

Radiogenic heat production (RHP) over an area in SE Alberta calculated from radioactive elements ^{238}U , ^{232}Th and ^{40}K detected by airborne gamma-ray spectrometry survey

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Summary

This study is aimed at calculating radiogenic heat production (RHP) generated from radioactive decay of uranium (^{238}U), thorium (^{232}Th) and potassium (^{40}K) isotopes in rocks. Upon their decay, U, Th and K generate a considerable amount of heat within the Earth's crust that could be exploited and utilized to generate a clean source of electric energy. A large portion (~ 50%) of the heat flow measured in the Earth's crust is contributed by radiogenic heat production derived from the decay of radioelements in Earth's crust. To compute the amount of radiogenic heat generated in rocks by radioactive elements decay, we first need to measure U, Th and K concentrations in rocks, and from there we would be able to compute their radiogenic heat production (RHP). We can compute RHP by measuring the U, Th and K concentrations in rock samples using chemical laboratories. Chemical labs yield very accurate results, however, it is relatively expensive. Potassium can be easily analyzed by using X-ray fluorescence at any local chemical lab, and for a reasonable price. However, U and Th need to be analyzed by neutron activation analysis (NAA), and normally it is more expensive and time-consuming because on one hand they need special sample preparation and on the other hand only few labs that have access to nuclear reactors can analyze the samples. An alternative way to estimate U, Th and K is to use gamma-ray spectrometry which is very fast and very cost-effective. Gamma-ray spectrometry measures gamma-radiation (γ) emitted by the decay of uranium (^{238}U), thorium (^{232}Th) and potassium (^{40}K) isotopes in rocks and it yields reasonably accurate results, assuming that the decay series of their isotopes reaches state of secular equilibrium. The ^{238}U , ^{232}Th and ^{40}K isotopes reach a state of equilibrium when the rate of produced daughter's isotopes is equal to the rate of decay of their parent's isotopes.

The radioactive elements, ^{238}U , ^{232}Th and ^{40}K normally emit alpha (α), beta (β), and gamma (γ) radiations. Among these three types of radiations, gamma-ray (γ) is the most powerful, and it has

a better depth of penetration than the ‘ α ’ and the ‘ β ’ radiations. Thus, gamma-rays are more suitable for exploration purposes, especially for airborne gamma-ray spectrometry surveys. Airborne gamma-ray spectrometry has been used for decades to measure the abundances of U, Th and K in the top 30cm of the Earth’s surface. Traditionally, it is mainly used for uranium exploration, but beyond uranium exploration, gamma-ray spectrometry is widely used for mapping geological features, identifying hydrothermal alteration zones related to mineralization, detecting hydrocarbon seepages in sedimentary basins, and to monitor radon gas in the environment. It could also be used indirectly to detect helium gas (^4He) produced from alpha (α) particles. Most of the helium-4 found in nature are formed as a result of natural radioactive decay of uranium and thorium in felsic igneous rocks such as granite, granodiorite and rhyolite.

The main goal of this study is, therefore, to use uranium (eU), thorium (eTh) and potassium (K) data measured by airborne gamma-ray spectrometry survey to compute radiogenic heat production (RHP) over the study area, which is located in southeastern Alberta, within Western Canada Sedimentary Basin (WCSB). The airborne gamma-ray spectrometry survey was flown with Cessna aircraft in 2010 by Fugro Airborne Surveys for the Geological Survey of Canada (GSC). The survey was carried out along a set of E-W oriented flight lines with 5km spacing, and a terrain clearance of 120m above the ground surface was. The gamma-ray system used in the survey consisted of an Exploranium GR-820 system with 256 channels and 50 litres of Sodium Iodide (NaI) detector. The data is sponsored and maintained by the Natural Resources Canada (NRC), and it is publicly available at their website. We used the measured equivalent uranium (eU), equivalent thorium (eTh), and potassium (K) concentrations to compute the radiogenic heat production (RHP) in the study area.

Introduction

Radiogenic heat is the geothermal energy that is produced by the decay of radioactive elements, uranium (^{238}U), thorium (^{232}Th) and potassium (^{40}K), in crustal rocks, and it represents the largest contributor to heat flow in the earth’s crust (Jaupart and Mareschal, 2007), and according to Vacquir (1991) almost half of the terrestrial heat flow measured at the earth’s surface is derived from the decay of uranium, thorium and potassium. Among all of the known rock types in the earth’s crust, felsic igneous rocks (i.e., rocks enriched with SiO_2) such as granite, granodiorite,

and rhyolite are usually contain significant amount of U, Th and K, whereas mafic igneous rocks (i.e., rocks with low SiO₂) such as gabbro and basalt are extremely low in U, Th and K. Accordingly, granitic and rhyolitic igneous rocks are considered as being good radiogenic heat sources.

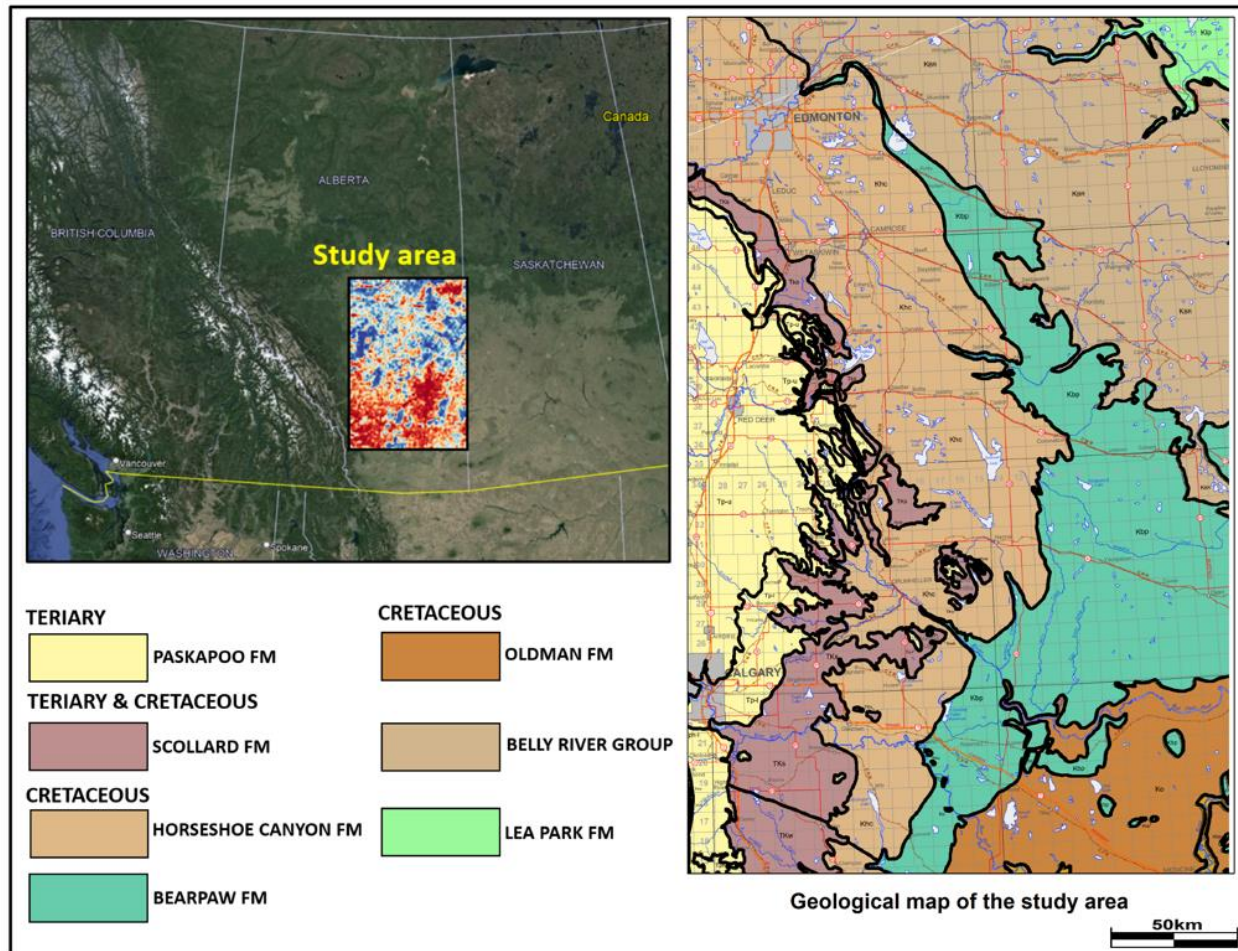


Figure 1. Generalized geology of the study area (After, AGS 1999, Map 236)

This study is aimed at calculating radiogenic heat production (RHP) in an area located in southeastern Alberta (Fig. 1) using equivalent uranium (eU), equivalent thorium (eTh) and potassium (K) concentrations (Figs. 2a, 2b and 2c, respectively) in the rocks of the study area.

Geologically (Fig. 1), the study area is situated within the WCSB, and it underlain by ~1.7km thick clastic sedimentary rocks that are occasionally interbedded with calcareous, coalbed, and ironstone rocks of mainly Tertiary and Cretaceous in age. The Precambrian crystalline basement

rocks underneath the sedimentary rocks is mainly composed of metasedimentary and metavolcanic rocks with significant amount of felsic igneous rocks (i.e., acidic rocks with high SiO₂ contents) such as granite and rhyolite. Generally, granite and rhyolite are considered to be good sources of radiogenic heat because they often contain high concentrations of radioactive elements; uranium, thorium and potassium. Mafic igneous rocks (i.e., basic and ultrabasic rocks with low SiO₂ contents) tend to have lower uranium, thorium and potassium content.

The data used in this study is derived from an airborne gamma-ray spectrometry data that was acquired in 2010 by Fugro on behalf of the Geological Survey of Canada (GSC). The data is publicly available at the Natural Resources Canada (NRC) website. The maps of the eU (ppm), eTh (ppm) and K (%) concentrations over the study area are shown in Figures 2a, 2b and 2c, respectively.

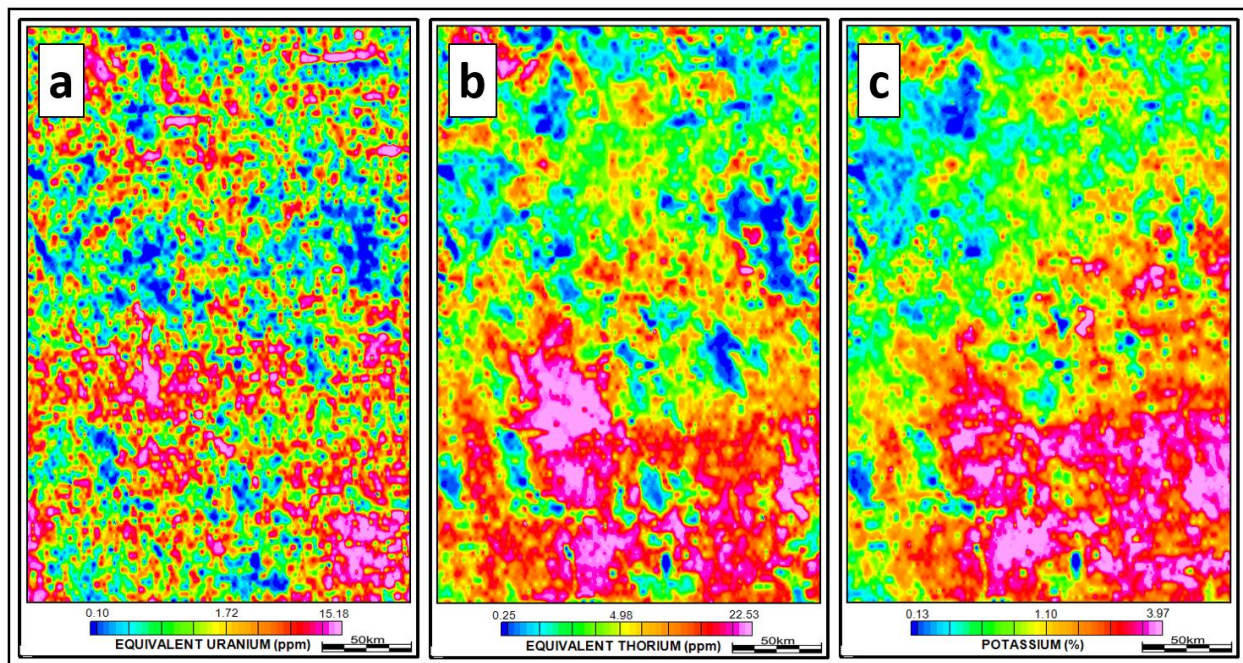


Figure 2. Measured radioactive element concentrations of the study area; (a). eU (ppm), (b). eTh (ppm), and (c). K (%).

Gamma ray spectrometers normally record all gamma rays absorbed by the sodium iodide (NaI) detector within the energy range 0.0 - 3.0 MeV as illustrated in Figure 3. Figure 3 shows a plot of a typical gamma-ray spectrum record. The spectrum displays three distinctive radiation peaks associated with ⁴⁰K (1.46MeV), ²¹⁴Bi (1.76MeV) and ²⁰⁸Tl (2.62MeV) that are used to calculate the abundances of K, U and Th, respectively by gamma-ray spectrometers (Minty, 1997). The

spectrum shows that potassium is measured directly from the gamma rays emitted by ^{40}K . Uranium and thorium are measured indirectly (eU and eTh) from gamma rays emitted by daughter products ^{214}Bi and ^{208}Tl , respectively, assuming that secular equilibrium between daughter and parent isotopes is reached.

Disequilibrium occurs when one or more decay products in a decay series are partially or entirely removed or added to the system, and it is more pronounced during the decay series of uranium (^{238}U). There are many factors that cause disequilibrium in uranium decay series. For example, when the Radon gas (^{222}Rn) which is highly mobile escapes from rocks into the atmosphere prior to the uranium decay series reaching an equilibrium. Potassium does not suffer from disequilibrium problem, and it is rare in the thorium decay series as well (IAEA, 2003).

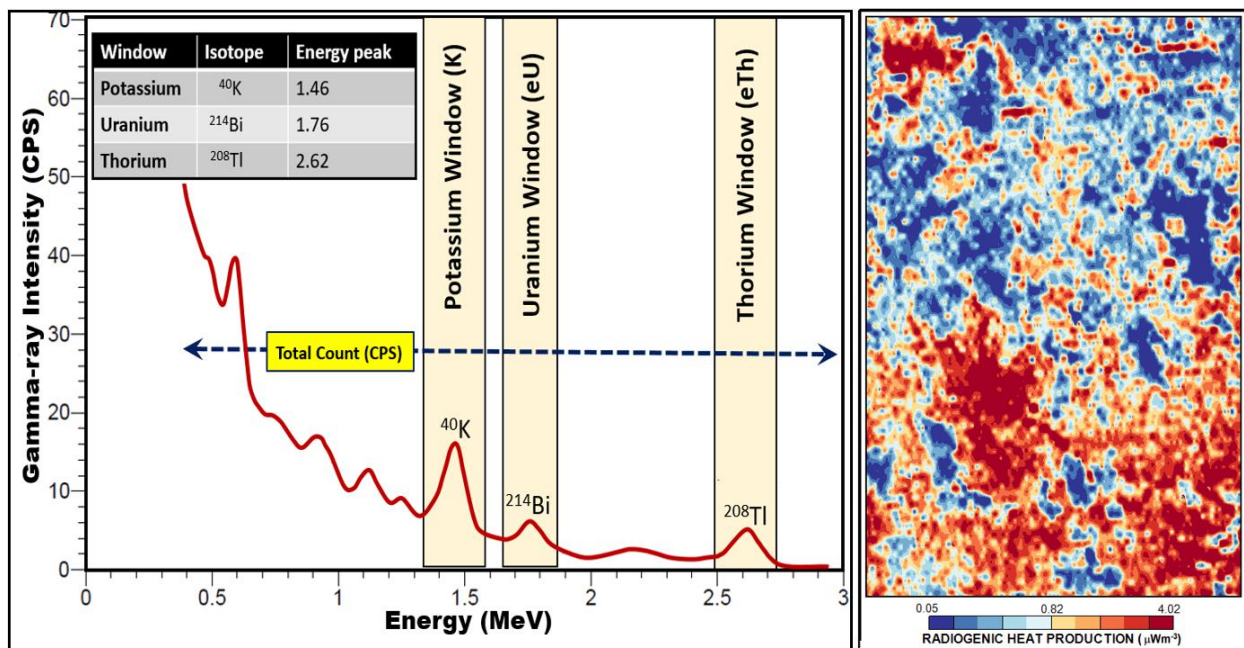


Figure 3. Typical gamma-ray spectrometry spectrum showing the windows and peaks of uranium, thorium and potassium.

Figure 4. Radiogenic heat production of the study area.

Methodology

In the early stages of the radioactive decay of natural uranium, thorium and potassium kinetic energy is initially released and afterward the kinetic energy converts into thermal energy in the RHP. There are only few empirical formulas available to compute the RHP released from the radioactive decay of uranium, thorium and potassium concentrations in rocks (For example, Birch, 1954; Rybach, 1988). Generally, all of them produce very close results, but in this study we used

the formula introduced by Rybach (1988) (Formula 1) to compute RHP from the eU (Fig. 2a), eTh (Fig. 2b), and K (Fig. 2c) concentrations obtained from the airborne gamma-ray spectrometry survey over the study area, using the following formula:

$$A (\mu Wm^{-3}) = 10^{-2} * \rho * [9.52C_U(ppm) + 2.56C_{Th}(ppm) + 3.48C_K(\%)] \quad (1)$$

Where A is the computed radioactive heat production ($\mu W/m^3$), ρ is rock density (gm/cm^3), and C_U , C_{Th} , and C_K represent the concentrations of eU (ppm), eTh (ppm), and K (%), respectively. We used a density of $2.50 gm/cm^3$ to represent the average density of the overburden sedimentary rocks of the study area. The result from computing the radiogenic heat production (A) of the study area is shown in Figure 4.

Results

The result of computing RHP for the study area is displayed in Figure 4 and summarized in Table 1. The result reveals that the range of the radiogenic heat production in the study area as estimated from the airborne gamma-ray survey data is between 0.05 and $4.02 \mu W/m^3$, with a mean value of $0.82 \mu W/m^3$. The computed RHP appears to be relatively higher in the southern and southeastern part of the study area, and perhaps due to high radioelement concentrations in the rocks underneath. The outcropping rocks in the areas with high RHP are mostly cretaceous sedimentary rocks (i.e., Bearpaw and Oldman formations) that are enriched with grey or dark color shale. Shale is usually radioactive due to the presence of potassium in the clay that created the shale. However, the main source of the RHP in the study area is most likely due to high uranium, thorium and potassium concentrations in felsic igneous rocks linked to the Precambrian basement rocks underneath the study area. Significant amounts of uranium, thorium and potassium within felsic igneous rocks in the Precambrian rocks could move upward into the sedimentary rocks and also to the surface by hydrothermal solutions.

It is also of interest to note that areas with elevated RHP coincide with areas known to contain high helium-4 deposits (4He). Helium gas (4He) is normally produced from alpha (α) particles released by the decay of uranium and thorium in granitic rocks.

Table 1. Statistical summary of the radiogenic heat production computed for the study area

Measured data	No. of Readings	Minimum	Maximum	Mean	Std deviation
Uranium (ppm)	504367	0.10	15.18	1.72	1.05
Thorium (ppm)	504367	0.25	22.53	4.98	1.77
K (%)	504367	0.13	3.97	1.10	0.29
Radiogenic Heat Production ($\mu\text{W}/\text{m}^3$)	504367	0.05	4.02	0.82	0.27

Conclusions

In this study, we used the abundances of radioactive elements, uranium, thorium and potassium measured from an airborne gamma-ray spectrometry survey to compute RHP in the study area which is located in southeastern Alberta. The computed RHP ranges between 0.05 and 4.02 $\mu\text{W}/\text{m}^3$ and the mean value is equal to 0.82 $\mu\text{W}/\text{m}^3$. Areas with high RHP values are located in the southern and southeastern part of the study area and it is most likely caused by high uranium, thorium and potassium concentrations in felsic igneous rocks linked to the Precambrian rock underneath the study area. Significant amount of uranium, thorium and potassium in the Precambrian rocks could have been migrated upward into the sedimentary rocks above through hydrothermal solutions.

Elevated geothermal gradients may be encountered and identified using the methodology described. This approach is beneficial because it provides an independent data source from which large areas can be analysed rapidly and efficiently, delineating potential geothermal resource fairways. Furthermore, the study also shows that the areas that are high in RHP may to contain elevated deposits of helium (^4He) gas. Further study should be done to calibrate the results of this methodology against measured heat flow and helium occurrences in the study area.

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