1 : 200 000 and results of detailed radon surveys. They concerned 630 and 968 building sites, respectively.

The comparisons showed, that the large-scale maps are generally reliable, the satisfactory reliability of radon risk maps was observed at a large number of areas (62.9 %; 56.7 % resp.). When the bedrock is formed by Cretaceous sediments or by granites or granodiorites, and/or the cover formed by loess and loess loams – a satisfactory coincidence between the results of building site characterization and the radon risk map prediction (about or more than 70 % of cases) was observed. Significant differences were found in areas with larger variability of soil environment (river terraces, or layers influenced by anthropogenic activity). In areas with the Quaternary cover formed by river terraces; or with some special rock types – chlorite-sericite phylite – detailed radon surveys did not confirmed the expected risk at more than 60 % of building sites.

Observed differences confirmed the usefulness of a direct building site characterization. The comparison found and demonstrated another disadvantage of the radon maps as well. The lowest reliability, even lower than 30 %, was found in expected high risk areas, i.e. with respect of the usefulness of maps in areas of the main interest (the search of existing houses with higher indoor values). Therefore, the Czech Geological Survey has been publishing new radon risk (index) maps at the scale 1 : 50 000 since 1999 (see Chap. 7).

The third and the fourth comparison were focused on the reliability analysis of those new radon risk maps at a scale 1 : 50 000. The reliability evaluation of maps 1 : 50 000 is more complicated, because the maps include the fourth category, called intermediate, which is not defined for detailed building site characterization and has in fact no corresponding counterpart.

In 2002, the reliability of radon risk prediction maps was analysed by comparing data from detailed radon surveys with data from the corresponding 4 radon map sheets (Neznal et al. 2004). We concentrated on the map sheets with expected all radon index categories or with predicted low and intermediate categories. The reliability was similar – about 62.2 %, when we used the rule that the intermediate category in the map corresponded to both low and medium detailed risk. But the differences between the indications from the map and the data from the survey were again substantial. The spatial distribution of radon indices was induced mainly by variations in geological conditions, which can only be characterized by a thorough geological survey. A geological map of 1 : 50 000 scale, as a basis for radon risk map, cannot register such details.

Finally, the comparison in 2007, when the whole territory of the Czech Republic had been covered by those radon maps, had to answer the question: "Is there a possibility to use the radon risk maps at a scale 1 : 50 000 for determination of radon index at a specific site and for preventive measures in new buildings without detailed in-situ investigation?". Hundreds of detailed radon index assessments (i.e. thousands of soil gas radon concentration measurements) were compared with expected radon index categories in chosen 5 map sheets.

Three ways (approaches) of testing the radon risk maps reliability have been used. The first one corresponds to the main purpose of maps, i.e. searching for existing houses with elevated radon levels, and it minimizes the influence of the intermediate category. In that case it is possible to use again the rule, that the intermediate category in the map corresponded to both low and medium detailed risk (the most important is the agreement in higher risks). The relevant reliability has varied from 63.0 to 67.1 %.

The second reliability test describes the probability, how often we can find the same category using the detailed assessment and/or reading the map. It takes into account the splitting of the intermediate category to both low and medium ones. The corresponding values have varied from 45.2 to 51.5 %.

In the third comparison, the doubtful intermediate category has been excluded. We have focused on the reliability of determination of a specific category. In areas marked as low risk areas in the maps, the reliability has been 37.3 %, i.e. in 62.7 % we have found a higher category during the detailed survey (the risk of underestimation 62.7 %). As for the medium risk, the reliability has been 52.9 %, the risk of underestimation 33.8 % and the risk of overestimation 13.3 %. As for the high risk areas, the reliability has been similar, 52.7 %, and the corresponding risk of overestimation 47.3%.

The answer of the above mentioned question was relatively easy. No, the radon risk maps cannot be recommended to be used for the determination of radon index of building sites for new buildings. On the other hand, the new maps have improved the input conditions for searching the old houses with elevated indoor radon levels.

7. Mapping of radon index

7.1. PURPOSE OF RADON RISK MAPS

The health risk coming from radon in underlying geological units can be partly regulated by monitoring of indoor radon concentrations. Due to the relatively "unfavourable" occurrence of crystalline and magmatic rocks within the territory of the Bohemian Massif, the radon hazard is very frequent compared to other European states. The areal extent of rock types having medium and high radon concentrations in bedrock is close to 50 % of the total state area. Therefore the radon and natural radionuclides exposure of citizens exceeds about 5 times the exposure coming from artificial radionuclides (Hůlka and Thomas 2007). The state financed programme of indoor radon measurements is aimed to discover the radon prone areas and to decrease the indoor radon exposure by remediation projects for particular buildings. The main task of radon risk mapping is confining the areal extent of high radon risk areas within the state territory up to detailed scales and setting the priorities of indoor radon measurements within the municipalities. The state authorities take the results of measurements in account when preparing the legislative support to Radon Programme as well as for estimating the necessity and extent of radon measurements in particular regions and districts. This is also connected with the amount of state-financed support for remediations of dwellings exceeding the action level. The role of radon coming from bedrock is the primary source of information for remediation of public and private water sources (drills, wells). The information of public and rising their interest in radon problematics, supported by the radon index maps publication on web pages, contributes also to decreasing the exposure of population caused by natural radionuclides. Since 1997 the building site assessment is obligatory prior to build a new house (Decree 307/2002 Sb.). The radon index maps are used by radon measuring companies as an completive information on radon index determination on a certain building site, however the resulting radon index category depends fully on the results of factual measurements. The practical experience from contact with public shows that even people-builders comprehend the probabilistic character of natural radioactivity and variability of geological bedrock and soil types.

7.2. RADON DATABASE

Since 1990 the Czech Geological Survey established the radon database being subsequently filled with all available data from soil gas radon measurements within the territory of the Czech Republic. At the beginning of soil gas radon measurements there was enormous bulk of emanometrical data coming from the former Uranium Exploration enterprise during the period of extensive uranium prospecting. Most of these data were gathered only with the aim of detecting uranium anomalies, which means that they did not cover the geological units with uniform density. Also the method used for the soil gas sampling and instrumentation has not insured the tightness of the sampling probes and method of low diameter drilled probes was time and human cost consuming.

Therefore the beginning of the uniform soil gas radon sampling demanded for developing the uniform method being used both for scientific purposes and building site assessment. This decision resulted in the close cooperation with radon-in-soil measuring companies joined in the Association Radon Risk. Members of this Association supported the Radon Programme by granting results of their measurements to the common database with the restriction of data assimilation for scientific purposes only and for developing the bedrock radon knowledge of the state territory (Barnet 1994, 1995a, b, 1998, Pacherová 2004). The radon database is administered by the Czech Geological Survey.

The position of the test sites was digitised in S-JTSK Krovak EastNorth projection from the base topographical maps (maps for the governmental purposes) (Fig. 7-1). The precision of digitising corresponds to the scale of these maps – 1 : 50 000. The rock type characterization was derived from the geological maps of the same scale, published by the Czech Geological Survey, the characterization of the soil cover resulted from the in situ description performed by the measurement provider. The rock type and the soil cover characterization was coded with the aim of easier data processing and generalization of mineralogically characterised lithotypes. Following items form one record in the radon database, their completeness depends on the data provider with the exceptions of obligatory data (Localization data, Radon data, Permeability and Resulting category of radon index). The database was originally performed in *.dbf format enabling selecting and filtering procedures as well as data import into other data processing and GIS programmes. For each measured test site following parameters were entered into the database:

Parameters for radon record:
Localization data – X and Y coordinates, number of map sheet 1 : 50 000, name of locality, object (description of test sites), number in database, reference number.
Radon data – number of measurements, radon mean, median, standard deviation, radon minimum, maximum, 75% quantil and resulting radon risk category, in case of a bigger test site also the distribution of radon risk categories.
Uranium data – content of uranium obtained by field gammaspectrometry, 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.

7.3. SCALES OF MAPPING

7.3.1. Scale 1 : 200 000

During the period 1980–1990 the enhanced gamma activities and indoor radon values exceeding the action levels were detected (Regional Hygienic Centers) in the ash-concrete panels used for prefab houses and specific type of houses START – single family houses built from the slag-concrete panels. The ash and slag material for the panels and form bricks came partly from the waste dumps of electric power stations in eastern Bohemia and west of Prague (Nové Strašecí), where Carboniferous black coal with localy increased uranium contents from a nearby mines was burned. The interest in the indoor activity led to pilot indoor radon study, performed within the Czech Republic by the Hygienic Stations oriented preferably to building materials as a main source of indoor radon. However this study has detected houses with increased indoor radon concentrations demonstrably coming not from the building materials but from the underlying rocks.

Therefore in 1989 the Czech Geological Survey iniciated the project of radon risk mapping based on the available geological and radiometric data from the Czech Republic. In that time the only existing geological maps with the full state coverage were finished at a scale 1 : 200 000 (Fig. 7-2). First 148 test sites for soil gas radon measurements covering all major rock types were measured by the former Uranium Exploration enterprise, which defined also the areas with increased frequency of the uranium

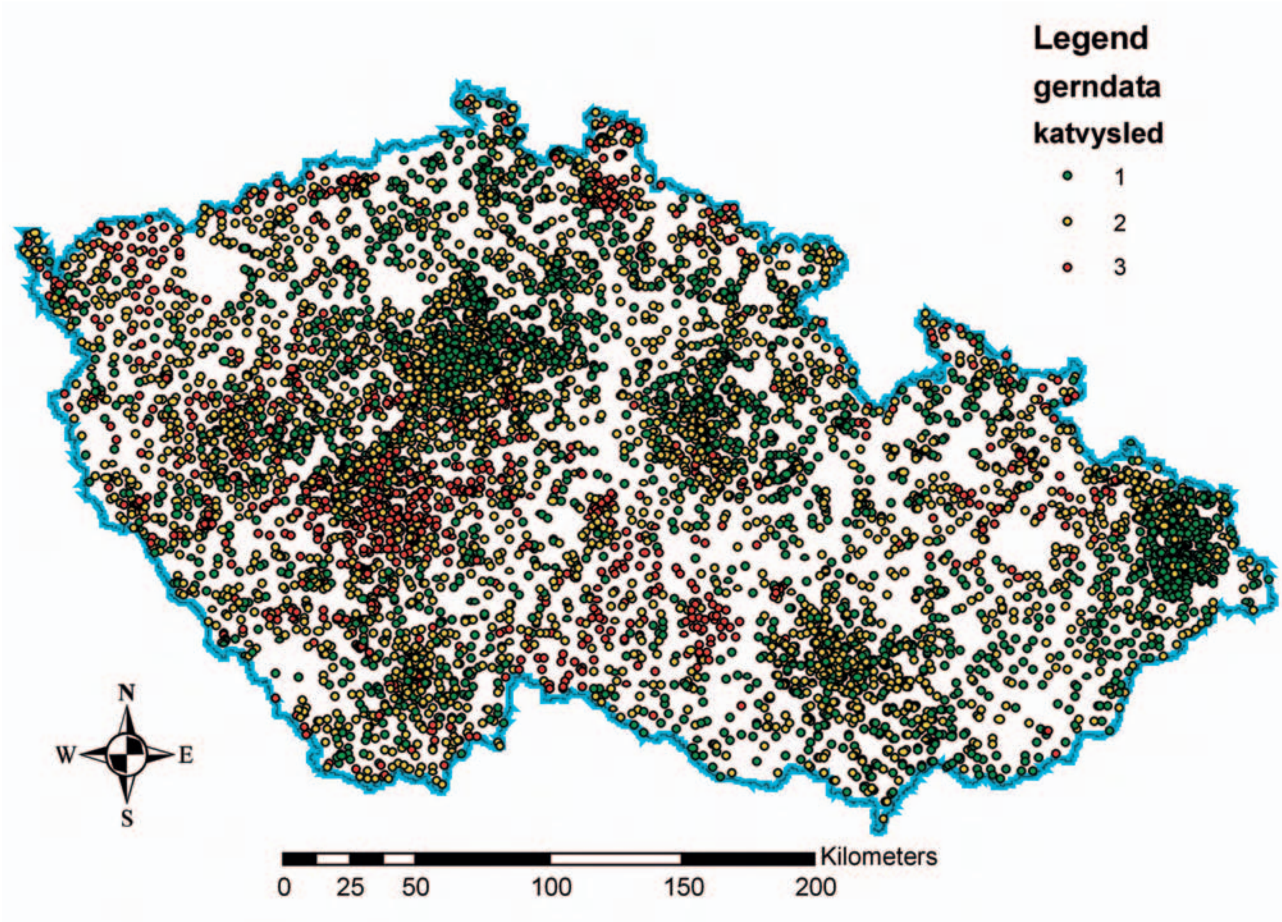

Fig. 7-1. Positions of the test sites from the radon database.

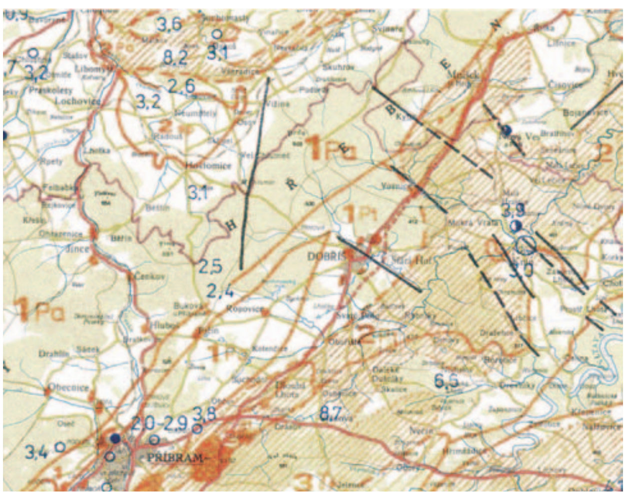

Fig. 7-2. Section of the Derived radon risk map 1 : 200 000 – Central Bohemia (Příbram vicinity).

anomalies and location of uranium waste dumps. Together with the airborne gammaspectrometric data processed by the Geophysics n.p. and Faculty of Science, Charles University in Prague and pedological maps produced by the Czech Geological Survey the first set of Derived radon risk maps 1 : 200 000 covering the whole state territory was finished until 1990 (Barnet 1990a, b, Barnet and Veselý 1990). The contours of major geological and lithological units were defined as a basis for radon risk expressing in three categories – low, medium and high. For each unit the existing data of soil gas radon measurements and permeability completed by the gammaspectrometric characteristics of the rock types were taken into consideration. The maps were hand drawn and not prepared for computer processing.

The Derived radon risk maps served as a first basis for targeted indoor radon surveys performed by the Regional Hygienic Centers and later by the National Radiation Protection Institute in widecountry scale.

Polygons of geological units are marked by the radon index category, the enhanced frequency of uranium anomalies is marked in dashed areas. The waste dumps are in orange colour.

7.3.2. Scale 1 : 500 000

The utilization and development of GIS methods in geological sciences has lead to exploiting the areal and point data including the soil gas radon measurements. During 1990–1998 the soil gas radon database was filled with 7800 data enabling much more precise determination of radon risk in particular rock units. In 1998 we took the

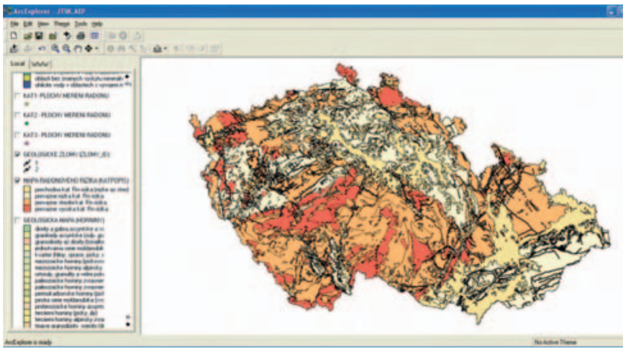

Fig. 7-3. Radon risk map on a scale 1 : 500 000 (light yellow – low, beige – interstage, orange – medium, red – high radon risk categories).

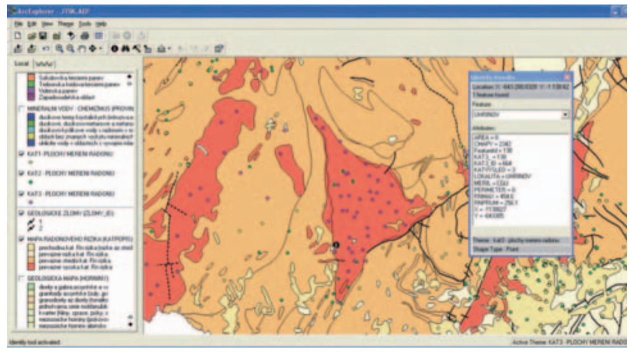

Fig. 7-4. Section of the radon risk covering the Třebíč syenite body with expanded window – selected information about the test site.

advantage of preparation the atlas of geoscientific maps at a scale 1 : 500 000 (published by the Czech Geological Survey). This atlas was fully based on the vectorised geoscientific data including the polygons of major geological units. GIS processing enabled to characterize rock units from the point of view of mean soil gas radon concentrations, permeability and prevailing radon risk category.

The radon risk map 1 : 500 000 is included in the Atlas of Maps of the Czech Republic – GEOČR500 (Barnet et al.1998a, b) together with 10 other maps with geoscientific themes, published on the CD ROM. Radon risk is characterized by three basic categories (low, medium and high) and one interstage category (typical for the radon risk from low category to medium in the inhomogeneous Quaternary sediments of allochthonous origin). The contours of geological units are filled after the prevailing radon risk in particular rock types. However the applied scale partly suppresses the areal extent of Quaternary sediments, which influences also the area of intermediate risk. On the other hand, for generalised analyses and decissions respecting the underlying geology this map is more suitable (Figs 7-3 and 7-4).

Due to the ArcExplorer – freeware application, the single layers from the CD ROM can be combined from all 11 maps with the geoscientific themes and enable to construct the maps after users' demand. The point data are connected with the databases, whose content can be presented in the window form on the screen. The CD-ROM with radon map application was widely used by the regional and district Hygienic Centers (later Regional Centers of National Radiation Protection Institute) and municipal authorities for the track-etch detectors' distribution into dwellings.

The areal extent of particular radon index categories after 1 : 500 000 map is given in Tables 7-1 and 7-2 and should be compared to Tables 7-3 and 7-4 illustrating the same parameter for detailed radon index maps at a scale 1 : 50 000. The role of scale namely expressed in the difference in intermediate category area is clearly visible.

Tab. 7-1. Areal extent of particular radon risk categories (scale 1 : 500 000)

Radon index category	Area in km^2
Low	24 029
Interstage	14 795
Medium	30 734
High	9 232

Tab. 7-2. Number of municipalities situated on particular radon risk categories (positioned after centroids of municipalities, scale 1 : 500 000)

Radon index category	Number of municipalities
Low	2 059
Interstage	1 350
Medium	2 374
High	613

Tab. 7-3. Areal extent of particular radon risk categories (scale 1 : 50 000)

Radon index category	Area in km^2
Low	16 701
Interstage	31 167
Medium	24 201
High	6 742

Tab. 7-4. Number of municipalities situated on particular radon risk categories (positioned after centroids of municipalities, scale 1 : 50 000)

Radon index category	Number of municipalities
Low	1 316
Interstage	2 927
Medium	1 745
High	406

7.3.3. Scale 1 : 50 000

The extensive application of the vectorised data in the state administation and research institutions opened way to supporting data sources which could be used in improving quality of radon risk maps. Also the widespreaded public knowledge about the radon hazard obliged the participants in the Radon Programme to targeted recommendation about the indoor radon detectors' distribution even in the scale of particular municipalities. The demands for the state-financed indoor radon measurements are yearly consulted with the officers responsible for the effectivity of Radon Programme within the districts (76 districts) and later within a new regional division (NUTS3 – 13 regions). The basis of the Radon Programme required setting the priorities to early finding out the dwellings above the action level. The response of the Czech Geological Survey resulted in preparing the detailed radon risk mapping programme, based on the geological maps at a scale 1 : 50 000 (full state coverage in 1999). Due to the administratively required terminological change the new maps are named "Maps of radon index of geological bedrock", even if the basic input parameter – radon risk category – is equal to the new term radon index category (Mikšová and Barnet 2002).

Input data sources:
Czech Geological Survey:
Soil gas radon database (test sites in rock units from the whole state territory 15 measurements each)
Vectorised polygons of geological units
Vectorised polylines – tectonics

Czech Office for Surveying, Mapping and Cadastre:
Raster topography

To follow the basic demands of the Radon Programme, the radon index mapping started in the areas of the most radioactive bodies within the Bohemian Massif – Třebíč syenite massif, Central Moldanubian pluton and Central Bohemian Plutonic Complex with Čertovo břemeno syenite (durbachite) body including the adjacent areas of medium radon index in Moldanubian. The mapping sequence followed in the areas of granitoids of Variscan and Prevariscan age in the western, east-western and northern part of the Bohemian Massif (Barnet et al. 2000a, b). The mapping programme was finished in the crystalline and Palaeozoic complexes of Northern Moravia (Brunovistulicum) and Carpathian foredeep in south-eastern Moravia, where low to intermediate radon risk was expected from the hitherto data. The whole mapping programme has covered the state territory of 78 800 km^2 area by 214 map sheets at a scale 1 : 50 000 within the period of 1999–2005 (Fig. 7-5).

Four categories are used in detailed radon index maps – low, interstage (for inhomogeneous Quaternary sediments), medium and high. The areal extent of particular radon index categories expressed in the maps 1 : 50 000 differs from the data for maps 1 : 500 000 as can be seen by comparing the Tab. 7-1 and Tab. 7-3. The areal decrease in low, medium and high category is compensated by increase in intermediate category (Quaternary sediments) clearly reflecting the difference in the scale – the detailness of geological mapping.

7.4. RADON INDEX MAPS 1 : 50 000 – METHOD OF PROCESSING

From the data of radon database (Visual FoxPro) the statistically prevailing radon index for particular rock type is the leading parameter for the radon index map construction. Usually at each geological map 40–90 rock types are specified. The rock types differ mostly by mineralogical

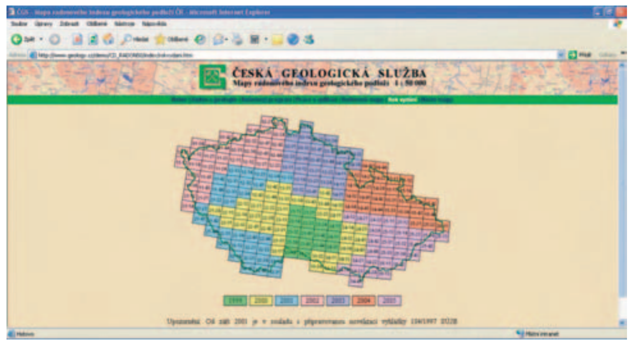

Fig. 7-5. The time sequence of radon risk mapping 1999–2005.

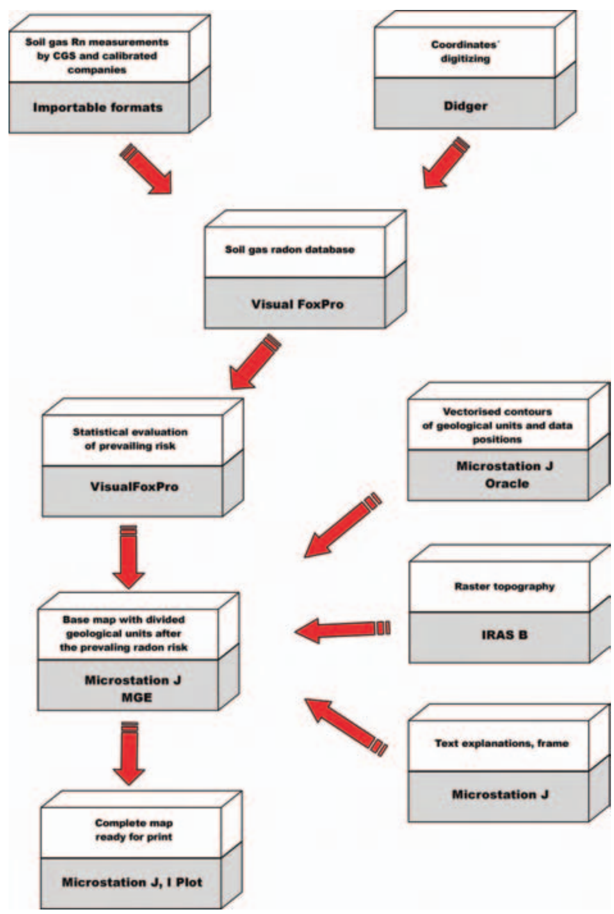

Fig. 7-6. The flow chart diagram of radon index maps' processing.

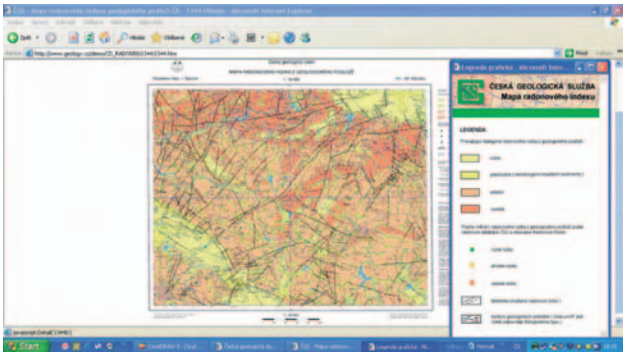

Fig. 7-7. The radon index map at a scale 1 : 50 000 and opened legend window.

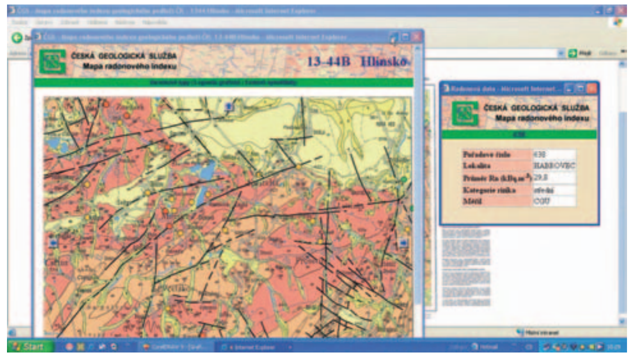

Fig. 7-8. Zoomed quadrant of radon index map at a scale 1 : 50 000 and information window for the particular test site (number, locality, mean soil gas radon, radon index category and provider of measurement).

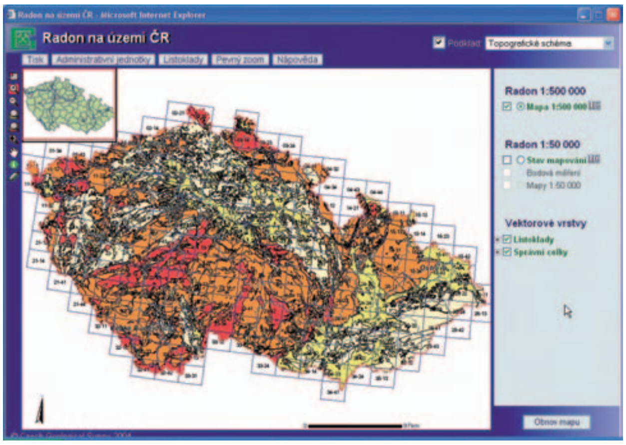

Fig. 7-9. The general radon index map 1 : 500 000 prepared for zooming the specified area.

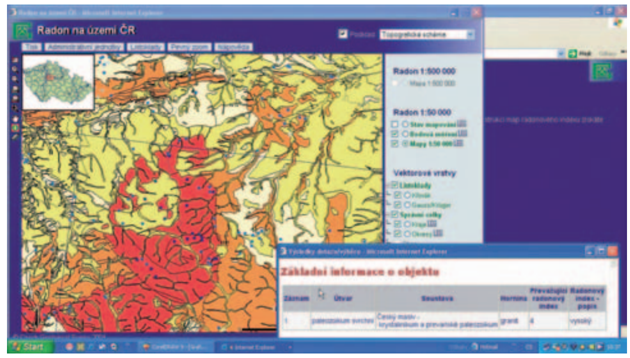

Fig.7-10. Zoomed section of the radon index map (Říčany granite pluton – Central Bohemia) and information window on the selected test site (basic information from the radon database is added – locality, mean soil gas Rn, provider of measurement, category of radon index).

composition or by stratigraphic position, the difference in primary uranium concentrations and subsequently in radon concentrations is not so expressive within particular lithological units (with some minute exceptions). In combination with results from the radon database the particular rock types can be grouped into prevailing categories of radon index.

Grouping of vectorized geological units was performed in MGE programme and transformed into Microstation J programme (Bentley) using the Oracle database of geological polygons, The grouped contours of rock units are filled according to the prevailing category of radon risk.

Raster layer of topography (intravilan plans, road network and watersheds) are attached in IRAS B programme. The layout of each map sheet comprises also the common information on radon risk, legend and division of the rock types with specified prevailing radon index. Finally the test sites' positions are loaded over the vectorized radon layer and topographic raster files (Fig. 7-6). All 214 map sheet were plotter printed and presented to the State Office for Nuclear Safety, archive of the Czech Geological Survey and Ministry of Environment. Printing of the separated map sheets is also custom-made by the Information Services of the Czech Geological Survey.

7.5. GIS AND INTERNET APPLICATIONS FOR RADON RISK MAPPING – CD-ROM AND MAP SERVER

The interest of municipal authorities and public in radon information demanded for publication of radon index maps in an electronic form (Barnet and Mikšová 2001, Barnet et al. 2001). The Czech Geological Survey has published all 214 radon index map sheets on the interactive CD-ROM. The application starting with installation of freeware ArcExplorer viewer enables to select the specified map sheet from the general map or from the list of map sheets. Each map is divided into four quadrants which can be zoomed to the scale close to 1 : 50 000. The windows of legend, radon index classification of rock types occuring in the map and explanations – information on radon risk can be displayed in the map window. The measurement data are linked to the selected parameters from the radon database (number, radon mean, resulting radon index and data provider) and for each data point the information window can be opened. The application enables also the moving of the displayed quadrant within one map sheet and within the adjacent map sheets (Figs 7-7 and 7-8). Printing of the displayed map is also available as the

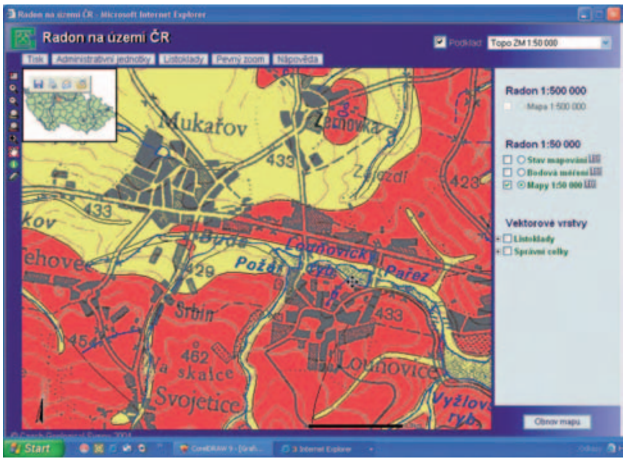

Fig.7-11. Zoomed section of radon index map, raster topography added. For local authorities this information enables to distribute the indoor radon detectors into high risk parts of municipalities with an enhanced efficiency.

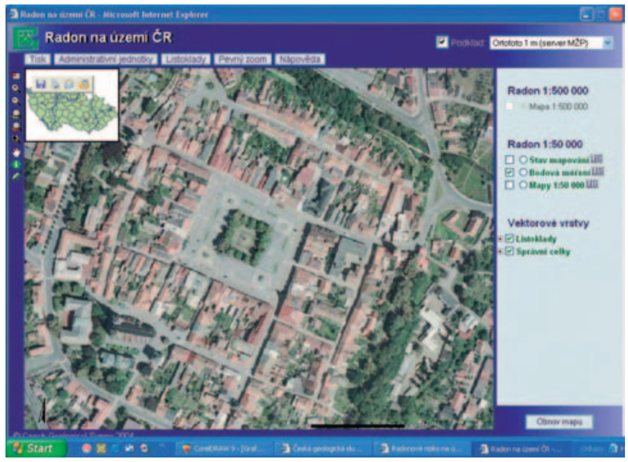

Fig. 7-12. The same frame with the ortophoto image background (1 m resolution) and information window on the selected test site. Administrative borders can be also added.

experience shows the customers' interest usually in a certain areas of the intended building activities. However the warning of not substituting the building site assessment by using the radon index map information is emphasized (Barnet – Pacherová – Neznal 2005).

The CD-ROM was also applied as a part of web pages oriented to radon problematics and radon programme. The web pages comprise the general information on sources of radon in bedrock, methods used for radon index determination, mapping programme within the Czech Republic, comparison of indoor and soil gas radon measurements, publication list and usefull links to radon pages of institutions involved in the Radon Programme of the Czech Republic and in some European countries. The radon web pages address is www.geology.cz in Czech and English version (http://nts2.cgu.cz/servlet/page?_pageid=350,366,352&_dad=portal30&_schema=PORTAL30).

The third internet application of radon index maps is located on the Map Server of the Czech Geological Survey (Figs 7-9 to 7-12). This application enables the continuos moving between the adjacent map sheets and linked general topography, raster topography at a scale 1 : 50 000, detailed topography at a scale 1 : 25 000 after the military mapping at in a close zooming the photogrammetric images with 1 m resolution.The basic information on the measurement points is also added.

8. Statistics of radon in the rock types

The geological situation of the area is the main factor influencing the resulting radon index of the building site. The determination of the radon index is based on two factors: soil gas radon concentration and the permeability of soil and rock for gasses (Neznal et al. 2004).

The statistical parameters of the radon distribution were calculated for the main rock types of the Czech Republic using the radon database of the Czech Geological Survey and the Arc Gis projection. The database consists of the data from the radon measurements performed on the area of the Czech Republic including the location data, the levels of volume radon activity and the resulting radon risk category.

The magmatic rocks have the highest both mean volume radon activity (51.4 kBq . m^{-3}) and percentage share of high radon risk index (37 %). Little bit smaller are the values of metamorphic rocks (mean soil gas radon is 33.7 kBq . m^{-3}, percentage share of high radon index is 16 %) and the minimal values have the sedimentary rocks (22.6 kBq . m^{-3}, 4 % of high radon risk category). The distribution of low, medium and high radon risk index, the categories of the permeability and the values of mean and median soil gas radon concentrations (kBq . m^{-3}) for magmatites, metamorphites and sediments are mentioned in Tab. 8-1. The portion of the extreme measurements shows the same trend when 12.3 % of all measurements performed on the magmatic rocks are higher than 100 kBq . m^{-3}, 4% in the case of metamorphic rocks and only 1.1 % in the case of sedimentary rocks. The distribution of mean soil gas radon concentrations, the categories of radon index and the permeability of magmatic, metamorphic and sedimentary rocks is shown in Fig. 8-1.

The mean and median values of mean soil gas radon concentrations and the distribution of low, medium and high radon risk category are listed in Tab. 2. Whereas the trend of growing mean soil gas radon concentrations of sedimentary, metamorphic and magmatic rocks, there are the differences in mean soil gas radon concentrations of different types of all three kinds of rocks. The relatively high values of Carboniferous sediments and Palaeozoic formations in general can be caused by the presence of uranium mineralization connected with the bitumenous sediments. The highest differences of radon concentrations show the magmatic rocks. The highest both mean volume radon activity and the distribution of high radon index have the syenites and durbachites (mean soil gas radon concen-