Geophysical survey of Neovolcanic complexes in the first protection zone of the Sliač Spa and the Baková jama

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Abstract: The main purpose of the survey in the 1st protection zone area of the Sliač Spa and the Baková jama was to clarify the geological-tectonical structure. The vertical electric sounding (VES) technique was selected as the main geophysical survey method. Additionally, the soil radon emanometry was carried out to verify tectonic lines' presence. The outcrop of Pre-Tertiary basement was discovered in the form of small isolated island. No tectonic line was identified based on the evaluation of profile radon concentration. The results of geoelectrical measurements are presented in 8 geological-geophysical cross-sections. The results and the tectonic lines' courses interpreted by the VES method are drawn in the map of new indications. The isoline maps and 3D model of Pre-Tertiary basement were constructed.

Key words: applied geophysics, vertical electric sounding (VES), soil radon (^{222}Rn), groundwater, Sliač Region

1. Introduction

The goal of this work was to make the geological structure in the area of the Baková jama and the 1st protection zone of the Sliač Spa more precise

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using geophysical survey and other accessible information.

The main target of the survey in the Baková jama area was to clarify the geological-tectonical structure down to the depth of approx. 100 meters. One of the main questions was whether the rocks of the Pre-Tertiary basement reached the surface.

The clarifying of the geological structure of the 1st protection zone of the Sliač Spa is important from the explanation point of the underground and mineral waters' regime in this area.

Previous geophysical works done in the Neovulcanic area of Central Slovakian confirm a very complicated geological structure (*Obernauer and Husák, 1971; Šefara et al., 1973, 1976; Bárta and Husák, 1974*).

The results of mineral water exploration in the Pohronie Region and of covered relief of the Pre-Tertiary basement tracing were sumarized mostly in works by *Májovský and Husák (1973)* and *Bárta et al. (1977).* They have detached two main geoelectrical horizons in wider surroundigs area. The gravity elevation in the area of the Lieskovský chrbát Hill, between Sliač and Lieskovec villages, was described by *Šefara et al. (1976).* These results were reinterpreted later by *Šefara and Komora (1983)* and confirmed that the basement of neovolcanic complexes is irregular and has horst-graben structure.

Hydrogeological studies of mineral and thermal waters in the Sliač aquifer line area (*Franko et al., 1970; Zakovič, 1980*) are other survey works. The surveys of *Rebro et al. (1971)*, *Bondarenková et al. (1986)* and others were focused on qualitative and quantitative evaluation of Sliač mineral waters.

Many works were devoted to exploration of Quaternary and Neogene waters for drinking purposes.

2. Study area

The study area between Sliač, Lukové and Lieskovec villages belongs to regional geomorphological units of the Sliač Depression and the Zvolen Highlands (*Mazúr and Lukniš, 1980*).

It is assigned to regional geological formation of Neogene volcanites of the Western Carpathians (*Vass et al., 1988*). Surface geological structure consists mostly of Neogene volcanic rocks and Neogene and Quaternary sediments, less from crystalline and Mesosoic complexes (Fig. 1).

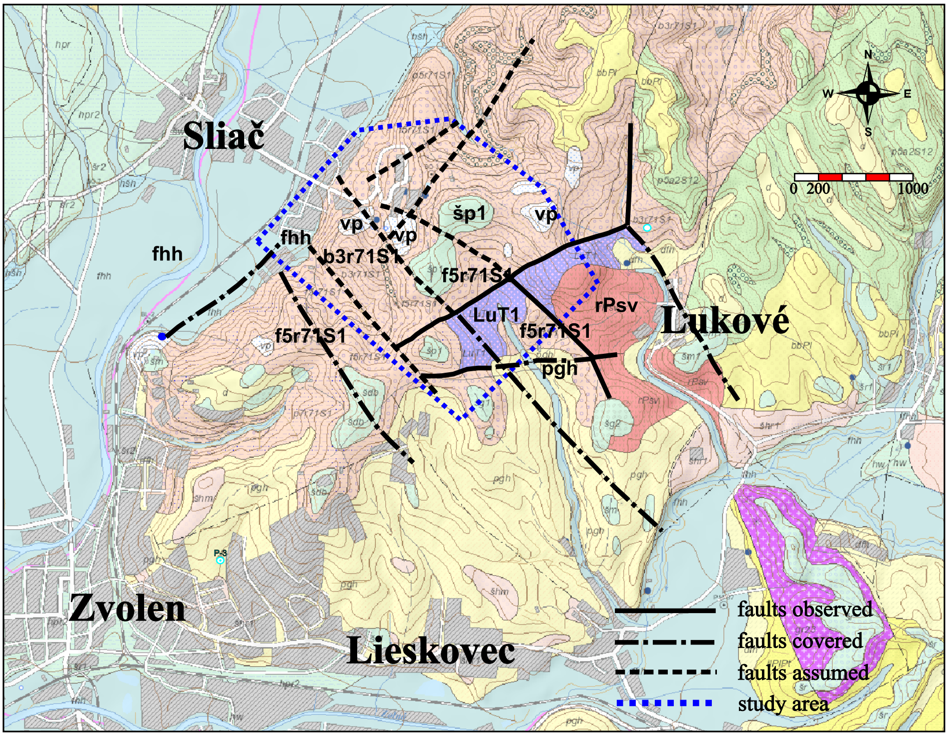

Fig. 1. Geological map of the study area (adopted from the map portal of the State Geological Institute of Dionýz Štúr (ŠGÚDŠ)).
Legend: fhh – lithofacially undivided plain clays; vp – chemogenous-organogenous sediments; šp1 – fluvial to sandy gravels; pgh – deluvial-polygenetic sediments; b3r71S1 – pumiceous and ryodacite tuffs; f5r71S1 – redeposited tuffs and epiclastic conglomerates of ryodacites; LuT1 – the Lúžna Formation (quartzites, quartz sandstones); rPsv – volcanogenous horizon of Harnobis (ryolites-dacites).

Pre-Tertiary basement of the study area is mostly built by Mesozoic quartzites of the Lúžna Formation together with sandy and sericite schists to sandstones. It is represented by an isolated island between Sliač and Lukové villages and is described also in close vicinity of the Sliač Spa. These quartzites consist exclusively of quartz. They were buried at the depth of 25 m (*Andrusov, 1942*) in the Well-1 close to Sliač cold acidulous water springs, in the well BO-3 (500 m NE from springs) at the depth of 217 m and in the well BL-2 (between the Borová hora and the Hron River) at the depth of 276 m (*Bondarenková et al., 1986*).

Neogene geological structure of the Sliač area is created by rocks of the external volcanic zone of the Poľana composite volcano deposited Early Tertiary rocks of andesite complex developed in two main lithogenetic types: as epiclastic volcanic psefites to conglomerates and re-deposited volcanic tuffs (*Dublan et al., 1997*).

The basic Quaternary sediments of studied area are mostly deposites of the Hron River: fluvial and proluvial sediments of terraces and alluvial cones, and deluvial and chemogenous-organogenous sediments.

Fluvial deposites, so-called sediments of high and middle terraces, consist mostly of quartzites, rounded pebbles from most different limestones and material floated from crystalline core of the Nízke Tatry Mts. and from the Kremnické vrchy Mts. (*Dublan et al., 1997*). Younger stages of higher terraces are preserved eastwardly from the Sliač Spa at the mountain ridge in the area of sheep farm called "Za kúpeľmi" (*Andrusov, 1942*).

Chemogenous-organogenous sediments (travertines) are present mostly in the Sliač Spa complex, at the Borová hora Hill and in the central part of studied area (Za kúpeľmi) in the form of irregular islands. Successive migration of mineral water springs, from Pliocene to recent, is deduced from travertines' distribution (*Andrusov, 1942*). Today, the actual spring place is the surroundigs of the Sliač Spa.

3. Methodology and results

Based on previous practical experience, the VES method was selected for investigation purposes in order to achieve the objectives of the study. This classical geoelectric method employs measurement and analysis of resistivity distribution in the subsurface.

Overall, 38 VES measurements were set up in the study area with varied depth range of AB/2 (meters) (Table 1). Quantitative interpretation was performed using Ves Interpretation (VesInt) software developed by *Cerovský (2001)*. Using interpreted VES measurements, 8 geological-geophysical cross-sections were constructed (Fig. 3). Configuration of exploration works (VES measurements) and interpreted profiles is described in Fig. 2.

We identified 6 geoelectrical horizons (Fig. 3) in the study area by em-

Table 1. Geographical coordinates (WGS 84), elevation above sea level (Google Earth) and AB/2 electrode spacing (m)

VES	WGS 84 latitude	WGS 84 longitude	elevat. [m a.s.l.]	AB/2	VES	WGS 84 latitude	WGS 84 longitude	elevat [m a.s.l.]	AB/2
K1	48° 36' 39.20"	19°10' 32.80"	442	**300**	K19	48° 36' 16.10"	19°10' 27.30"	376	**300**
K2	48° 36' 42.30"	19°10' 18.20"	428	**500**	K20	48° 36' 07.74"	19°10' 31.25"	378	**300**
K3	48° 36' 47.60"	19°10' 01.20"	408	**390**	K21	48° 36' 00.20"	19°10' 45.50"	361	**300**
K4	48° 36' 39.10"	19°10' 20.30"	430	**300**	K22	48° 36' 55.20"	19°11' 06.30"	372	**300**
K5	48° 36' 38.30"	19°10' 10.40"	442	**300**	K23	48° 36' 04.55"	19°11' 03.10"	386	**300**
K6	48° 36' 28.00"	19°09' 52.00"	411	**300**	D1	48° 36' 37.00"	19°10' 24.40"	431	**300**
K7	48° 36' 29.20"	19°09' 35.00"	369	**300**	D2	48° 36' 35.10"	19°10' 29.70"	435	**300**
K8	48° 36' 18.20"	19°09' 51.40"	418	**300**	D3	48° 36' 30.10"	19°10' 41.70"	448	**300**
K9	48° 36' 12.90"	19°09' 59.40"	410	**300**	D4	48° 36' 23.50"	19°10' 46.40"	444	**230**
K10	48° 36' 19.60"	19°09' 57.10"	422	**500**	D5	48° 36' 17.05"	19°10' 52.91"	436	**230**
K11	48° 36' 30.60"	19°10' 04.80"	420	**300**	D6	48° 36' 10.59"	19°11' 00.00"	406	**230**
K12	48° 36' 32.20"	19°09' 58.70"	428	**300**	M1	48° 35' 58.06"	19°10' 29.78"	390	**300**
K13	48° 36' 44.20"	19°09' 53.80"	410	**300**	M2	48° 36' 02.83"	19°10' 14.66"	412	**300**
K14	48° 36' 44.50"	19°09' 17.70"	320	**300**	M3	48° 35' 59.37"	19°10' 01.45"	420	**500**
K15	48° 36' 11.71"	19°10' 14.10"	384	**300**	M4	48° 36' 07.48"	19°09' 49.40"	392	**300**
K16	48° 36' 19.10"	19°10' 12.30"	391	**500**	M5	48° 36' 14.92"	19°09' 45.29"	403	**300**
K17	48° 36' 25.20"	19°10' 25.40"	398	**500**	M6	48° 36' 27.56"	19°09' 28.32"	370	**300**
K18	48° 36' 29.40"	19°10' 35.00"	429	**300**	M7	48° 36' 31.02"	19°09' 18.66"	375	**300**

ploying qualitative and quantitative interpretation techniques of VES measurements and by implementing available information from previous exploration works, wells (BO3, BL-2, PK-1, P-9, P-2) and also from the well-1 and Ia spa wells.

The first (1) geoelectrical horizon is characterized by the resistivity of 50 – 200 Ωm. It is the horizon lying in the uppermost structural position among the interpreted profiles. According to archive geoelectrical and drilling works and current geological knowledge, the horizon is represented by fluvial coarse grained gravels and sands mixed with calcareous sediments.

Deposits of sand and gravel form the bodies of upper and middle fluvial terraces of the Hron River. Based on interpreted geophysical sections it can be observed that the terraces extend beyond the boundary of the Hron River valley itself; they lie at the crests of the Zvolen highlands.

The sediments reach the largest extent at the area designated as "Za kúpeľmi" and at the banks of "Bakova jama". Gravel facies show smooth

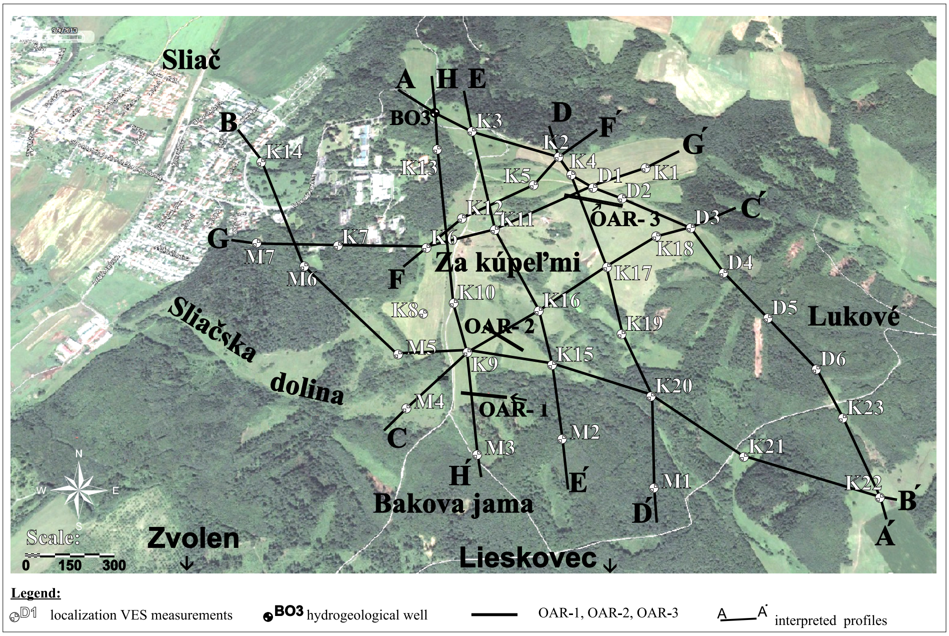

Fig. 2. Configuration of exploration works (VES measurements) and interpreted profiles.

transition from gravel to the bodies characterized as upper andezite conglomerates facies (*the 5th geoelectrical horizon*), which lie below the base of gravel fluvial terraces. Accumulations of gravels and sands are built by boulders of quartzites, sandstones and granites. They also contain intercalations of sands, sometimes with strong content of silt. The boulders reach diameters of 20 to 100 mm. Terraces are overlaid by deluvial slope silts at several places in the area of Bakova jama (*the* 2nd *geoelectical horizon*) (Fig. 3).

Calcareous sediments (calc tuffs) appear at the surface in AA' and CC' sections, in the vicinity of the VES-D3. They form an island, elongated in the direction to the valley (to VES K-18). We assume that the body extends to the vicinity of the K4 and K2 VES stations, where it gradually pinches out. It is highly probable that this was the exact point of mineral water discharge to the gravel terrace. At this place, the calc tuffs are covered by 5 to 10 m thick layer of deluvial silts.

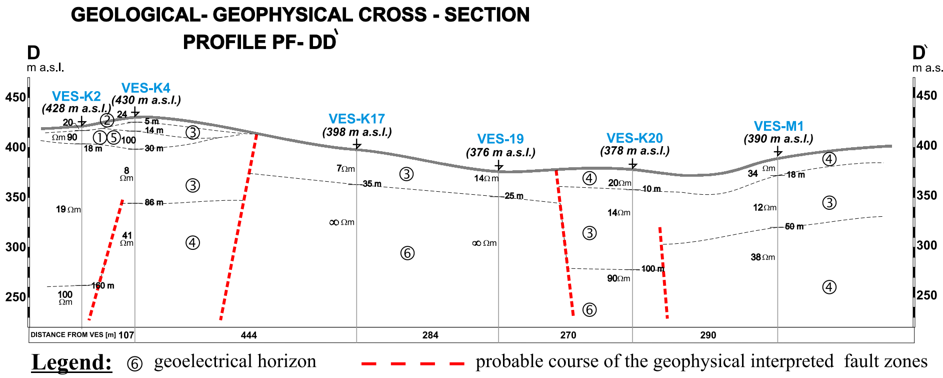

Fig. 3. Interpreted geological-geophysical cross-section DD'.

Another region of the travertine occurrence is an area around the VES M6 station, directly in the Sliač Spa, southwards at slopes from the Lenkey stream and also to the east from the Spa stream situated at the western slopes of the elevation so-called "Za kúpeľmi" nearby the VES K6 and VES K11 stations. The travertine body achieves a huge areal expansion here. Tectonic lines are always followed by the travertine occurrence in the region (Fig. 3).

The second (2) geoelectrical horizon is characterized by the resistivity of 8 – 26 Ωm. It is represented by polygenetic deluvial slope deposits which are created mainly by the slope silts with over-silted gravel presence also with debris in some places. Material is very often redeposited by the gravity power effects (hillwash, soil runoff, landslides or solifluction). Silts are passing into the loess in many places (Fig. 3).

The third (3) geoelectrical horizon is characterized by the resistivity of 5 – 19 Ωm. The horizon consists of redeposited coarse-grained to fine-grained tuffs transmigrating in upper levels into epiclastic volcanic clays or silts. There are also their indurated equivalents, volcanic clay-stones or silt-stones in deeper buried levels. The tuff positions are filled in lens of andezite conglomerates and sandstones in some parts. From the general point of view, the horizon represents pyroclastic material deposits arisen out from ash clouds originated from highly explosive eruptions of the Poľana caldera (occidentally the Kremnické vrchy and Javorie volcanos). Deposits are typical for extra-caldera peripheral zones.

The fourth (4) geoelectrical horizon is characterized by the resistivity of 15 – 49 Ωm. Rhyo-dacite epiclastic sandstones, sandstones and clayey sandstones are represented there. It has a feature of coarse-grained to very coarse-grained sedimentary formation. The horizon includes a mixture of rhyo-dacite tuffs and andesite conglomerates.

There is a characteristic profile from horizon described above situated southwards from the Veľká Lúka village, over the Hron River bottom land in a cut of southern hillslope. Horizon thickness reaches 33 m. There are fine-grained rhyo-dacite tuffs in the overlying and also in basement rocks (*Dublan et al., 1997*).

The fifth (5) geoelectrical horizon is characterized by the resistivity of 36 – 190 Ωm. Over-lapping andesite conglomerates – very corrupted coarse-grained rocks with sandstone, tuff clay filling to epiclastic volcanic breccia, are concentrated here. Conglomerates consist mainly of pyroxen-andesite material. Pebbles predominate over fine-grained sandy – clay filling in the horizon. Granularity of the conglomerates is coarse-grained to block sized with diameter to 400–500 mm. The horizon is located in the research area at slopes over the Sliač Spa and interferes even in "Za kúpeľmi" district or in the Bakova jama slopes. The horizon was indicated in the monitored profiles by the VES: K5, K6, K9, K11, K12, K15, M3, M2 (Fig. 2).

The sediments are described as a stuff of paleo-river trough. They are ranged in a wider environment of several places, but the greatest thickness of the formation (from 13 to 25 m) was detected in the surroundings of the Veľká Lúka village (*Dublan et al., 1997*).

There are also wells of natural ground water at various places in the surroundings. It is assumed that this horizon represented by coarse-grained andesite conglomerates in hanging-wall with a fluvial coarse-grained sandstone facies belongs to infiltrating and hydratropic zone of the natural ground waters with meteoric water as a source.

The sixth (6) geoelectrical horizon is characterized by the resistivity of 70 – ∞ Ωm. This horizon is built by rocks of Pre-Tertiary basement. This Pre-Tertiary basement consists of Lower Triasic quartzite (quartzites to quartz-arkose sandstones) and siliceous porphyry lithology. The rocks get off at the surface in the form of an isolated enclave in the area of D4 and D5 stations. The body of Pre-Tertiary rocks is broken into the block system descending alongside the tectonic failures into the deeper levels at southern, western and north-western directions.

The phenomenon of the high resistivity (100 Ωm) area, which was interpreted in the ground of VES K3, at depth of 160 m is likely caused by the limestone presence. In the BO3 drill hole, approximately 203 m far away of the K3 station, the limestone position was mined in a depth ranged from 187 to 214 m. There was also detected a siliceous shales bearing horizon traversing into siliceous sandstones in limestone basement (*Bondarenková et al., 1986*).

Tectonic fault lines are the most well-known transportation ways of radon gas (^{222}Rn) from a deeper parts of earth crust up to the superficial parts. Emanation of radon from a geological environment was an object of many research papers dealing with the radon concentration in the ground waters (*Gluch et al., 2011*) and further with mapping of tectonic lines and geological units according to the radon concetration changes (*Miles and Appleton, 2005; Mojzeš, 2005; Mojzeš et al., 2006; Gluch et al., 2011; Putiška et al., 2012*).

To verify a course of tectonic lines, there was measured volume activity of soil ^{222}Rn gas (VAR) in kBq/m^3, along three profiles (OAR-1, OAR-2 and OAR-3).

The profiles were situated perpendiculary to the assumed tectonic lines (Fig. 2) with step of measurements approx. 5 meters. All profile data are in Table 2 and their graphic representation is presented in Fig. 4.

On the basis of radon data evaluation it is not possible to have any fault line along the profiles. The near-surface layer shows weak gas-permeability, because of deluvial silts and clays tending to loess loam character.

From the analytical results of VAR measurements it is clear that the vertical character should always be taken into account, because the presence of impermeable clay near-surface layer could negatively affect radon distribution in the rock environment and this is also the reason why the location of real existing fault systems becomes undetectable. That is why the use of this method is useless to indicate any tectonic failure.

There was arranged a new map of geological indication data obtained from the latest-interpreted geoelectrical cross-sections of the research area (Fig. 7A, B) and also the map of isolines (Fig. 5) and 3D model of Pre-Tertiary basement relief of the area (Fig. 6).

Table 2. ^{222}Rn volume activity value measured along the profiles

Profile OAR - 1				Profile OAR - 2				Profile OAR - 3					
point	222Rn [kBq.m-3]	point	222Rn [kBq.m-3]	point	222Rn [kBq.m-3]	point	222Rn [kBq.m-3]	point	222Rn [kBq.m-3]	point	222Rn [kBq.m-3]	point	222Rn [kBq.m-3]
0	0.128	**18**	3.779	**0**	2.772	**18**	1.749	**0**	1.228	**18**	1.917	**36**	1.948
1	3.544	**19**	0.652	**1**	5.998	**19**	1.192	**1**	1.459	**19**	1.543	**37**	1.245
2	1.118	**20**	1.348	**2**	1.128	**20**	2.882	**2**	6.055	**20**	1.336	**38**	1.118
3	7.641	**21**	1.587	**3**	1.438	**21**	3.565	**3**	5.267	**21**	1.697	**39**	0.831
4	0.456	**22**	0.234	**4**	4.716	**22**	1.233	**4**	1.114	**22**	1.514	**40**	0.169
5	1.991	**23**	2.196	**5**	0.230	**23**	1.085	**5**	1.927	**23**	0.237	**41**	1.697
6	0.325	**24**	1.071	**6**	3.548	**24**	0.340	**6**	1.726	**24**	0.119	**42**	1.861
7	1.963	**25**	0.378	**7**	0.020	**25**	0.729	**7**	1.114	**25**	0.304	**43**	4.721
8	2.449	**26**	1.392	**8**	0.392	**26**	0.900	**8**	1.388	**26**	0.009	**44**	0.034
9	0.902	**27**	0.879	**9**	1.364	**27**	3.238	**9**	3.268	**27**	2.117	**45**	2.083
10	0.328	**28**	1.275	**10**	3.566	**28**	3.545	**10**	1.191	**28**	1.238	**46**	1.893
11	0.543	**29**	1.143	**11**	1.774	**29**	3.544	**11**	4.88	**29**	1.149	**47**	6.11
12	2.864	**30**	1.214	**12**	1.347	**30**	3.825	**12**	5.613	**30**	1.557	**48**	0.630
13	1.112	**31**	1.541	**13**	1.301	**31**	1.237	**13**	1.656	**31**	1.231	**49**	1.718
14	1.417	**32**	0.538	**14**	5.151	**32**	1.233	**14**	1.944	**32**	4.028	**50**	1.915
15	1.458	**33**	1.923	**15**	1.906	**33**	1.887	**15**	1.110	**33**	1.338		
16	2.116	**34**	2.008	**16**	1.128	**34**	1.567	**16**	1.606	**34**	1.519		
17	1.921			**17**	1.520			**17**	1.283	**35**	1.328		

According to Fig. 7 it is clear that the map of latest-obtained indications (Fig. 7A, up) is different from the basic geological map of Slovak Republic 1 : 50 000 (Fig. 7B, down). The Lúžna Formation (LuT1) represented by quartzites and quartz-sandstones is in the geological map plotted in a area among VES stations – K19, K16, M2 and M1. However the map of latest indications (Fig. 7A, up), made from the VES interpretation, did not support the theory of an outcrop of the Pre-Tertiary basement at the surface.

VES measurements M1, M2 and M3 were situated at an opposite slope of the valley with the tectonic line going through. For a better orientation it was marked as the Fault-1. This extensive fault line (Fig. 7A, 7B) separates two different geological environments. To the north of the fault a high resistive environment was detected in a basement. This kind of environment goes up to the surface only in the vicinity of the VES D4 and D5 stations.

To the south of the mentioned fault line, no Pre-Tertiary high resistive environment was detected in the basement. Maximal depth range of VES measurements was approximately 80 to 100 m that implies the depth of Pre-Tertiary basement to the south of the fault is probably deeper.

All assumed and covered tectonic lines determined by mapping and by previous research from the archival works – plotted in the map (Fig. 7B)

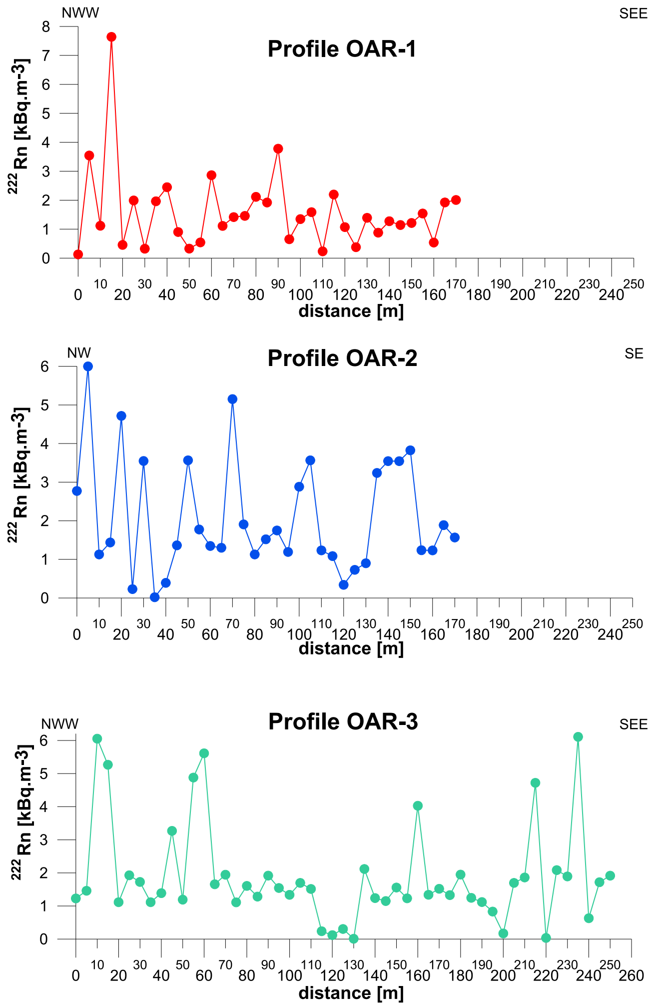

Fig. 4. ^{222}Rn volume activity value measured along the profiles.

were confirmed also by the VES measurements (Fig. 7A).

The tectonic line in 9B picture which separates the Lúžna Formation (LuT1) from clayey sediments, tuffs and conglomerates was indicated by the VES method. Its N–S direction was interpreted (Fig. 7A). In previous works, the NE–SW direction was interpreted (Fig. 7B).

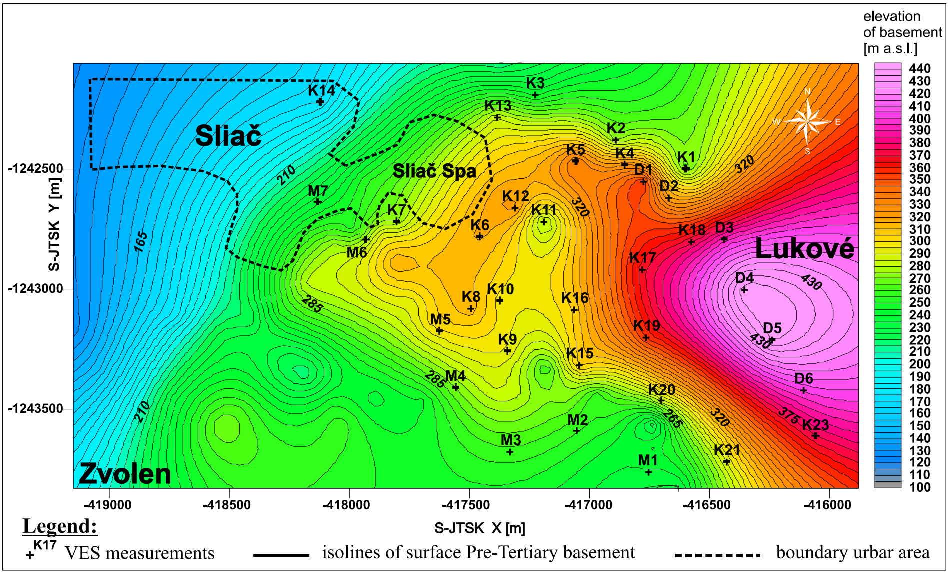

Fig. 5. Map of the Pre-Tertiary basement relief.

There were also interpreted tectonic lines not mentioned in previous works and their linear directions are shown in Fig. 7A. The latest-indicated tectonic lines were confirmed only by the VES method. There was no tectonic line confirmed by the VAR method, any other geophysical or exploration method in the study area. Tectonic lines allocate two different general orientations: NW–SE and NE–SW directions.

As it is evident from the map, the main fault line in the monitored territory is the one specified as the Fault-1, which is NW–SE oriented. The tectonic line starts right in the Sliač Spa area near the spring system of the cold acidulous waters. It might be assumed that this line markedly affected descending tectonic movements in the Sliač Spa region.

According to the archival works, there is another tectonic line assumed in the Spa complex which was marked as the Fault-2 in the geological map. This line was not definitely confirmed by the VES method.

There was a map of Pre-Tertiary basement relief constructed from VES data interpretation (Fig. 5). The course of isolines confirms an elevation in the area "Za kúpeľmi" with a maximum close to VES D4 and D5 stations.

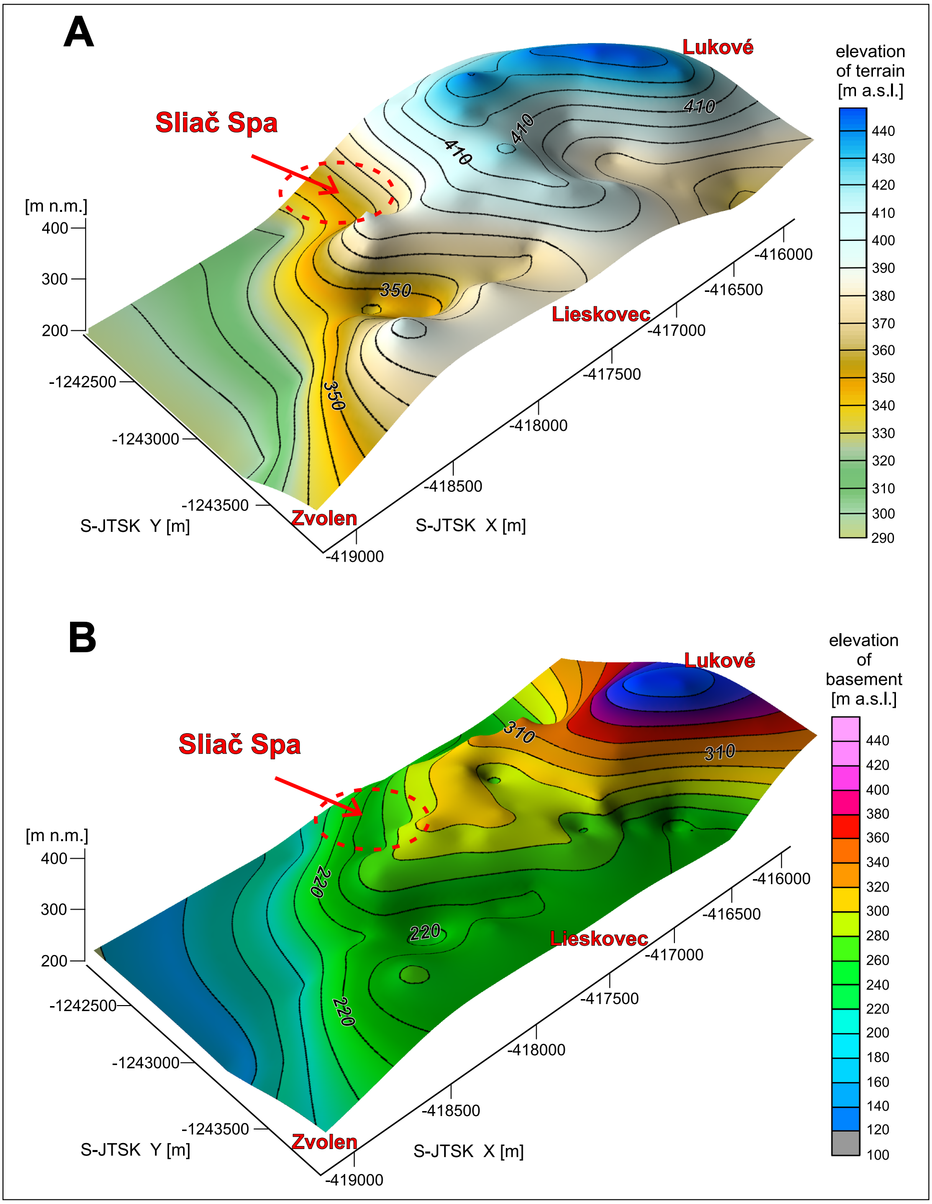

Fig. 6. 3D model of surface terrain (A); 3D model of Pre-Tertiary basement relief (B).

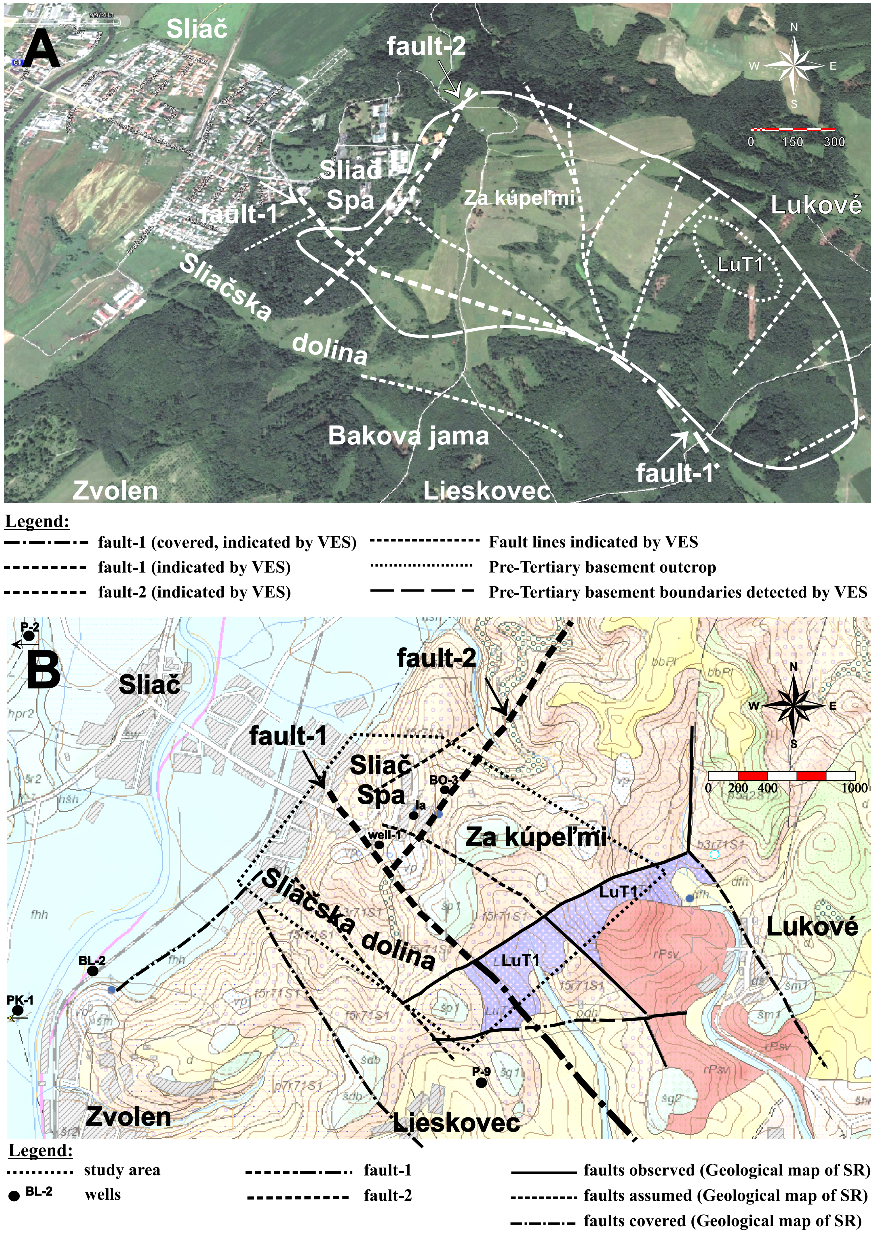

Fig. 7. Comparison of new geological knowledge in the study area (A) with the geological map of SR 1 : 50 000.

The isolines at a map characterize places with equal height above sea level to which the basement of neo-volcanic complexes ascend. It is possible to indicate places with the greatest gradient of height values, which characterize zones where Pre-Tertiary rocks subsided most expressively into the basement.

A model (Fig. 5) and 3D model of the Pre-Tertiary basement relief were established (Fig. 6). There is also a 3D model of a landscape surface displayed in Fig. 6A. Where the VES method was not able to detect a depth of basement (besides a sector described in Fig. 6A as a restriction of Pre-Tertiary basement indicated by the VES method), the information was approximated from the drill holes found in the area and from old archival works (*Májovský and Husák, 1973; Rebro et al., 1971*).

4. Conclusion

Based on qualitative and quantitative interpretation of the VES measurements, six geoeletrical horizons were selected according to different resistivity properties in the study area. They are represented by Quaternary and Neogene sediments and also by the Pre-Tertiary basement rocks.

It was confirmed that rocks of the Pre-Tertiary basement ascend to the surface in the form of an isolated island only in the area of VES D4 and D5 stations, although some authors declare a wider areal extension of the outcrop body at the earth's surface.

The results and course of tectonic lines interpreted with the help of VES method are presented in the map of the latest-acquired indications.

To verify the fault lines primarily detected by the VES method, also the VAR method was used along the three selected profiles. But profile radon concetration measurements were not able to identify any of the fault lines assumed.

From the given extent of geophysical research and from the results of the geoeletrical measurements in the first protection zone of the Sliač Spa area, it is possible to assume that mineral and also natural waters are bound to descending fault tectonics. Furthermore, there is a real assumtion that overlaying impermeable neo-volcanic complexes of the Sliač Spa and even in the Bakova jama area might play a very important role in underground water regime circulation.

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