^{-1}} \right) \quad 4.13
\]

Or \[ \text{Ra}_{eq} = A_{Ra} + (A_{Th} \times 1.43) + (A_{K} \times 0.077) \quad 4.14 \]

Where; $A_{Ra}$, $A_{Th}$ and $A_{K}$ are the activity concentrations of $^{222}$Ra, $^{232}$Th and $^{40}$K respectively in Bq kg$^{-1}$. For safe use, the recommended value of radium equivalent in building materials and products must be less than 370 Bq Kg$^{-1}$.

### 4.8 Hazard indices

Three indices were calculated in this work to assess the gamma ray radiation hazards due to specified radionuclides $^{226}$Ra, $^{232}$Th and $^{40}$K;

#### 4.8.1 Representative level index

The radiation hazard index of the representative level index ($I_g$) which is used to assess the gamma radiation hazards associated with natural radioactivity in the environment, was calculated using equation 4.15 (NEA-OECD, 1979; Abbady, 2004):

\[
I_g = \left( \frac{A_{Ra}}{150} + \frac{A_{Th}}{100} + \frac{A_{K}}{1500} \right) \quad 4.15
\]

Where $A_{Ra}$, $A_{Th}$ and $A_{K}$ are the activity concentrations of $^{222}$Ra, $^{232}$Th and $^{40}$K respectively in Bq kg$^{-1}$. 

4.8.2 External Hazard Index

In this work, a conservative model based on infinitely thick walls without windows and doors as was proposed by Krieger (1981) was used to serve as a criterion for calculating the external hazard index.

\[
H_{ex} = \left( \frac{A_{Ra}}{370} + \frac{A_{Th}}{259} + \frac{A_{K}}{4810} \right)
\]  

Where \( A_{Ra}, A_{Th} \) and \( A_{K} \) are the activity concentrations of \(^{222}\text{Ra}, ^{232}\text{Th} \) and \(^{40}\text{K} \) respectively in Bqkg\(^{-1}\) in building materials. The value of external hazard index must be less than unity for the radiation associated with natural radioactivity in the building materials to be considered acceptable. This corresponds to \( Ra_{eq} \) of 370 BqKg\(^{-1}\).

4.8.3 Internal Hazard Index

In addition to the external radiation radon, its short-lived products are also hazardous to the respiratory organs. The internal exposure to radon and its daughter products was quantified by the internal hazard index which was calculated using equation 4.17 (Krieger, 1981);

\[
H_{ex} = \left( \frac{A_{Ra}}{185} + \frac{A_{Th}}{259} + \frac{A_{K}}{4810} \right)
\]  

The value of internal hazard index should at least be less than unity for the materials to be considered safe.
4.9 Annual effective dose rate

To estimate the annual effective dose, the conversion factor from the absorbed dose in air to effective dose and the outdoor occupancy were taken into account. UNSCEAR, (2008) report, a value of 0.7 SvGy$^{-1}$ was used to convert the absorbed dose in air to effective dose received by adults. In this research work this coefficient of 0.7 SvGy$^{-1}$ and outdoor occupancy of 0.42 ($\approx$10 hours) was used in equation 4.17 to obtain annual effective dose in mSv$^{-1}$ (Turhanet et al., 2008).

$$H_{AED} = D_{AD}Tf_c$$  \hspace{1cm} 4.18

Where; $H_{AED}$ is the annual effective dose (mSv$^{-1}$); $D_{AD}$ is the absorbed dose rate(nGyh$^{-1}$); $T$ is the outdoor occupancy time (hours); $f_c$ is the conversion factor (SvGy$^{-1}$)

4.10 Dose risk conversion

This was calculated using equation 4.20 (James, 2007; Martin, 2011)

$$G = fHP$$  \hspace{1cm} 4.19

Where; $G$ is the number of estimated casualties (those likely to die out of radiation related complications); $f$ is the dose risk conversion factor and 5% per Sievert was used (ICRP, 1991); $H$ is the annual effective dose and $P$ is the total population of the sampling area and for this work a population of 486,996 of Migori gold belt complex was used.
5 RESULTS AND DISCUSSIONS

5.1 Introduction

In this chapter, results obtained from the rocks and soil samples from the Migori gold belt complex are presented and discussed in details. Quality assurance control was observed throughout the research period. For instance, the spectrometer stability was regularly monitored through daily calibration using $^{137}\text{Cs}$ and $^{60}\text{Co}$ peaks to minimize systematic errors; only one sample was run in the spectrometer per day to avoid over heating the detector so as to obtain higher energy resolution. The results obtained was compared to the recommended acceptable limits to assess whether the rocks and soil samples collected from Migori, Kenya pose any risk to the population within the mining complex of.

5.2 Activity concentration of natural radionuclides

Naturally occurring radionuclides of $^{238}\text{U}$, $^{232}\text{Th}$ and $^{40}\text{K}$ were detected in all the rock and soil samples analyzed. The activity concentration in BqKg$^{-1}$ was computed using the method of comparison (Equation 4.9) as given by UNSCEAR (1988, 2000); Abbady et al. (2005)

5.3 Rock samples

The average activity concentration in the rock samples varied from $1540.12\pm12.56$ Bqkg$^{-1}$ in granite to $583.94\pm20.15$ Bqkg$^{-1}$ in shale for $^{40}\text{K}$, $118.64\pm4.11$ Bqkg$^{-1}$ in granite to $24.47\pm4.21$ Bqkg$^{-1}$ in basalt for $^{238}\text{U}$ and $115.11\pm21.58$ Bqkg$^{-1}$ in quartz to $18.69\pm5.6$ Bqkg$^{-1}$ in talc for $^{232}\text{Th}$. There is variation in mean activity concentration of the natural radionuclides in different rock samples analyzed depending on the type and location
where the rock was collected. The arithmetic mean activity concentration for all the rock samples collected are; $1012.20\pm 22.81 \text{ Bqkg}^{-1}$ for $^{40}\text{K}$; $70.57\pm 18.77 \text{ Bqkg}^{-1}$ for $^{232}\text{Th}$ and $69.19\pm 11.29 \text{ Bqkg}^{-1}$ for $^{238}\text{U}$. It is evident from the above result that potassium contributes to the most specific activity in the area compared to thorium and uranium. This could be due to high content of potash feldspar such as microline and orthoclase or micas like muscovite and biotitesince rocks which are rich in these minerals have high content of potassium (Abdel-Monem et al., 1996). All different rock types analyzed in this work produced activity concentration that exceeded the world average values of $33 \text{ Bqkg}^{-1}$ for $^{238}\text{U}$, $45 \text{ Bqkg}^{-1}$ for $^{232}\text{Th}$ and $420 \text{ Bqkg}^{-1}$ for $^{40}\text{K}$ (UNSCEAR, 2008).

Granite rock which is an igneous rock registered high content of $^{40}\text{K}$ on average ($1440.97\pm 23.94\text{Bqkg}^{-1}$) while talc registered the least ($657.81\pm 21.76 \text{ Bqkg}^{-1}$); highest average $^{232}\text{Th}$ content was registered in granite ($111.98\pm 4.89 \text{ Bqkg}^{-1}$) and the least $^{232}\text{Th}$ content registered in shale ($24.47\pm 4.93 \text{ Bqkg}^{-1}$); average $^{238}\text{U}$ content was high in granite ($102.06\pm 13.62 \text{ Bqkg}^{-1}$) and the least $^{238}\text{U}$ content was recorded in shale ($18.70\pm 4.66 \text{ Bqkg}^{-1}$). The high content of potassium in granites could be due to formation of silicate ($\text{SiO}_2$) during the cooling and solidification of igneous rocks. Potassium which is highly compatible to silicate than thorium and uranium therefore form the main component of these rocks. Generally, granite exhibited an enhanced elemental concentration of $^{40}\text{K}$, $^{238}\text{U}$ and $^{232}\text{Th}$. The geologists explain this behavior to be due to partial melting and fractional crystallization of magma, which enables Uranium and Thorium to be concentrated in the liquid phase and become incorporated into the more silica-rich minerals (Abdel-Monem et al., 1996). Other rocks that registered high content
of potassium are; tuff (1327.54 Bqkg\(^{-1}\)), quartz (943.95 Bqkg\(^{-1}\)), rhyolite (1228.45 Bqkg\(^{-1}\)) and conglomerate (1278.08 Bqkg\(^{-1}\)).

Figure 5.1: The activity concentration of \(^{40}\)K, \(^{238}\)U and \(^{232}\)Th in all the rock samples analyzed.

Table 5.1: The mean activity concentration of all the rocks investigated

<table>
<thead>
<tr>
<th>Rock type</th>
<th>(^{40})K</th>
<th>(^{232})Th</th>
<th>(^{232})U</th>
<th>U/Th</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 QUARTZ</td>
<td>943.32±9.42</td>
<td>70.45±4.97</td>
<td>58.35±14.07</td>
<td>1.21</td>
</tr>
<tr>
<td>2 PHYLITE</td>
<td>1033.79±19.32</td>
<td>45.79±4.89</td>
<td>57.27±13.62</td>
<td>0.80</td>
</tr>
<tr>
<td>3 GRANITE</td>
<td>1440.97±23.94</td>
<td>111.98±13.05</td>
<td>102.06±19.47</td>
<td>1.10</td>
</tr>
<tr>
<td>4 CONGLOMERATE</td>
<td>1278.08±12.33</td>
<td>95.31±3.51</td>
<td>76.79±9.10</td>
<td>1.24</td>
</tr>
<tr>
<td>5 TUFF</td>
<td>1327.54±22.29</td>
<td>78.79±4.72</td>
<td>86.20±6.64</td>
<td>0.76</td>
</tr>
<tr>
<td>6 RHAYOLITE</td>
<td>1228.45±14.07</td>
<td>68.78±3.75</td>
<td>77.92±3.07</td>
<td>0.91</td>
</tr>
<tr>
<td>7 GRAYWACKE</td>
<td>916.22±20.30</td>
<td>64.28±4.51</td>
<td>87.81±8.28</td>
<td>0.88</td>
</tr>
<tr>
<td>8 LATERITE</td>
<td>1025.68±10.20</td>
<td>61.58±3.19</td>
<td>48.83±7.84</td>
<td>0.73</td>
</tr>
<tr>
<td>9 DIORITE</td>
<td>836.60±14.23</td>
<td>58.57±3.77</td>
<td>64.05±12.94</td>
<td>1.26</td>
</tr>
<tr>
<td>10 COVELLITE</td>
<td>841.59±19.74</td>
<td>77.43±4.44</td>
<td>55.26±2.70</td>
<td>0.91</td>
</tr>
<tr>
<td>11 TALC</td>
<td>657.81±21.76</td>
<td>31.14±2.49</td>
<td>39.79±11.00</td>
<td>1.40</td>
</tr>
<tr>
<td>12 BASALT</td>
<td>702.81±20.62</td>
<td>36.34±4.54</td>
<td>37.17±7.73</td>
<td>0.78</td>
</tr>
<tr>
<td>13 SHALE</td>
<td>892.66±6.15</td>
<td>24.47±4.93</td>
<td>18.70±4.66</td>
<td>0.98</td>
</tr>
<tr>
<td><strong>AVERAGE</strong></td>
<td><strong>1012.20±22.81</strong></td>
<td><strong>70.57±18.77</strong></td>
<td><strong>69.19±11.29</strong></td>
<td><strong>0.98</strong></td>
</tr>
</tbody>
</table>
The activity concentration of granite rock type obtained in this work was compared with other published data from other countries (Table 5.2). It is noted that there is no great variation of concentration of the naturally occurring radionuclides between the reported values in other countries and values reported in this work. The conversion of specific activity in BqKg$^{-1}$ to radioelement concentration in parts per million (ppm) was done using the following values; 1 %K in rocks is equivalent to 313 BqKg$^{-1}$; 1 ppm of $^{238}$U in rock is equivalent to 12.35 BqKg$^{-1}$; 1 ppm of $^{232}$Th in rocks is equivalent to 4.06 BqKg$^{-1}$ (Alharbi et al., 2011).
Table 5.2: Mean Activity concentration of $^{238}\text{U}$, $^{40}\text{K}$ and $^{232}\text{Th}$ for granite rocks compared to other published data

<table>
<thead>
<tr>
<th>Place/Country</th>
<th>$^{40}\text{K}$ (%K)</th>
<th>$^{238}\text{U}$ (ppm)</th>
<th>$^{232}\text{Th}$ (ppm)</th>
<th>Author/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Migori gold belt, Kenya</td>
<td>4.56</td>
<td>8.26</td>
<td>27.58</td>
<td>This work</td>
</tr>
<tr>
<td>2 Kerio Valley, Kenya</td>
<td>4.53</td>
<td>8.05</td>
<td>11.72</td>
<td>Agora, 2012</td>
</tr>
<tr>
<td>4 Kingdom of saudi Arabia</td>
<td>3.6</td>
<td>6.2</td>
<td>19.6</td>
<td>Alharbi et al., 2011</td>
</tr>
<tr>
<td>5 Eastern desert, Egypt</td>
<td>3.6</td>
<td>30.5</td>
<td>21.1</td>
<td>Abbady et al., 2006</td>
</tr>
<tr>
<td>6 Granite, south africa</td>
<td>4.15</td>
<td>6.5</td>
<td>21.6</td>
<td>Cermak et al., 1982</td>
</tr>
<tr>
<td>7 Turkey</td>
<td>4.2</td>
<td>24.8</td>
<td>61.0</td>
<td>Orgun, 2005</td>
</tr>
<tr>
<td>8 Brazilian</td>
<td>5.2</td>
<td>2.4</td>
<td>18.0</td>
<td>Anjos, R.M. 2005</td>
</tr>
</tbody>
</table>

Figure 5.3: Mean Activity concentration of $^{40}\text{K}$, $^{238}\text{U}$ and $^{232}\text{Th}$ for granite rocks in this work compared with other published data.
It is worth noting that Shale which is a sedimentary rock registered the least content of thorium (24.4 Bq kg\(^{-1}\)) and uranium (18.7 Bq kg\(^{-1}\)). This may be attributed to high solubility of Uranium in sedimentary rocks. Thorium is usually depleted by depositing water and at the same time not metabolized by microorganisms making it also be low in concentration in sedimentary rocks (Martin, 2011).

The result obtained in this work also indicates that the radiation level is higher in igneous rock types than in sedimentary rocks, which is in line with the earlier reports from different parts of the world (Table 5.3 and Figure 5.4). Sedimentary rocks are normally formed through Lithification process that involves compaction and cementation of sediments. During this process materials like debris of plants and animals fragments find their way into these rocks. These materials are known to contain less radioactive content than the fragments of the weathered igneous rocks that form sedimentary rocks; therefore overall radioactivity is usually lower in sedimentary rocks (Yu et al., 1992).

Generally, Weathering and metamorphism can modify the radioelement content of rocks profoundly. Uranium is easily oxidized to a water-soluble form; and can be readily leached and become deposited in sediments at large distances from the source rock. Thorium has no soluble ion and therefore tends to remain with the parent rock or is transported over relatively short distances in the form of solid mineral grains. Common thorium-bearing minerals such as zircon and monazite are heavy and thus accumulate in placers and in the heavy mineral fraction of clastic sediments. Weathering, therefore, produces significant effects upon the distribution of radioelements (Yu et al., 1992).
Table 5.3: The mean activity concentration of the three classes of rocks investigated in this work

<table>
<thead>
<tr>
<th>S.N</th>
<th>Type</th>
<th>Activity concentrations (BqKg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$^{232}$Th</td>
</tr>
<tr>
<td>1</td>
<td>IGNEOUS ROCKS</td>
<td>75.13</td>
</tr>
<tr>
<td>2</td>
<td>SEDIMENTARY ROCKS</td>
<td>60.97</td>
</tr>
<tr>
<td>3</td>
<td>METAMORPHIC ROCKS</td>
<td>49.13</td>
</tr>
</tbody>
</table>

Figure 5.4: Comparison of the activity concentration of $^{40}$K, $^{238}$U and $^{232}$Th in different classes of rocks.

5.3.1 Uranium to Thorium ratio

To assess the elemental abundances of these natural radionuclides in the area, the uranium to thorium ratio was computed and an average value of 0.98±0.60 was found (Table 5.1). This makes it possible to determine the enrichment or depletion process as a result of the complex metamorphic history, alteration and or weathering that affected the investigated rocks (Chiozzi et al., 2002). For instance the $\frac{U}{Th}$ ratio has particular value in exploration for uranium deposits because it has been found to increase locally within
regions containing uranium (Wollenberg et al., 1990). The profiles that include this ratio have been useful for picking specific target anomalies for ground follow-up. In this research work the ratio of U/Th did not show any anomalies hence we may conclude that the Migori gold belt complex does not have ores worth exploring for the uranium or thorium minerals (Figure 5.5 and Table 5.1). It is also worth noting that some rocks have inherently low Thorium content compared to Uranium and are not associated with mineralization process (Wollenberg et al., 1994). The difference in uranium and thorium content in rocks can also be attributed to high solubility of $U^{+6}$ in sedimentary rocks whereas thorium ions are less soluble. The uranium to thorium ratio decreases in weathered rock and it leads to dispersion halos, particularly in the case of uranium, that extend over a much greater area than does the parent formation.

![U/Th Ratio](image)

**Figure 5.5:** Histogram showing the U/Th ratio for the different rocks analyzed.
Table 5.4: A table showing average activity concentration from the sampled rocks

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Mean</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}$K</td>
<td>1012.20±22.81</td>
<td>657.81± 21.76 – 1440.97±23.94</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>69.19±11.29</td>
<td>18.70±4.46 – 102.06±19.47</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>70.57±18.77</td>
<td>24.47±4.93 – 111.98±13.05</td>
</tr>
</tbody>
</table>

It is noted that there is no great variation of concentration of the naturally occurring radionuclides between the reported values in other countries and values reported in this work. However, the activity concentration for all the NORM analyzed in this work and other published data recorded higher values than the world average for background radiation of 33 BqKg$^{-1}$ for $^{238}$U; 45 BqKg$^{-1}$ for $^{232}$Th; 420 BqKg$^{-1}$ for $^{40}$K (UNSCEAR, 2008).

Table 5.5: Average activity concentrations of radionuclides in rocks from Migori Gold belt complex compared to values from other parts of Kenya and the world

<table>
<thead>
<tr>
<th>Place/ Country</th>
<th>Activity concentration (BqKg$^{-1}$)</th>
<th>Author/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$^{40}$K</td>
<td>$^{232}$Th</td>
</tr>
<tr>
<td>Migori gold belt, Kenya</td>
<td>1012.2±22.81 (657± 22 – 1440 ±24)</td>
<td>70.6±18.8 (18±5 – 111±13)</td>
</tr>
<tr>
<td>Kibwezi, Kenya</td>
<td>1229.5±189.4</td>
<td>139.7±26.1</td>
</tr>
<tr>
<td>Kerio Valley, Kenya</td>
<td>1004.4±9.9</td>
<td>64.9±3.1</td>
</tr>
<tr>
<td>Egypt</td>
<td>202.0-1213</td>
<td>3.9-51.3</td>
</tr>
<tr>
<td>Nigeria</td>
<td>487.0</td>
<td>63.4</td>
</tr>
<tr>
<td>Turkey</td>
<td>1018.3</td>
<td>43.7</td>
</tr>
<tr>
<td>Yemen</td>
<td>1424.9</td>
<td>90.1</td>
</tr>
</tbody>
</table>
5.4 Soil samples

The mean activity concentration for soil samples were also computed in BqKg\(^{-1}\) using the method of comparison (Equation 4.9). The results obtained are displayed in Table 5.6.

**Table 5.6: A table showing mean activity concentration of soil samples investigated**

| Sampled areas | \(^{40}\)K \(|\pm|\) | \(^{238}\)U \(|\pm|\) | \(^{232}\)Th \(|\pm|\) | U/Th |
|---------------|-----------------|-----------------|-----------------|-----|
| MACALDER      | 981.01±18.38    | 80.77±6.08      | 99.43±5.63      | 0.81|
| KITERE        | 377.73±16.60    | 35.09±5.05      | 37.07±5.39      | 0.94|
| MASARA        | 875.83±17.52    | 85.11±4.78      | 81.75±7.29      | 1.04|
| KAMWANGO      | 396.43±16.23    | 26.68±3.16      | 29.36±4.09      | 0.91|
| OSIRI         | 919.21±15.22    | 97.30±4.21      | 75.36±3.67      | 1.29|
| NYAMOME       | 233.46±21.06    | 19.50±3.18      | 17.68±2.36      | 1.10|
| MIGORI        | 567.78±19.63    | 75.51±6.19      | 52.52±5.23      | 1.44|
| MICKEY        | 896.77±10.21    | 62.19±5.69      | 50.66±4.12      | 1.22|
| NYATWORO      | 321.75±18.65    | 45.83±5.55      | 34.58±3.25      | 1.32|

The activity concentration from the NORM form the soil samples varied as follows:

Maximum activity concentration for the \(^{40}\)K \(^{238}\)U and \(^{232}\)Th were recorded in Macalder (981.01±18.38BqKg\(^{-1}\)), Osiri (97.30±4.21BqKg\(^{-1}\)) and Macalder (99.43±5.63BqKg\(^{-1}\)) respectively while minimum values were all recorded in Nyamome with (233.46±21.06BqKg\(^{-1}\)) for \(^{40}\)K, (19.50±3.18BqKg\(^{-1}\)) for \(^{238}\)U and (17.68±2.36 BqKg\(^{-1}\)) for \(^{232}\)Th. Figure 5.6 show the graphical representation of activity concentration in the soil samples investigated.
From figure 5.6, it can be seen that there is elevated level of natural radioactivity in Macalder, Masara, Osiri and Mikey. This can be attributed to the following; the regions are not far from each other they therefore share almost the same type of soil; there is a lot of gold mining activities going on currently with several holes dug up and fresh rocks exposed to the surface which undergo weathering process on these sites hence may elevate the natural radioactivity levels; Macalder and Osiri are located almost at the meeting point of the two major rivers in the area (river Migori and river Kuja and other small tributaries). These rivers may act as agents of immobilization of radionuclides from
other regions which then get deposited in these areas hence increasing the level of concentration of $^{238}\text{U}$, $^{40}\text{K}$ and $^{232}\text{Th}$.

Kitere, Nyamome and Kamwango registered the least activity concentration. This could be due to the fact that there are very little mining activities taking place in these areas implying that few fresh radioactive rocks are exposed to the surface. However, Kitere and Kamwango registered relatively high values than Nyamome this can be attributed to high agricultural activities. For instance the use of artificial fertilizers in sugarcane plantations in Kitere and Kamwango could probably elevate the activity level of NORN in the area.

The average activity concentrations for all the soil samples analyzed were computed (Table 5.7). The values were found to be above the world averages of $33\ Bqkg^{-1}$ for $^{238}\text{U}$, $45\ Bqkg^{-1}$ for $^{232}\text{Th}$ and $420\ Bqkg^{-1}$ for $^{40}\text{K}$ (UNSCEAR, 2008) which could be an indicator of high background radiation area (HBRA).

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Activity Concentration BqKg$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}\text{K}$</td>
<td>Mean: $618.89\pm16.17$</td>
</tr>
<tr>
<td>$^{232}\text{Th}$</td>
<td>Mean: $57.55\pm5.58$</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>Mean: $52.04\pm5.12$</td>
</tr>
</tbody>
</table>

5.5 Activity concentration in Rocks compared to those in soil

In this research work, it was noted that the rocks contain higher radioactivity concentrations than soil. This could be due to the mixing of the debris from weathered
parent rocks that form soil with organic and other materials (Yu et al., 1992). Table 5.8 and figure 5.7 show the comparison of activity between rocks and soil.

**Table 5.8: Comparison of activity concentrations in rocks to those in soil**

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Activity concentration ( BqKg$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$^{40}$K</td>
</tr>
<tr>
<td>1 ROCKS</td>
<td>1012.20±22.8</td>
</tr>
<tr>
<td>2 SOIL</td>
<td>618.89±16.17</td>
</tr>
<tr>
<td>3 World Average</td>
<td>420.00</td>
</tr>
</tbody>
</table>

**Figure 5.7: Pie charts showing the percentage distribution of radionuclides in rocks and soil samples investigated.**

The difference in Uranium to Thorium content in rocks (Tables 5.1) may be attributed to high solubility of Uranium in sedimentary rocks whereas Thorium ions are less soluble (Martin, 2011). There is also a difference in uranium to thorium content in soil (Table 5.6). This can be attributed to more radon from the soil escaping to the atmosphere. About 10% on average value of radon is escaping to the atmosphere from soil with the annual amount of radon escaping from the total land area of $1.5 \times 10^8$ Km$^2$ is estimated to be $7.57 \times 10^{16}$Ci (NCRP, 1984). There is also a lower concentration of $^{40}$K in soils than in rocks this may be due to its high solubility. From the results above its evident that
$^{40}$K contributes to the most specific activity concentration in the area compared to $^{238}$U and $^{232}$Th.

5.5 Correlation studies on soil and Rock

In order to determine the existence of these radioactive nuclides together at a particular place, correlation studies were performed between combinations of radionuclides $^{238}$U, $^{232}$Th and $^{40}$K. A good positive but non-linear correlation was observed between individual activity concentrations of radionuclides, which fairly indicate that individual results for any one of the radionuclides, is a good predictor of the concentration of the other. Figure 5.8 and figure 5.9 shows regression plot showing the correlation between $^{238}$U and $^{232}$Th concentrations for both soil and rocks.

![Regression plot showing correlation between $^{238}$U and $^{232}$Th concentrations in rock samples](image)

**Figure 5.8**: Regression plot showing correlation between $^{238}$U and $^{232}$Th concentrations in rock samples.
Figure 5.9: Regression plot showing correlation between $^{238}\text{U}$ and $^{232}\text{Th}$ concentrations in soil samples.

5.6 Radiological hazard Indices

The Radiological hazard Indices were calculated using the standard values recommended by United Nation scientific Committee on Effect of Atomic Radiation (UNSCEAR, 2008).

5.6.1 Absorbed Dose and Annual Effective Dose Rate

The activity concentrations of the radionuclides calculated (Table 5.1 and Table 5.6) were used to calculate the absorbed dose rate using equation 4.10. Column 4 of (Table 5.9) gives the results for absorbed dose rate (nGy h$^{-1}$) in air for the rock samples collected within the Migori gold belt complex of western Kenya. Column 4 of table (5.10) also gives the results for absorbed dose rate in air for the soil samples from the same region. It was noted that granite, tuff, conglomerate, rhyolite greywacke and quartz recorded the highest values of 174.77 nGy h$^{-1}$, 144.90 nGy h$^{-1}$, 144.63 nGy h$^{-1}$, 131.02 nGy h$^{-1}$, 122.16 nGy h$^{-1}$ respectively with granite giving the highest absorbed dose rate of 174.77 nGy h$^{-1}$. The least values were recorded in rock like; basalt, talc and shale with 68.97 nGy h$^{-1}$, 66.33 nGy h$^{-1}$, 60.79 nGy h$^{-1}$ respectively. These values were higher than the world
background average of 60nGyh\(^{-1}\) (UNSCEAR, 2000; Isinkaye, 2008). Figure 5.9 displays the average dose rate and annual effective dose compared to the world averages.

Table 5.9: Absorbed dose and annual effective dose rates for rock samples

<table>
<thead>
<tr>
<th>Rock type</th>
<th>No. of samples</th>
<th>Absorbed Dose rate (nGyh(^{-1}))</th>
<th>Ann. Eff. Dose Rate (mSvy(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>QUATZ</td>
<td>3</td>
<td>107.84±4.79</td>
<td>0.28±0.01</td>
</tr>
<tr>
<td>PHYLITE</td>
<td>3</td>
<td>99.52±4.01</td>
<td>0.26±0.02</td>
</tr>
<tr>
<td>GRANITE</td>
<td>4</td>
<td>174.77±7.69</td>
<td>0.45±0.05</td>
</tr>
<tr>
<td>CONGLOMENATE</td>
<td>3</td>
<td>144.63±7.66</td>
<td>0.37±0.03</td>
</tr>
<tr>
<td>SHALE</td>
<td>3</td>
<td>60.79±7.40</td>
<td>0.16±0.01</td>
</tr>
<tr>
<td>TUFF</td>
<td>3</td>
<td>144.90±5.41</td>
<td>0.37±0.03</td>
</tr>
<tr>
<td>RHAYOLITE</td>
<td>3</td>
<td>131.02±3.93</td>
<td>0.34±0.04</td>
</tr>
<tr>
<td>GRAYWACKE</td>
<td>3</td>
<td>122.16±2.56</td>
<td>0.31±0.05</td>
</tr>
<tr>
<td>LATERITE</td>
<td>3</td>
<td>101.24±3.79</td>
<td>0.26±0.02</td>
</tr>
<tr>
<td>DIORITE</td>
<td>3</td>
<td>101.47±3.76</td>
<td>0.26±0.02</td>
</tr>
<tr>
<td>COVELITE</td>
<td>3</td>
<td>104.93±3.27</td>
<td>0.27±0.02</td>
</tr>
<tr>
<td>TALC</td>
<td>2</td>
<td>66.33±7.02</td>
<td>0.17±0.04</td>
</tr>
<tr>
<td>BASALT</td>
<td>3</td>
<td>68.97±6.83</td>
<td>0.18±0.02</td>
</tr>
<tr>
<td>AVERAGE</td>
<td></td>
<td>115.62±6.34</td>
<td>0.30±0.01</td>
</tr>
</tbody>
</table>

Figure 5.10: Dose Rate and Radium Equivalent compared with the world Averages
For the case of soil samples, the highest absorbed dose rate was recorded at Macalder, Osiri and Masara with 139.68nGy\textsuperscript{-1}, 126.35nGy\textsuperscript{-1} and 129.80 nGy\textsuperscript{-1} respectively, with the lowest being registered in Nyamome, Kitere and Kamwango; 18.83nGy\textsuperscript{-1}, 54.87nGy\textsuperscript{-1} and 46.97nGy\textsuperscript{-1} respectively.

**Table 5.10: Absorbed dose and annual effective dose rates for soil samples**

<table>
<thead>
<tr>
<th>Area of Study</th>
<th>No. of samples</th>
<th>Absorbed Dose Rate (nGy\textsuperscript{-1})</th>
<th>Ann. Eff. Dose Rate (mSv\textsuperscript{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MACALDER</td>
<td>3</td>
<td>139.68±4.91</td>
<td>0.36±0.06</td>
</tr>
<tr>
<td>2 KITERE</td>
<td>3</td>
<td>54.87±7.79</td>
<td>0.14±0.04</td>
</tr>
<tr>
<td>3 MASARA</td>
<td>3</td>
<td>126.35±3.28</td>
<td>0.33±0.06</td>
</tr>
<tr>
<td>4 KAMWANGO</td>
<td>3</td>
<td>46.97±8.29</td>
<td>0.12±0.03</td>
</tr>
<tr>
<td>5 OSIRI</td>
<td>3</td>
<td>129.80±3.77</td>
<td>0.33±0.06</td>
</tr>
<tr>
<td>6 NYAMOME</td>
<td>3</td>
<td>18.83±9.84</td>
<td>0.05±0.02</td>
</tr>
<tr>
<td>7 MIGORI</td>
<td>3</td>
<td>91.00±4.96</td>
<td>0.23±0.05</td>
</tr>
<tr>
<td>8 MICKEY</td>
<td>3</td>
<td>97.31±4.28</td>
<td>0.25±0.05</td>
</tr>
<tr>
<td>9 NYATWORO</td>
<td>3</td>
<td>55.96±7.72</td>
<td>0.14±0.04</td>
</tr>
<tr>
<td><strong>AVERAGE</strong></td>
<td></td>
<td><strong>84.53±5.58</strong></td>
<td><strong>0.22±0.05</strong></td>
</tr>
</tbody>
</table>

To estimate the annual effective dose, the conversion coefficient from absorbed dose in air to effective dose of $0.7\text{SvGy}^{-1}$ (UNSCEAR, 2000) and the occupancy factor of 0.42 ($\approx 10$ hours) were used considering the fact that the miners spend more time in the mines. It is also worth noting that the occupancy factor normally varies with age and climate of the area. Columns 4 of table 5.9 and column 4 of table 5.10 give the annual effective dose for the rocks and soil respectively. In this work an average annual effective dose of 0.30mSv\textsuperscript{-1} and 0.22mSv\textsuperscript{-1} for the rocks and soil respectively. These values are below the world wide average of 0.48 mSv\textsuperscript{-1} (UNSCEAR, 2000) for both the rocks and soil samples. It is worth noting that granite rock recorded relatively high value of 0.45mSv\textsuperscript{-1} however, this value is still below the world average of 0.48 mSv\textsuperscript{-1}. 
Figure 5.11: The range of annual effective dose in both the soil and rocks from the gold belt complex.

5.6.2 Radium Equivalent and Radiation Hazard Index

The gamma-ray radiation hazards due to the specified radionuclides Ra, Th and K were assessed by two indices; radium equivalent given by equations (4.12); external hazard index was calculated using equation (4.15); internal hazard index using equation (4.16) and representative level hazard index was calculated using equation (4.14). The results are tabulated in table 5.11 for rock samples and table 5.12 for soil samples. The histograms showing the distribution of $H_{ex}$, $H_{in}$, $I_g$ from different rocks and soil samples collected within the Migori gold belt complex are also plotted in figure 5.12 for rocks and figure 5.13 for soil.
Table 5.11: A table showing radium equivalent and hazard indices for rock samples

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Radium equivalent (Ra(_{eq})) (BqKg(^{-1}))</th>
<th>Representative level index(I(_g))</th>
<th>External Hazard index (H(_{ex}))</th>
<th>Internal Hazard index (H(_{in}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>QUATZ</td>
<td>226.53±4.08</td>
<td>1.68±0.01</td>
<td>0.61±0.0</td>
<td>0.80±0.0</td>
</tr>
<tr>
<td>PHYLITE</td>
<td>207.29±5.29</td>
<td>1.57±0.02</td>
<td>0.56±0.0</td>
<td>0.68±0.0</td>
</tr>
<tr>
<td>GRANITE</td>
<td>368.87±13.25</td>
<td>2.73±0.01</td>
<td>0.97±0.0</td>
<td>1.20±0.0</td>
</tr>
<tr>
<td>CONGLOMERATE</td>
<td>303.54±7.53</td>
<td>2.26±0.03</td>
<td>0.82±0.0</td>
<td>1.08±0.0</td>
</tr>
<tr>
<td>SHALE</td>
<td>122.43±15.64</td>
<td>0.96±0.00</td>
<td>0.33±0.0</td>
<td>0.38±0.0</td>
</tr>
<tr>
<td>TUFF</td>
<td>304.29±6.95</td>
<td>2.27±0.01</td>
<td>0.82±0.0</td>
<td>1.03±0.0</td>
</tr>
<tr>
<td>RHAYOLITE</td>
<td>274.79±8.44</td>
<td>2.06±0.01</td>
<td>0.74±0.0</td>
<td>0.93±0.0</td>
</tr>
<tr>
<td>GRAYWACKE</td>
<td>260.39±10.18</td>
<td>1.92±0.00</td>
<td>0.70±0.0</td>
<td>0.88±0.0</td>
</tr>
<tr>
<td>LATERITE</td>
<td>210.39±13.69</td>
<td>1.58±0.00</td>
<td>0.57±0.0</td>
<td>0.73±0.0</td>
</tr>
<tr>
<td>DIORITE</td>
<td>214.59±7.73</td>
<td>1.59±0.01</td>
<td>0.58±0.0</td>
<td>0.74±0.0</td>
</tr>
<tr>
<td>COVELITE</td>
<td>221.26±6.24</td>
<td>1.63±0.02</td>
<td>0.60±0.0</td>
<td>0.81±0.0</td>
</tr>
<tr>
<td>TALC</td>
<td>138.69±6.01</td>
<td>1.04±0.01</td>
<td>0.37±0.0</td>
<td>0.46±0.0</td>
</tr>
<tr>
<td>BASALT</td>
<td>143.61±7.52</td>
<td>1.08±0.00</td>
<td>0.39±0.0</td>
<td>0.49±0.0</td>
</tr>
<tr>
<td><strong>AVERAGE</strong></td>
<td><strong>243.17±4.21</strong></td>
<td><strong>1.81±0.01</strong></td>
<td><strong>0.66±0.0</strong></td>
<td><strong>0.85±0.0</strong></td>
</tr>
</tbody>
</table>

Figure 5.12: Distribution of H\(_{ex}\); H\(_{in}\); I\(_g\) from different rocks collected within the Migori gold belt complex.
Table 5.12: A table showing radium equivalent and hazard indices for soil samples

<table>
<thead>
<tr>
<th>Area of study</th>
<th>Radium equivalent ((Ra_{eq})) ((\text{BqKg}^{-1}))</th>
<th>Representative level index ((I_g))</th>
<th>External Hazard index ((H_{ex}))</th>
<th>Internal Hazard index ((H_{in}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MACALDER</td>
<td>298.50±17.28</td>
<td>2.19±0.0</td>
<td>0.81±0.0</td>
<td>1.02±0.0</td>
</tr>
<tr>
<td>2 KITERE</td>
<td>117.19±10.83</td>
<td>0.86±0.0</td>
<td>0.32±0.0</td>
<td>0.41±0.0</td>
</tr>
<tr>
<td>3 MASARA</td>
<td>269.45±16.41</td>
<td>1.97±0.0</td>
<td>0.73±0.0</td>
<td>0.96±0.0</td>
</tr>
<tr>
<td>4 KAMWANGO</td>
<td>99.19±9.96</td>
<td>0.74±0.0</td>
<td>0.27±0.0</td>
<td>0.34±0.0</td>
</tr>
<tr>
<td>5 OSIRI</td>
<td>275.84±16.61</td>
<td>2.02±0.0</td>
<td>0.75±0.0</td>
<td>1.01±0.0</td>
</tr>
<tr>
<td>6 NYAMOME</td>
<td>38.46±6.20</td>
<td>0.30±0.0</td>
<td>0.10±0.0</td>
<td>0.13±0.0</td>
</tr>
<tr>
<td>7 MIGORI</td>
<td>194.32±13.94</td>
<td>1.41±0.0</td>
<td>0.52±0.0</td>
<td>0.73±0.0</td>
</tr>
<tr>
<td>8 MICKEY</td>
<td>203.68±14.27</td>
<td>1.52±0.0</td>
<td>0.55±0.0</td>
<td>0.72±0.0</td>
</tr>
<tr>
<td>9 NYATWORO</td>
<td>120.05±10.96</td>
<td>0.87±0.0</td>
<td>0.32±0.0</td>
<td>0.45±0.0</td>
</tr>
<tr>
<td>AVERAGE</td>
<td>179.63±13.40</td>
<td>1.32±0.0</td>
<td>0.49±0.0</td>
<td>0.64±0.0</td>
</tr>
</tbody>
</table>

Figure 5.13: Distribution of \(H_{ex}\); \(H_{in}\); \(I_g\); from different soil samples collected within the Migori gold belt complex.
The results presented in table (5.11 and 5.12) indicate that the rocks and soil from the Migori gold belt complex can be used in building without exceeding the proposed radioactivity criterion levels. For instance the values of radium equivalent for rocks ranged from 122.43 Bq Kg$^{-1}$ for shale to 368.87 Bq Kg$^{-1}$ for granite and for soil samples it ranged from 38.46 Bq Kg$^{-1}$ for Nyamome and 298.50 Bq Kg$^{-1}$ for Macalder, with rocks giving an average value of 243.17 Bq Kg$^{-1}$ and soil giving an average of 179.63 Bq Kg$^{-1}$. All these values were below the recommended maximum value of 370 Bq Kg$^{-1}$ suggested for building materials.

However, granite (368.87 Bq Kg$^{-1}$) recorded radium equivalent value close to the maximum acceptable limits and may be hazardous especially if occupancy time is greater than the one used in this work. This was also confirmed by the calculation or representative level index, according to European Commission (1999), values of index $I_g \leq 2$ corresponds to a annual effective dose rate criterion of 0.3 mSv y$^{-1}$, whereas $2 \leq I_g \leq 6$ corresponds to a criterion of 1 mSv y$^{-1}$. Thus, areas with $I_g > 6$ has annual effective dose rates higher than 1 mSv y$^{-1}$ which is higher than the recommended level hence pose danger to the surrounding population. In this work the representative level index obtained ranges from 0.96 in shale to 2.73 in granite rock with an average value of 1.88 for rocks while for soil it ranges from 0.30 in Nyamome to 2.19 in Macalder with an average value of 1.32. Therefore from the results obtained, it can be clearly seen that all the values were less than the maximum recommended values hence do not pose any great danger to the population leaving within the Migori gold belt complex. However, it is worth noting that according to the ICRP-60 (1990), it is recommended
that any exposure above the natural background radiation should be kept as low as reasonably achievable (ALARA). The dose limits have been established on the prudent approach by assuming that there is no threshold dose below which there would be no effect ICRP-60 (1990), this means that any additional dose will cause a proportional increase in the chance of a health effect.

### 5.6.3 Dose Risk

The average annual effective dose rate due to both the rocks and soil samples were used to estimate the adverse health effect from the exposure due to gamma ray radiations from the naturally occurring radionuclides in terms of fatal cancers occurring per Sievert (Sv) from the Migori gold belt complex. In this work, it was assumed that one Sievert carries with it 5% chance of eventually developing cancer i.e. a DRCF of 5% per Sievert (ICRP, 1991). Table 5.13 displays the results obtained in this work using equation 4.18 of chapter 4, and a population density of 486,996 residents of Migori gold belt complex (Muhuru, Awendo, Nyatike, Migori and Uriri divisions) (Kenya census report 2009).

**Table 5.13: A table showing a dose risk from both the rocks and soil**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Average Effective Dose Rate (Sv y⁻¹)</th>
<th>Annual. Dose Rate</th>
<th>Dose Risk Conversion Factor (DRCF) (5 % Sv⁻¹)</th>
<th>Dose Risk per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rocks</td>
<td>0.00030</td>
<td>0.05</td>
<td>7.304</td>
<td></td>
</tr>
<tr>
<td>Soil</td>
<td>0.00022</td>
<td>0.05</td>
<td>5.357</td>
<td></td>
</tr>
</tbody>
</table>
From table 5.13 it can be predicted that the number of gamma-ray radiation exposure induced deaths per year to the population living in the area is between 7 and 8 persons and between 5 to 6 persons due to radiation from rocks and soil respectively.

![Figure 5.14: Predicted Dose risk per year from Migori gold belt complex.](image)

However, the value of DRCF varies with age, sex and sensitivity to radiation induced cancer of the individuals exposed to the radiation. (Wollenberger et al., 1990; UNSCEAR, 2000), also reported that the effective dose due to ionizing radiation for members of the public varies substantially depending on where they live, occupation, personal habits, diet, building type and house utilization pattern. Therefore the number of radiation induced deaths in the area could be greatly affected by these factors over the years hence constant monitoring of radiation levels in the area is recommended.
6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

The results of activity concentration obtained from the rocks and soil samples using NaI (TI) spectrometry were used to do natural radiometric survey of the Migori gold belt complex. The results obtained were compared with the recommended acceptable limits to assess whether the rock sample pose any risk to the population within the mining complex of Migori, Kenya.

The results of $^{238}\text{U}, \quad ^{232}\text{Th}$ and $^{40}\text{K}$ showed that the concentration values of specific activities of the rock and soil samples collected from the Migori gold belt complex, were estimated to be relatively within the acceptable limits but above the world average background with arithmetic mean of $1012.20\pm 22.8$ BqKg$^{-1}$ for $^{40}\text{K}; \quad 70.57\pm 18.8$ BqKg$^{-1}$ for $^{232}\text{Th}; \quad 66.19\pm 11.3$ BqKg$^{-1}$ for $^{238}\text{U}$ in rock samples and $618.89\pm 16.17$ BqKg$^{-1}$ for $^{40}\text{K}; \quad 57.55\pm 5.58$ BqKg$^{-1}$ for $^{232}\text{Th} \quad 52.04\pm 5.12$ BqKg$^{-1}$ for $^{238}\text{U}$; in soil samples.

The radium equivalent average value was found to be $234.17\pm 4.21$ BqKg$^{-1}$ in rocks and an average of $197.63\pm 13.40$ BqKg$^{-1}$ in soil. The average values of radium equivalent was below the recommended maximum values of $370$ BqKg$^{-1}$ except for granite samples that recorded value which are close to this limit ($368.87$ BqKg$^{-1}$). Therefore materials from the Migori gold belt complex could be used as building materials without exceeding the proposed radioactivity criterion level.
The total absorbed dose had arithmetic mean of $115.62 \pm 6.34 \text{ nGyh}^{-1}$ in rock samples and $84.53 \pm 5.58 \text{ nGyh}^{-1}$ in the soil samples. The average values of the gamma-ray absorbed dose rate in air obtained from both the rock samples and soil samples are comparable to the world range of $(28-120) \text{ nGyh}^{-1}$ (UNSCEAR, 2000). These values were found to be below the range observed by other researchers in regions of high natural background (Mohanty et al., 2004; Termizi et al., 2005; Kebwaro, 2009). 

The external hazard index and internal hazard index for all rock samples recorded values of 0.85 and 0.66 respectively. These were less than unity which is within the recommended value.

The annual effective dose rate obtained had an arithmetic mean of $0.30 \text{ mSvy}^{-1}$ in rocks and $0.22 \text{ mSvy}^{-1}$ in soil. These values were below the world average of $0.48 \text{ mSvy}^{-1}$. The values were also below the individual dose limit which for members of the public should not be above $1 \text{ mSvy}^{-1}$ ICRP-60 (1990). However, the ICRP-60 (1990) report, recommends that any exposure above the natural background radiation should be kept as low as reasonably achievable (ALARA).

With a population density of 486,996 residents of the gold belt complex and using a DRCF of 5% per Sievert (ICRP, 1991), about 5 persons and around 8 persons are likely to die per year due to radiation exposure from rocks and soil respectively. Nevertheless, the health burden due to natural background radiation from rocks on the inhabitants of this
area is not abnormal hence carries insignificant health hazards compared to other areas that have been declared as HBRA like Mrima hills in Kwale (Kebwaro, 2009).

### 6.2 Recommendations

1. Since this research work did not take into consideration the vertical distribution of concentration of radionuclides in the soil profile, another numerical modeling of the activity concentration in the soil is recommended.

2. Determination of natural radioactivity in Water (rivers, ponds and wells), Crops and indoor air especially within the traditional huts within the Migori gold belt complex should also be carried out.

It is my sincere hope that data obtained in this project will go a long way to provide baseline map of radioactivity background level in the mining zones and the surrounding environment and will be used as reference information to assess any future possible changes in the radioactive background level due to mining and geological process. The data will also create risk awareness and provide general public knowledge and also will be used to influence technical and political decision making for sustainable quality environment within the Migori gold belt complex, Kenya.
REFERENCES


Radiation information network (2004). Radioactivity, Idaho State University, U.S.A


APPENDIX I

ROCK SAMPLES THAT WERE COLLECTED FROM MIGORI GOLD BELT
APPENDIX II
Artisan mining at Macalder. Both young and old are involved.
APPENDIX III
The Migori County Map. (Mines and Geology, Kenya)
### APPENDIX IV

Basic information on common primordial, Cosmogenic and Anthropogenic radionuclides

#### Primordial Nuclides

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Symbol</th>
<th>Half-life</th>
<th>Natural Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium 235</td>
<td>$^{235}$U</td>
<td>7.04 x 10^8 yr</td>
<td>0.72% of all natural uranium</td>
</tr>
<tr>
<td>Uranium 238</td>
<td>$^{238}$U</td>
<td>4.47 x 10^9 yr</td>
<td>99.2745% of all natural uranium; 0.5 to 4.7 ppm total uranium in the common rock types</td>
</tr>
<tr>
<td>Thorium 232</td>
<td>$^{232}$Th</td>
<td>1.41 x 10^10 yr</td>
<td>1.6 to 20 ppm in the common rock types with a crustal average of 10.7 ppm</td>
</tr>
<tr>
<td>Radium 226</td>
<td>$^{226}$Ra</td>
<td>1.60 x 10^3 yr</td>
<td>0.42 pCi/g (16 Bq/kg) in limestone and 1.3 pCi/g (48 Bq/kg) in igneous rock</td>
</tr>
<tr>
<td>Radon 222</td>
<td>$^{222}$Rn</td>
<td>3.82 days</td>
<td>Noble Gas; annual average air concentrations range in the US from 0.016 pCi/L (0.6 Bq/m$^3$) to 0.75 pCi/L (28 Bq/m$^3$)</td>
</tr>
<tr>
<td>Potassium 40</td>
<td>$^{40}$K</td>
<td>1.28 x 10^9 yr</td>
<td>soil - 1-30 pCi/g (0.037-1.1 Bq/g)</td>
</tr>
</tbody>
</table>

#### Cosmogenic Nuclides

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Symbol</th>
<th>Half-life</th>
<th>Source</th>
<th>Natural Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon 14</td>
<td>$^{14}$C</td>
<td>5730 yr</td>
<td>Cosmic-ray interactions, $^{14}$N(n,p)$^{14}$C</td>
<td>6 pCi/g (0.22 Bq/g) in organic material</td>
</tr>
<tr>
<td>Hydrogen 3 (Tritium)</td>
<td>$^3$H</td>
<td>12.3 yr</td>
<td>Cosmic-ray interactions with N and O, spallation from cosmic-rays, $^6$Li(n, alpha)$^3$H</td>
<td>0.032 pCi/kg (1.2 x 10^{-3} Bq/kg)</td>
</tr>
<tr>
<td>Beryllium 7</td>
<td>$^7$Be</td>
<td>53.28 days</td>
<td>Cosmic-ray interactions with N and O</td>
<td>0.27 pCi/kg (0.01 Bq/kg)</td>
</tr>
</tbody>
</table>

#### Human Produced Nuclides

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Symbol</th>
<th>Half-life</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tritium</td>
<td>$^3$H</td>
<td>12.3 yr</td>
<td>Produced from weapons testing and fission reactors; reprocessing facilities, nuclear weapons manufacturing</td>
</tr>
<tr>
<td>Iodine 131</td>
<td>$^{131}$I</td>
<td>8.04 days</td>
<td>Fission product produced from weapons testing and fission reactors, used in medical treatment of thyroid problems</td>
</tr>
<tr>
<td>Iodine 129</td>
<td>$^{129}$I</td>
<td>1.57 x 10^7 yr</td>
<td>Fission product produced from weapons testing and fission reactors</td>
</tr>
<tr>
<td>Cesium 137</td>
<td>$^{137}$Cs</td>
<td>30.17 yr</td>
<td>Fission product produced from weapons testing and fission reactors</td>
</tr>
<tr>
<td>Strontium 90</td>
<td>$^{90}$Sr</td>
<td>28.78 yr</td>
<td>Fission product produced from weapons testing and fission reactors</td>
</tr>
<tr>
<td>Technetium</td>
<td>$^{99}$Tc</td>
<td>2.11 x 10^4 yr</td>
<td>Decay product of $^{99}$Mo, used in medical diagnosis</td>
</tr>
</tbody>
</table>
Plutonium 239  $^{239}$Pu  $2.41 \times 10^{6}$yr  Produced by neutron bombardment of $^{238}$U ($^{238}$U + n $\rightarrow ^{239}$U $\rightarrow ^{239}$Np $\rightarrow ^{239}$Pu $\beta$)

### Appendix V

<table>
<thead>
<tr>
<th>no</th>
<th>nuclide</th>
<th>energy</th>
<th>half-life (seconds)</th>
<th>decay mode</th>
<th>decay energy (MeV)</th>
<th>approx ratio half-life to age of universe</th>
</tr>
</thead>
<tbody>
<tr>
<td>255</td>
<td>$^{126}$Te</td>
<td>8.743261</td>
<td>$6.9 \times 10^{21}$</td>
<td>2 $\beta^-$</td>
<td>2.53</td>
<td>160 trillion</td>
</tr>
<tr>
<td>256</td>
<td>$^{136}$Xe</td>
<td>8.706805</td>
<td>$6.66 \times 10^{24}$</td>
<td>2 $\beta^-$</td>
<td>2.462</td>
<td>150 billion</td>
</tr>
<tr>
<td>257</td>
<td>$^{74}$Se</td>
<td>9.034656</td>
<td>$5.62 \times 10^{26}$</td>
<td>2 $\beta^-$</td>
<td>2.039</td>
<td>130 billion</td>
</tr>
<tr>
<td>258</td>
<td>$^{110}$Cd</td>
<td>9.017596</td>
<td>$3.408 \times 10^{27}$</td>
<td>2 $\beta^-$</td>
<td>2.995</td>
<td>8 billion</td>
</tr>
<tr>
<td>259</td>
<td>$^{86}$Zr</td>
<td>8.836146</td>
<td>$9.783 \times 10^{26}$</td>
<td>2 $\beta^-$</td>
<td>2.809</td>
<td>2 billion</td>
</tr>
<tr>
<td>260</td>
<td>$^{48}$Ca</td>
<td>8.992452</td>
<td>$7.258 \times 10^{26}$</td>
<td>2 $\beta^-$</td>
<td>4.274, .0058</td>
<td>2 billion</td>
</tr>
<tr>
<td>261</td>
<td>$^{255}$Te</td>
<td>8.961359</td>
<td>$6.3 \times 10^{26}$</td>
<td>2 $\beta^-$</td>
<td>3.4</td>
<td>1 billion</td>
</tr>
<tr>
<td>262</td>
<td>$^{139}$Bi</td>
<td>8.158689</td>
<td>$5.996 \times 10^{20}$</td>
<td>$\alpha$</td>
<td>3.137</td>
<td>1 billion</td>
</tr>
<tr>
<td>263</td>
<td>$^{138}$Xe</td>
<td>8.766578</td>
<td>$2.777 \times 10^{26}$</td>
<td>2 $\beta^-$</td>
<td>0.868</td>
<td>600 million</td>
</tr>
<tr>
<td>264</td>
<td>$^{130}$Nd</td>
<td>8.562594</td>
<td>$2.493 \times 10^{26}$</td>
<td>2 $\beta^-$</td>
<td>3.367</td>
<td>600 million</td>
</tr>
<tr>
<td>265</td>
<td>$^{129}$Mo</td>
<td>8.933167</td>
<td>$2.461 \times 10^{26}$</td>
<td>2 $\beta^-$</td>
<td>3.035</td>
<td>600 million</td>
</tr>
<tr>
<td>266</td>
<td>$^{137}$Eu</td>
<td>8.565759</td>
<td>$1.578 \times 10^{26}$</td>
<td>$\alpha$</td>
<td>1.9644</td>
<td>300 million</td>
</tr>
<tr>
<td>267</td>
<td>$^{148}$W</td>
<td>8.347127</td>
<td>$5.680 \times 10^{25}$</td>
<td>$\alpha$</td>
<td>2.509</td>
<td>100 million</td>
</tr>
<tr>
<td>268</td>
<td>$^{30}$V</td>
<td>9.055759</td>
<td>$4.418 \times 10^{24}$</td>
<td>$\beta^+ \beta^-$</td>
<td>2.205, 1.038</td>
<td>10 million</td>
</tr>
<tr>
<td>269</td>
<td>$^{114}$Cd</td>
<td>8.859372</td>
<td>$2.430 \times 10^{23}$</td>
<td>$\beta$</td>
<td>0.321</td>
<td>600,000</td>
</tr>
<tr>
<td>270</td>
<td>$^{148}$Sm</td>
<td>8.607423</td>
<td>$2.209 \times 10^{23}$</td>
<td>$\alpha$</td>
<td>1.986</td>
<td>500,000</td>
</tr>
<tr>
<td>271</td>
<td>$^{144}$Nd</td>
<td>8.652947</td>
<td>$7.227 \times 10^{22}$</td>
<td>$\alpha$</td>
<td>1.905</td>
<td>200,000</td>
</tr>
<tr>
<td>272</td>
<td>$^{150}$Os</td>
<td>8.302508</td>
<td>$6.312 \times 10^{22}$</td>
<td>$\alpha$</td>
<td>2.823</td>
<td>100,000</td>
</tr>
<tr>
<td>273</td>
<td>$^{174}$Hf</td>
<td>8.392287</td>
<td>$6.312 \times 10^{22}$</td>
<td>$\alpha$</td>
<td>2.497</td>
<td>100,000</td>
</tr>
<tr>
<td>274</td>
<td>$^{113}$In</td>
<td>8.84991</td>
<td>$1.392 \times 10^{22}$</td>
<td>$\beta^-$</td>
<td>0.499</td>
<td>30,000</td>
</tr>
<tr>
<td>275</td>
<td>$^{139}$Gd</td>
<td>8.562868</td>
<td>$3.408 \times 10^{21}$</td>
<td>$\alpha$</td>
<td>2.203</td>
<td>8000</td>
</tr>
<tr>
<td>276</td>
<td>$^{138}$Ba</td>
<td>8.742574</td>
<td>$2.2 \times 10^{21}$</td>
<td>KK</td>
<td>2.62</td>
<td>5000</td>
</tr>
<tr>
<td>277</td>
<td>$^{197}$Pt</td>
<td>8.267764</td>
<td>$2.051 \times 10^{19}$</td>
<td>$\alpha$</td>
<td>3.252</td>
<td>60</td>
</tr>
<tr>
<td>278</td>
<td>$^{147}$Sm</td>
<td>8.610593</td>
<td>$3.345 \times 10^{18}$</td>
<td>$\alpha$</td>
<td>2.31</td>
<td>8</td>
</tr>
<tr>
<td>279</td>
<td>$^{173}$La</td>
<td>8.69832</td>
<td>$3.219 \times 10^{18}$</td>
<td>K $\beta^-$</td>
<td>1.737, 1.044</td>
<td>7</td>
</tr>
<tr>
<td>280</td>
<td>$^{85}$Rb</td>
<td>9.043718</td>
<td>$1.568 \times 10^{18}$</td>
<td>$\beta^-$</td>
<td>0.283</td>
<td>4</td>
</tr>
<tr>
<td>281</td>
<td>$^{137}$Re</td>
<td>8.291732</td>
<td>$1.300 \times 10^{18}$</td>
<td>$\beta^+ \alpha$</td>
<td>.0026, 1.653</td>
<td>3</td>
</tr>
<tr>
<td>282</td>
<td>$^{177}$Lu</td>
<td>8.374665</td>
<td>$1.187 \times 10^{18}$</td>
<td>$\beta$</td>
<td>1.193</td>
<td>3</td>
</tr>
<tr>
<td>283</td>
<td>$^{222}$Th</td>
<td>7.918533</td>
<td>$4.434 \times 10^{17}$</td>
<td>$\alpha$ SF</td>
<td>4.083</td>
<td>1</td>
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<td>284</td>
<td>$^{235}$U</td>
<td>7.872551</td>
<td>$1.410 \times 10^{17}$</td>
<td>$\alpha$ SF</td>
<td>4.27</td>
<td>0.3</td>
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<tr>
<td>285</td>
<td>$^{40}$K</td>
<td>8.909707</td>
<td>$3.938 \times 10^{16}$</td>
<td>$\beta^+ K \beta^-$</td>
<td>1.311, 1.505, 1.505</td>
<td>0.09</td>
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<tr>
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<td>$^{235}$U</td>
<td>7.897198</td>
<td>$2.222 \times 10^{16}$</td>
<td>α SF</td>
<td>4.679</td>
<td>0.05</td>
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<td>287</td>
<td>$^{169}$Sm</td>
<td>8.626136</td>
<td>$3.250 \times 10^{13}$</td>
<td>α</td>
<td>2.529</td>
<td>0.008</td>
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<tr>
<td>288</td>
<td>$^{244}$Pu</td>
<td>7.826221</td>
<td>$2.525 \times 10^{13}$</td>
<td>α SF</td>
<td>4.666</td>
<td>0.006</td>
</tr>
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APPENDIX VI
Radioactive decay in Thorium and Uranium Series
APPENDIX VII
Sample weighing and air-tight sealing preparation;

Gamma ray spectrum from the NaI (TI) detector displayed on the computer screen in the Kenyatta University Physics Research Laboratory
APPENDIX VIII
Samples dried at 110°C in an oven at Kenyatta University Physics Research Laboratory.

Sun drying of the samples
APPENDIX IX
Macalder tailings;
APPENDIX X
Geology of one of the areas in the Migori Gold belt