Journal of Environmental Radioactivity 122 (2013) 70–78

Contents lists available at SciVerse ScienceDirect

Journal of Environmental Radioactivity

journal homepage: www.elsevier.com/locate/jenvrad

# Systematic survey of natural radioactivity of soil in Slovenia

Tibor Kovács [a,b], Gábor Szeiler [a], Ferenc Fábián [a], Richárd Kardos [a], Asta Gregorič [c,*], Janja Vaupotič [c]

[a] University of Pannonia, Institute of Radiochemistry and Radioecology, P.O. Box 158, 8200 Veszprém, Hungary
[b] Social Organisation for Radioecological Cleanliness, P.O. Box 158, 8200 Veszprém, Hungary
[c] Jožef Stefan Institute, Department of Environmental Sciences, Radon Center, P.O. Box 3000, 1001 Ljubljana, Slovenia

ARTICLE INFO

*Article history:*
Received 8 November 2012
Received in revised form
13 February 2013
Accepted 16 February 2013
Available online 1 April 2013

*Keywords:*
Natural radioactivity
Soil analysis
Gamma-spectrometry
Alpha-spectrometry
Lithology
Gamma dose rate

ABSTRACT

Soil samples, from 70 points uniformly distributed over entire Slovenia, were analysed for $^{40}$K, $^{232}$Th and $^{226}$Ra using gamma spectrometry, and for $^{234}$U and $^{238}$U using alpha spectrometry. The following ranges and averages of activity concentrations (Bq kg$^{-1}$) were obtained: 98–2600 and 800 ± 520 for $^{40}$K, 9–170 and 77 ± 33 for $^{232}$Th, 12–270 and 63 ± 44 for $^{226}$Ra, 12–84 and 34 ± 19 for $^{234}$U, and 11–90 and 34 ± 19 for $^{238}$U. With respect to lithology, the highest average values for $^{40}$K and $^{232}$Th were found at clastic sediments containing clay and for $^{226}$Ra on carbonate rocks. Based on the measured activity concentrations, terrestrial gamma dose rates were calculated. The total dose rate ranged from 15 to 260 nGy h$^{-1}$, with arithmetic mean of 110 ± 49 nGy h$^{-1}$, being the highest over carbonates.



## 1. Introduction

Naturally occurring radionuclides in soil are the major source of external gamma radiation. These are $^{40}$K and several members of the $^{232}$Th, $^{235}$U and $^{238}$U natural radioactive decay chains. Of them, $^{40}$K contributes 13.8%, $^{232}$Th 14% and $^{226}$Ra 55.8% to the worldwide average of the terrestrial gamma dose rate of 60 nGy h$^{-1}$ (UNSCEAR, 2000). In addition, alpha transformation of radium in the $^{232}$Th chain generates radioactive noble gases $^{220}$Rn (thoron) and in the $^{238}$U chain, $^{222}$Rn (radon). Their appearance (ubiquitously accompanied by their short-lived decay products) in the ambient air contributes more than half to the effective dose a member of the general public receives from all natural radioactive sources on the worldwide average (UNSCEAR, 2000) and is the second major cause of lung cancer, soon after cigarette smoking (Darby et al., 2005). The concentration of radium as the radon source in soil is one of the crucial data to estimate radon concentration in soil gas (Jönsson et al., 1999; Kunz et al., 1996), radon potential of the ground on which a building is standing (Friedmann and Gröller, 2010; Kemski et al., 2001; Neznal et al., 1996) and consequently, radon levels in indoor air (Celik et al., 2008; Vaupotič et al., 2002). Radium as radon source is also a key parameter in model calculations for both radon transport and entry into buildings (Abumurad and Al-Tamimi, 2001; Andersen, 2001; Bossew, 2003; Font and Baixeras, 2003; Iskandar et al., 2005; Wang and Ward, 2000) and movements of air masses with radon as tracer (Griffiths et al., 2010; Hirao et al., 2010). For these reasons, natural radioactivity in soil attracts researchers worldwide and systematic measurements of $^{40}$K, $^{232}$Th and $^{226}$Ra have been performed in a number of countries (Anagnostakis et al., 1996; Baeza et al., 1992; Bikit et al., 2004; Isinkaye and Shitta, 2010; Kannan et al., 2002; Megumi et al., 1988; Mehra et al., 2010; Mujahid and Hussain, 2010; Papp, 2010; Quindós et al., 1994; Ramola et al., 2008; Singh et al., 2005).

Considering natural radioactivity in Slovenia, a systematic radon survey in living and working environments has been conducted over the last two decades (Humar et al., 1992; Vaupotič, 2010). Radium and uranium have been analysed in ground, spring and surface waters (Kobal et al., 1990; Popit et al., 2004; Vaupotič, 2002), and equivalent uranium and equivalent thorium concentrations were determined in soil samples from 30 cm depths at sixty points all over the country (Andjelov and Brajnik, 1996; Brajnik et al., 1992). Recently, $^{40}$K, $^{232}$Th, $^{238}$U, $^{226}$Ra and $^{228}$Ra were analysed in the *terra rossa* and *eutric cambisol* soil samples from 80 cm depths within regular 25 m × 25 m grid squares at two sites (Vaupotič et al., 2007, 2012). In order to upgrade and complete the

* Corresponding author. Jožef Stefan Institute, Department of Environmental Sciences, Jamova 39, 1000 Ljubljana, Slovenia. Tel.: +386 1 477 3239; fax: +386 1 477 3811.
*E-mail address:* asta.gregoric@ijs.si (A. Gregorič).

0265-931X/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jenvrad.2013.02.007

previous information, during our radon measurements in soil gas at seventy points (Vaupotič et al., 2008), soil samples were collected and analysed for $^{40}$K, $^{232}$Th, $^{226}$Ra and at 29 points also for $^{234}$U and $^{238}$U. In the paper, measurements are described, and results of the analysis are presented and commented upon.

## 2. Geology and tectonics of Slovenia

The most important geologic characteristics influencing radon concentration in soil gas are the lithology and the presence of faults. For this purpose, our measurement points were classified into 7 units, based on the lithological classification:

- alluvial and glacial deposits (A) represent mainly unconsolidated clastic sediments,
- consolidated clastic sediments (B) are divided into three groups: clastic sediments containing clay (B1), coarse clastic sediments (B2), flysch (B3)
- carbonates (C)
- metamorphic rocks (D)
- sea and lake sediments (E)

Slovenia lies on the junction region between the Alps and the Dinarides which incorporates the Eastern Alps, Southern Alps, Dinarides, Panonian basin and the Adriatic-Apulia foreland (Placer, 2008). The present tectonic structure of the Slovenian territory originated during the Tertiary orogeny following the collision of the Apulia lithospheric plate with the Eurasian lithospheric plate on which the Apulian plate was overthrust (Schmid et al., 2004). The western and south-western parts of Slovenia are characterised by NW-SE trending dextral strike-slip faults (Fig. 1). Some of them are accompanied by wide fault deformation zones. The Adriatic-Apulia foreland comprises the larger part of Istria in the south-western corner of Slovenia consisting of rocks of the Adriatic segment of the Adriatic-Dinaric Mesozoic carbonate platform, and the flysch rocks resulting from its degradation (Placer, 2008).

The entire southern part of Slovenia belongs to the Dinarides, characterised by the thrust and nappe structure, consisting mainly of carbonate rocks and sediments resulting from disintegration of the Adriatic-Dinaric carbonate platform: Upper Cretaceous carbonate turbidites, Cretaceous-Palaeocene and Eocene flysch (Placer, 2008). The Southern Alps are palaeogeographically a part of Dinarides. Mesozoic rocks of the Slovenian basin and Upper Triassic rocks of the Julian carbonate platform are exposed within them (Placer, 2008). The Eastern Alps are a geologic-orographic term comprising the complex of Precambrian and Old Palaeozoic high and low grade metamorphic rocks and of Permian and Mesozoic sedimentary rocks north of the Periadriatic fault (Placer, 2008). The Pannonian basin, in the north-eastern part of Slovenia, consists of individual depressions that originated during Palaeogene and Neogene. They are filled with sediments of the Paratethys deposited on subsided continuations of the Eastern and Southern Alps and Dinarides (Placer, 2008). In addition to the major lithological units described above, alluvial and glacial deposits, extending along major valleys, have to be considered. In the Ljubljana basin, situated in the central part of Slovenia and in the Krško basin in south-east, sea and lake sediments prevail.

## 3. Materials and methods

### 3.1. Sample collection and preparation

At seventy points uniformly distributed (except in high mountains) across Slovenia, radon in soil gas was measured (Vaupotič et al., 2010, 2008). When exposing radon detectors, soil samples were also taken from a depth of 80 cm (Fig. 1). Samples were dried in air, first at room temperature and then at 105 °C until constant weight was achieved.

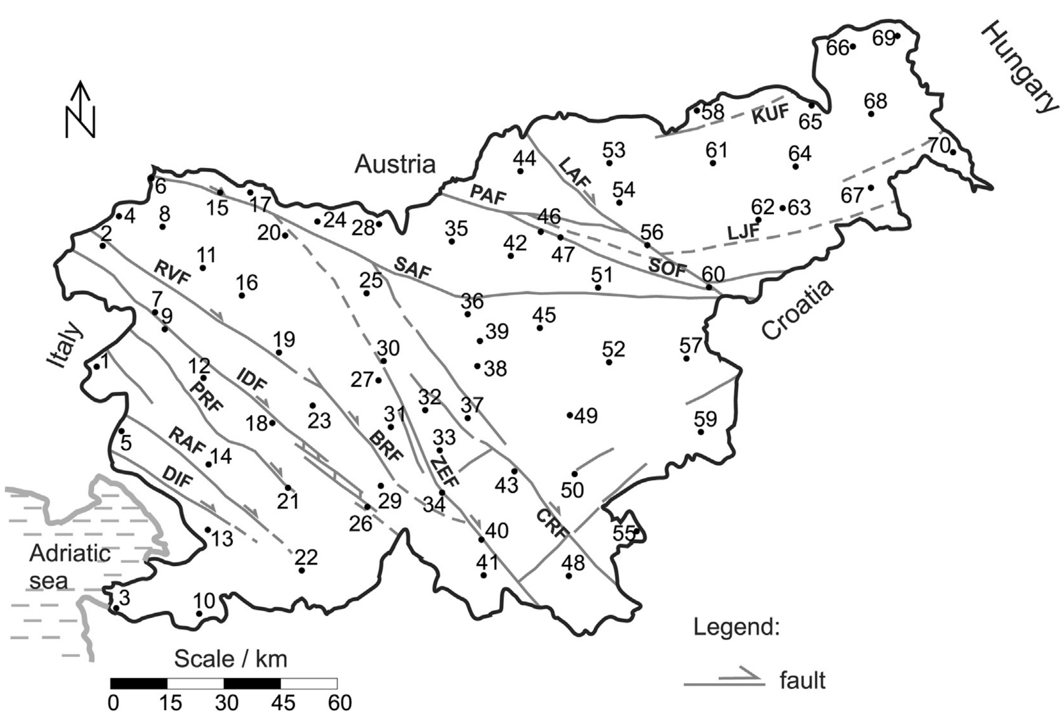


**Fig. 1.** Map of Slovenia (surface area 20.3 thousand km$^2$); indicated are tectonic faults and sampling points. Faults: RVF – Ravne, IDF – Idrija, PRF – Predjama, RAF – Raša, DIF – Divača, SAF – Sava, BRF – Borovnica, ZEF – Želimlje, CRF – Črnomelj, PAF – Periadriatic, SOF – Šoštanj, LAF – Labot, LJF – Ljutomer, KUF – Kungota.