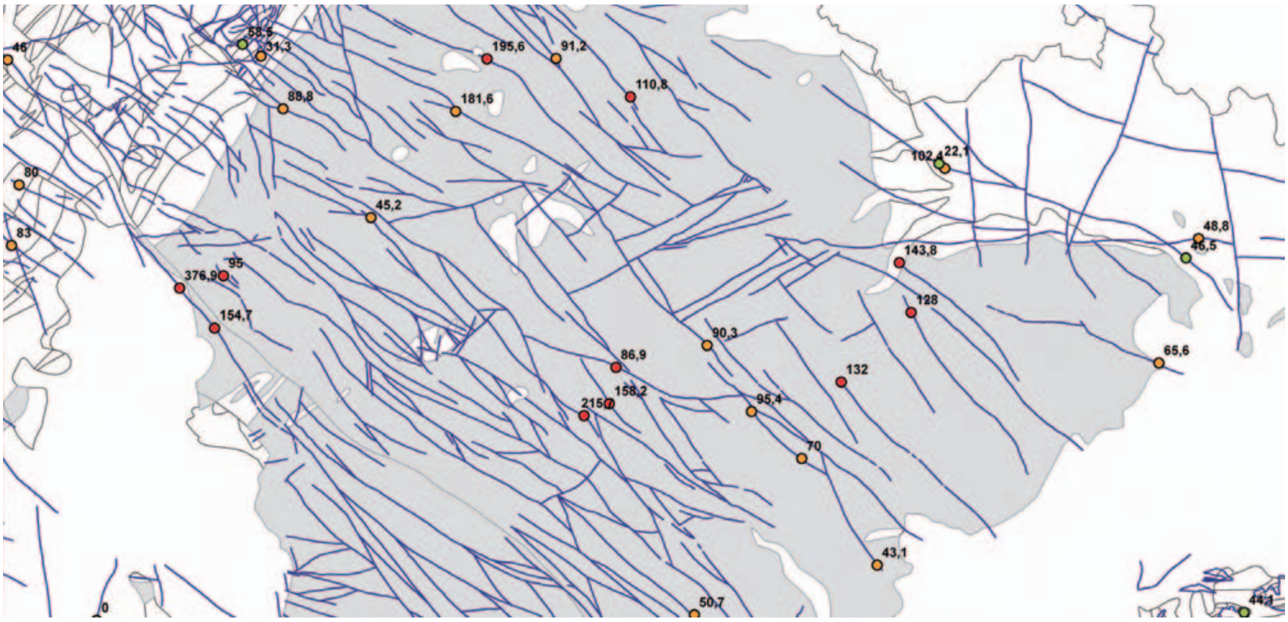


Fig. 9-5. The maximum soil gas radon concentrations on the test sites bound to tectonic structures in Culm metasediments of Northern Moravia. • high radon index, • medium radon index, • low radon index.

metasediments of Northern Moravia. Culm flysch metasediments are formed mostly by shales, greywackes, sandstones and conglomerates and from the radiometric point of view they are relatively monotonous. The Culm flysch formation is generally classified by medium radon index (mean soil gas radon concentration is 41 kBq . m^{-3}). The soil gas radon measurements were performed during the radon mapping programme at a scale 1 : 50 000. The selected test sites (shown in Fig. 9-5) are situated in the distance to 100 m from the faults oriented NW-SE. In most cases the maximum soil gas radon concentration (from 15 measurements at each test sites) exceeds 90 kBq . m^{-3} and the test sites are classified by high or medium radon index. Compared to mean radon concentration 41 kBq . m^{-3} the extreme outliers on the tectonically influenced test sites are obvious. From the geodynamic point of view the whole area reflects the stress processes in the Carpathian belt, which is evidenced also by recent microseismic activity (Havíř 2002) and by vectors of GPS monitored movements (Schenk et al. 2002)

Even in the areas of low geodynamic activity (Bohemian Massif) the tectonic structures of all orders play an important role in radon migration from deeper basement. The evidences of soil gas radon anomalies on the tectonic structures are pronounced mainly in general scales and are partly reflected also in the enhanced indoor radon concentrations. Resulting from the above mentioned studies, the radon migration on the tectonic structures is dependent on the structure type and namely on the fill of structure. Most of tectonic structures formed in granitoid and crystalline basement underwent the mineralogical alteration of the structure fill and the presence of clayey minerals directly in the structure plane decreses the radon release from bedrock. On the other hand, the ways for radon transport are shifted to marginal parts of structure in the contact with tectonically unaffected rocks. Therefore in detailed scale the increasing of radon concentration range must be expected and the presence of outlier concentrations is an frequent phenomenon. Thus the areas influenced by tectonics must be considered as radon active areas.

10. Geostatistical methods for radon risk evaluation

Supposing that radon coming from the geological basement is the major source of radon in houses (and radon from building materials and water originates also from rock material and surrounding rocks) the soil gas radon research brings the basic information for targeted indoor radon studies. The rock material is very inhomogeneous even in a small scale of several tens of meters, therefore the statistical approach is necessary to characterize particular rock types. Sufficient number of soil gas sampling points (probes) is the basic demand for determining the radon concentration ranges in particular lithological types.

The basic difference between rock types can be found in the petrogenesis of lithotype – magmatic, metamorphic and sedimentary. The source element for radon origin is uranium ^{238}U and generally it can be said that the mean uranium concentration decreases with the above mentioned sequence of the genetic rock types. However the magmatic and metamorphic processes give rise to new rock types and redistribution of the parent element uranium in the newly formed rocks is commonplace. Therefore some geological units with generally lower uranium concentration can contain the uranium enriched areas resulting also in the enhanced radon release from bedrock. The main role of radiation protection against radon is to localize these areas up to the level of particular houses and subsequently to take the remedial measures for lowering the indoor radon concentration in the houses exceeding the action level.

10.1. RADON RISK DERIVED FROM GEOLOGICAL BASEMENT

This method is based on the rock types' characterization from the soil gas radon point of view. Nowadays the geological, pedological and hydrogeological maps in different scales are available nearly in all states in printed or vectorised form and except of some genetically problematic ares the basic petrogenetic distribution of rock types is sufficiently explained. The soil gas radon measurements performed in various lithological and genetical types give the first radon characterization of the studied area. The radiometric data (mostly taken from the airborne and ground uranium prospecting or environmental studies) should be also taken into account if available.

The classification methods (based usually on the soil gas radon concentration and permeability – Czech Republic, Germany, Poland, Scandinavian) divide the rock types into different categories after the expected radon release from bedrock and enable to localize the areas, where the indoor radon measurements should be concentrated. The difference in basic genetical rock types of the Czech Republic in the ratio of radon index categories and statistical characteristics are given in Fig. 10-1 and Tab. 10-1. The data were obtained both from radon mapping programmes, research projects and from building site assessment data, granted by Association Radon Risk (Barnet 1994b, 1995b, Barnet et al. 2000, Pacherová 2004)

Fig. 10-2 illustrates the more detailed division of the rock types with the ratio of test sites situated on low and high radon index categories calculated from all test sites being measured on particular rock types. Sorted by ascending percentage of test sites classified by high radon index, the rock types exhibit the least percentage of high radon index test sites in younger sedimentary formations (low radon index – 1). A group of Quaternary sediments (alluvial, glacifluvial, river terraces and loesses) belongs to intermediate radon index – 2. The ratio of high radon index test sites is growing from unmetamorphosed Palaeozoic sediments to medium to high metamorphosed crystalline formations (medium radon index – 3). The Variscan granitoids are marked with a substantial rise of high radon index ratio (4). For the classification of the Czech radon index maps the prevailing radon index in the specified rock types was used.

Tab. 10-1. Basic statistic in the petrogenetic types of rocks of the Czech Republic

	Magmatites	Metamorphites	Sediments
Mean value	**51,28**	**32,27**	**22,53**
Std. error	1.52	1.06	0.40
Median	31.90	23.50	17.00
Modus	17.00	14.00	12.00
Std. deviation	58.37	40.68	30.13
Maximum	582.50	1003.60	1633.90

The division of rock types according to radon index from bedrock clearly delineates the areas of expected high radon risk especially when the most detailed geological maps are used. The coincidence of detected areas with measured indoor radon concentration is exhautively described in Chapter 11.

The experience from geologically based radon risk mapping in the Czech Republic enabled also to set up a cross-border radon map covering the territory of Triregion Czech Republic – Germany – Poland in the northern rim of the Bohemian Massif. The geological background of the map was taken from the already published Geological map Lausitz–Jizera–Karkonosze 1 : 100 000 (Czech Geological Survey, Geological Survey of Poland, Sächsisches Landesamt für Umwelt und Geologie). The classification of radon risk of particular rock types respects the Czech classification (Neznal et al. 2004). The presented section (Fig. 10-3) illustrates the position of high radon index rocks (Variscan granitoids – SE part and phonolites – W part, the low radon index Cretaceous sediments –

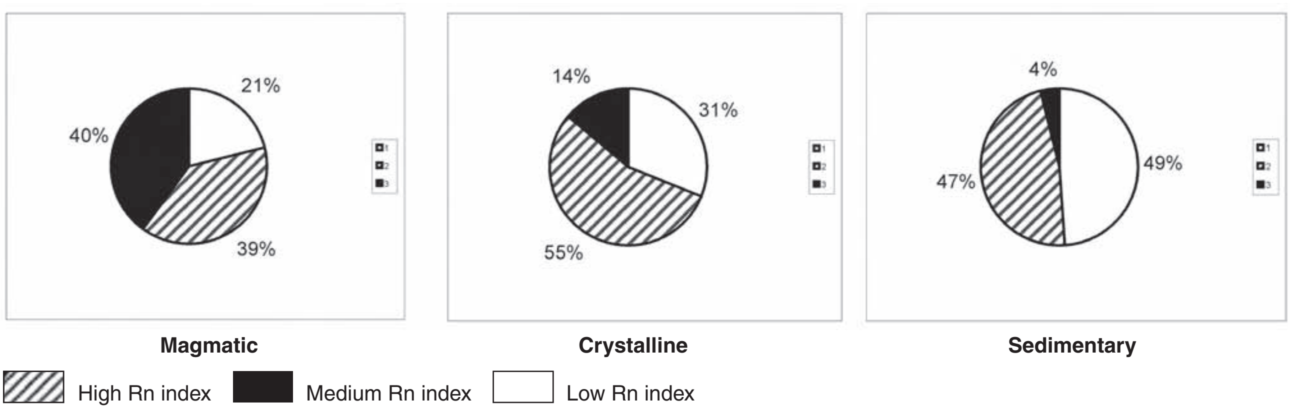


Fig. 10-1. Difference in ratio of radon index categories in the petrogenetic types of rocks of the Czech Republic.

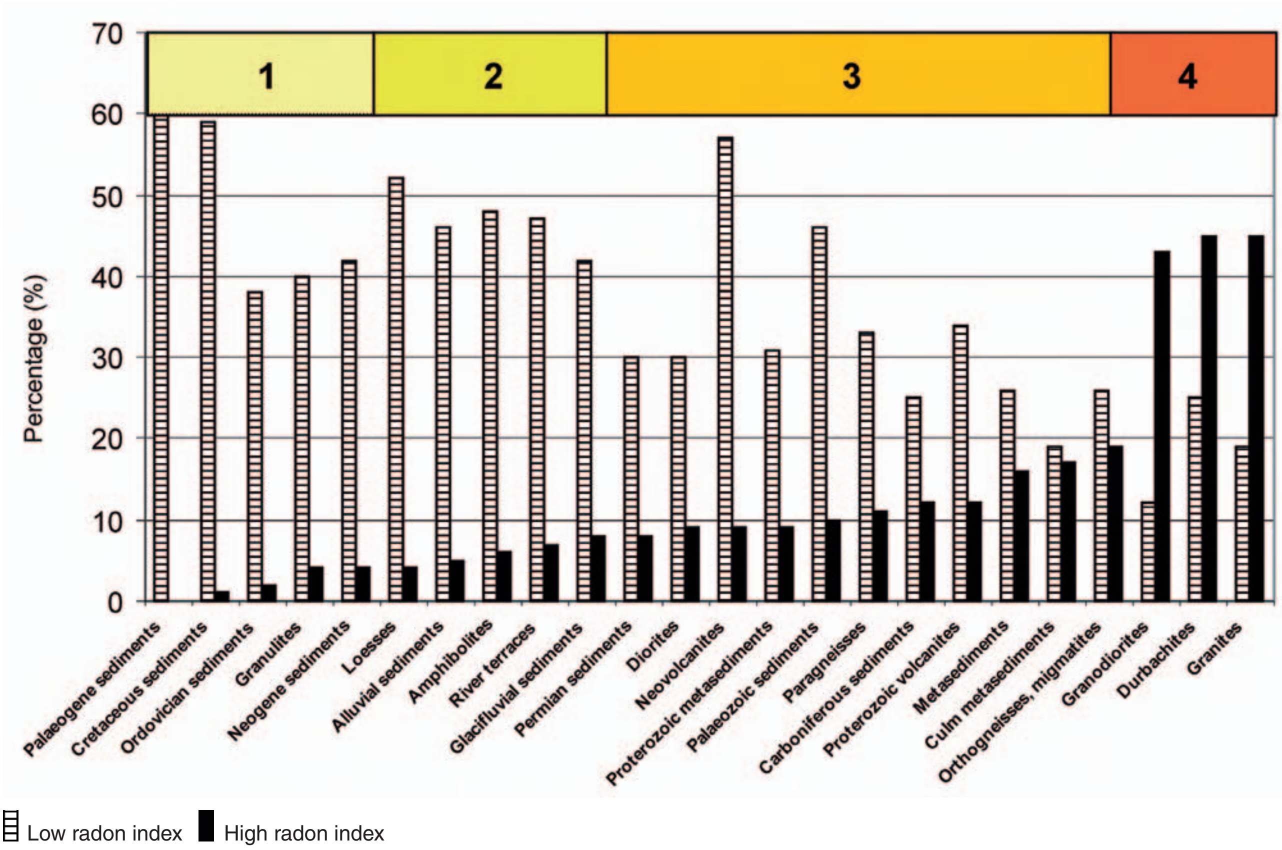


Fig. 10-2. Percentage of the test sites classified by low and high radon index in 24 major rock types (geological units) of the Czech Republic. The coloured row indicates the radon index categories 1 – low, 2 – intermediate, 3 – medium, 4 – high.

Fig. 10-3. A section of the cross border radon map Lausitz–Jizera –Karkonosze region (Poland, Germany, Czech Republic) at a original scale 1 : 100 000.

SW part and the medium radon index in crystalline formations – N part). The classification of the rock types was performed on the statistical basis of soil gas radon measurements (Czech Republic 663 test sites + results from the radon database, Germany 61 test sites – BfS Berlin and Poland 94 test sites – Geological Survey of Poland for the whole map).

10.2. SPATIAL EVALUATION OF RADON RISK BASED ON ADMINISTRATIVE UNITS

Most of indoor radon mesurement projects is financed from the state budget. The role of the state radioprotection bodies together with high instrumental quality of their laboratories requires also the meaningful policy in distri-

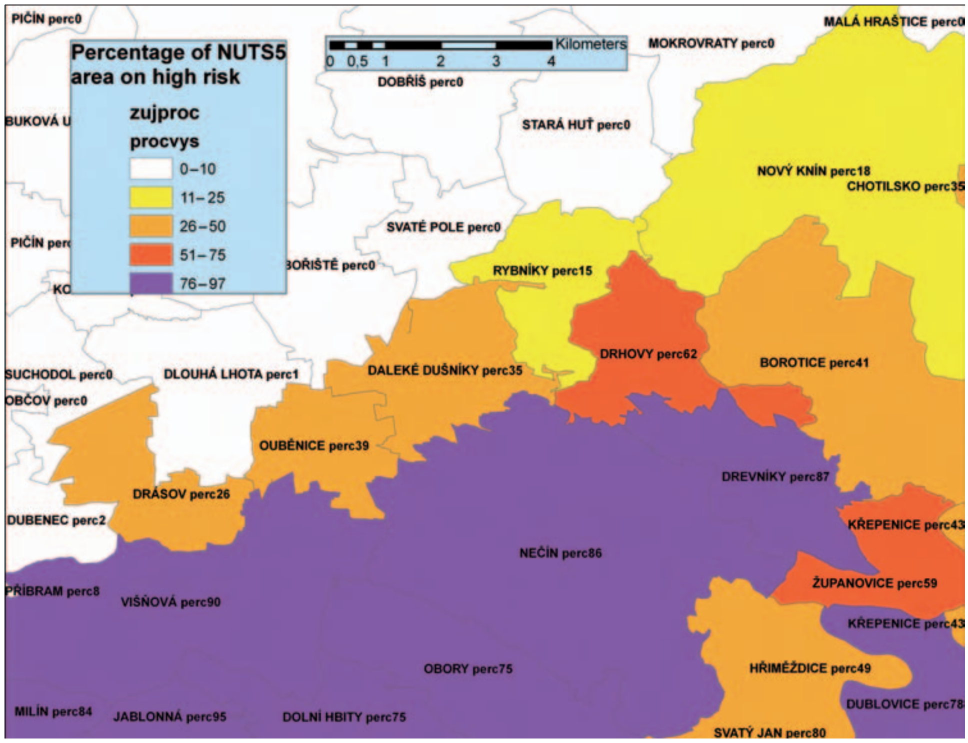


Fig. 10-4. Percentage of municipalities' area (NUTS5) situated on high radon index bedrock (example from Central Bohemia).

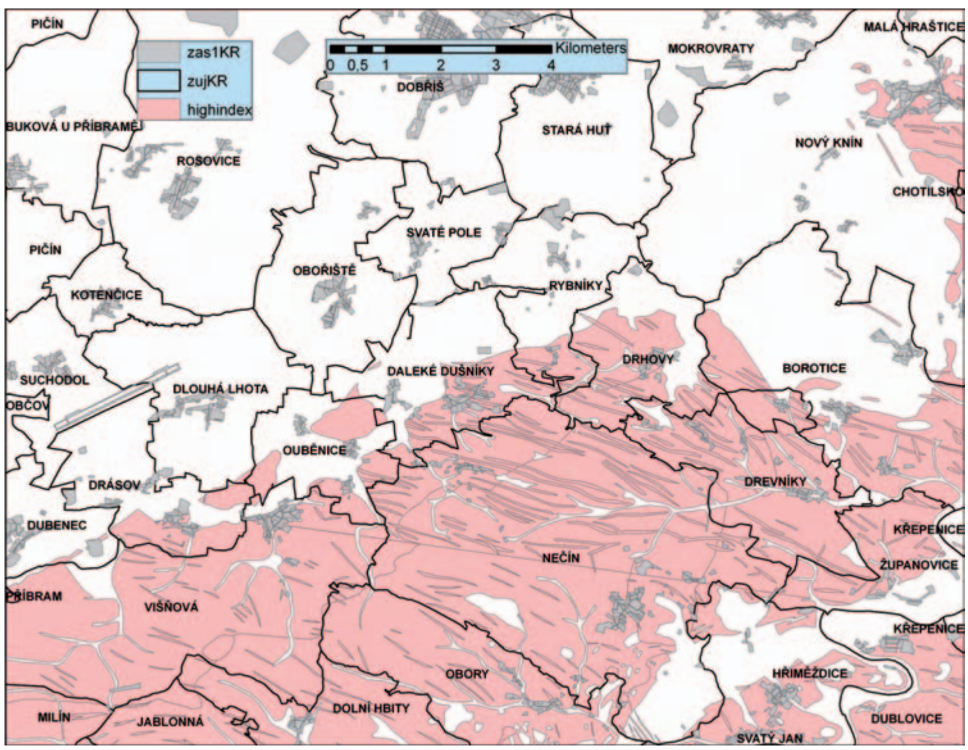


Fig. 10-5. Areal extent of high radon index (granitoids) within municipalities (example from Central Bohemia).

bution of the indoor radon measurements. As borders of administrative units are available from Cadastral bureaus, state Statistical Offices etc., they can serve a basic parameter for characterizing the radon risk within particular municipalities.

The input data, expressed in one municipality polygon, can be both soil gas radon concentration, radiometric parameters, indoor radon concentrations' statistical parameters, areal ratio of different radon risk levels from bedrock or statistical parameters calculated from the above mentioned types of input data. The detailness of the cadastral mapping can even distinguish the different parts of municipality according to expected radon risk, which enables the administrative staff to target the indoor radon measurements

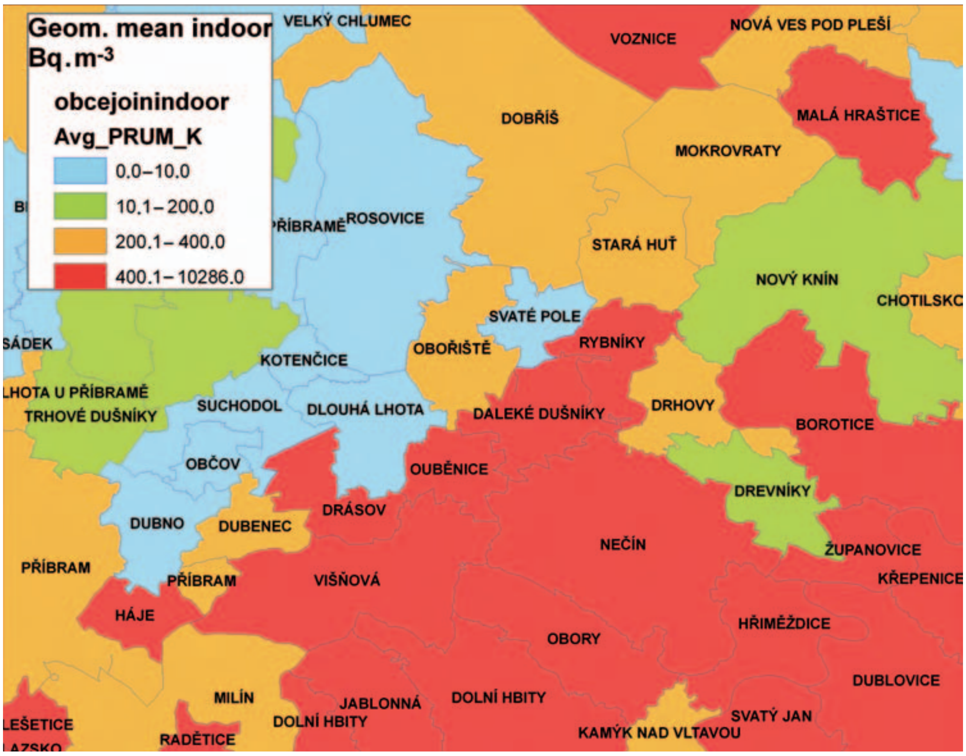


Fig. 10-6. Indoor geometric mean in municipalities (example from Central Bohemia).

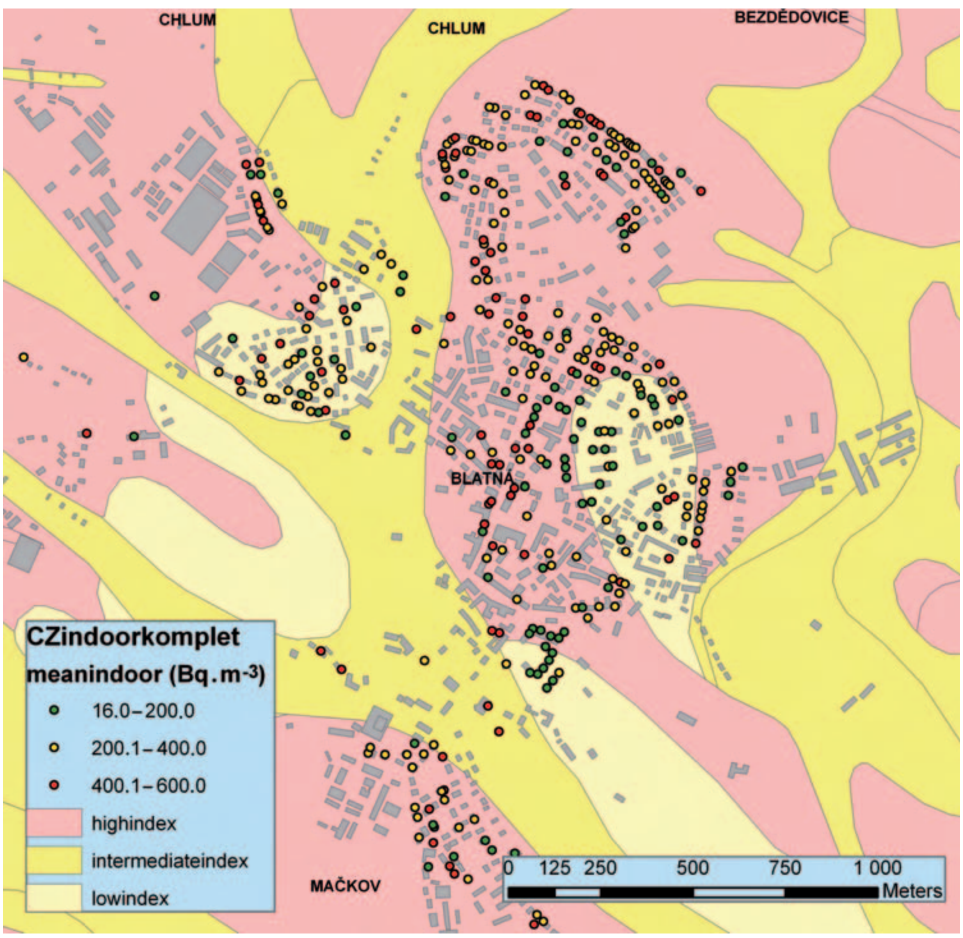


Fig. 10-7. The detailed view of indoor radon measurements within one municipality (Blatná, Central Bohemia) on the radon index background layer. The difference between indoor radon concentrations on high radon index and low radon index bedrock after maps at a scale 1 : 50 000 (central part of figure) is obvious.

into concrete houses most effitiently. Following Figs 10-4 to 10-7 illustrate the possibilities of different parameters' expression on a scale of particular municipalities.

The statistical evaluation based on the administrative units seems to be the most efficient from the radioprotection point of view. It enables the transfer of radon risk prediction directly from research phase to administrative authorities that bear part of responsibility for the health and environmental risks of the citizens living in the affected areas. The economic factor is also important, as the targeted radon surveys can set the priorities of indoor radon measurements into high risk areas and further measures like remediation of existing houses and project modifications for newly built houses can be taken without delays.

10.3. GRID METHODS FOR EXPRESSING THE RADON RISK

For preparation of the European Atlas of Natural Radiations the Joint Research Center REM Group has suggested the grid net covering the whole European territory. The testing of the grid net was performed on the Czech radon data with a cell size 10 × 10 km and 1 × 1 km. The grid was calculated in ArcGIS 9.2. programme in GISCO Lambert Azimuthal Equal Area projection with central longitude 9°, central latitude 48° and radius of reference sphere 6378388 m. The territory of the Czech Republic with border overlap is coved by 891 grid cells 10 × 10 km. For each grid cell the following parameters were calculated to be presented in the form of unified European radon map: soil gas radon concentration mean, maximum, percentage of high radon index area after the geological maps 1 : 50 000 and mean radon index. From the indoor radon concentrations there were calculated mean, maximum indoor radon concentration and geometric mean. The same parameters were also tested for the grid cell 1 × 1 km, however the density of radon measurements causes many empty cells. Filling these cells using the predefined computer functions for one parameter only can be misleading, as deriving e.g. the indoor radon concentration in empty cells between two remote data cells without respect to underlying geology can bring only some calculated value without linkage to natural environment. The use of the grid net 10 × 10 km is not very suitable for countries with dense soil gas and indoor radon measurements and relatively small area. It also must not be forgotten that indoor data are usually clustered in the intravilans of municipalities.

On the other hand, for covering the large country or continental territories with scarce radon data the method seems to be efficient for basic radon information and computer processing. The examples of radon data testing in a grid net 10 × 10 km are presented in Figs 10-8 (soil gas radon) and 10-9 (indoor radon).

The detailization of the grid into the net 1 × 1 km is illustrated in the Fig. 10-10. The selected area coveres the granitoid Central Bohemian Plutonic Complex (about 3200 km^2) and the percentage of high radon index area (calculated after the geological maps 1 : 50 000 is expressed for one square km). Compared to the contours of grani-

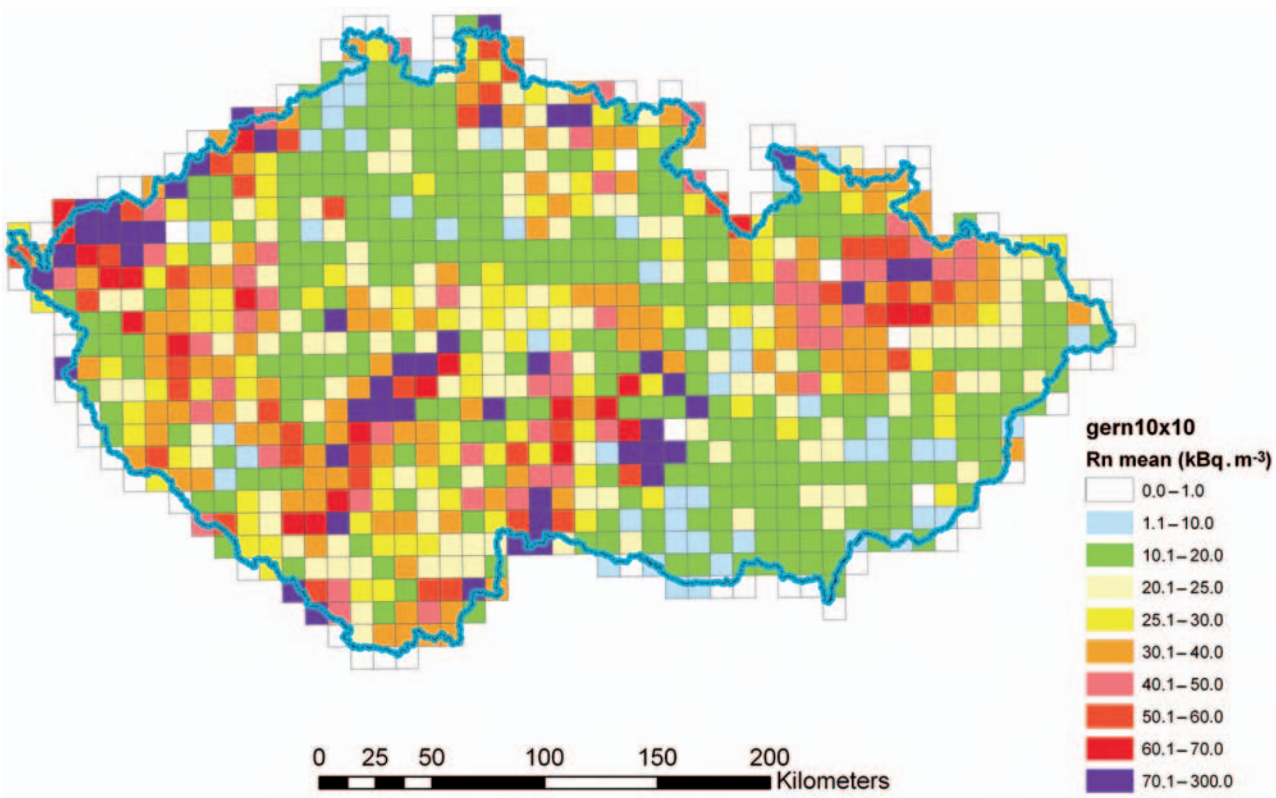


Fig.10-8. The mean soil gas radon concentrations in the grid net 10 × 10 km.

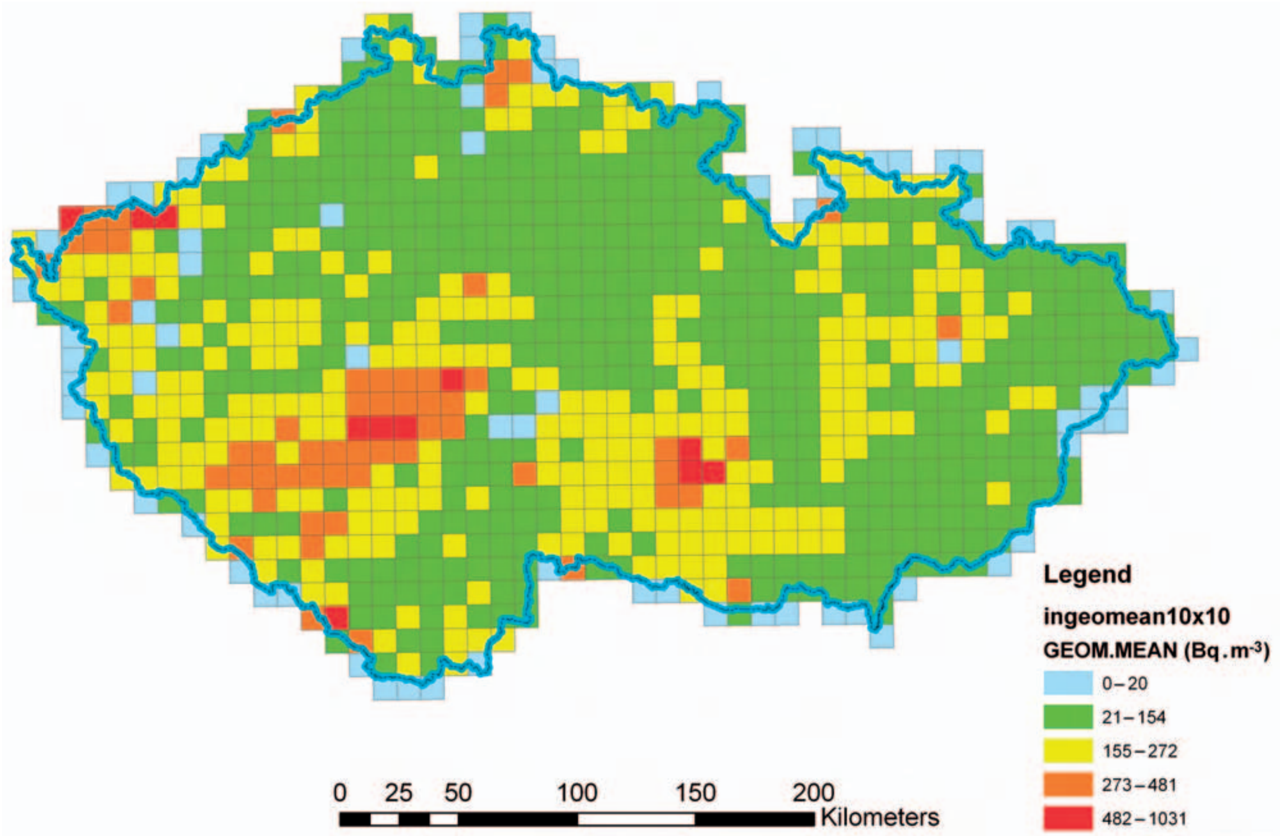


Fig. 10-9. The indoor radon geometric mean in the grid net 10×10 km.

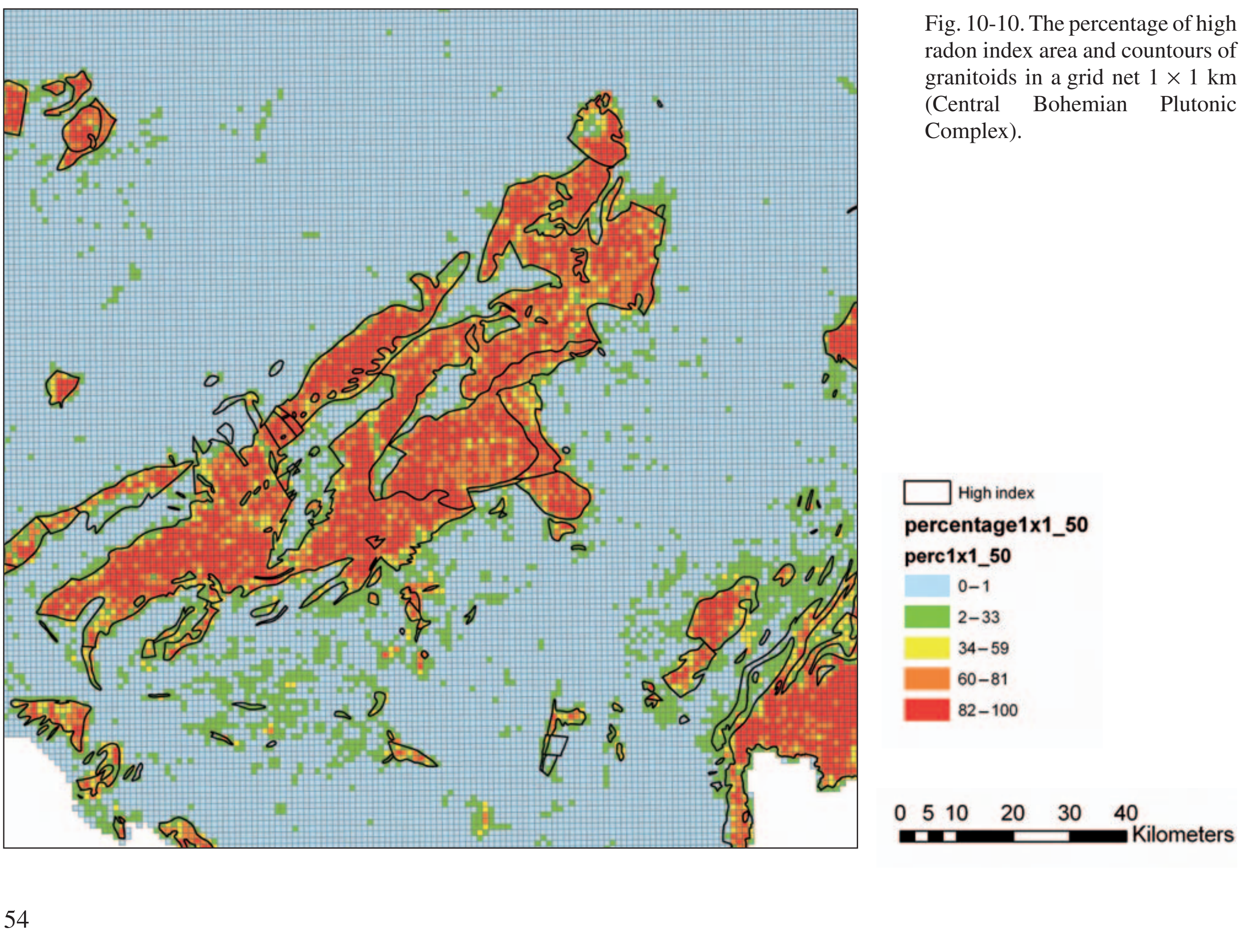
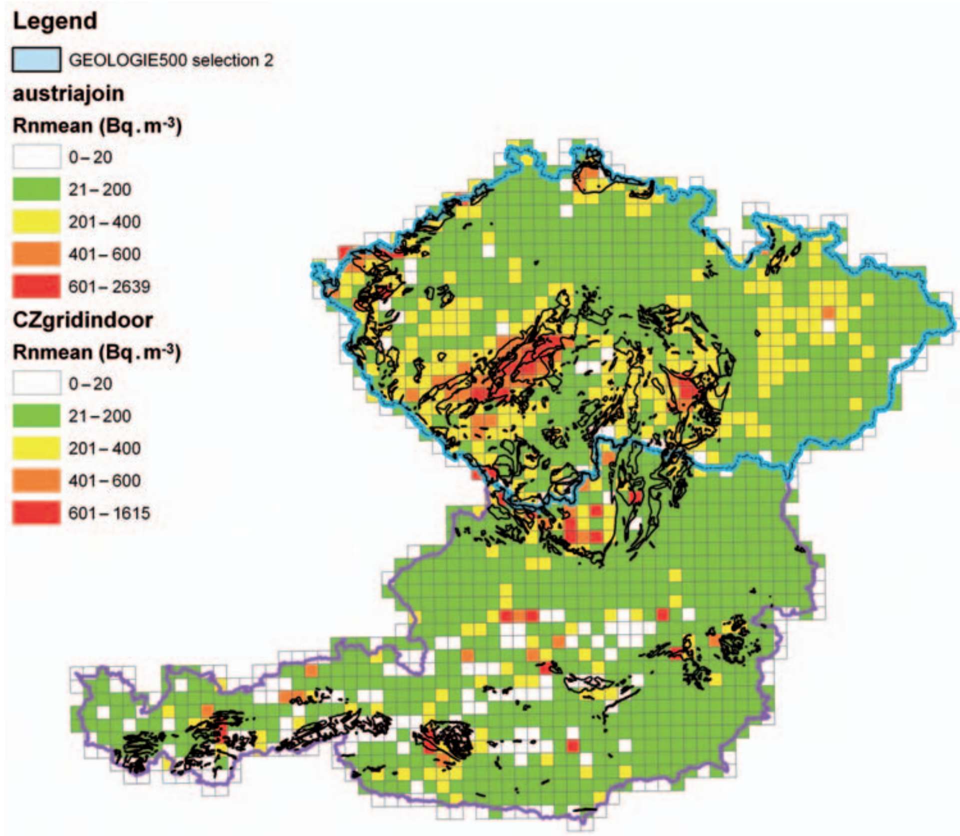


Fig. 10-10. The percentage of high radon index area and countours of granitoids in a grid net 1×1 km (Central Bohemian Plutonic Complex).

Fig. 10-11. The mean indoor radon concentration in a grid net 10 × 10 km and position of Variscan granitoids and orthogneisses in the Czech Republic and Austria.



toids (in black) the extent of the highest percentage cells is nearly identical to the extent of mapped granitoid bodies (geographical vector information is much more precise than grid 1 × 1 km). Therefore the more detailed grid is chosen, the resulting information approximates the information obtained more easily from vectorised geologically based radon maps.

An example of the mean indoor radon data calculated in the grid net 10 × 10 km and areal occurence of Variscan granitoids and orthogneisses is presented in Fig. 10-11. In the Czech Republic the position of these rock types (classified by high and medium radon index) corresponds well to indoor radon mean concentrations above 200 $Bq.m^{-3}$. The granitoid and orthogneiss bodies as a part of the Bohemian Massif form also a substantial part of the geological basement of the Upper Austria district (southern border at the Danube River) and indoor radon concentrations in grid cells are comparable to those from Southern Bohemia region. The central part of the Austrian Alpes exhibits also increased indoor radon concentrations in really confined areas of magmatic and crystalline basement (the areal extent is influenced by the hilly character of alpine relief).

10.4. COMBINED METHODS

Different geostatistical methods are used to express the radon risk in a defined area. These methods are based both on soil gas and indoor radon data with respect to the influence of other additional parameters like bedrock geology, superficial deposits, gamma spectrometry and gamma dose rate, permeability of soils etc. Combined methods usually respect the present state of art in particular European countries and generally can be divided into two procedures. The first procedure supposes the existence of soil gas radon measurements and geologically based radon risk maps from bedrock resulting in geological prediction of radon prone areas and consequent orientation of indoor radon measurements campaigns into these areas. These maps have also the advantage of fulfilling the radiation protection demands of development plans of municipalities out of the intravilans. The second procedure uses the indoor radon data as a generalized input information proceeded by geological explanations of indoor radon prone areas. The summary of different radon mapping data within EU countries and examples of their outputs is given in Dubois (2005). Some examples from using the combined methods in European countries are described there inafter.

In Germany the radon risk classification is based on the soil gas radon measurements (geogenic radon potential) and indoor data (Kemski et al. 2005, 2006). The geogenic radon potential was measured on 4019 test sites within the frame of project of the Federal Office of Radiation Protection. The generalized geogenic radon potential delineates some types of bedrock with enhanced radon potential (Variscan basement, sedimentary formations formed by detritus of Variscan rocks and glacifluvial sediments influenced by contents of Precambrian rocks from Scandinavia). The indoor data are connected also to housing conditions and transfer factor (indoor/soil gas concentration) 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 com-