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Geological support to the National Radon Programme (Czech Republic)

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Abstract. Radon ^{222}Rn release from bedrock contributes substantially to the internal irradiation of the human body. The negative health impact of unregulated long-term exposure to radon has been proved in epidemiological studies. Because radon is generated by the radioactive decay from uranium-bearing rocks and soils, geological knowledge can contribute to defining the areas with enhanced radon exhalation from rocks and soils. In large plutonic rock bodies accessory minerals such as zircon or zirconium minerals in phonolites are considered to be some of the most intensive sources of radon. A uniform method for soil gas radon measurements applied in the Czech Republic as well as soil gas data processing have enabled us to construct maps of radon risk from bedrock in various scales. Different approaches to the constructing of the maps are discussed in the paper. The prediction of radon risk maps is illustrated using comparisons of indoor radon measurements and bedrock radon data. Detailed radon risk maps primarily serve for locating the indoor radon detectors, which, consequently, leads to advancing the detection of existing dwellings, which have exceeded indoor radon guidance level and their mitigation.

Abstrakt. Uvolňování radonu ^{222}Rn z geologického podloží přispívá podstatným podílem k vnitřnímu ozáření lidského organismu. Negativní účinky neregulované dlouhodobé expozice radonu byly prokázány v epidemiologických studiích. Protože radon vzniká radioaktivní přeměnou uranu obsaženého v horninách a půdách, geologický přístup umožňuje vymezit oblasti se zvýšenou exhalací radonu. Za nejintenzivnější zdroj radonu jsou považovány akcesorické minerály (zejména zirkon) v plošně rozsáhlých tělesech plutonických hornin a minerály zirkonia ve fonolitech. Jednotná metoda měření radonu v půdním plynu, aplikovaná v České republice, a zpracování dat měření radonu v půdním plynu umožňuje vytvářet mapy radonového rizika různých měřítek. Prediktivita radonových map je ilustrována na příkladu srovnání měření radonu v objektech a v geologickém podloží. V článku jsou diskutovány rozdílné přístupy k tvorbě map. Detailní radonové mapy slouží především pro efektivní rozmísťování stopových detektorů pro měření radonu v objektech. Tím je urychleno vyhledávání existujících objektů překračujících zásahovou úroveň koncentrace radonu a jejich následné ozdravování.

Key words: environmental geology, environment, radioactivity, uranium, radon, zirconium, geological hazards, radioactivity surveys, geoenvironmental maps, radon risk maps, National Radon Programme

Introduction

The human body is exposed to natural radiation from different sources. Besides extraterrestrial radiation, exposure to terrestrial sources and particularly to radon ^{222}Rn is considered to be the most important. The isotopic form ^{222}Rn, generated by radioactive decay of uranium ^{238}U, has the longest half-life (3.284 days) compared to radon ^{220}Rn (^{232}Th decay chain) and ^{219}Rn (^{235}U decay chain). Daughter products of the radioactive decay of ^{222}Rn are attached to aerosol particles, which, if inhaled into the lungs, cause an increase in the internal exposure of the human body and may consequently result in a higher incidence of lung cancer. The medical effect of internal radiation was already observed by Agricola on the population of Joachimsthal miners ("Joachimsthal disease") in mid-16th century, even though the diagnosis was not connected directly to radon. In the latter half of the 20th century, the health risk of radon inhalation was proved in the population of uranium miners. Since then, observations of the health impacts of radon have spread to all populations. The summarizing paper of Monchaux (2000) illustrates the role of radon exposure in human health. Epidemiological studies performed in different countries (Klener ed. 2000, Tomášek et al. 2000) refer to the increase in relative risk of lung cancer in a range of 9–15% in the exposure to indoor radon activity of 100 Bq.m^{-3}. The measurements of radon in dwellings initially recognized the building material as the main source of radiation for the specified population. The following research of sources of radon in building materials and internal atmosphere of dwellings led to studies of the distribution of radon in geological bedrock (Reimer and Tanner 1991, Gundersen and Wanty 1991, Gates and Gundersen 1992, Clavensjö and Åkerblom 1994). At present, the geological bedrock is considered to be the major source of radon. Human health protection requires the detection of radon in already built dwellings exceeding the guidance level (200 Bq.m^{-3} of equivalent equilibrium radon concentration in the Czech Republic, corresponding to other European countries) by means of indoor radon measurements and subsequent mitigation. Therefore, the predictive maps of radon risk based on geological knowledge can serve efficiently to locate the indoor track-etch detectors into particular areas and dwellings and can advance this process. The grounds for newly built houses are checked by radon building-site assessments, which already help to apply adequate protective measures against radon from bedrock during building construction.

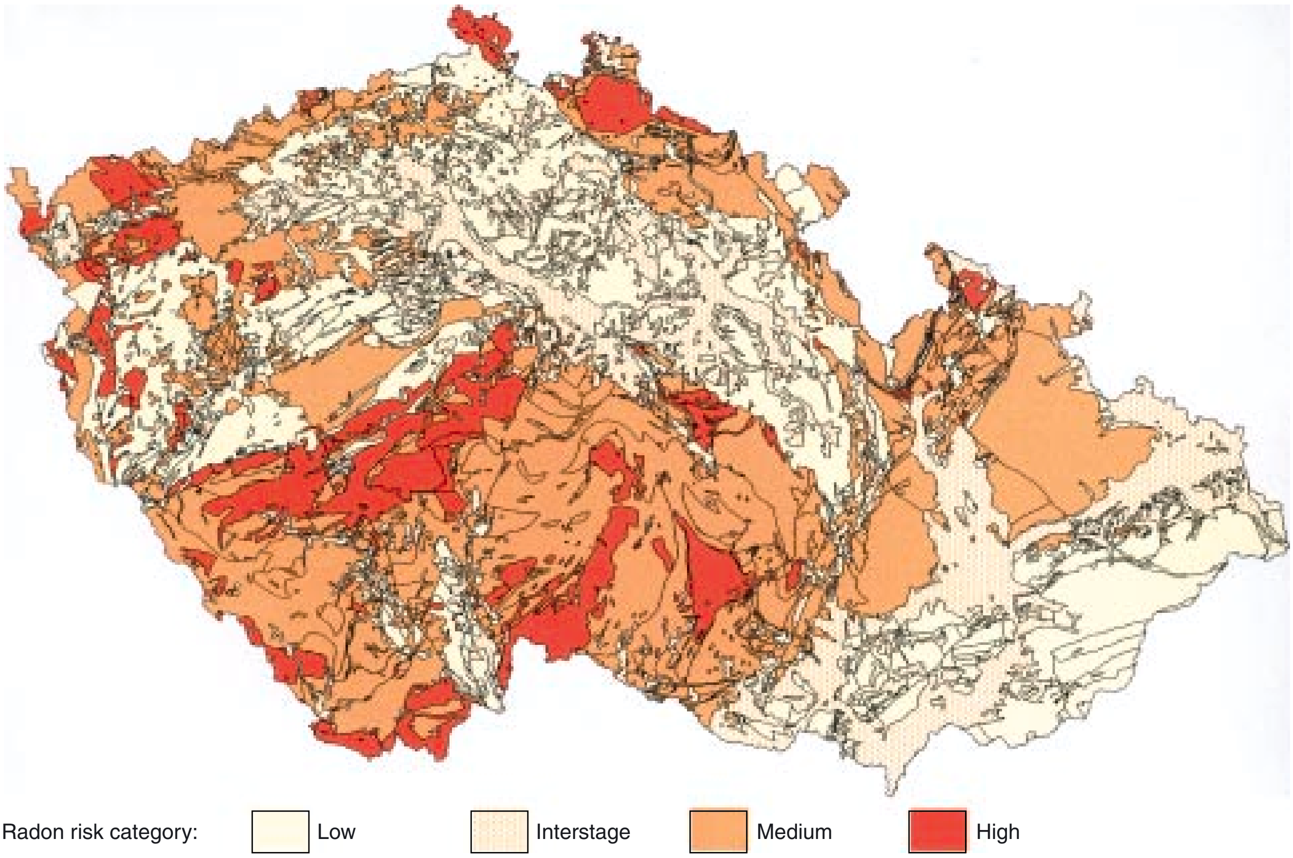

Fig. 1. The radon risk map of the Czech Republic (original scale 1 : 500 000).

Radon Programme in the Czech Republic

The present research of radionuclides in dwellings has revealed that the Czech Republic is one of the countries with the highest level of average radon concentrations in buildings in the world.

The Czech Republic belongs among countries with a significant proportion of igneous, especially granitic, and metamorphic rocks in its bedrock. These rocks can be the source of enhanced natural radiation. Due to its geological abnormality the Czech Republic requires a multidisciplinary approach to this problem, which resulted in the Radon Programme (The Governmental Decision No. 538 valid from 31st May 1999 "Radon Programme of the Czech Republic"). This decision was preceded by a number of legislative acts. Initially, the problem of public protection from radiation caused by natural radionuclides was resolved in 1991 by the legislative Decree of Ministry of Health No. 76 "Lowering of radiation from radon and other natural radionuclides". In 1993, the Decree of the Government No. 709 "Protection of the public from radiation caused by radon and other natural radionuclides" was issued. This legal norm was followed by the Act No. 18/1997 effective as of 24th January 1997, amended as the Act No. 38/1998 "Act No.18/1997 Coll., on Peaceful Utilization of Nuclear Energy and Ionising Radiation (the Atomic Act) and on Amendments and Additions to Related Acts". Irradiation caused by natural sources was mentioned in paragraph 6. This act was followed by the Decree of the State Office of Nuclear Safety No. 184/1997 "Requirements for the radiation protection". Radiation security against radon risk from geological background was presented in paragraph 63.

Assuming that the increased values of radon concentration in dwellings were caused by geological bedrock, the Czech Geological Survey offered its experience in geological knowledge of the state territory by proposing the methodology and locating the areas where indoor radon level could exceed the guidance level (over 200 $Bq.m^{-3}$ equivalent equilibrium concentration). The following institutions are involved in the Radon Programme of the Czech Republic:

State organizations:

State Office of Nuclear Safety – head organization managing Radon Programme.

National Radiation Protection Institute – deals with the impact of irradiation on health of the population, directs the locating and evaluating of track-etch detectors in particular dwellings and allocates the donation for mitigation precautions.

National Institute for Nuclear, Chemical and Biological Protection – ensures the calibration of instruments and analyses of samples, etc.

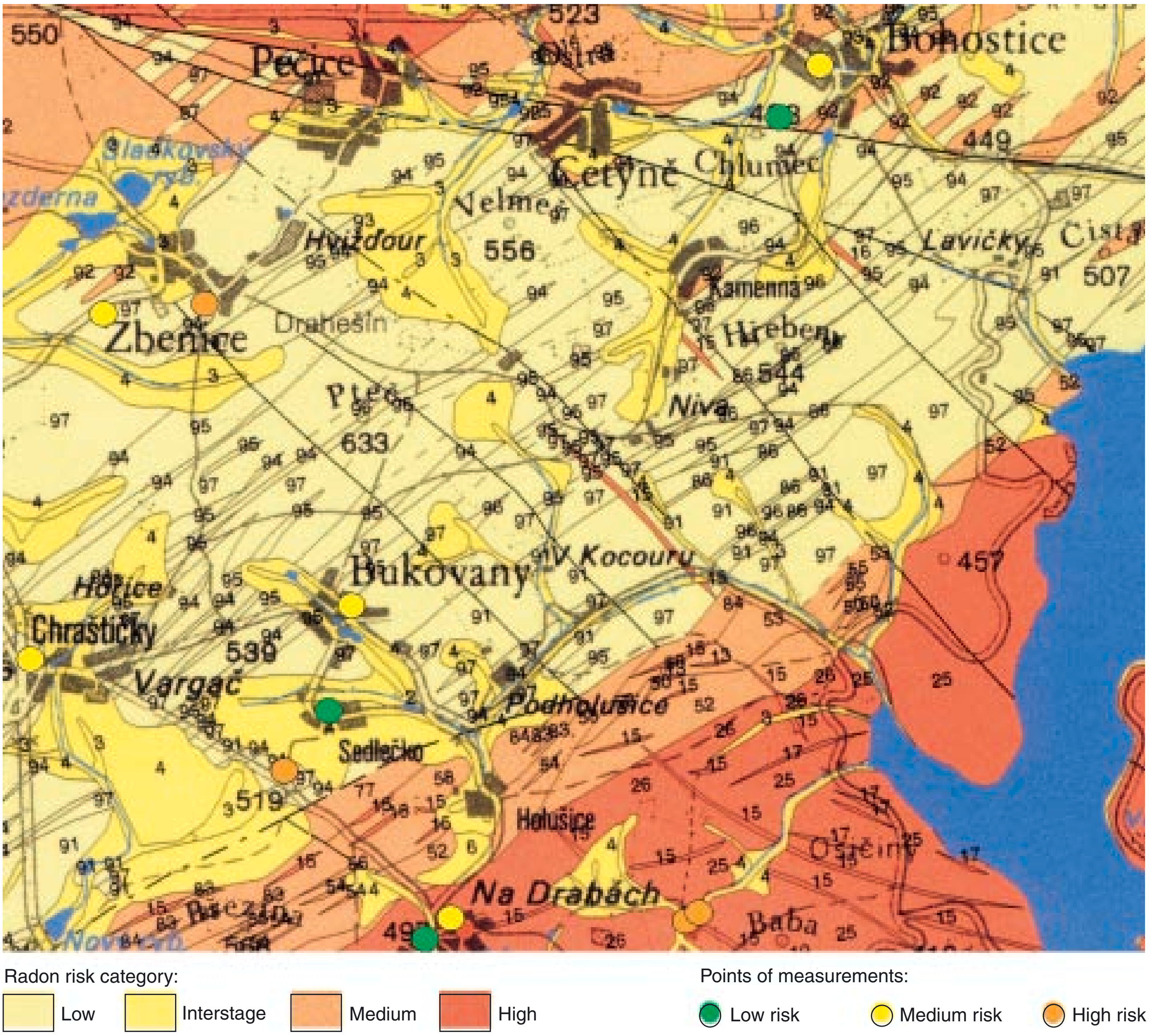

Fig. 2. The section of the radon risk map, sheet 2221 Příbram (original scale 1 : 50 000).

Czech Geological Survey – develops the measuring methodology and the methodology of radon risk maps construction, realizes the radon risk mapping from geological bedrock, co-ordinates data collecting from field measurements, administrates the radon database and guides state office employees for locating track-etch detectors.

Faculty of Science, Charles University – in cooperation with the Czech Geological Survey develops the measuring methodology, locates the reference test sites.

Czech Technical University – develops building mitigation systems.

Other participants in the Radon Programme:

Municipal authorities – especially building offices and district radiation protection stations.

Radon Risk Association – association of private firms, which contribute to the radon database and participate in the research programmes.

During the past ten years the Czech Geological Survey took part in preparing the legislation. In 1990, a standardized methodology for the classification of radon risk on building properties was issued, the Interministerial Radon Commission was established and the first radon risk maps on the scale of 1 : 200 000 were published. This was followed by the detailed research of radon characteristics in tectonic deformations, the influence of permeability and influence of climatic conditions, etc. A unified soil gas radon database was founded in 1992. The need for the unification of measurements led to the establishment of reference test sites in 1990. In the same year, the Radon Risk Association was established, affiliating private firms engaged in soil gas radon measurements.

Vectorization of geological and radiometric maps (1 : 500 000) was finished in 1998 and a radon risk map to the same scale was published.

Methods and Instruments

The instruments are based on different principles depending on how they are utilized. The principles of the widely applied techniques for radon measurements used in the National Radon Programme are:

alpha track foils – this principle is used in track-etch detectors for indoor measurements;

luminescence caused by alpha particles – Lucas cells, emanometers.

Emanometers operate on the principle of an ionization chamber or scintillation Lucas cells. Scintrex RDA 200 portable instrument with exchangeable Lucas cells is used in the Czech Geological Survey. A sample of soil gas is pumped from probes driven to a depth of 80 cm. We use the method of small-diameter steel tubes with the "lost tip". On the basis of the different effects of the alpha radiation of ^{222}Rn and ^{220}Rn both isotopes can be determined qualitatively and quantitatively by 3 measurements at one-minute intervals after the soil gas has been introduced into the detection chamber. All units participating in the Czech Radon Programme must be calibrated in the national radon chamber and field-tested at the reference sites to ensure comparability and reliability of results. All instruments used for radon risk mapping have to obtain a certificate of calibration, which is issued by the National Institute for Nuclear, Chemical and Biological Protection, located at Kamenná (Příbram district, central Bohemia). Three reference test sites are situated near Příbram in the field in natural conditions. Each of these test sites is formed by a typical rock generating specific radon activity concentration in soil gas.

For a small building site assessment usually 15 samples of soil gas are measured. The resulting category of radon risk (or radon index – terminology used since September 2001) is a combination of radon activity concentration in the soil gas and soil permeability measured in situ or obtained from grain-size analyses. An increase in radon activity concentration with depth depends on the rock type – it is observed in granitic rocks but mostly absent in sedimentary or metamorphic rocks. The effect of inhomogeneity in radon activity concentrations is suppressed by using a 75% quantile of the radon data set as an input parameter for the radon risk classification. Seasonal variations of radon have no relevant influence on the classification because the changes in radon concentration activity are related to changes in permeability.

Soil gas radon database

In 1990, a standardized methodology for soil gas radon measurements was introduced and reference test sites were founded. This means that the results of measurements from different companies are compatible; their measuring devices obtained the state certificate of competency and all radon companies in the Czech Republic (presently more than 100 companies) use a uniform classification of radon risk. This has enabled the input of data into the soil gas radon database, administered by the Czech Geological Survey.

Since then, the number of test sites has increased to more than 8 900 and the acquired data already cover all major geological and lithological units. The sufficient number of measured samples permits to use statistical analyses for the evaluation of the categories of radon risk in a geological unit.

The soil gas radon database contains the following items:

Location data – X and Y coordinates, number of map sheet (1 : 50 000), name of locality, description of test sites, number in database, reference number.

Radon data – number of measurements, radon mean, median, standard deviation, radon minimum, maximum, 75% quantil (all data in kBq.m^{-3}) and the resulting radon risk category.

Uranium data – content of uranium (in ppm) obtained by field gamma-ray spectrometry, if measured.

Soil data – category of permeability, fine fraction f (%).

Geological data – bedrock, cover, anthropogenous influence, tectonics.

Other data – date of measurement, source of data, method of measurement, method of soil air sampling.

The source of radon in bedrock

Radon ^{222}Rn, which enters the internal atmosphere of dwellings, is generated in bedrock by radioactive decay of uranium ^{238}U. This element is present in all rock types in different concentrations. Rather than discussing rock types with small areal extent over the territory of the Czech Republic (like black shales), we shall concentrate on the high-U rocks forming large bodies. Generally speaking, the spatial distribution of uranium can serve as basic supporting information for determining the areas with enhanced soil gas radon activity (not considering many other factors influencing radon entry into dwellings). We must distinguish two types of uranium occurrence in rocks. Uranium occurs in locally anomalous areas (as uranium mineralization) and is unevenly distributed in the rock-forming minerals. From the viewpoint of radon entry into dwellings more attention must be given to uranium bound in rock-forming minerals (much more abundant).

In the Czech Republic, a general radiometric overview was published by Manová and Matolín (1995). The gamma dose rate map (even if compiled from the contributions of ^{40}K, ^{238}U, and ^{232}Th concentrations) demarcates the most radioactive rocks within the country. These are mostly plutonic rocks (durbachites and syenites) and Tertiary volcanic rocks – phonolites.

Fiala et al. (1983) reported the maximum U concentrations of 19.8 ppm in durbachite and syenite rocks of the Čertovo břemeno massif, the Třebíč massif, the Tábor massif and the Jihlava massif (the mean concentrations in the mentioned bodies are 11.5, 12.0, 10.2 and 5.2 ppm). The authors also mentioned the fact that U (and Th) concentration has no relation to the petrographic character of the durbachites (namely the contents of alkali feldspar and plagioclase). Uranium concentrations in rocks of the durbachite series presented by Holub (1997) show generally the same range (10.1–26.6 ppm). Zircon is considered to be an important accessory mineral (Zr concentration varies between 50–520 ppm). A similar observation is described by Leichmann et al. (1998) from alkali feldspar syenites of the Gföhl Unit, where uranium concentration up to 370 ppm and zircon contents up to 5% have been reported from leucocratic syenite. A summarizing table of uranium concentrations in rock-forming minerals was cited by Siehl (1996). Uranium concentrations increase in a succession from light rock-forming minerals (0.1–8 ppm) across dark minerals (0.01–40 ppm) to accessory minerals with the highest concentrations in zircon (300–3 000 ppm) and xenotime (500–35 000 ppm).

A similar radiometric pattern as in plutonic rocks of durbachite and syenite series can be observed in phonolites of northern Bohemia. Matolín (1970) placed phonolites among rocks with the highest radioactivity (reported U-range 16–22 ppm). Analyses summarized by Shrbený (1995) confirm the phonolites as the rocks with the highest U concentration (mean 9.93 ppm) compared to other neovolcanic rock types. Previous sources reported U concentrations in phonolites of 10–15 ppm (Krutský 1991) and 25–35 ppm (Chlupáčová et al. 1991). The latter paper also mentioned a correlation among Th, U and Zr (U-Zr correlation is weaker than Th-Zr). In the mineralogical study of Ulrych et al. (1992), the highest zirconium concentration among phonolites of the Bohemian Massif was reported from Sokol Hill in northern Bohemia (2 650 ppm), where Zr is bound to the mode of fluorian eudialyte. An increased concentration of U in phonolites (mean 10.2 ppm) was confirmed on the slopes of Sokol Hill by ground gamma-ray spectrometry measurements performed by the Czech Geological Survey. The soil gas radon measurements detected maximum values of 61.1 $kBq.m^{-3}$ at the same place. The highest soil gas radon value (465 $kBq.m^{-3}$) was encountered in phonolites north of Čeřeniště near Ústí nad Labem (northern Bohemia). Some other zirconium minerals such as calzirtite from ijolite (Osečná locality, northern Bohemia) exhibit UO_2 contents of up to 0.1%. Geochemical abnormality of phonolites was confirmed by another chemical analysis of phonolite: Zlatník Hill, northern Bohemia, with Zr content of 1460 ppm (Pazdernik 1998). A relationship of uranium and zirconium with low-temperature mineralization was observed in northern Bohemia (Majer and Čadek 1979), and a spatial relationship of the latter with high-zirconium rocks was observed in the vicinity of the Lužice (Lusatian) Fault.

Increased zirconium content was also described by Kodymová and Štemprok (1993) from the highly radioactive Teplice rhyolite and granite porphyry. A clear Zr-Th and U-Th relationship in porphyritic biotite granite of the Smrčiny (Fichtelgebirge) pluton was observed by Chlupáčová et al. (1998). The same Zr-Th relationship was reported by Breiter et al. (1998) from the granites of the Central Moldanubian pluton.

Considering the fact that the most radioactive plutonic and volcanic rocks within the Bohemian Massif are rich in zircon (or other zirconium minerals in case of volcanic rocks), it seems that zircon content in plutonic rocks and the presence of other zirconium minerals in volcanic rocks are the leading factors for their radioactive potential and consequently radon potential, when considering the rock body as a whole.

Uranium contained in rock-forming minerals represents a much more significant source of radon than uranium connected with U-mineralizations because it occurs in relatively small and areally confined, usually uninhabited areas.

Radon risk mapping in the Czech Republic

The first radon risk maps on the scale of 1 : 200 000 were published in 1990. The set of 7 maps included regional maps, which covered the whole country. These maps were based on 148 reference test sites situated in major lithological units. The maps were hand-drawn, not suitable for computer processing. They were sent to regional radon protection institutions to select the location and distribution of track-etch detectors in the whole country.

Vectorization of geological, radon and gamma dose rate maps on the scale of 1 : 500 000 was finished by the Czech Geological Survey in 1998. The radon risk map was based on a statistical evaluation of 6 900 test-sites from the radon database. The first version was prepared in the MapViewer 2.0 program, transformed to *.dxf files. Vectorized contours of geological units were filled according to the prevailing radon risk. The point data of the radon test sites as well as the contours of enhanced gamma dose rate from the radiometric map were shown.

In 1998, the Czech Geological Survey initiated activities on a joint project involving seven state and private subjects to publish a special CD with a geoscientific theme – GEOČR500. The radon risk map was one of eleven maps of a digital atlas presented by the Geographic Information System. Additional maps were included in the GIS Atlas GEOČR500: geological map, gamma dose rate map, geomagnetic map, radon risk map, gravimetric map, map of mineral waters, metallogenic map, map of the land cover, topographic map, satellite image and digital altitude map. The CD was made "user-friendly" for the municipal authorities, with no demands for additional software (opened in AutoRun and ArcExplorer). An example of a radon risk map 1 : 500 000 is given in Fig. 1.

Vector data on the CD are in the Esri shape file, raster

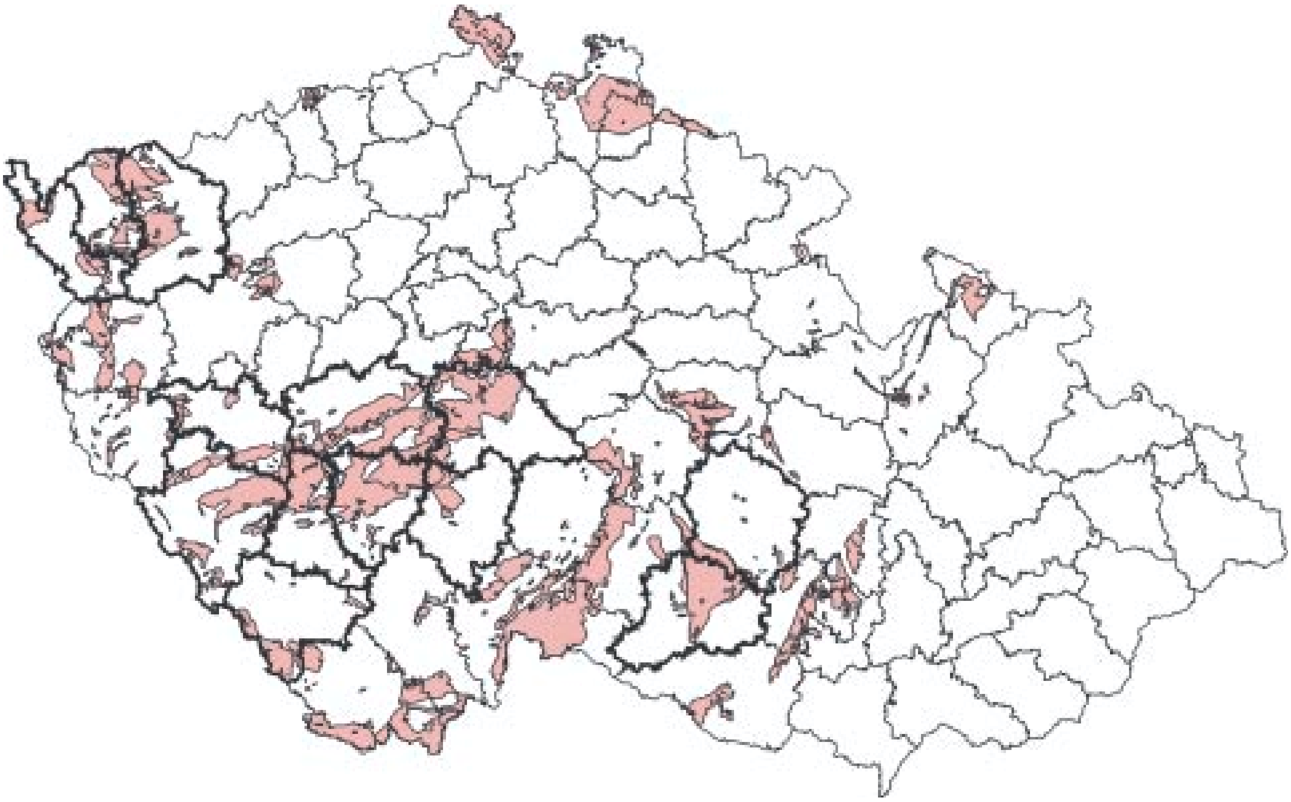

Fig. 3. Areal extent of granitic rocks and districts where more than 20 % of indoor radon measurements exceeded the guidance level of 200 Bq.m^{-3} equivalent equilibrium concentration (bold frame, source of data www.suro.cz).

data in *.tiff format and tabulated data in *.dbf format. The project allows the user to choose from 3 coordinate systems (Křovák, Gauss Krüger and S42).

The maps on the scale 1 : 500 000 are used just for overview information. In 1999, the Czech Geological Survey started the construction of the radon risk maps to scale 1 : 50 000. In the future, the whole country will be covered by a total of 214 map sheets. 89 map sheets have been published by 2001.

Vectorized contours of particular rock units were used. Each geological map sheet usually contains approximately 40 to 90 rock types, which are grouped according to the prevailing radon risk derived from the radon database in MGE program. Transformed into the MicroStation program, the modified contours of rock units are filled according to the prevailing category of radon risk. The filled contours form the most important vector layer over which the layer of faults and tectonic zones is placed. The test site positions, digitized using the Didger program, are also shown on the map. The radon risk of particular rock units is expressed in four categories – low, interstage for inhomogeneous Quaternary sediments, medium and high. The whole computer procedure for constructing the maps was described by Barnet et al. (2000).

Besides printouts, the maps 1: 50 000 are published on a CD. The points of the test-sites (about 8900 for the whole country) are linked to selected items from the radon database in a separate window. Transitions to quadrangles of adjacent map sheets are performed in four directions on each of the map sheets. Explanations concerning the behaviour of radon in bedrock and information about the national Radon Programme are added as well as the geological explanations of rock units. The CD application (AutoRun, Internet Explorer 4.5 or higher) is used by municipal authorities for the distribution of track-etch detectors within the districts and villages. A sample of the map is presented in Fig. 2.

Prediction of radon risk

The main use of the radon risk maps is to identify the dwellings exceeding the guidance level of indoor radon (200 Bq.m^{-3} of equivalent equilibrium concentration). Some 115 000 indoor radon measurements have been performed since 1990. The first radon maps published in 1990 to scale 1 : 200 000 helped to locate the track-etch detectors used for indoor radon measurements preferably to areas where, according to geological knowledge, increased radon risk from bedrock was expected. The general efficiency of the distribution of track-etch detectors can be illustrated on the summarized results of indoor radon measurements in the districts, published by the National Radiation Protection Institute (NRPI) on www.suro.cz. The districts, where more than 20% of indoor radon measurements exceeded the guidance level of 200 Bq.m^{-3}, lie in the area of the granitic Central Bohemian pluton and the syenite Třebíč massif (see

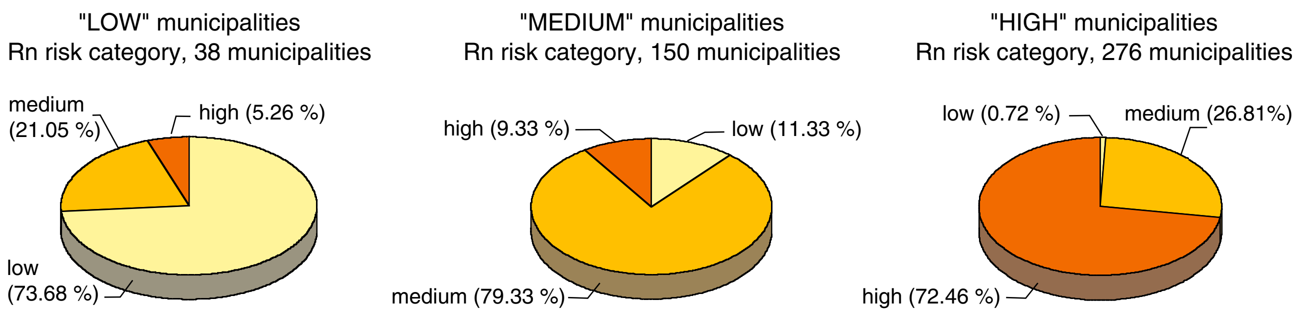

Fig. 4. A comparison of indoor geometric means in 464 municipalities and prevailing radon risk category in bedrock of municipalities according to radon maps 1 : 200 000. "Low" municipalities (<1% of dwellings expected to exceed the guidance level of 200 Bq.m^{-3} EEC), "medium municipalities" (1–10% of dwellings expected to exceed the guidance level of 200 Bq.m^{-3} EEC), "high municipalities" (>10% of dwellings expected to exceed the guidance level of 200 Bq.m^{-3} EEC).

Fig. 3). This comparison leads to the conclusion that the areas with expected increase in indoor radon activity concentration can be generally confined according to a basic knowledge of the geology of the studied area.

As the number of indoor radon measurements and soil gas radon measurements has increased since 2000, another comparison of indoor results and geological prediction was performed. The results of indoor radon measurements are stored in the database of the NRPI. From this database, indoor geometric means for 464 municipalities were selected, where more than 30% of dwellings were measured. These municipalities were divided into three subsets – where < 1%, 1–10% and > 10% of dwellings are expected to exceed the guidance level of 200 Bq.m^{-3}. The prevailing radon risk from bedrock was derived from maps 1 : 200 000. The results of this comparison show a coincidence of the predicted radon risk from bedrock and the expected radon levels in dwellings in 75% on average (Fig. 4). The remaining 25% of underestimation or overestimation of radon risk from bedrock are caused mainly by the differences between the detailed geological situation and generalized geology in maps 1 : 200 000 as well as by unknown structural status of the houses (type of house, quality of sealing of the basement slab, etc.).

A more detailed comparison of geological prediction and indoor radon levels was performed on the basis of radon risk maps from bedrock to scale 1 : 50 000. The codes of municipalities from the indoor radon database of NRPI were linked to the coordinates of the centres of the municipalities (Ministry for Regional Development). A new layer of topographically situated indoor geometric means for municipalities in two districts (Jindřichův Hradec – 51 municipalities and Příbram – 77 municipalities) with the highest level of indoor measurements coverage was added to the already existing radon risk maps 1 : 50 000, and indoor radon levels were compared to the prevailing category of radon risk in the municipalities. The results of this comparison are shown in Figs 5 and 6. In the Jindřichův Hradec district, the increase in indoor geometric means corresponds to the predicted category of radon risk from bedrock from the Neogene and Cretaceous sediments (lowest) to granitic plutonic rocks of the Central Moldanubian pluton (highest).

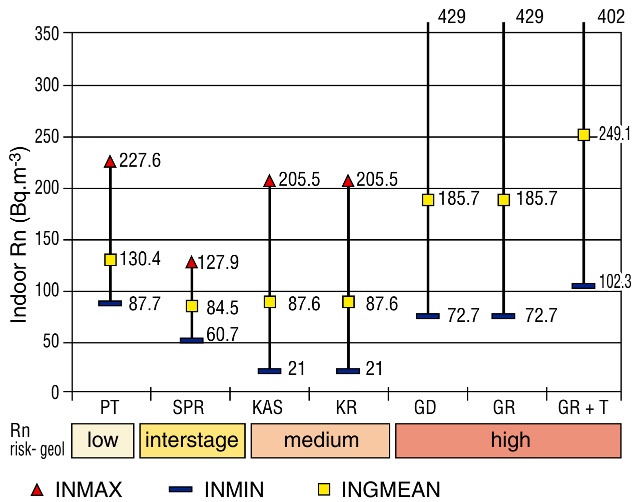

Fig. 5. A comparison of indoor geometric means (ingmean), minimum (inmin), maximum (inmax) and radon risk categories in 77 municipalities of the Příbram district according to radon maps 1 : 50 000. Explanation of rock types: PT – Proterozoic, SPR – loess, KAS – Cambrian, KR – paragneisses, GD – granodiorites, GR – granites, GR+T – tectonically affected granites.

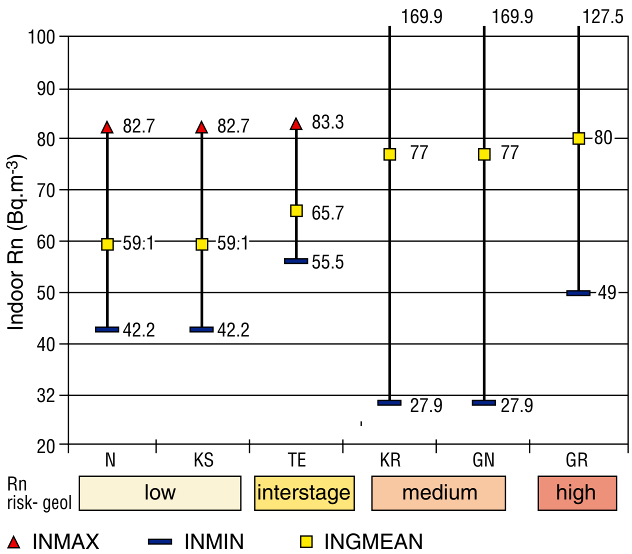

Fig. 6. A comparison of indoor geometric means (ingmean), minimum (inmin), maximum (inmax) and radon risk categories in 51 municipalities of the Jindřichův Hradec district according to radon maps 1 : 50 000. Explanation of rock types: N – Neogene, KS – Cretaceous, TE – river terraces, KR – paragneisses, GN – orthogneisses, GR – granitoids.

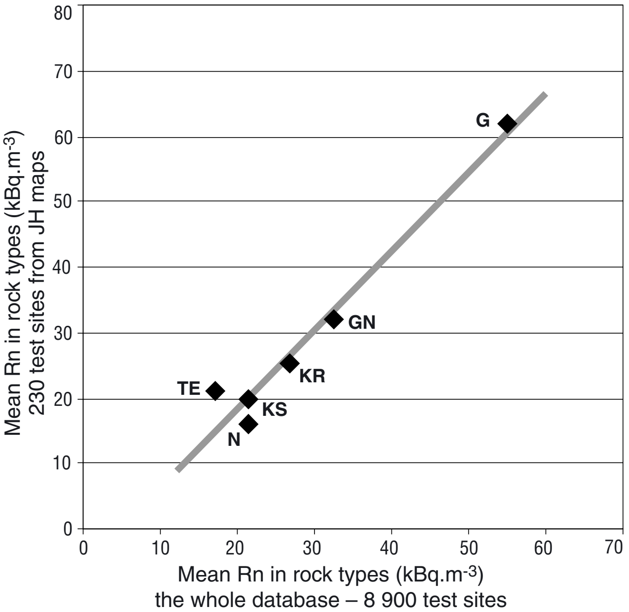

Fig. 7. Relationship between mean soil gas radon values in different rock types calculated from 8 900 test sites from the radon database (whole state territory) and those from 230 test sites situated on 9 map sheets 1 : 50 000 covering the Jindřichův Hradec district. Explanation of rock types: N – Neogene, KS – Cretaceous, TE – river terraces, KR – paragneisses, GN – orthogneisses, G – granitoids.

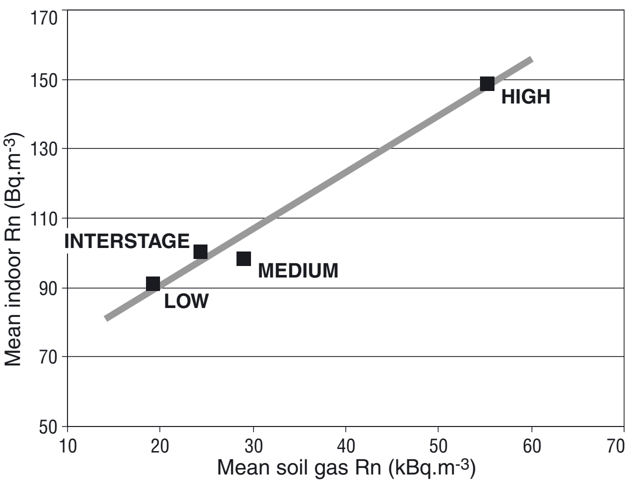

Fig. 8. Relationship between mean soil gas radon values in four radon risk categories and mean indoor radon values in 3631 dwellings in the Jindřichův Hradec district.

In the Příbram district, the relationship between indoor radon and soil gas radon levels is not so obvious. The general trend of increasing indoor radon with increasing soil gas radon is affected by the high indoor radon mean in Proterozoic metasediments. A detailed study of this divergence leads to a statement that most of the indoor data come from the municipalities in the NE prolongation of the Příbram U-mining district where the increased frequency of U anomalies was detected by previous airborne and ground gamma-ray spectrometry. It is also obvious that a substantial increase in indoor geometric means is found in municipalities where granitic bedrock is influenced by tectonics. The above mentioned detailed indoor radon vs. soil gas radon comparisons reflect the relationship between radon in bedrock and indoor radon concentrations. They are, however, more sensitive to the influence of local geological situation.

The most exact indoor radon vs. soil gas radon comparison so far performed was using coordinates of particular buildings (the coordinate test file from the Czech Statistical Office – 3 631 dwellings, corresponding to indoor radon data from NRPI database). This comparison was performed in the Jindřichův Hradec district with its variegated geological situation (presence of all radon risk categories in predictive maps) and sufficient coverage of indoor radon measurements. The exact link of particular dwellings with the bedrock geology was done using the Arc View project. The only uncertainities are the structural conditions of the buildings (data sets are not sufficient) and the difference between geology in situ and geology presented in maps 1 : 50 000. This is the highest level of precision so far achieved.

In the Arc View project the predicted radon risk category from the bedrock as well as the rock type were derived by linking the position of a particular dwelling to its corresponding radon risk map 1 : 50 000. As the available positions of dwellings do not coincide with the positions of the test sites of soil gas radon measurements, for each rock type the mean radon value from the whole soil gas Rn database was substituted and attributed to particular houses. The means calculated from the whole database (8900 test-sites) do not differ substantially from those calculated from the 9 selected map sheets covering the area of the Jindřichův Hradec district (Fig. 7). The whole data set was divided according to the resulting radon risk category expressed in the maps (low, interstage, medium and high). Results of indoor radon – soil gas radon concentrations are given in Fig. 8 for a total of 3 631 dwellings. It is obvious that a high level of radon in the bedrock causes an increase in indoor radon, though not considering the technical state of the houses, which may sometimes substantially influence the soil gas radon entry into the buildings.

The results of indoor radon vs. soil gas radon comparisons performed at different scales clearly show the importance of geological prediction for confining the areas exceeding the indoor radon guidance level.

Discussion

It is necessary to realize that the levels and methods of radon risk mapping closely depend on the structure of national radon programmes. Different approaches are applied to determine the areas with increased levels of indoor radon in national radon programmes. Soon after launching indoor radon measurements on a nation-wide scale, it became obvious that the areas with high indoor radon values show a relationship to geological characteristics of the bedrock. The role of geology in national radon programmes was emphasized by Åkerblom (1987). In the early stage of radon programmes, the countries were intensively using airborne gamma-ray spectrometric data for determining the radon potential areas (Lindgren 1998, Gundersen 1991, Nero et al. 1996). This type of radon prediction was based on the uranium concentration in the rock types and additional soil cover characteristics. The technical development of instrumentation for soil gas radon measurements as well as the development of methods and studies of factors influencing the radon release from soils helped to exactly determine radon potential on a nation-wide scale. The geological approach for compiling the radon risk or radon potential maps based on soil gas radon measurements was applied in the Czech Republic (Barnet et al. 1998, Barnet and Mikšová 2001), in Germany (Kemski et al. 1994), Luxembourg (Kies et al. 1994), Belgium (Tondeur et al. 2001), Great Britain (Ball 1994, Appleton and Adlam 2000), Austria (Maringer et al. 2001), Italy (Astorri et al. 2000) and other countries. At the beginning of constructing the maps, the indoor data were considered more important than geology in some countries. The data sets were usually treated by gridding statistical methods, which, in fact, smoothed out the exact topographical position of indoor data and weakened their link to underlying geology. Adding further factors (soil type, thickness of cover, permeability, soil moisture etc.) into the grid cells emphasized the role of the bedrock, however, the gathering of these data was financially demanding and time-consuming. Confining of the grid extent to the contours of geological units and rock types was therefore applied (Kemski et al. 1998). The development of GIS systems allowed the radon risk maps to be based on the vectorized contours of rock types with additional indoor radon information. Some further trends in radon risk mapping are orientated to calculating the transfer factor (Klingel et al. 2001) between radon in soil and indoor radon, which necessitates data from studies on technical characteristics of the houses and corresponding indoor concentrations. The limits of radon risk maps must be, however, taken into account. The first restriction is the detail of input geological data in the maps. Non-geologists (who are in fact the main users of radon risk maps) usually believe that the probability of correct prediction increases as the maps become more detailed. In fact this idea consequently leads to a building site assessment for each building site, and the maps lose their predictive character. The second restriction concerns the technical characteristics of newly built houses. It must be emphasized that houses below the action level can be built even on high-risk bedrock if construction requirements are strictly followed (Jiránek 2000), but the prediction of radon risk from bedrock is necessary for adjusting the project in terms of tightness of the construction. We have come to a conclusion that a building site assessment will be necessary for new constructions due to the variability of local geological situation. Pre-calculating the indoor radon concentration from soil gas radon concentration in particular cases may be speculative and strongly dependent on the quality and reliability of input data.

Conclusions

The change in the orientation from nation-wide indoor radon surveys to detailed particular dwelling surveys has emphasized the importance of geology to protect the public from geogenic radiation. The mapping of radon risk from bedrock has become an integral part of national radon programmes. The results of surveys performed in the recent years permit to make the following conclusions:

1. The experience with different approaches to radon risk map construction has proved that maps based only on U concentration in rock types cannot achieve the precision and reliability of maps based on soil gas radon measurements.
2. A necessary condition for any type of statistical treatment of radon data is the calibration of instruments in a radon chamber as well as the field testing at reference test-sites to ensure reliability of data.
3. The use of vectorized contours of rock types is recommended in geologically based radon risk maps. Grid processing does not respect the complexity of geological setting, and topographically linked outputs illustrating radon characteristic of a particular area can be misleading.
4. Durbachites and syenites have been so far considered to show the highest radon activity concentration within the territory of the Czech Republic. The latest observations based on petrological and mineralogical studies as well as field-testing discovered that radon activity concentration of phonolites reaches levels comparable with the above mentioned rock types; phonolites should be considered as a new high-radon potential rock type in the Czech Republic. The elevated radon activity concentration of the above mentioned rock types is caused by the presence of accessory minerals with high U concentrations (predominantly zircon and zirconium minerals).
5. The Czech Geological Survey issues radon risk maps on the scale 1 : 50 000 based on vectorized contours of rock types. The unique process enables to compare the bedrock radon prediction to indoor radon data down to the scale of a particular dwelling. The potential for correct prediction reaches 70–80% in all radon risk categories (low, interstage, medium and high) in different lithological environments. This fact supports the use of radon risk maps as an effective tool for the identification of dwellings exceeding the guidance level.
6. It must be emphasized that further detailization of mapping and comparisons down to the scale of particular dwellings is strongly influenced by the structural state of the house construction. Therefore, building site assessments are required prior to constructing new houses to fit the project to local geological and radon situation.

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