



Studies on the Spatial Distribution of Radiogenic Elements in the Crystalline Basement Used for the Evaluation of Deep Geothermal Resources in the Southwestern Québec

Hejuan Liu^(✉)

State Key Laboratory of Geomechanics and Geotechnical Engineering,
Institute of Rock and Soil Mechanics, Chinese Academy of Sciences,
Wuhan 430071, China
hjlju@whrsm.ac.cn

Abstract. Accurate assessment on the subsurface geothermal resources remains challengeable from the scientific point of view. The parameter uncertainties and incomplete knowledge of initial conditions for the subsurface environment make the prediction of subsurface temperature based on the thermal models present a strong uncertainty. Forward modeling of the temperature at depth may be highly dependent on the radiogenic heat production of the geological layers which are affected by the concentration of uranium, thorium and potassium, and density. It shows that the average concentration of uranium, thorium and potassium is 1.78 ppm, 6.01 ppm and 2.64%, with the standard deviation error of 3.57, 7.27 and 1.85 respectively for the selected region in southwestern Quebec. The sequential gaussian simulation (SGS) method was used to obtain the spatial distribution of the radiogenic elements in a selected region with the size of 35 km × 80 km. Using the density values for specific rocks, the distribution of the radiogenic heat production over the study area is also simulated. Results show that the difference between the minimum and the maximum radiogenic heat production value is 30% when considering the difference in density.

Keywords: Ordinary kriging · Sequential gaussian simulation
Radiogenic elements · Uncertainty · Geothermal energy

1 Introduction

The production of geothermal energy at depth has become a worldwide hot topic in recent years with the reduction in the drilling cost and the development of the reservoir stimulation technologies. However, the reliable assessment on the geothermal resources at depth is very challengeable because of the great uncertainties subsurface (Fuchs and Balling 2016). There are many methods for the spatial interpolation on variables (e.g. radiogenic elements concentration, thermal conductivity etc.) related with the geothermal energy assessment and they can be classified into three categories (Li and

Heap 2008): (1) non-geostatistical methods, (2) geostatistical methods and (3) combined methods. The stochastic simulation is a variogram based-model, general means for generating multiple realizations of a specific variable, rather than a map of local best estimates produced by kriging (Goovaerts 1997). Unlike kriging methods, the simulation approaches take into account both the spatial variation of raw data at sampled locations and the variation of estimates at unsampled locations (Delbari et al. 2009). Since 1990s, as a popular stochastic simulation method, the Sequential Gaussian Conditional Simulation method (SGCS) has been developed and often applied in the fields of hydrogeology, ecology, pedology, mining, petroleum etc. (Dubrule 1989; Caers 2005). It is used to model the continuous variables such as porosity, permeability, concentration of elements etc. SGCS is based on the Monte Carlo method and overcomes the smoothing effect induced by the kriging interpolation method. In comparison with the partial optimization of the estimator value in the kriging interpolation algorithm, the geostatistical stochastic simulation is able to assess the spatial distribution of desired variables and analyzing its uncertainty (Soltani et al. 2013), realizing the optimization of the estimator values in the whole region through multiple realizations based on the same input data (Zhao et al. 2010).

Parameters involved in the calculation of radiogenic heat production that may strongly affect the subsurface temperature distribution, include the concentration of uranium, thorium, potassium and density. However, because of the limited samples in the subsurface and the strong heterogeneity of the lithology in different geological formations, it is difficult to have a clear understanding on their spatial distribution over a large region. The assessment of the geothermal potential in the western St. Lawrence Lowlands located at the southwestern Quebec is highly dependent on the clear understanding on the characteristics of its basement. However, because of the limited samples and incomplete knowledge of the uncertainty associated with the distribution of radiogenic elements, it is meaningful to make a comparison by investigating the radiogenic characteristics of its neighbored outcropping regions (e.g., Portneuf-Mauricie domain, Parc des Laurentides domain, Morin Terrane etc.). The main objective of this study is to understand the spatial distribution of the radiogenic elements and the radiogenic heat production in the Grenville basement of the western St. Lawrence Lowlands using the geostatistics studies and the Sequential Gaussian Simulation (SGS) method.

2 Study Area

The Grenville Province (Fig. 1a) is composed of high-grade metamorphic terranes and thrust stacks along ductile shear zones, equivalent to the roots of a Himalayan-type collisional orogeny (Rivers 2015; Davidson 1984; Dufrechou et al. 2014). It was found that the north-south strike of the Grenville structure belt extends from Canada southward into the subsurface of the Appalachian basin (or foreland) (Shumaker and Wilson 1996), which belongs to part of the Appalachian orogeny that extends from Newfoundland to North Carolina. Grenvillian age rocks outcrop in southwestern Quebec in lithotectonic domains including Morin Terrane, Portneuf-Mauricie Domain and Parc des Laurentides Domain etc.

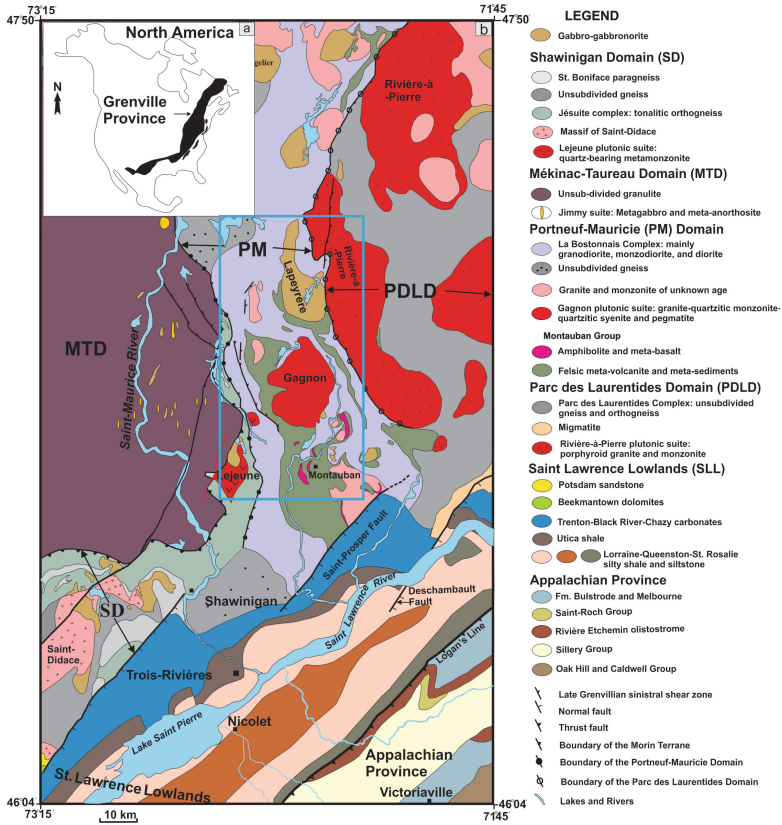


Fig. 1. Study area (surrounded by the blue rectangle) in the Grenville Province. (a) Location of the Grenville Province; (b) simplified geological map of the western St. Lawrence Lowlands and its neighbored geological regions composed of Grenville age rocks including Portneuf-Mauricie (PM) domain, Shawinigan domain (SD) that is part of the Morin Terrane (MT), Parc des Laurentides domain (PDL) etc. (modified from Nadeau and Brouillette 1994, 1995; Sappin 2012).

The St. Lawrence Lowlands located at the southwestern Quebec is comprised of Cambrian to Ordovician sedimentary rocks and their crystalline basement is made up of rocks including granite, granitic gneiss, paragneiss, orthogneiss, gabbro-norite, monzonite, and amphibolite etc. (Tremblay et al. 2003; Lavoie et al. 2009). Figure 1b shows the simplified geological map of the western part of the St. Lawrence Lowlands and its neighbored geological regions at Grenvillian age including the Portneuf-Mauricie (PM) domain, Morin Terrane (MT) and Parc des Laurentides domain (PDL). The study area bounded by the blue rectangle covering intrusions of Gagnon, Lapeyrière and Montauban group is selected because of the rich data in the concentration of the radiogenic elements.

3 Methodology

3.1 Sampling

In the study area shown in Fig. 1b bounded by the blue rectangle, 170 samples were collected by using RS-230 spectrometer and compiled the available data from the Quebec Ministère des Ressources naturelles et de la Faune (SIGEOM). For the data collected from the SIGEOM database, most of the uranium concentration samples are based on NAA-neutron activation method, while the thorium concentration are mainly based on NAA and X-ray fluorescence, the potassium concentration are based on X-ray fluorescence and plasma emission spectrum. When a much larger region with the longitude in the range of W73°15' and W71°45' and the latitude in the range of N46°04' and N47°50' shown in Fig. 1b is considered in the Grenville Province covering Morin Terrane, Portneuf-Mauricie domain, Parc des Laurentides domain, a total of 404 uranium data, 357 thorium data and 411 potassium data were collected.

3.2 Sequential Gaussian Simulation

In the SGS algorithm the mean and variance of the Gaussian distribution at any location along the simulation path is estimated by the kriging estimate and the kriging variance (Vidal and Archer 2015). Rather than choosing the mean as the estimate at each grid node like the kriging interpolation method, SGS uses a random deviate from the normal distribution. This random deviate is selected according to a uniform random number representing the probability level. The variable at each unknown grid node is simulated sequentially according to its normal conditional cumulative distribution function (ccdf). During the multiple realizations, it uses not only the original data but also all previous simulated values.

3.3 Calculation of Radiogenic Heat Production

When the concentration of the radiogenic elements including uranium, thorium and potassium is known, together with the values of density for the samples, the radiogenic heat production can be calculated using the following empirical function (Mareschal and Jaupart 2004; Rybach 1976):

$$A = \rho_r [9.52C_u + 2.56C_{Th} + 3.48C_k] \times 10^{-5} \quad (1)$$

where ρ_r is dry density of rock (kg/m^3), C_u is the uranium content (ppm), C_{Th} is the thorium content (ppm), and C_k is the potassium content (%).

4 Results and Discussion

4.1 Concentration of Radiogenic Elements at Sampled Sites

The average concentration of uranium, thorium and potassium is 1.78 ppm, 6.01 ppm and 2.64%, with the standard deviation error of 3.57, 7.27 and 1.85 respectively.

It presents that 90% of the total samples have the uranium concentration less than 3 ppm, 64% of the samples have the thorium concentration less than 5 ppm, and 56% of the samples have the potassium concentration less than 3%.

4.2 Spatial Distribution of Uranium, Thorium and Potassium Based on SGS

Based on SGS modeling method and the omni-directional variogram with the range of 3400 m shown in Fig. 2, spatial distribution of the uranium under 100 realizations is generated (see Fig. 3a) in the study area of $35 \times 80 \text{ km}^2$, with the cell size of $175 \text{ m} \times 400 \text{ m}$ performed using the geostatistics software - SGeMS (Remy et al. 2009). Using the same process above, the spatial distributions of the thorium and potassium are also simulated.

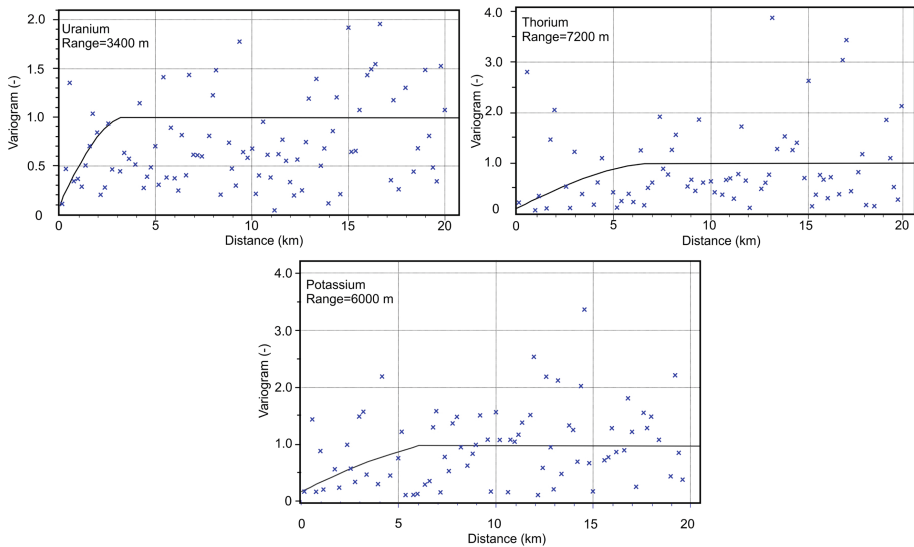


Fig. 2. The omni-directional variograms for the concentration of uranium, thorium and potassium in the study area

Except the uranium concentration, the distribution of the thorium (Fig. 3b) and potassium (Fig. 3c) using SGS simulation method are also shown by applying the omni-directional variograms with the range of 7200 m and 6000 m respectively (see in Fig. 2).

4.3 Spatial Distribution of the Radiogenic Heat Production Based on SGS

Based on the range of the density value (minimum, average and maximum) for the specific rock in the study area, using the empirical function Eq. 1, accordingly, three types of radiogenic heat production can be calculated and their spatial distribution can

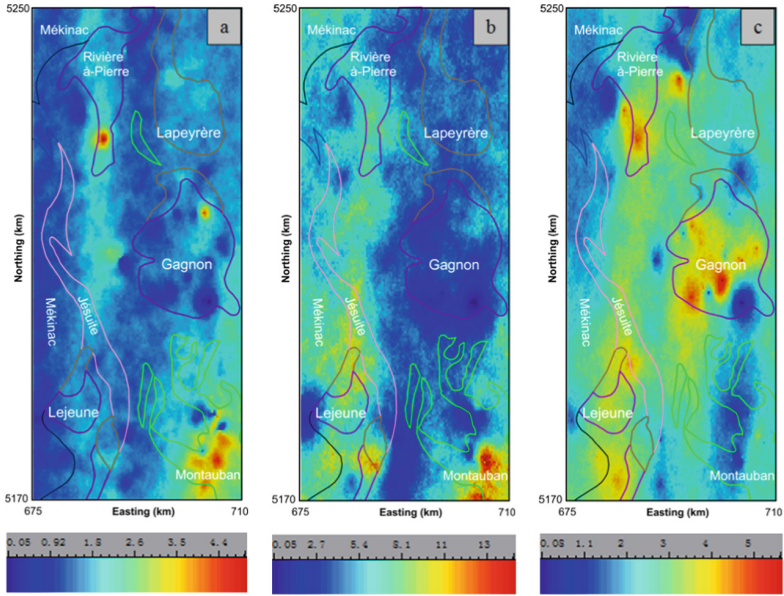


Fig. 3. The concentration of uranium(a), thorium(b) and potassium(c) by using conditional SGS simulation based on 100 realizations applying the omni-directional variograms shown in Fig. 2.

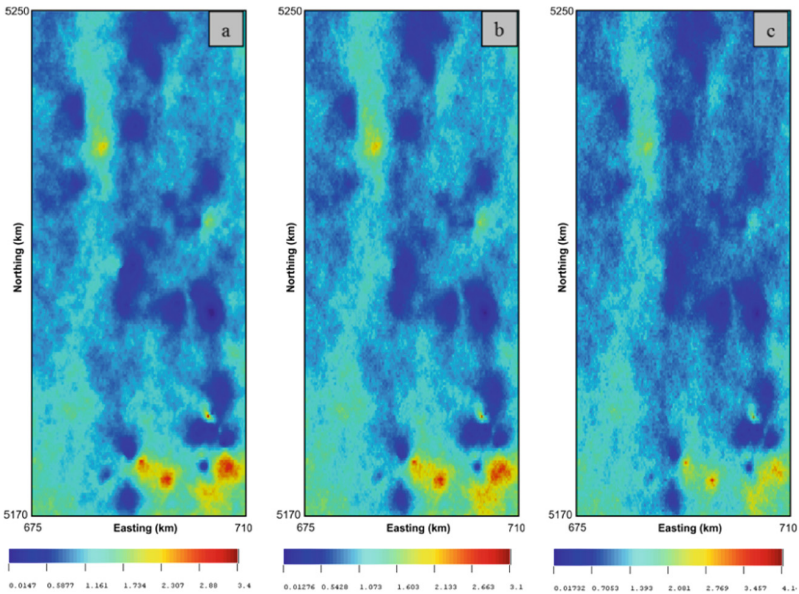


Fig. 4. Spatial distribution of the radiogenic heat production using the average (a), minimum (b) and maximum (c) density values for specific rocks at the sample points through applying the conditional SGS with 100 realizations

be simulated by applying the SGS method (Fig. 4). It shows that the difference between the minimum and maximum radiogenic heat production can reach to an extent of 30% compared Fig. 4a and c.

5 Conclusions

In the western St. Lawrence Lowlands, the radiogenic characteristics of its basement is less known. The information from the neighbored Grenville Province may provide a reference in understanding the heterogeneity of basement buried by the sedimentary rocks in the western St. Lawrence Lowlands. Some main conclusions are as follows: (1) radiogenic elements concentration for most samples in the research region is low; (2) The minimum and the maximum radiogenic heat production value is 30%. Results from this paper on the spatial distribution of the radiogenic heat production will be applied in the forward modeling of the subsurface temperature and the assessment on the geothermal resources in the western St. Lawrence Lowlands in the future.

Acknowledgements. The author acknowledge the support of the CAS Pioneer Hundred Talents Program in China. Besides, special thanks to Bernard Giroux and Erwan Gloaguen at INRS-ETE for their invaluable help in technical support of SGeMS software. Thanks to Aurelie Gicquel for providing some radiogenic elements data in the research region.

References

- Caers J (2005) Petroleum geostatistics. SPE
- Davidson A (1984) Identification of ductile shear zones in the south-western Grenville Province of the Canadian Shield. In: Kroner A, Greiling R (eds) Precambrian tectonics illustrated: Schweitzerbart'sche Verlagsbuchhandlung, Stuttgart, pp 263–279
- Delbari M, Afrasiab P, Loiskandl W (2009) Using sequential Gaussian simulation to assess the field-scale spatial uncertainty of soil water content. CATENA 79:163–169
- Dubrule O (1989) A review of stochastic models for petroleum reservoirs. In: Armstrong M (ed) Quantitative geology and geostatistics. Springer, Dordrecht, pp 493–506
- Dufréchoy G, Harris LB, Corriveau L (2014) Tectonic reactivation of transverse basement structures in the Grenville orogeny of SW Quebec, Canada: insights from gravity and aeromagnetic data. Precambr Res 241:61–84
- Fuchs S, Balling N (2016) Improving the temperature predictions of subsurface thermal models by using high-quality input data. Part 1: uncertainty analysis of the thermal-conductivity parameterization. Geothermics 64:42–54
- Goovaerts P (1997) Geostatistics for natural resources evaluation. Oxford University Press, New York
- Lavoie D, Pinet N, Castonguay S, Dietrich J, Giles P, Fowler M, Thériault R, Laliberté JY, St P, Hinds S, Hicks L, Klassen H (2009) Hydrocarbon systems in the Paleozoic basins of eastern Canada-Presentations at the Calgary 2007 workshop. Geol. Surv. Canada Open File 5980:9–79
- Li, J., Heap, A.D.: A review of spatial interpolation methods for environmental scientists. Geoscience Australia, p. 137. Record 2008/23 (2008)
- Mareschal JC, Jaupart C (2004) Variations of surface heat flow and lithospheric thermal structure beneath the North American craton. Earth Planet Sci Lett 223:65–77

- Nadeau L, Brouillette P (1994) Carte structurale de la région de La Tuque (SNRC 31P), Province de Grenville, Québec. Commission Géologique du Canada, dossier public 2938(1):250 000
- Nadeau L, Brouillette P (1995) Carte structurale de la région de Shawinigan (SNRC 31I), Province de Grenville, Québec. Commission Géologique du Canada, dossier public 3012 (1):250 000
- Remy N, Boucher A, Wu J (2009) *Applied Geostatistics with SGeMS: A User's Guide*. Cambridge University Press, Cambridge
- Rivers T (2015) Tectonic setting and evolution of the Grenville orogeny: an assessment of progress over the last 40 years. *Geosci Can* 42:77–124
- Rybach L (1976) Radioactive heat production in rocks and its relation to other petrophysical parameters. *Pure appl Geophys* 114:309–318
- Sappin AA (2012) *Pétrologie et métallogénie d'indices de Ni-Cu-éléments du Groupe du Platine du Domaine de Portneuf-Mauricie, Québec (Canada)*, Thèse de doctorat at Université Laval, p 70
- Shumaker RC, Wilson TH (1996) Basement structure of the Appalachian foreland in West Virginia: its style and effect on sedimentation. In: Van der Pluijm BA, Catocinos PA (eds), *Basement and basins of Eastern North America*, pp 139–155. Geol Soc Am
- SIGEOM. <http://sigeom.mines.gouv.qc.ca>
- Soltani F, Afzal P, Asghari O (2013) Sequential Gaussian simulation in the Sungun Cu porphyry deposit and comparing the stationary reproduction with ordinary kriging. *Univ J Geosci* 1(2):106–113
- Tremblay A, Long B, Massé M (2003) Supracrustal faults of the St. Lawrence rift system, Québec: kinematics and geometry as revealed by field mapping and marine seismic reflection data. *Tectonophysics* 369:231–252
- Vidal A, Archer R (2015) Geostatistical simulations of geothermal reservoirs: two-and multiple-point statistic models. In: *Proceedings world geothermal congress 2015, Melbourne, Australia*
- Zhao YF, Sun ZY, Chen J (2010) Analysis and comparison in arithmetic for kriging interpolation and sequential gaussian conditional simulation. *J Geo-Inf Sci* 12(6):767–776