1. Introduction

1.1. PROPERTIES AND BEHAVIOUR OF RADON AND ITS PROGENY

Radon is a noble gas with a large number of isotopes. All are radioactive, and three of them (^{219}Rn, ^{220}Rn and ^{222}Rn) occur in nature as members of the primordial actinium, thorium and uranium series, respectively. The name "radon" is customarily reserved for ^{222}Rn. Isotopes ^{219}Rn and ^{220}Rn are usually called actinon and thoron respectively, after their series parents. All three isotopes are alpha emitters. Their half-lives are: 3.96 s for actinon, 55.6 s for thoron, and 3.82 d for radon. The parent atoms of these series can be found in all natural materials, so all three radon isotopes are released into the air from the surfaces of rocks, soils and building materials. The low ^{235}U/^{238}U atomic ratio in natural uranium and the short half life of actinon make it of negligible interest as a contributor to dose. Because of its relatively short half-life, the atmospheric concentrations of thoron are much less than those of radon, and in most circumstances the dose from thoron and its progeny is much less than that from radon and its progeny. For these reasons, there is no discussion of actinon, and only a minimal mention of thoron, in this paper.

Radon itself originates from the radioactive decay of ^{226}Ra. The decay is accompanied by the emission of an alpha particle with kinetic energy of 5.49 MeV. An atom of radon with kinetic energy of 0.1 MeV is emitted in the oposite direction than the alpha particle. Just this back recoil is responsible for the escape of the radon atom from the crystaline structure of minerals and for its migration.

The radon exhaled from the earth's surface or from other materials into the atmosphere is rapidly dispersed and diluted by vertical convection and turbulence. There is less opportunity for dispersion in confined air spaces such as houses and underground mines. In such areas the radon concentration increases with decreasing ventilation rate.

The radon gradually decays into so-called short-lived radon progeny: ^{218}Po (half-life of 3.05 m), ^{214}Pb (26.8 m), ^{214}Bi (19.9 m), and ^{214}Po (164 µs). Two of these isotopes, namely ^{218}Po and ^{214}Po, are also the alpha-emitters. It is the short-lived radon progeny which, when inhaled, deliver the alpha radiation dose to bronchial tissue. The dose causes an increase of risk of the radiogenic lung cancer incidence.

Note: The long-lived radon progeny ^{210}Pb and ^{210}Po do not contribute to the dose, because their concentrations in the atmosphere are substantially lower than the concentrations of radon and its short-lived progeny.

1.2. GEOLOGICAL OVERVIEW

The geological basement of the Czech Republic bears the footprints of the long-term geological development since Palaeoproterozoic (approx. 2.1 Ga old) to recent. At present two basic components of geological basement occur on the territory of the Czech Republic – the Bohemian Massif extending over the state border to N and NW (Germany and Poland) and to SW and S (Germany and Austria) and Carpathian belt in the eastern part of country.

The Bohemian Massif belongs to the most eastern part of the European Hercynides (Variscan belt) reflecting the main Variscan orogenic event whose implications are relatively well preserved in the crystalline basement. However the palaeogeological record of the European continental development reaches the Palaeo- and the Neoproterozoic time but due to complexity of different geological processes and namely their repeating and consequent overprinting it is worse interpretable.

From NW to SE the Czech territory is formed by five basic units – regions, having been amalgamated into their present positions by plate tectonic movements during the oldest Cadomian, then Variscan and younger Alpine orogenic events. The complicated collision history expresses itself also in general lithological differencies between basic geological regions with relatively similar lithological composition of basement rock types divided by zones evidencing the increased tectonomagmatic activity in sutures between colliding rigid microcontinents.

The basic geological regions in the Bohemian Massif are from NW to SE the Saxothuringian, Teplá-Barrandian, Moldanubian and Moravosilesian regions. On the SW rim (Moravosilesian region) the Bohemian Massif dips under several km thick folded sediments of the Eastern Carpathian belt and its foredeep. Formerly in geological past the four regional units of the Bohemian Massif are considered to be in a position of separated microcontinents or crustal block. During Palaeozoic the accretion to the East European platform was probably started by Moravosilesian region (in Cambrium) and the amalgamation of group of Armorician microcontinents including the remaining above mentioned geological units faded down during and after the Variscan orogeny (Devonian to Carboniferous) accompanied by extensive magmatic activity forming up the major granitoid bodies of the Bohemian Massif. The dextral strike slip movements parallel to the Tornquist line were closing the accretion processes.

The crystalline basement is partly covered by Lower and Upper Palaeozoic sediments, whose relics form the sedimentary basins of Cambrian to Permian age. The Mesozoic sediments cover the substantial part of the Czech territory – the Bohemian Cretaceous table in the northern part of Bohemia, stretching along the Elbe zone to Germany. The younger sedimentary Tertiary formations are bound mostly to areally delineated rifting zones (border of Saxothuringian and Teplá-Barrandian regions) accompanied by effusive and extrusive complexes of neovolcanites. The youngest Quaternary sediments are mostly of fluvial and aeolian origin, smaller part of them is represented by glacifluvial deposits (close to northern border of the Czech Republic with Poland in northern Bohemia and Moravia).

The most eastern part of the Czech territory is formed by flysch sediments of Outer Carpathian belt, repositioned by nappe tectonics over the thick sedimentary formations of Carpathian Foredeep. The younger geodynamic processes initiated also the volcanic activity during Miocene.

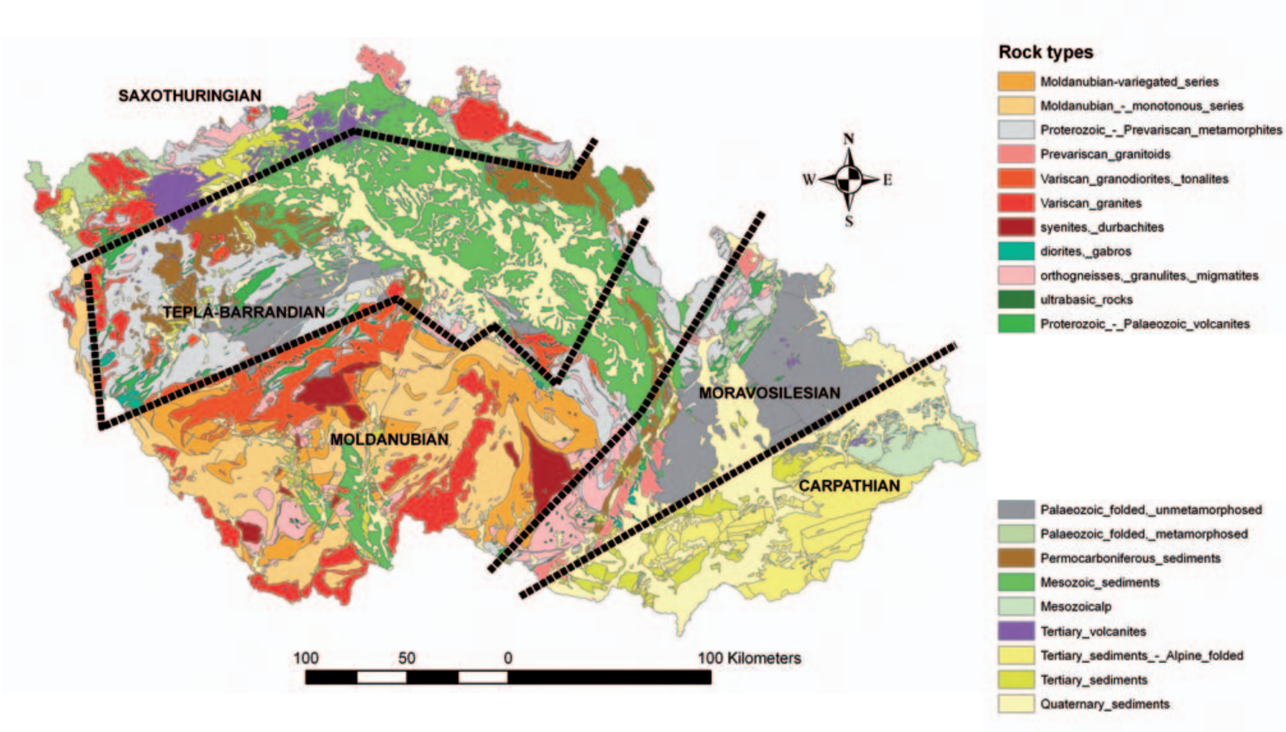

Fig. 1-1. Regional geological division of the territory of the Czech Republic.

The geological scheme of the Czech Republic with approx. borders of basic geological regional units is given in Fig. 1-1. The approximation reflects not only the scale of map and figure, but also the evolution of different palaeogeological theories based on the different interpretations of rock types' origin and events leading to their formation. Fig. 1-2 illustrate the gamma dose rate within the territory of the Czech Republic (Manová – Matolín 1995). The detailed ranges of gamma dose rate in particular regional geological units are discribed in Manová – Matolín (1998).

This geological overview is not to describe thoroughly all the geological events leading to the present image of the Czech geological basement. For detailed information we refer to textbooks of regional geology and some of the synthetic papers and references therein (Mísař et al. 1983, Suk et al. 1984, Matte et al. 1990, Working Group 1994, Scheuvens and Zulauf 2000, Franke 2000, Janoušek et al. 2000, Pharaoh 1999, Chlupáč et al. 2002, Kováč and Plašienka 2002, Scheck et al. 2002, Schenk and Schenková 2002, Kachlík 2003, Edel et al. 2003, Kryza et al. 2004, Mazur et al. 2006, Franke 2006, Finger et al. 2007, Kalvoda et al. 2007). The following text is therefore composed to present the basic regions from the lithological point of view with respect to basic radiometrical and radon concentration characteristics.

Saxothuringian region

Most of the NW, N, and NE part of the Czech territory belongs to Saxothuringian region, which is clearly separated from Teplá-Barrandian Unit by the Eger rift (active until recent). The southern limitation of Saxothuringian is covered under the platform (Carboniferous to Quaternary sediments). The Cadomian basement is formed mostly by para- and orthogneisses with intrusions of Lusatian granitoids. Variscan orogeny gave rise to bigger granitoid plutons (Karlovy Vary pluton, Krkonoše-Jizera pluton). The Lower Palaeozoic metamorphosed complexes are mostly represented by phyllites, metagreywackes, metaconglomerates and metavolcanites. From the radiometric point of view the gamma dose rate is inhomogeneous but generally close to central values (50–80 $nGy . h^{-1}$) with increase in areas of Variscan granitoid plutons. On the other hand the Cadomian magmatites do not reflect any anomalies both in gamma dose rate and in Rn concentration (mean for Cadomian granitoids is in the range 25–31 $kBq . m^{-3}$.

Teplá-Barrandian region

Teplá Barrandian region comprises the geological units from Neoproterozoic up to sedimentary Palaeozoic cover (Cambrian to Devonian). The older Neoproterozoic series is represented by marine shales, graywackes, siltstones and slatestones slightly metamorphosed during Cadomian orogeny. From the radiometric point of view the metasedimets belong to the rocks with the lowest gamma dose rate (less than 50 $nGy . h^{-1}$) with the exceptions of silicites (U-concentrations in organic matter). During Cadomian orogeny also the smaller bodies of basic intrusives were emplaced close to the contact with Moldanubian unit together with small granitoid massifs in the central part of unit. The Variscan orogeny gave rise to granitoid magmatism, concentrated again along the border with Moldanubian unit. The discordantly sedimented series of Cambrium–Devonian upper layer contain only one rock suite distinguished by high radon concentration – the Silurian black shales (Rn concentrations mean 96.9 $kBq . m^{-3}$). Fortunately due to the synclinal position of black shales the surficial projection is not continuous and the shales represent only the discrete outcrops with low thickness. Therefore the Silu-

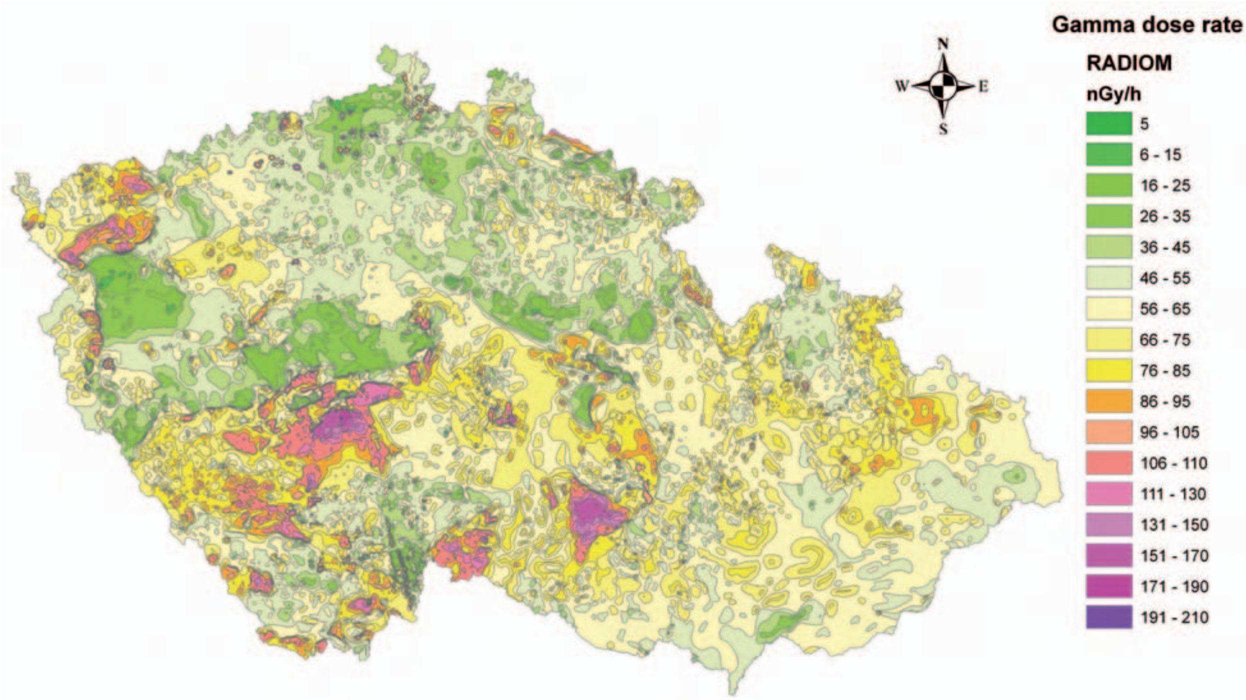

Fig. 1-2. Gamma dose rate map of the Czech Republic (original scale 1 : 500 000, after MANOVÁ and MATOLÍN 1995).

rian black shales are considered as locally confined radon risk areas.

Moldanubian region

Moldanubian region represents the core part of the Bohemian Massif. It underwent the intensive tectonometamorphic history, leading into formation of thick series of biotite-cordierite paragneisses, migmatites, orthogneisses and mica schists (Monotonous series) and biotite-sillimanitic paragneisses and orthogneisses with intercalations of erlans, quartzites, marmors, graphitic phyllites and basic volcanites (Variegated series). During Variscan orogeny the major granitoid bodies of the Bohemian Massif intruded (syntectonic alkali-feldspar massifs of western Bohemia, Central Bohemian Plutonic Complex and Železné hory pluton following the supposed course of the Central Bohemian shear zone (suture) dividing the Moldanubian and Teplá-Barrandian regions). The younger posttectonic magmatic activity was connected with emplacement of Central Moldanubian pluton and K-rich syenite massifs of Čertovo Břemeno and Třebíč syenite massif. The latter mentioned syenite massifs belong to "radon hot spots" within the granitoids of the Bohemian Massif, reaching the mean soil gas radon concentrations 96 $kBq \cdot m^{-3}$ compared to lower radon concentrations in granodiorites and granites (52–70 $kBq \cdot m^{-3}$). Also in the radiometric image the granitoids differ from crystalline series by enhanced gamma dose rate (100–210 $nGy \cdot h^{-1}$ compared to 40–80 $nGy \cdot h^{-1}$).

Moravosilesian region

The basement of Moravosilesian region can be divided into two parts according to influence of orogenetic processes. The western part is tectonometamorphically reworked during the Cadomian and later Variscan orogenesis and comprises mostly orthogneisses, phyllites and greenschists. The southeastern part reflects the influence of Cadomian tectonometamorphism only, including also the intrusion of Brno massif. The eastern part dips under the Carpathian Foredeep and nappes of Carpathian belt. From NW to SE the basement of Moravosilesian region is divided by extension of the Elbe zone (Haná zone – Variscan age). Radiometric image clearly demonstrates the border with Moldanubian region (40–70 $nGy \cdot h^{-1}$). The indoor radon concentrations are one of lowest in the Czech Republic and the anomalies (scarcely exceeding 80 to 90 $kBq \cdot m^{-3}$ can be traced only directly on the tectonically affected fault structures in Culmian sediments (northern part of Moravia). The Variscan magmatism is suppresed compared to above discussed regions and demonstrates itself only in the northern part close to the Polish border (Žulová pluton and tonalites).

Platform cover

Since the end of Variscan orogeny the Bohemian Massif was relatively stable consolidated part of Europe, having been subsequently covered by sedimentary series from Carboniferous, Permian, Cretaceous, Paleogene, Neogene up to Quaternary sediments. Radiometrically the Permo-Carboniferous sediments record gamma dose rate close to mean values, however the presence of U-enriched bitumenous series and coal seams represents the local radon problems. It must be noted, that even the "birth" of radon programme in the Czech Republic was in fact iniciated by discovery of enhanced gamma radiation in some types of building materials being partly produced from slag and ash coming from burning of specified Carboniferous coal seams in Central and NE Bohemia. The Rudník Permo-Carboniferous lithohorizon in northern Bohemia (enriched in

U sorbed in bitumenous layer) holds a record in the extreme measured soil gas radon concentration within the Czech Republic (1633.9 kBq . m^{-3} mean from 15 test probes and 3218 kBq . m^{-3} maximum value). Younger sedimentary formations have not brought any radon surprise in the surficial measurements (mean for Cretaceous sediments – sandstones and claystones 17.4 kBq . m^{-3}), however we must not forget the existence of synform uranium deposit Stráž pod Ralskem situated in the basal Cretaceous sediments in the depth of 200 m. The manifestations of inreased radon concentrations in this area are bound to local fault systems. Paleogene and Neogene sediments are far away from usual radon ranges in bedrock. The Tertiary neovolcanites have mean radon concentrations about 23 kB.m^{-3} with exclusion of phonolites, which exceed in certain cases 80 kBq . m^{-3}. However, due to the steep relief of phonolite cones, these areas are not usually settled and therefore together with a limited areal extent the phonolites do not represent and important radon prone areas.

Quaternary sediments can be considered as a special question (?problem?) in radon geology. First, the area covered by Quaternary sediments (calculated according to the geological maps 1 : 50 000 covers the area of 31 167 km^2, which is nearly one half of the Czech territory. Second, due to the historical reasons, nearly 57 % of municipalities are situated on the Quaternary sediments (mostly fluvial, along the watersheds). Third, the Quaternary sediments are usually allochthonous, formed by mixture of material transported from distance (non usually exactly determined) sources and represent also the geological environment with great inhomogeneities in permeability. Therefore, the attention should be given to radon risk assessment with respect to underlying rock types and considering the original sources of the sediments.

Carpathian belt

The Carpathian belt represents the youngest orogenic event (Palaeogene – Neogene) on the territory of the Czech Republic. Concentrically arranged nappes exhibit the pressure field from SE to NW and they are formed mostly by flysch sediments – sandstones, claystones, siltstones and conglomerates. This rocks' composition does not produce any radiometric and soil gas radon anomalies itself, but sligtly increased indoor radon concentrations can be observed in the dwellings situated in the tectonically disturbed zones along the nappes' fronts and deeper fault systems perpendicular to them. The Palaeogene and Neogene sediments exhibit the range of radon concentrations between 15 to 20 kBq . m^{-3}, gamma dose rate between 45–65 nGy . h^{-1}.

2. Brief history of Radon Programme in the Czech Republic

The first reference to negative health effects of radon appeared in the 16th century: Paracelsus described a specific "miners disease" that occurred in silver mines in Jáchymov (Joachimstahl) and Schneeberg. The symptoms and the development of the disease differed from those of tuberculosis. But as late as in 1951, Bale discovered the reason: inhalation of short-term radon decay products. The discovery was followed by first epidemiological studies, in the Czech Republic organized by Ševc et al. (1993). Other papers (Åkerblom and Wilson 1981, Åkerblom et al. 1984) described radon from bedrock as a main source of daughter products in dwellings.

In 1956, Hultquist observed high indoor radon concentrations in Sweden. In 80-ies, high indoor radon concentrations were observed also in Czech houses, at first in houses built from materials with higher content of ^{226}Ra (aerated concrete Poříčí and slag concrete – START houses).

The first governmental resolution about radon, as well as the first proposal of the uniform method for radon risk classification of foundation soils appeared in 1990 (Barnet et al. 1990). At the same time, the first radon risk maps of the territory of the Czech Republic at a scale 1 : 200 000 were published.

In 1991, the Decree of the Ministry of Health of the Czech Republic on the requirements for limiting radiation exposure due to radon and other natural radionuclides (No. 76/1991) was accepted. Two basic reference levels of indoor radon equivalent energy concentration (EEC) were defined: action level 200 Bq . m^{-3} of EEC for existing houses; guidance level 100 Bq . m^{-3} of EEC for new buildings. Preventive investigation levels for the content of ^{226}Ra in building materials and of ^{222}Rn in supplied water were also defined. In the same year, the governmental resolution No. 520 about purchase and remediation of START houses, and guidelines of the Ministry of Finance giving the rules for purchasing and supporting remediation activities were published. A complete set of uniform measurement methods has been available. Two years later, the governmental resolution No. 709 supporting the search for high radon houses and remediation in schools and action on water supplies was accepted.

In 1994, a modification of the origin proposal of the classification method for radon risk classification of foundation soils was published (Barnet 1994a, b).

In 1995, the competency in the field of radiation protection was transferred from the Ministry of Health to the State Office for Nuclear Safety by the Law No. 85/1995. The first version of the Czech National Standard CSN 73 0601 Protection of houses against radon from the soil was published.

In 1997, the Atomic Law (No. 18/1997) containing regulation and control of all possible radon sources and the Decree of the State Office for Nuclear Safety No. 184/1997 on requirements of radiation protection were accepted. The Czech National Standard CSN 73 0602 Protection of houses against radon and gamma radiation from building materials was published.

The year 1999 is the year of the acceptance of the governmental resolution No. 538 about radon programme.

In 2002, the Atomic Law was modified (No.13/2002) and the new Decree of the State Office for Nuclear Safety No. 307/2002 on radiation protection was accepted. Also