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Research note

# Determining the radon exhalation rate from a gold mine tailings dump by measuring the gamma radiation

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ABSTRACT

The mining activities taking place in Gauteng province, South Africa have caused millions of tons of rocks to be taken from underground to be milled and processed to extract gold. The uranium bearing tailings are placed in an estimated 250 dumps covering a total area of about 7000 ha. These tailings dumps contain considerable amounts of radium and have therefore been identified as large sources of radon. The size of these dumps make traditional radon exhalation measurements time consuming and it is difficult to get representative measurements for the whole dump.

In this work radon exhalation measurements from the non-operational Kloof mine dump have been performed by measuring the gamma radiation from the dump fairly accurately over an area of more than 1 km$^2$. Radon exhalation from the mine dump have been inferred from this by laboratory-based and in-situ gamma measurements. Thirty four soil samples were collected at depths of 30 cm and 50 cm. The weighted average activity concentrations in the soil samples were 308 ± 7 Bq kg$^{-1}$, 255 ± 5 Bq kg$^{-1}$ and 18 ± 1 Bq kg$^{-1}$ for $^{238}$U, $^{40}$K and $^{232}$Th, respectively. The MEDUSA (**M**ulti-**E**lement **D**etector for **U**nder-water **S**ediment **A**ctivity) $\gamma$-ray detection system was used for field measurements.

The radium concentrations were then used with soil parameters to obtain the radon flux using different approaches such as the IAEA (International Atomic Energy Agency) formula. Another technique the MEDUSA Laboratory Technique (MELT) was developed to map radon exhalation based on (1) recognising that radon exhalation does not affect $^{40}$K and $^{232}$Th activity concentrations and (2) that the ratio of the activity concentration of the field (MEDUSA) to the laboratory (HPGe) for $^{238}$U and $^{40}$K or $^{238}$U and $^{232}$Th will give a measure of the radon exhalation at a particular location in the dump. The average, normalised radon flux was found to be 0.12 ± 0.02 Bq m$^{-2}$ s$^{-1}$ for the mine dump.



## 1. Introduction

Radon (herein referring to $^{222}$Rn) gas has attracted the attention of various researchers ever since it was understood that radon and its progeny are harmful to human health. The short-lived daughter products of radon, $^{218}$Po, $^{214}$Pb, $^{214}$Bi and $^{214}$Po have such short half-lives that they probably decay through to the longer-lived $^{210}$Pb before the lung can clear them. Due to that, the alpha decays of $^{218}$Po and $^{214}$Po give the epithelial layer of the bronchi a substantial radiation dose; consequently radon and its progeny pose risks to human health (Durrani and Ilic, 1997; BEIR VI, 1999; WHO, 2009).

In the soil, radon gas is released by the decay of radium and afterwards some radon atoms get to the pore spaces. The atoms become available to migrate over large distances within the earth and in the atmosphere through the diffusion process as described by Fick's Law (Crank, 1975) or by advection as described by Darcy's Law. Radon transport equations and numerical models have been developed to explain the underlying processes involved in radon gas transport (Nazaroff et al., 1988; Loureiro, 1990; Owczarski, 1990; Rogers and Nielson, 1991; Kohl, 1994; Van der Spoel, 1997, 1998, 1999; Andersen, 2000, 2001; Schubert, 2002; Antonopoulos-Domis, 2009). In-situ measurements have also been carried out to investigate the processes involved in radon gas transport (Bigu, 1984; Åkerblom and Mellander, 1997; Tsela and Brits, 1998; Lindsay et al. (2004a, 2004b, 2008); Antonopoulos-Domis, 2009).

Radon releases to the atmosphere have been measured from materials such as soil, cement, building materials, granite, uranium tailings and concrete (UNSCEAR, 1982; Ingersoll, 1983; Schery,

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1989; Graustein, 1990; Aldenkamp et al., 1992; Chen, 1993; De Jong, 1996; Escobar, 1999; Arafa, 2004; Kovler, 2005; Mudd, 2008a,b; Lawrence, 2009; Sahoo, 2010).

Some of the techniques that measure radon releases either in the laboratory or in the field include the accumulation can method, the flow-through method, adsorption method, vertical profile method, soil concentration gradient method and the diffusion tube method (Clements, 1974; Fleischer, 1980; NCRP, 1988; Wilkening, 1990; IAEA, 1992, 2013; Durrani and Ilic, 1997; Hosoda et al., 2007). These techniques require direct measurements and for most they turn out to be labour-intensive. In recent years, concerns over the shortcomings of some techniques have been raised since they are prone to a number of uncertainties, like back-diffusion and uncontrollable advection due to pressure differences induced by temperatures or wind. As a result, some of these techniques have been critiqued (Samuelsson and Pettersson, 1984). On a large scale, radon flux maps can be generated using indirect methods (see Table 1) given that the knowledge about parameters related to radon flux has improved.

The main objective of this paper is to investigate an alternative technique for mapping radon exhalation from a gold mine tailings dump by measuring the gamma radiation from the dump fairly accurately over an area of more than 1 $km^2$. The mine tailings dumps are considered to have potentially high radon release rate especially during uranium mining, milling and tailings disposal operations (IAEA, 1992). The technique obviates the need for collecting hundreds of samples or making many individual direct flux measurements.

## 2. Materials and methods

### 2.1. Study area

The mining activities taking place in Gauteng Province, South Africa have caused millions of tons of rocks to be taken from underground to be milled and processed to extract gold. Uranium is extracted by some mines as a by-product of gold. However, most of the mines do not do this as it is often not economically viable. The uranium bearing tailings are placed on large dumps. Even if uranium is extracted, the dumps will still contain radium, the parent of radon, with a half life of 1600 years. The dumps are usually one or more kilometres in diameter in the environment. It is estimated that there are approximately 250 gold mine tailings dumps covering a total area of about 7000 ha (Lindsay et al., 2004a). These gold mine tailings dumps contain considerable amounts of radium ($^{226}Ra$) and have therefore been identified as potentially large sources of radon ($^{222}Rn$).

Considering the above statements, the non-operational Kloof mine dump (see Fig. 1) which belongs to the Carletonville Gold Field was considered to be suitable to apply the alternative technique for mapping radon exhalation rates by measuring the gamma radiation from the mine dump.


**Fig. 1.** (Top) A bird's eye view of Kloof mine dump. (Bottom) Pictures of the vegetation on the mine dump. N indicates north.

Kloof mine dump lies on the north-western edge of the Witwatersrand basin, 35 km west of Johannesburg, South Africa. The Witwatersrand gold repository is estimated to have yielded over 47 000 tonnes of gold between 1886 and 2002 which represents between 33% and 40% of all gold ever produced (GDACE, 2008; Hartnady, 2009).

### 2.2. In-field gamma-ray measurements

#### 2.2.1. Gamma-ray detection

The MEDUSA (**M**ulti **E**lement **D**etector for **U**nderwater **S**ediment **A**ctivity) detector system was used for field measurements. The

**Table 1**
A summary of some of the indirect methods used to generate radon flux maps.

| Method | Region | $^{222}Rn$ flux ($mBq\ m^{-2}\ s^{-1}$) | Reference |
|---|---|---|---|
| Radon transport model (TRACHGEO) | France | 52.0 | Ielsch et al., 2002 |
| Automatic monitoring of Gamma Dose Rate (GDR) | Finland | 27.7 | Szegvary et al., 2007 |
| A radon exhalation rate distribution model | East Asia | 18.0 | Goto et al., 2008 |
| A model for estimating seasonal and annual radon flux densities | China | 29.7 | Zhuo et al., 2008 |
| A model utilising data from national gamma-ray aerial surveys | Australia | 24.1 | Griffiths et al., 2010 |
| Radon flux densities estimation using the Bayesian inversion technique | India | 33.0 | Hirao et al., 2010 |
| Continuous and integrated measurement techniques | Spain | 11.1–25.0 | Grossi et al., 2011 |
| Terrestrial gamma radiation used to calculate radon flux density | Netherlands & Europe | | Manohar et al., 2013 |
| A numerical model used to calculate radon exhalation rate of European soils | Europe | | Lopez-Coto et al., 2013 |