tion) characteristics. Both types of data are regionalized in the 3 × 3 km grid with distance weighted interpolation within geological units and detailized into 0.5 × 0.5 km grid. The predition of indoor radon levels from geogenic radon potential emphasizes also the role of housing conditions and density of sampling plus the scale of geological maps used to improve the accuracy of prediction. Detailed studies soil gas – indoor radon performed in 68 counties with different geological basement support the presented method.

In Belgium the present methodics is oriented to 8 radon prone areas derived both from geological data (985 soil gas radon measurements) and indoor radon measurements (1366). Within the project of Federal Agency for Nuclear Control (Dehandschutter 2006) the soil gas and indoor radon measurements were performed in the grid net 1 × 1 km, where transfer factor (indoor/soil gas) was calculated for each grid cell to determine the radon potential. The detailization is performed into grid 250 × 250 m. After solving problems with clustering data the geological and pedological factors seem to be the main source of regularity or anisotropy of data. Further studies are oriented to using the kriging with various parameters (Tondeur 2006) and geometric indoor mean is considered to reflect best the variations between areal units.

Miles et al. (2005, 2007) have presented the Indicative Atlas of Radon in England and Wales based on indoor radon measurements in 460 000 homes and further implying the selection criteria after the geological boundaries between geological units and 1 km grid cells. Bedrock and superficial layers georeferenced after maps of British Geological Survey at a scale 1 : 50 000. Together with georeferencing the indoor measurements geometric indoor mean and percentage of houses above action level in one grid square were calculated. The radon potential is derived within 1 grid square where criterion of more than one percent occurence limit of the highest radon potential was set for indicating the highest radon potential in the whole cell.

Additional method was presented by Scheib et al. (2006). The method was tested in Derbyshire (Central England, area 14 000 km^2) and is based on the 1 × 1 km gridded data of airborne and ground gammaspectrometry accompanied by 70 m long soil gas radon traverses. The correlations of geometric mean eU data and geometric mean indoor radon data with estimated percentage of houses above the action level showed a very good correlation (R^2 = 0.89 to 0.97). The resulting correlation is also influenced by clay contents of soil which can be related to K concentration from gammaspectrometric measurements.

The indoor radon survey (about 40 000 measurements in 17 000 rooms in 8500 dwellings) was performed in Austria within the radon project Önrap (Friedmann and Gröller 2006, Dubois et al. 2007). The indoor data were gathered and grouped within municipalities' borders. The indoor data were expressed in the 3 radon potential levels. Further specification required implying the bedrock characteristics. The radon potential is therefore newly calculated using Bayes statistics (Gröller and Friedmann 2007) as the weighted average of radon potential at the measurement sites and the weight is probability derived from the geological information. Due to the geological similarity the soil gas data from the Czech Republic and Germany are used for characterization of particular rock types in Austria (Bohemian Masssif for crystalline and magmatic formations and Alpine belt for sedimentary formations).

A wide range of soil and geological radiometric methods was used for setting the radon risk map of Estonia 1 : 500 000 (Petersell et al. 2005). On 566 observation points covering the major geological units and lithological types the soil gas radon concentration (direct) and recalculated from U, gammaspectrometry K, U, Th and natural radiation of soil. The resulting radon risk map from bedrock is also accompanied by indoor radon measurements (annual mean indoor concentrations) for municipalities.

11. Comparison of radon in soil gas and indoor radon

11.1. METHOD AND DATA SOURCES

The soil gas – indoor radon comparison is based on the results of indoor radon measurements (National Radiation Protection Institute – NRPI) and radon database of the Czech Geological Survey. Until 2007 the indoor measurements were performed in about 130 000 dwellings within the Czech Republic. Even if the track etch detectors were situated preferably into areas of predicted high risk, the resulting coverage of indoor measurements within particular rock types seems to be relatively equable (see Tab. 11-2) and reflects partly the areal occurrence of different rocks. The Czech Statistical Office granted the coordinates of centroids of municipalities and dwellings coming from the digitised cadastral maps from census. These data were linked to data of indoor radon measurements using the house number, which is unique and nonrecurring for each house in one administrative unit – municipality (or part of municipality in case of cities). The link to underlying geological units and rock types was made in ArcGIS 9.1. programme.

11.2. PILOT STUDY OF SOIL GAS AND INDOOR RADON CORRELATIONS

The first regionally based comparison of indoor radon concentrations and rock types' prevailing radon index was started in 2001. After the statistical evaluation of till then performed indoor measurements the NRPI has selected three types of municipalities concerning the prediction of indoor radon values. The centroids of municipalities and radon risk map at a scale 1 : 500 000 was used for georeferencing. The basic selection criterion was at least 30 % of measured dwellings within the particular municipality (464 municipalities were selected). The first type comprises the municipalities where less than 1 % of dwellings was expected to exceed the action level – “low municipalities” (200 Bq . m^{-3} equivalent radon concentration used in that time, this value is equal to present value of indoor radon concentration 400 Bq . m^{-3}). The second type was chosen for the same criterion 1–10 % dwellings exceeding the action level (“medium minicipalities“) and the third type was over 10 % above the action level (“high municipalities“). The prevailing radon risk from bedrock in intravilans of these municipalities was derived from the radon risk map at a scale 1 : 500 000. The main aim of this pilot sudy was to test the influence of bedrock on generalised indoor levels in three geologically defined radon risk

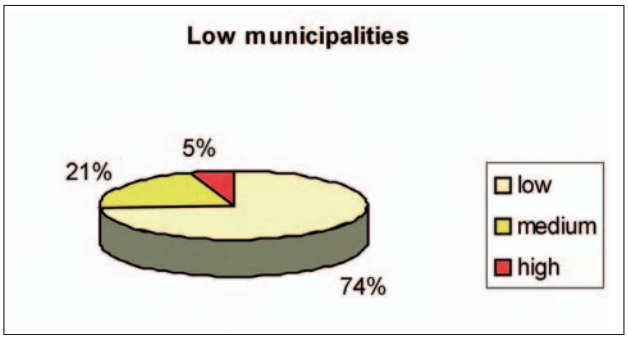

Fig. 11-1. Percentage of prevailing radon risk category in intravilan of municipalities (expected less than 1 % of dwellings above the action level) – 38 municipalities.

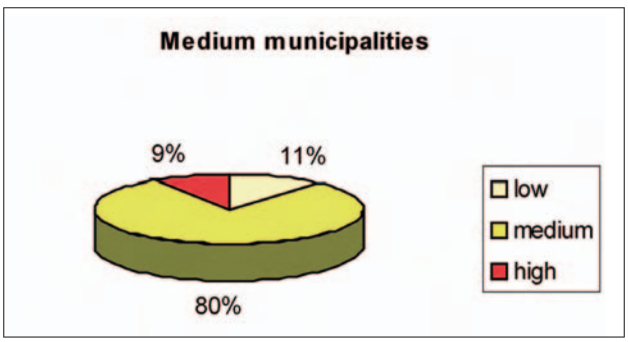

Fig.11-2. Percentage of prevailing radon risk category in intravilan of municipalities (expected 1–10 % of dwellings above the action level) – 150 municipalities.

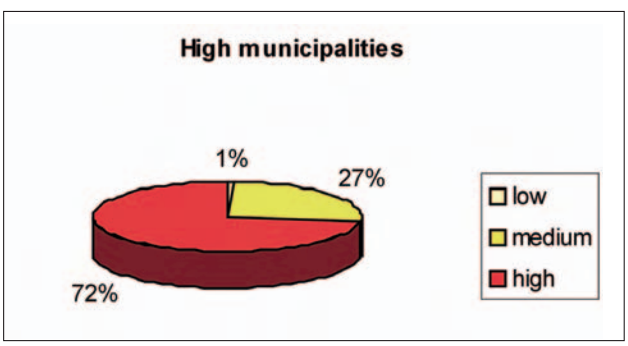

Fig.11-3. Percentage of prevailing radon risk category in intravilan of municipalities (expected more than 10 % of dwellings above the action level) – 276 municipalities.

Fig. 11-4. Position of studied districts.

categories. The results of this comparison are given in the following figures (Figs 11-1 to 11-3).

From the above presented figures it is obvious that the probability of correct geological prediction of indoor radon levels in municipalities reaches 70–80 %. The differences remaining to 100 % fit are caused by variability of local geological environment and also by the fact that the intermediate radon risk category used for inhomogeneous Quaternary sediments was suppressed due to the scale of used geological map serving as a base for determining radon risk categories. However the results allowed to follow the targeted indoor radon distribution preferably into areas of defined high radon risk from bedrock.

11.3. COMPARISON IN CENTRAL BOHEMIAN PLUTONIC COMPLEX

The growing number of targeted indoor radon measurements as well as improving the detailness of radon risk maps published since 1999 (term radon index maps is used for the scale 1 : 50 000) enabled to concentrate the attention to the largest radon prone area of the Bohemian Massif – the granitoid Central Bohemian Plutonic Complex (CBPC). The plutonic complex is emplaced between two terranes – the weakly metamorphosed Barrandian on the NW and medium to high grade metamorphosed Moldanubian assemblage of Precambrian and Proterozoic rocks on the SE. The granitoids intruded along probable suture zone with major axis SW (Klatovy) – NE (Říčany) on the area of about 3200 km^{2} and they are considered to be the major radon prone are in the Czech Republic.

For comparison of soil gas – indoor radon relationship four databases of indoor radon measurements, soil gas radon measurements, vectorised geological and radon maps and geographical coordinates of particular dwellings were used (Barnet et al. 2003, 2005). The positioning of particular dwellings with geographical coordinates (Czech Statistical Office) was linked to the indoor radon database of the National Radiation Protection Institute via the unique evidence number of house within the particular municipalities. The georeferencing resulted in building the common database with annual mean indoor radon concentration and corresponding lithological type and mean soil

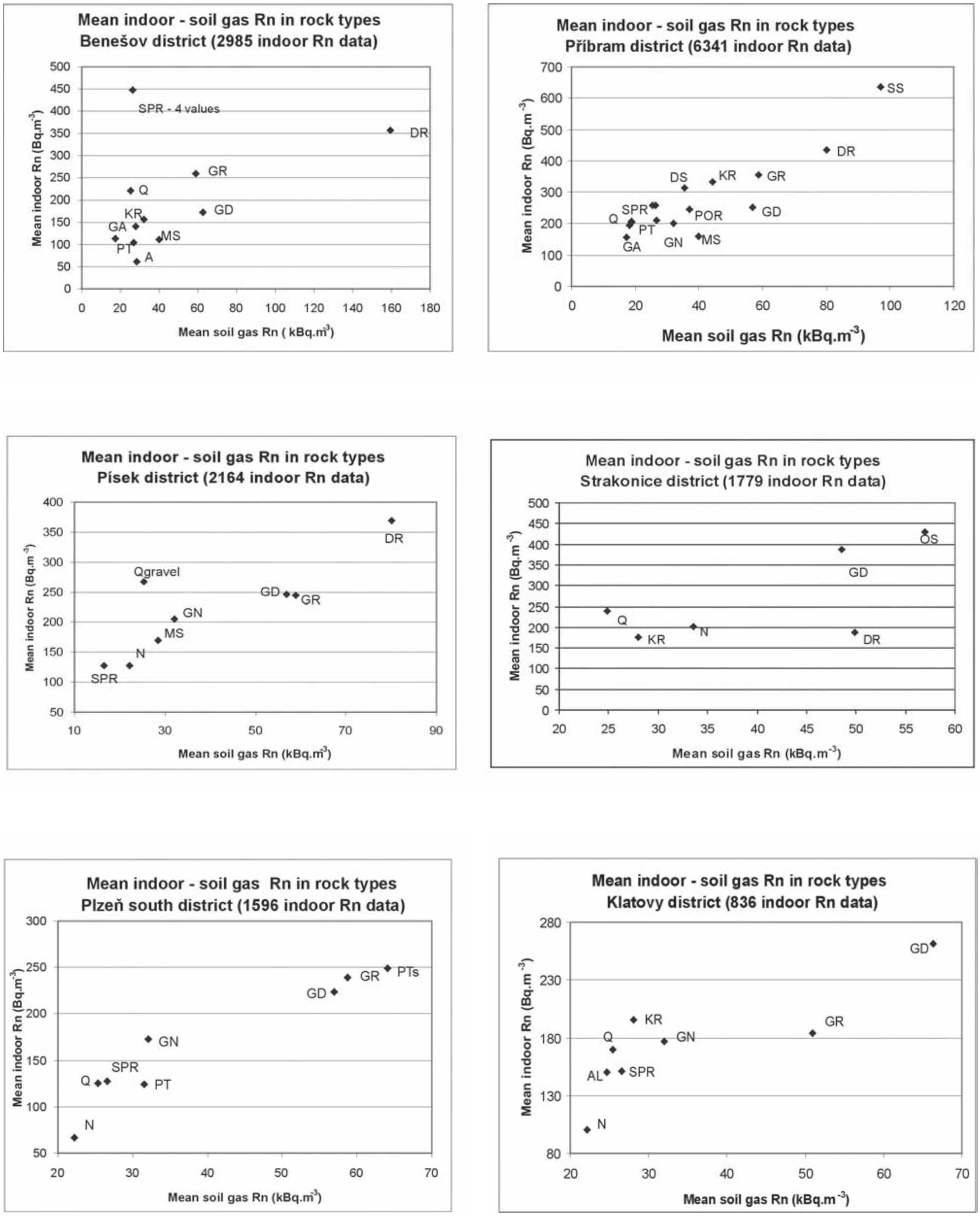

Fig. 11-5. Comparison of indoor Rn and soil gas Rn in the rock types of 6 Central Bohemian districts. – Explanation of rock types: SS – Silurian sediments, DR – durbachites (syenites), GR – granites, GD – granodiorites, KR – Moldanubian paragneisses, POR – Palaeozoic volcanites, MS – quartzites, erlanes, GN – Moldanubian orthogneisses, DS – Devonian sediments, PT – Proterozoic metasediments, SPR – loess, A – amphibolites, Q – Quaternary, GA – gabbros, OS – Ordovician sediments, KAS – Cambrian sediments, Qgravel – Quaternary gravel, N – Neogene sediments, AL – alluvial sediments, PTs – Proterozoic silicites.

gas radon value for each house. The data were processed in ArcGIS 9.1 programme. The resulting database comprises 16145 data enabling to find correlation between radon in dwellings and radon in rock types occurring within the area of CBPC (Figs 11-4 and 11-5, Tab. 11-1). The database follows the administrative division into 7 districts, covering the area of CBPC: Praha – east (444), Benešov (2985), Příbram (6341), Písek (2164), Strakonice (1779), Plzeň – south (1596) and Klatovy (836) covering the areal extent of CBPC.

Except of Prague east district, where houses were situated only on Quaternary sediments and granites (insufficient for graphical presentation), in all other mentioned districts there was found positive correlation between soil gas radon in geological basement and indoor radon concentration within particular lithological types. The highest indoor and soil gas radon concentrations among the rock types of the CBPC were measured in durbachites, granites and granodiorites. The Silurian black shales and Proterozoic metasilicites (both concentrating uranium) also belong to the rocks with enhanced soil gas and indoor radon concentration. The differences in indoor radon concentration can be found also in local types of granitoids of the CPBC (see Tab. 11-1).

11.4. COMPARISON OF SOIL GAS Rn AND INDOOR Rn IN DOMAŽLICE AND PRACHATICE DISTRICTS

The similar indoor-soil gas radon concentration relationship was studied in West Bohemian districts Domažlice and Prachatice based on 1386 indoor radon data and vectorised contours of geological units at a scale 1 : 50 000 (Pacherová et al. 2005). The bedrock is formed mostly by low – to medium metamorphosed Proterozoic shales, crystalline rock from paragneisses to migmatites, and by smaller bodies of Variscan granites partly covered by younger sedimentary formations. The results confirmed generally the positive regression of indoor radon data to soil gas radon data, however this relationship on granitic bedrock strongly depends on the local radiometric characteristics of various granitic types.

The differences between local mean values calculated from district area and values calculated for all data from the radon database can be observed namely for granites, influences by local radiometric characteristics (Figs 11-6 and 11-7).

Tab. 11-1. Mean and maximum indoor Rn concentrations in granitoids of CBPC

Type of granitoid	Mean Rn ($Bq.m^{-3}$) EEC	Max Rn ($Bq.m^{-3}$) EEC
GD Sedlčany	488.2	572.4
DR Čertovo břemeno	397.2	463.4
GD Kozárovice	350.0	400.8
GD Benešov	311.5	388.3
GR Marginal NW	310.2	377.4
GD Blatná – Zvíkov	270.5	340.8
GD Červenský	219.8	285.6
GR Říčany	167.9	211.4
GD Kozlovice--Maršovice	157.9	191.7
GD Požáry	78.9	91.2

GR – granite, GD – granodiorite, DR – durbachite

11. 5. RADON PROFILE ACROSS THE MAJOR GRANITOID BODIES

The regional influence of geological basement of the Bohemian Massif on the geometric indoor radon mean in municipalities was demonstrated on the radon profile transsecting the major granitoid intrusions and radon prone areas (Barnet et al. 2006). The profile 356 km long and 27 km wide is situated from NW to SE across the regional units

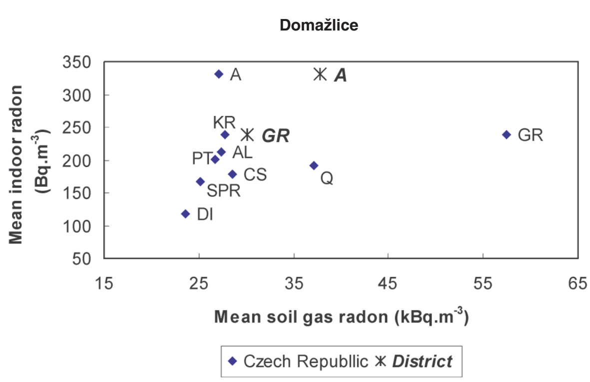

Fig. 11-6. The relationship of mean soil gas and indoor radon in Domažlice district. Rock code explanations: GR – granite, KR – paragneiss, PT – Proterozoic metasediments, A – amphibolite, DI – diorite, CS – Carboniferous sediments, SPR – loess, Q – Quaternary and AL – alluvial sediments.

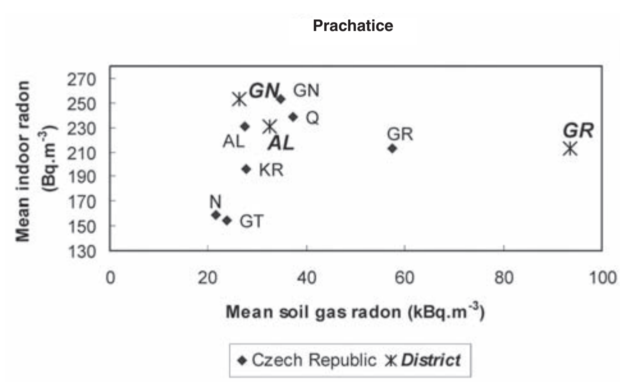

Fig.11-7. The relationship of mean soil gas and indoor radon in Prachatice district. Rock code explanations: GR – granite, KR – paragneiss, N – Neogene sediments, GT – granulite, GN – granulite, A – amphibolite, Q – Quaternary and AL – alluvial sediments.

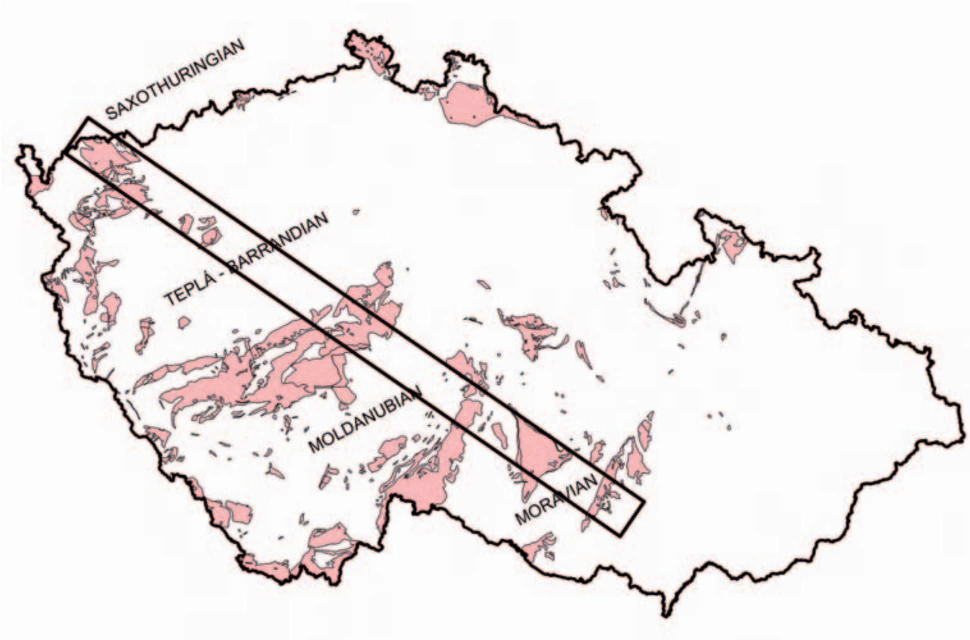

Fig. 11-8. Radon profile across the Bohemian Massif (based on the radon risk map 1 : 500 000).

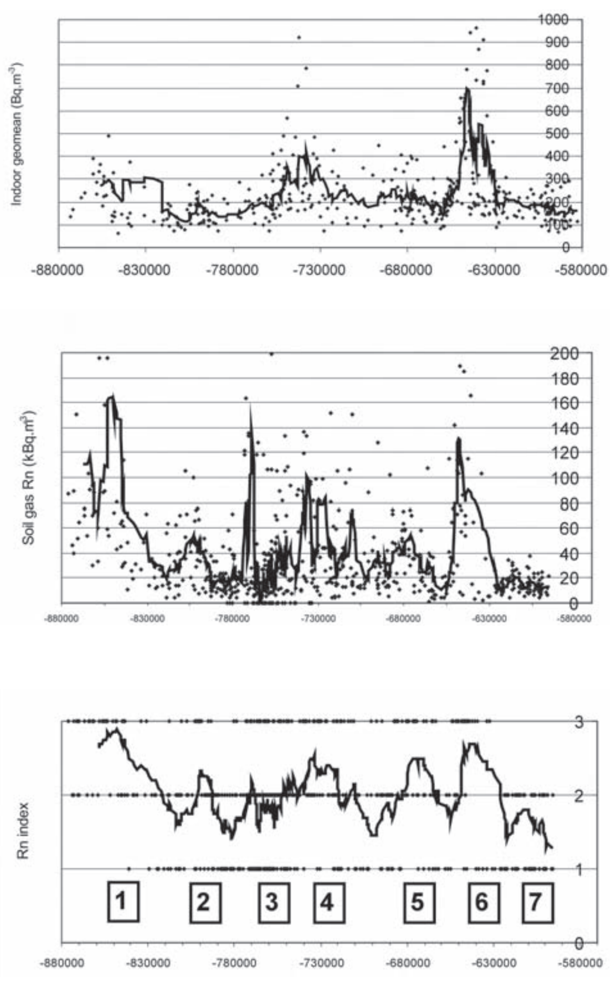

Fig. 11-9. The indoor radon, soil gas radon and radon index along the profile. Georeferenced positions of granitoid bodies and Silurian black shales: 1 – Krušné hory pluton, 2 – Čistá-Jesenice massif, 3 – Silurian black shales in Barrandian, 4 – Central Bohemian Plutonic Complex, 5 – Central Moldanubian Pluton, 6 – Třebíč syenite massif and 7 – Brno pluton.

– terranes – Saxothuringian, Teplá-Barrandian, Moldanubian and Moravian between covering Krušné hory pluton, Čistá-Jesenice massif, Central Bohemian Plutonic Complex, area of Silurian black shales, Central Moldanubian Pluton, Třebíč syenite massif and Brno pluton. 705 test sites of soil gas radon measurements and 421 indoor radon geometric means in municipalities were selected after the geographical coordinates (Fig. 11-8) and converted into graphs given in Fig. 11-9.

The relationship of inreased radon concentrations both in bedrock and indoor was observed in Variscan granitoid bodies throughout the whole profile. The radiopotential influence of granitoid bodies is not limited only to present surficial outcrops (after the geological maps) but extends to distance of about 15 rim around them. This fact is important in using the geologically based radon risk maps and in targeting the indoor radon surveys.

From top to bottom Fig. 11-9 comprises the moving average 10 of indoor geometric mean radon in municipalities along the profile. The central graph displays the raw mean soil gas radon data in $kBq \cdot m^{-3}$ and the bottom graph shows the moving average 10 of the radon index on particular test sites along the profile. All three graphs are displayed above the hypothetical geological profile identical with the course of the radon profile transsecting the granitoid bodies. The lithological exception in the profile are the Silurian black shales of Barrandian marked by number 3. These shales differ from other sedimentary formations of the Bohemian Massif by high concentration of uranium, bound to the organic matter (Barnet 1994). The extreme soil gas radon concentrations in the black shales even exceed the top mean values for Variscan granitoid plutons (approx. 300 $kBq \cdot m^{-3}$). However the area of surficial outcrops is small compared to granitoid bodies and therefore the Silurian black shales constitute only the radon hazard of a local scale. All Variscan granitoid bodies are manifested both by increase of mean soil gas radon values, of mean radon index at the test sites and of increased radon geometric mean in municipalities with the exception of older Cadomian granites of Brno pluton (number 7).

11.6. INDOOR AND SOIL GAS Rn IN MAJOR ROCK TYPES OF THE CZECH REPUBLIC

The growing number of data from soil gas and indoor Rn measurements enables to compare the relationship of both mentioned quantities in major rock types, forming the basement and sedimentary cover of the Czech Republic. The 92 276 indoor radon data were georeferenced to vectorised geological units after the atlas GEOČR500 (1998). The basic statistical results are given in the Tab. 11-2 and graphically presented in Fig. 11-10. The detailed statistics for particular rock types is described in chapter 8.

From Fig. 11-10 it is obvious that the relationship of mean soil gas Rn and indoor Rn can be found in all rock types with a fair determination coefficient (R^2 = 0.85) along the whole range of indoor and soil gas Rn concentrations, the greater deviations can be found in magmatic rocks (difference from the ideal regression line in Variscan granodiorites – higher indoor Rn due to the increased gammadose rate in the CBPC compared to Variscan granites). The highest soil gas and indoor Rn values are observed in durbachites of Čertovo břemeno type and Třebíč syenite pluton. The resulting category of radon index determined from the soil gas Rn concentrations and permeability corresponds well to the expected indoor Rn values.

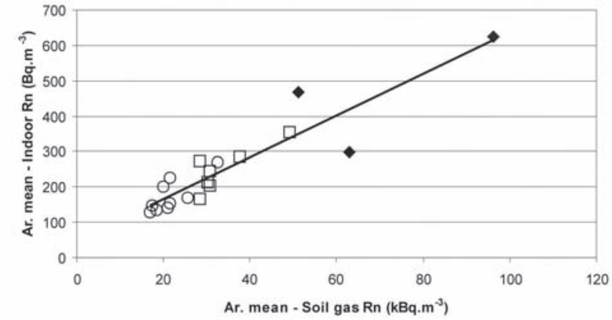

Fig. 11-10. Relationship of mean indoor radon concentration and mean soil gas radon concentration in major rock types of the Czech Republic. ○ sedimentary with prevailing low radon index, □ metamorphic with prevailing medium radon index, ♦ magmatic with prevailing high radon index.

11.7. SOIL GAS RN AND INDOOR Rn COMPARISON BASED ON GAMMA DOSE RATE CATEGORIES

The gamma dose rate map of the Czech Republic (Manová and Matolín 1998) was divided into areas < 35, 36–55, 56–85, 86–105, > 105 nGy.h^{-1} (mean value in the Czech

Tab. 11-2. Mean soilgas Rn and indoor Rn in major rock types of the Czech Republic

Rock type	Geolmean (kBq . m^{-3})	Inmean (Bq . m^{-3})	code	Num indoor	Num geol
Syenites	96.2	624.5	DR	5 651	84
Variscan granodiorites	51.3	468.2	GD	10 936	333
Palaeozoic metamorphites	49.2	353.6	MS	1 039	145
Variscan granitoids	63.0	299.5	GR	6 583	379
Orthogneisses	37.6	286.7	GN	2 601	224
Proterozoic–Palaeozoic volcanites	28.5	273.0	PV	1 658	172
Proterozoic–Prevariscan metamorphites	32.5	269.3	PT	5 996	719
Palaeozoic unmetamorphosed	30.7	243.7	PAL	5 037	732
Diorites, gabbros	21.6	226.7	DI	410	44
Moldanubian variagated	30.1	212.9	KRV	5 415	252
Moldanubian paragneisses	30.8	203.2	KR	7 094	472
Prevariscan granitoids	19.9	200.2	GRP	1 364	141
Tertiary sediments	25.7	168.9	N	1 989	356
Permo-Carboniferous sediments	28.3	167.9	PCS	4 791	297
Quaternary	21.6	155.1	Q	19 418	2259
Tertiary Alpine folded	17.4	147.9	NK	1 257	244
Tertiary volcanites	21.1	142.8	NV	582	69
Mesozoic sediments	18.3	135.6	KS	9 524	987
Mesozoic Alpine folded	16.9	129.0	KSK	870	226

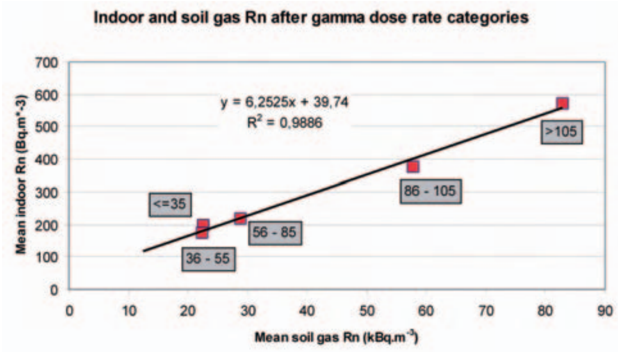

Fig. 11-11. Relationship of indoor and soil gas Rn in gamma dose rate categories (categories in nGy . h^{-1}).

Republic is calculated from polygons of vectorised gamma dose rate map to 72 nGy . h^{-1}, the upper range of mean interval was set to 85 nGy . h^{-1}). The position of 92 276 dwellings with existing indoor Rn measurements was georeferenced to 5 gamma dose rate categories in ArcGIS 9.2. programme and mean values of indoor radon concentration was calculated for particular groups of dwellings (Barnet and Fojtíková 2007). The results given in Fig. 11-11 show that a tight relationship of indoor Rn concentration and gamma dose rate from underlying rock types can be observed only in the above-mean categories, which means that the detailed prognosis of indoor Rn based on the gamma dose rate is an unsuitable method for lower ranges. However, the gamma dose rate can support the targeted indoor radon search for houses exceeding the action level in the rock types with enhanced natural radioactivity (Fig. 11-11).

11.8. INDOOR RADON IN MUNICIPALITIES RELATED TO RADON INDEX FROM BEDROCK

The relationship of geometric indoor Rn mean and radon index of underlying rock was also calculated from data of the National Radiation Protection Insitute. From all municipalities (6395) only those were selected, where at least 20 % of dwellings were measured within the municipality and currently more than 20 dwellings were measured. The selected database comprised 1627 municipalities Barnet and Fojtíková 2006). After that the centroids of these municipalities (coordinates by the Czech Statistical Office) were positioned over the radon index map at a scale 1 : 500 000 and corresponding radon index was determined. The numbers of municipalities in different radon index categories are relatively even (353 on low radon index, 336 on intermediate radon index, 602 on medium radon index and 336 on high radon index). The clear difference in indoor radon distributions can be seen between low, medium and high radon index bedrock, the close position of indoor Rn distributions in low and intermediate index is explained by difference in permeability as can be seen from Tab. 11-3 (lower permeability in intermedi-

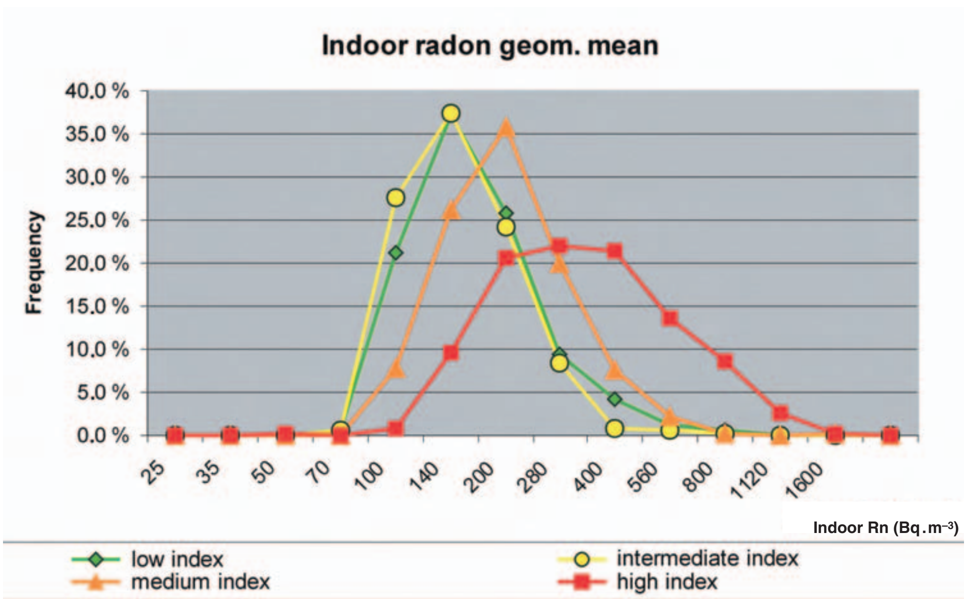

Fig. 11-12. Distribution of geometric indoor Rn means of municipalities in radon index categories.

	Mean Rn index	Mean permeability	% of clay cover	Mean Rn (kBq . m^{-3})	Number
Intermediate Rn index	1.56	1.67	44.1	24.7	1188
Low Rn index	1.51	2.26	28.9	19.8	3894

Tab. 11-3. Differences in mean Rn index and concentration and mean permeability between low and intermediate Rn index bedrock

ate index bedrock decreases the indoor Rn concentration, however the soil gas Rn concentrations are higher in intermediate than in low radon index bedrock).

11.9. PERCENTAGE OF RADON INDEX CATEGORIES WITHIN THE MUNICIPALITIES

The above presented comparisons of soil gas Rn and indoor Rn relationships are focused to select the municipalities, where the indoor Rn measurements of majority of dwellings is required due to the expected high indoor Rn concentrations from bedrock. The general calculation can be based also on the percentage ratio of particular radon index categories within the area of municipality (NUTS5 borders). This calculation is performed in ArcGIS 9.2. programme using the intersection of vectorised polygons of radon index category (after the radon index maps at a scale 1 : 50 000 and the area of municipality (datasets of the Czech Geological Survey and the Czech Statistical Office).

The percentage of low, intermediate, medium and high radon index categories within the area of municipality are presented in Figs 11-13 to 11-16. The areal conformity of the high radon index rocks with the indoor Rn concentrations in municipalitites is clearly demonstrated on Fig. 11-17.

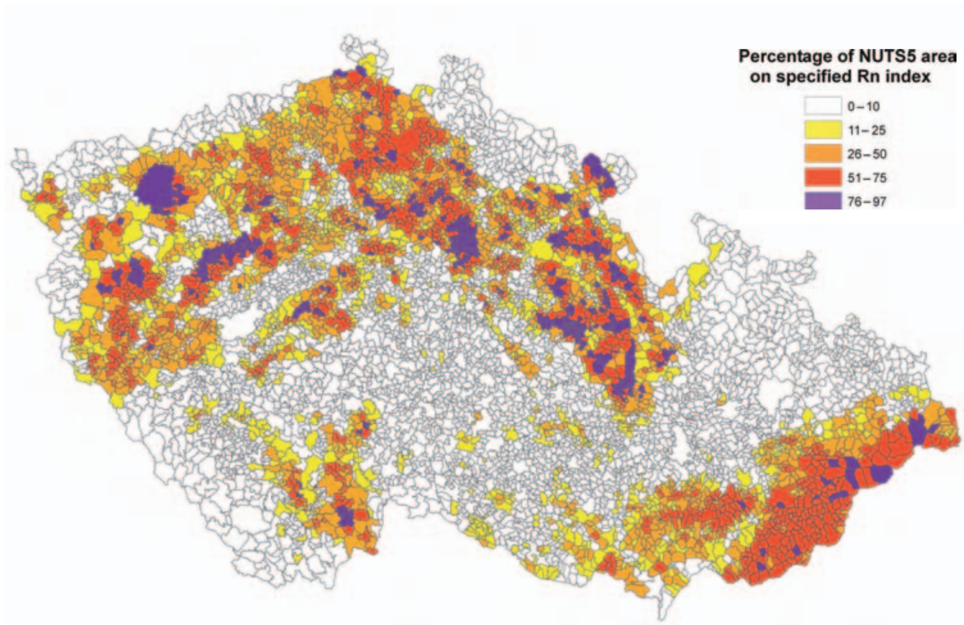

Fig.11-13. Percentage of low radon index.

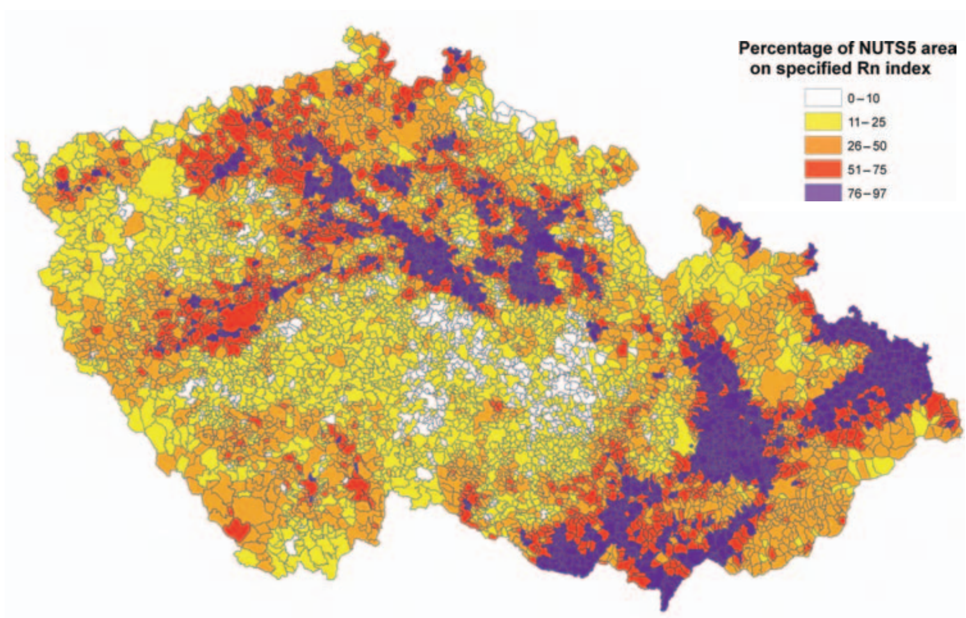

Fig. 11-14. Percentage of intermediate radon index.

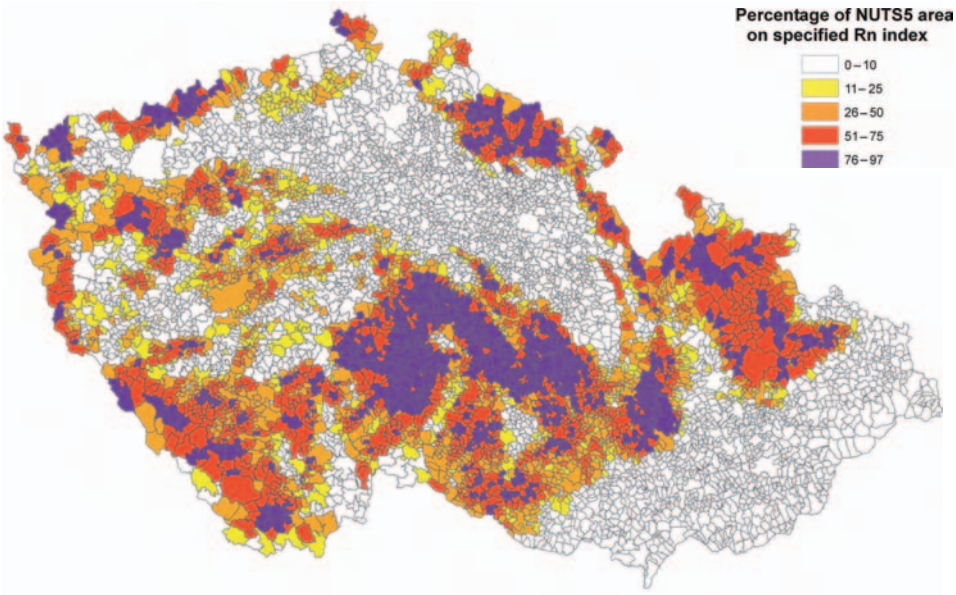

Fig. 11-15. Percentage of medium radon index.

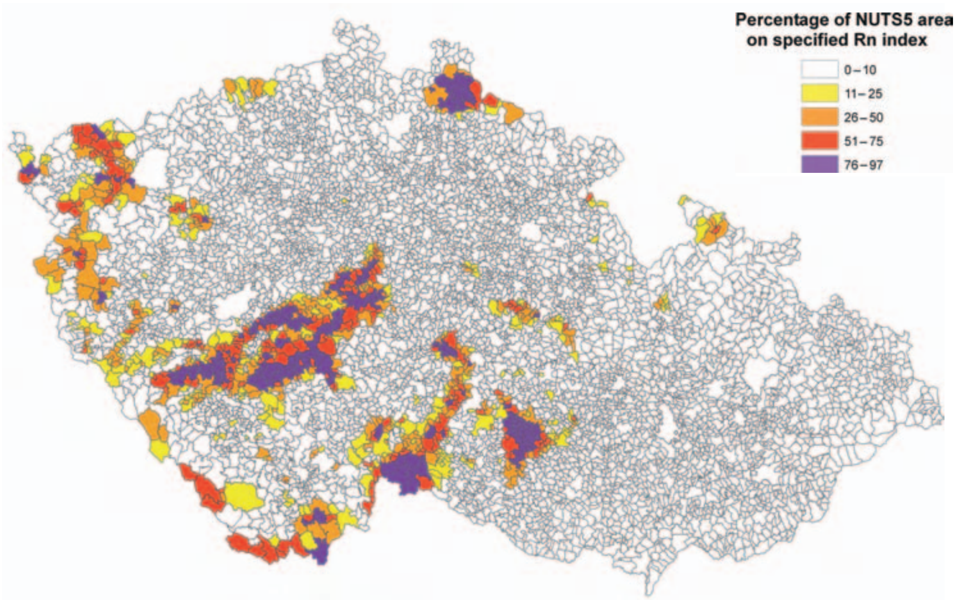

Fig. 11-16. Percentage of high radon index.

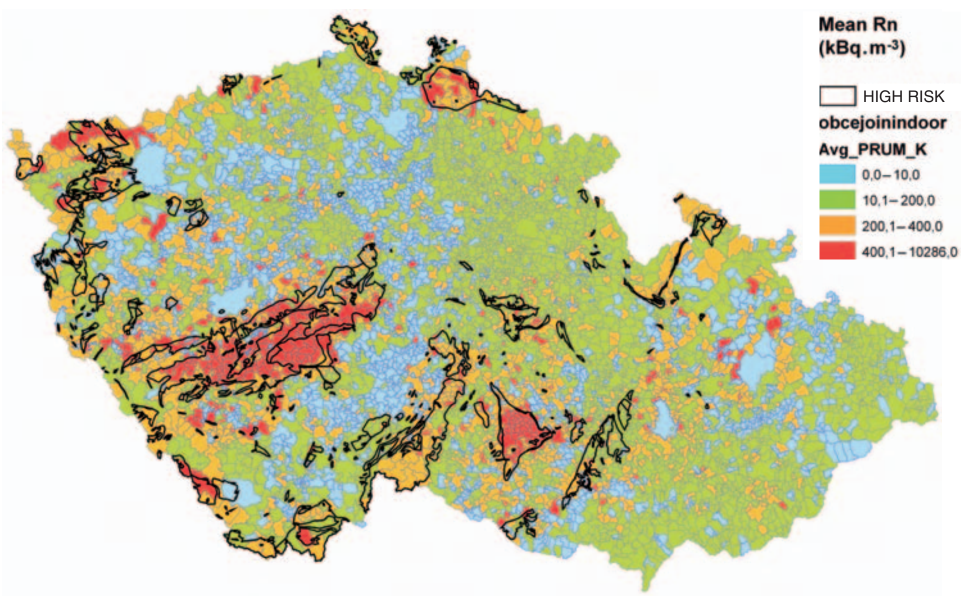

Fig. 11-17. Extent of high Rn index rocks and mean indoor Rn concentration in municipalities.