The pre-Cainozoic basement delineation by magnetotelluric methods in the western part of the Liptovská kotlina Depression (Western Carpathians, Slovakia)

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Abstract: The geology and hydrogeology of the Liptovská Kotlina Depression were studied by means of new geophysical methods. Controlled source audio-frequency magnetotellurics enabled us to delineate the relief of the pre-Cainozoic basement in the western part of the Liptovská Kotlina Depression into two segments with different lithostratigraphic units. Our complex findings disprove the interconnection between the Bešeňová and Lúčky water bearing structures located in the study area. The results were interpreted in the form of a resistivity cross section and resistivity model. The geological interpretation of the obtained results, taking into account the other geophysical and geological constrains showed that the pre-Cainozoic basement has a tectonically disrupted, broken relief. The Bešeňová and Lúčky structures appear to be isolated by the Palaeogene sediments (sandstone, claystone) and in the deeper part also by marly carbonates and marlstones of the Jurassic age belonging to the Fatricum. It was confirmed that the structural connectivity of geothermal aquifers in the area between the Bešeňová and Lúčky–Kaľameny should not exist. The assumption of different circulation depth was also confirmed by geothermometry and existing radiocarbon analyses applied on groundwater in both areas.

Keywords: geothermal aquifer, mineral water, magnetotellurics, geothermometry, radiocarbon analysis, Liptovská Kotlina Depression, Western Carpathians.

Introduction

Geological structure is one of the essential conditions for infiltration, accumulation and exploitation of geothermal and mineral waters. Successful simultaneous long-term exploitation of both types of groundwater is conditioned by isolation of aquifers in respective structures. The structure of the geothermal waters in the western part of the Liptovská Kotlina Depression in Bešeňová elevation and structure of mineral waters in Lúčky–Kaľameny area can be used as an example. The Liptovská Kotlina Depression is one of the 27 prospective geothermal areas of the Slovak Republic. This 611 km^2 depression is located in northern Slovakia (Fig. 1a). It is elongated in the E–W direction and bordered by the Chočské vrchy Mts., Západné Tatry Mts., Veľká Fatra Mts., Nízke Tatry Mts. and Kozie Chrbty Mts. The possibility of obtaining and utilizing the geothermal and mineral waters in the basin was manifested in the past by a number of natural springs of mineral water in the area of Bešeňová, Lúčky, Liptovská Štiavnička, Liptovský Ján and in other localities. Boreholes were drilled in all of these localities in the last century (Remšík & Fendek 2005).

Both structures: (1) structure of geothermal waters in Bešeňová and (2) structure of mineral waters in Lúčky are located close to each other in the western part of the basin. Bešeňová is located in the central western part of the basin; the Lúčky mineral water structure is located on the north-western margin of the basin in the Chočské vrchy Mts. (Fig. 1b). The discharge area of the geothermal structure in Bešeňová is located at a distance of 4.0–4.5 km to the south-east from the area of the mineral water structure in Lúčky.

The mineral waters in Bešeňová manifested themselves for centuries in the form of natural outflows producing Quaternary limestone deposits — travertines. These can be found in the surroundings of the village, e.g. in an abandoned travertine quarry, but also in travertine cascades, which were included into Slovak natural heritage list in 1951. Geothermal water exploration in Bešeňová started in the late 1970s by drilling the borehole BEH-1. Because of borehole casing corrosion, the borehole was destroyed and a new borehole ZGL-1 was drilled in 1987 (Fendek 1998). This borehole was the basis for building of geothermal facilities in Bešeňová. It is

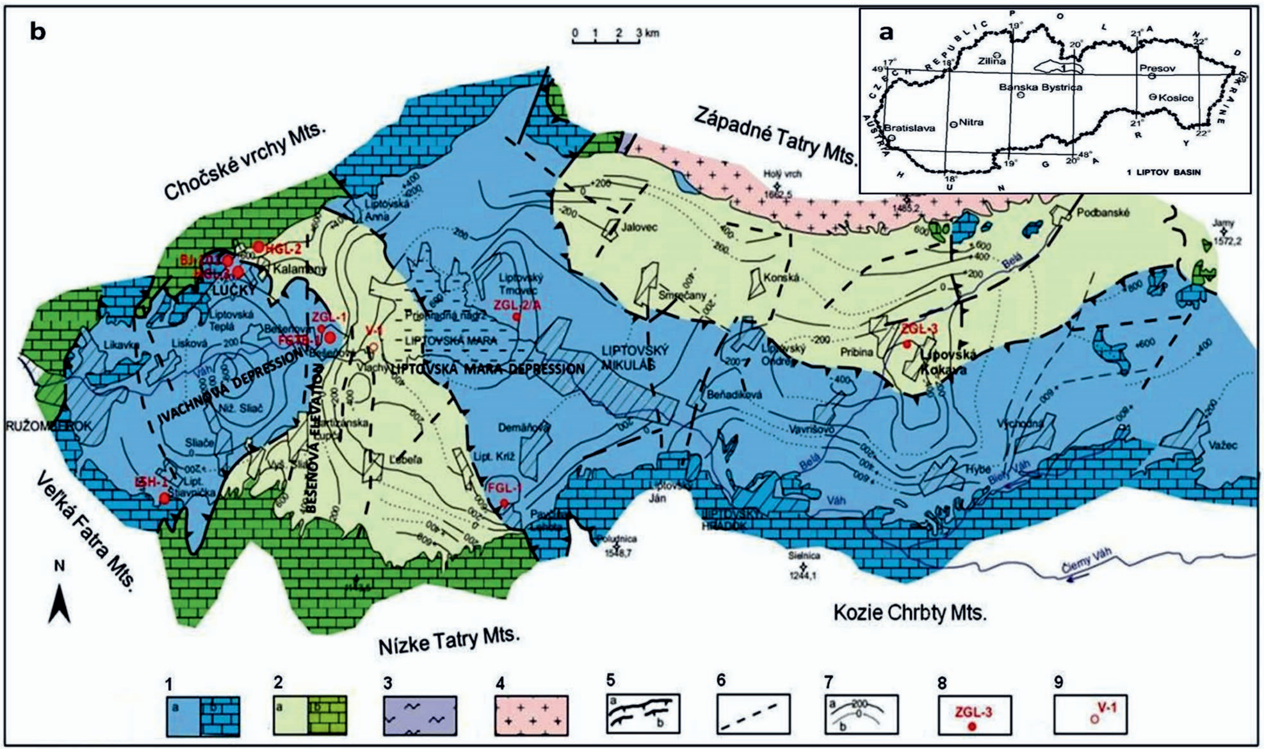

Fig. 1. a — Location of the Liptovská kotlina Depression. **b** — Geological conditions and location of objects of interest in the Liptovská Kotlina Depression (Remšík et al. 1998; Maďar et al. 2005). Explanation: 1 — Hronicum (a – bedrock, b – on the surface); 2 — Fatricum (a – bedrock, b – on the surface); 3 — cover Unit; 4 — Crystalline; 5 — overthrust line (a – proved, b – assumed); 6 — faults (assumed); 7 — isolines of the Palaeogene bottom in m a.s.l. (a – proved, b – assumed); 8 — geothermal borehole; 9 — oil borehole.

complemented by two other boreholes FGTB-1 and FBe-1 (Fendek & Fendeková 2015).

The history of use of mineral springs in Lúčky area as a real spa began already in 1761 (Fendek et al. 1999). In modern history, the Lúčky Spa was focusing on the treatment of gynecological and oncological diseases since 1950; however in 2005 Spa returned to the treatment of the kinetic apparatus, also offering suitable conditions for prevention and treatment of osteoporosis. Mineral water from the boreholes HGL-3 and BJ-101 (Valentina) is being used in all pools and separate spas. The water is also suitable for drinking and is available not only for the accommodated guests, but also for the general public.

The discussion on possible interferences of water utilization from the two structures was raised because of intense utilization of geothermal and mineral waters in the area. The use of mineral water for curative purposes is preferred to energy use in Slovakia, as is codified by Act No. 538/2005 Z.z. on natural curative waters, natural curative spas, spa places and natural mineral water.

No structural-geological investigation was done in this area up to the present aiming to confirm or disprove the interconnection between the two structures, from which water is intensively utilized.

There were three main objectives of the research: (1) to delineate the relief of the pre-Cainozoic basement, (2) to segment it into lithostratigraphic units, and (3) to confirm or disprove the interconnection between the Bešeňová and Lúčky water bearing structures. Controlled source audio-frequency magnetotellurics (CSAMT) was the main method used. This was the first utilization of the CSAMT method in geothermal research in Slovakia. The geothermometry and analysis of radiocarbon dating results, applied to sources in both areas were used as supporting methods.

Hydrogeothermal conditions of the Liptovská Kotlina Depression

The Liptovská Kotlina Depression is an intra-montane depression in the Inner Western Carpathians. It is filled by Palaeogene sediments with thicknesses ranging from 100 m (Bešeňová elevation) to 1700 m (Liptovská Mara depression). Palaeogene flysch sediments are represented by alternation of clays and clayey shales with sandstones. Clays mostly prevail. At the base, basal conglomerates are developed.

The substratum consists of the Mesozoic Hronicum and Fatricum, which form elevated and sunken morphostructures. The Hronicum is a higher tectonic unit then the Fatricum (Fig. 1b). The lowest tectonic unit is the Tatricum cover Unit with the same rock composition as in the Fatricum; however, its presence has not been proven yet by drilling works. The vertical, tectonically derived superposition of Mesozoic successions gave arise to aquifer-aquitard stratification. The Fatricum is referred as a bottom, while the Hronicum along with the Central Carpathian Palaeogene Basin (CCPB) is referred as a top system. The bottom system includes base aquiclude represented by a Lower Triassic horizon typically comprising quartzites, sandstones and sandy shales (Werfenian shales) beneath the bottom aquifer of Middle Triassic carbonates — limestones and dolomites complex. The aquifer of the bottom system is overlain by an aquitard corresponding to Upper Triassic–Middle Jurassic organogene and detritic limestones overlapping to Middle Jurassic–Lower Cretaceous pelitic limestones (clayey, marly) that alternate spatially with radiolarites, nodular limestones, claystones and marlstones. The top hydrogeological system involves aquifers of the Hronicum, represented by Middle Triassic carbonates hydraulically connected to CCPB represented by the Middle–Upper Eocene Borové basal formation (Gross et al. 1980) composed of breccias and conglomerates that pass to detritic carbonates and rare organogene limestones; beneath the top aquifuge recognized as Upper Eocene–Oligocene formations of Huty (claystones dominated) and Zuberec (flysch dominated). The hydrogeological function of Quaternary cover varies with regard to grain size. The maximal thickness of the Hronicum sequence is up to 1000 m; The Fatricum sequence reaches the maximal thickness of 1500 m (Remšík et al. 2005).

The spatial distribution of the Hronicum and Fatricum in the basement of the Palaeogene sediments is very variable (Fig. 1b). Both units are presented equally in the western part of the basin and they can occur next to each other. The Hronicum dominates in the middle and southern part of the basin, whereas the Fatricum sequence prevails in the northern part. Sequences of the Hronicum and Fatricum form the mountain ranges which surround the basin and represent infiltration areas for the hydrogeothermal structures (Remšík & Fendek 2005).

Hydrogeological conditions in the area are controlled by the geological-tectonic structure. Geothermal waters in the Liptovská Kotlina Depression are discharged through natural springs and boreholes. Beneath the Palaeogene filling there may be one to three hydrogeothermal structures positioned one above another in which geothermal waters are mostly associated with Triassic dolomites and limestones ("carbonates" throughout the following text) of the Hronicum and Fatricum and, possibly, also of the cover (autochthonous) Unit (Fig. 1b). These hydrogeological structures are largely open (having recharge areas on the adjacent slopes of surrounding mountains, as well as transit-accumulation and discharge areas) or semi-open (discharge area is missing). The Triassic carbonate aquifers with geothermal water are from 300 to 1200 m thick (Remšík et al. 2005).

The mineral waters in Lúčky are bound to Triassic carbonates of the Fatricum as proved by the results of BJ-101 and HGL-3 boreholes in Lúčky (Teplianka brook valley) and HGL-2 borehole in Kaľameny, located in the neighbouring Kaľamenianka brook valley. Results of geothermal boreholes ZGL-1, FGTB-1 and FBe-1 in Bešeňová showed that geothermal waters accumulate in Triassic carbonates of the the Hronicum and Fatricum. It is supposed that formation of geothermal water takes place in Fatricum carbonates. Both structures (Lúčky and Bešeňová) are classified as open structures with infiltration, transit-accumulation and natural discharge areas (Fričovský et al. 2016).

Geothermal waters occurring in the Hronicum Triassic carbonates at depths of 500 to 2800 m have the temperature of 20 to 90 ºC while those in similar rocks of the Fatricum at depths of 900 to 4000 m could be 25 to 125 ºC hot (Fričovský et al. 2014). The temperature of geothermal waters occurring in Triassic carbonates of the cover Unit at depths of 2500 to 5000 m might amount to 70–150 ºC. It is necessary to accent that expected temperatures are given by geological conditions and the geometry of the geothermal structure and calculated by stationary thermal modelling. Temperatures measured in the borehole ZGL-1 Bešeňová in static conditions are given in Table 1.

The Liptovská Kotlina Depression is tectonically divided into a system of elevations and depressions. The Bešeňová elevation hydrogeothermal structure is associated with a N–S protuberant morphological elevation of the pre-Cainozoic basement in the western part of the Liptovská Kotlina Depression. The elevation is tectonically limited to the surrounding depressed structures. The Ivachnová depression on the west is divided by the Bešeňová–Partizánska Ľupča fault and Liptovská Mara depression on the east is divided by the Liptovské Kľačany–Vlachy–Ľubela fault system (Gross et al. 1980). The Chočské vrchy Mts. to the north are divided by the Prosiecky fault (Bezák et al. 2004) and to the south, fault swarms lineate a system to the Nízke Tatry Mts. The Bešeňová elevation is considered the most active zone regarding geothermal activity, with a mean heat flow density recalculated for 66.04 $mW.m^{-2}$ (Fričovský 2011) in comparison to a mean heat flow for the whole Liptovská Kotlina Depression geothermal field calculated for 55 $mW.m^{-2}$. The local maximum measured rises to 76.9 $mW.m^{-2}$ in the ZGL-1 Bešeňová borehole within a centre, while the local minimum decreases down to 55 $mW.m^{-2}$ towards the southern margin (Král & Remšík 1996).

Laterally, the Bešeňová elevation is recognized as an open hydrogeological structure (Remšík & Fendek 2005). Infiltration zones are identified at the distal northern slopes of the Nízke Tatry Mts. close to Demänova valley or at its

Table 1: Temperatures measured in the borehole ZGL-1 Bešeňová at static conditions.

Depth (m)	Temperature (°C)	Depth (m)	Temperature (°C)
0	7.0	1100	48.0
100	15.0	1200	52.0
200	19.0	1300	55.0
300	22.0	1400	59.0
400	25.0	1500	62.5
500	28.5	1600	66.0
600	32.0	1700	68.0
700	35.0	1800	71.0
800	38.0	1900	73.0
900	42.0	2000	76.0
1000	45.0		

southern margin considered as the preference recharge area (Fričovský et al. 2016). However, there is the migration of fluids from the Liptovská Mara depression structure (located to the east) expected, as shown by analysing the regional piezometric level distribution (Fendek & Remšík 2005).

The infiltration area of the Lúčky mineral water structure was placed by Kullman & Zakovič (1975) in the area with occurrence of the Fatricum carbonates in the upper part of the Suchá dolina valley and in the area of occurrence of the Hronicum dolomites to the north-east of the Liptovské Matiašovce village. The transit-accumulation area was placed in the carbonate complex of limestone and dolomites of the Fatricum in the Chočské vrchy Mts. between the Suchá dolina valley and the Ráztočné valley. The groundwater flows mostly along the Prosiecky fault which separates the Chočské vrchy Mts. from the Liptovská Kotlina Depression.

The main Ca-Mg-HCO_3-SO_4 chemical type of geothermal/mineral water prevails in the basin, values of total dissolved solids (T.D.S.) amount to about 0.4–5.0 g.l^{-1}. Data on selected geothermal boreholes in the basin are in Table 2.

Gases are represented mainly by CO_2. Sulphates in geothermal waters (Remšík & Fendek 2005) came largely from Lower Triassic formations with evaporates ($\delta^{34}S$=23.3 to 27.1 ‰); the isotopic composition of oxygen in the geothermal waters shows that they are of meteoric origin.

Methods

Geophysical methods

The CSAMT measurement is a geophysical technique classified as an electromagnetic frequency domain method belonging to the group of magnetotelluric methods (Zonge & Hughes 1991; Routh & Oldenburg 1999; Simpson & Bahr 2005). A manmade controlled primary electromagnetic field is transmitted into the ground using wide range of frequencies. The primary field generates eddy currents in the rocks as the electromagnetic waves propagate through the Earth. The secondary electromagnetic field produced by the eddy currents is registered by the receiver and the signal is used to calculate the electric resistivity of the rocks below the surface. The depth penetration of the method is determined by the frequency of the electromagnetic signal, each of the used frequencies provides information on rock resistivity from a different depth. A wide range of frequencies enables us to receive a semi-continuous resistivity structured profile from the surface up to the maximum depth of penetration (Simpson & Bahr 2005).

The method can be utilized for various geological (Zhiguo & Qingyun 2007; Grandis & Menvielle 2015) and hydrogeological applications including geothermal exploration. Depth penetration, high production and relatively low costs comparing with seismic, predetermine CSAMT as a fast and effective method utilized in geothermal exploration and recently it became one of the principal geophysical techniques. Application of the magnetotelluric methods at the sites of the Bešeňová and Lúčky hydrogeothermal structures faced two challenges. One of them was the required depth penetration of 2 km determined by the assumed depth of the pre-Cainozoic basement. The required depth of penetration is on the edge of the applicability of the CSAMT method and may require use of the lowest possible frequencies in the AMT (audio magnetotelluric) range which are utilized in far-field zone modification. Therefore, the logical solution would be to use the classic magnetotelluric (MT) method utilizing Earth's natural electromagnetic fields at frequencies far below 1 Hz. This approach would assure the overreaching of the required depth of penetration of 2 km. However, the existence of external cultural noise was a factor playing a role against usage of the classic MT technique. Considering the facts above, a straight magnetotelluric (MT) testing survey was conducted at a couple of

Table 2: Data on selected geothermal boreholes in the Liptovská Kotlina Depression.

Borehole Locality	Aquifers	Perforated interval [m]	Discharge [l.s^{-1}]	Water temperature [°C]	Thermal power [MW$_t$]	T.D.S. [g.l^{-1}]	Chemical type of water
FGL-1 Pavčina Lehota	Triassic limestones and dolomites[1]	1315–1570	6.0*	32.0	0.42	0.40	Ca-Mg-HCO_3
ZGL-1 Bešeňová	Triassic dolomites[2]	1420–1964	27.0**	62.0	5.30	5.30	Ca-Mg-SO_4-HCO_3
FGTB-1 Bešeňová	Triassic limestones and dolomites[2]	1622–1813	32.0**	66.9	6.83	3.02	Ca-Mg-SO_4-HCO_3
ZGL-2/A Liptovský Trnovec	Triassic dolomites and limestones[1]	1624–2486	31.0**	60.7	5.89	5.90	Ca-Na-Mg-HCO_3-SO_4
ZGL-3 Liptovská Kokava	Triassic limestones and dolomites[2]	1475–2365	20.0*	43.5	2.42	2.40	Ca-Mg-HCO_3-SO_4
HGL-2 Kaľameny	Tectonic disruption in Carpathian Keuper´s shale[2]	185–500	23.5**	33.4	1.77	2.90	Ca-Mg-SO_4-HCO_3
HGL-3 Lúčky	Triassic dolomites[2]	322–476	25.0*	35.8	2.18	3.10	Ca-Mg-SO_4-HCO_3
BJ-101 Lúčky	Triassic dolomites[2]	54–92	20.0*	32.0	1.42	2.80	Ca-Mg-SO_4-HCO_3
LSH-1 Liptovská Štiavnička	Triassic dolomites[1]	89–165	10.0*	21.0	0.25	3.56	Ca-Mg-HCO_3-SO_4

[1] Hronicum, [2] Fatricum, * pumping, ** free outflow

stations prior to employment of CSAMT. The objective was to check if a classic MT survey could not be utilized instead of CSAMT. One station was surveyed near the borehole HGL-2 with a known geological profile. The acquired data could not be utilized due to high noise level. The measurements from other stations away from the Liptovská Kotlina Depression in Suchá dolina at the Chočské vrchy Mts. have shown lower noise and the data was interpretable. The results have finally confirmed the general assumption that the classic MT survey could not be used in the parts of the Liptovská Kotlina Depression with a well developed infrastructure at all. This was also the case for the area of interest. The only solution was to employ the CSAMT method in conjunction with several chosen factors linked to equipment setting and survey techniques, which would allow us to achieve the required penetration depth and to eliminate the external noise factors at the same time. A solution was found thanks to the unique METRONIX MT technology (http://www.geo-metronix.de/mtxgeo/) allowing tensor measurements in a state of scalar measurements and other factors as careful selection and testing of the transmitter site and its distance to survey stations, parametric test surveys on boreholes and finally use of the maximum possible power on transmitters and use of lowest possible AMT frequencies.

Prior to the actual survey, a set of test measurements was conducted at the location of existing boreholes. Parametric test measurements were undertaken near the location of boreholes HGL-2 and ZGL-1 (Fig. 2). Test measurements at borehole ZGL-1 were assisting in adjustment of the survey parameters and equipment settings including the applicable range of frequencies.

The test survey confirmed the capability of the actual settings to achieve the required depth of 2 km. Inversion of the parametric test survey also provided important information about apparent resistivity of individual geological settings and structures. Based on resistivity, it was not only possible to clearly separate the low-resistive Palaeogene sediments from the pre-Cainozoic basement, but also to assign apparent resistivity to individual lithological-tectonic units within the basement. This information could be later utilized in inversions and modelling of actual survey data.

CSAMT measurements were conducted along survey line connecting both boreholes HGL-2 and ZGL-1 (Fig. 2). It is placed within the elevated part of the pre-Cainozoic basement called as the Bešeňová elevation.

The total length of the survey line was 4 km and comprised a total of 21 stations with 200 m separation. Grounded tripole electrode system with arm length of 600 m enabling rotation of electric current vector controlled by METRONIX TXM-22/TXB-07 transmitter was used as source of stable, manmade electromagnetic signal in the AMT range (0.5 Hz–8192 Hz). Currents reaching a maximum possible level of 30–40 Amp were used to reduce the effect of external background noise. Far-field zone modification was applied for a transmitter distance of 10.5 km from the survey line. The METRONIX receiver ADU-7 was employed to register the EM field at the survey stations. Two horizontal vectors of electric component of EM field were measured using two pairs of grounded electrodes perpendicularly oriented in N–S and E–W directions. All three vectors of magnetic component of EM field were registered by three magnetometer probes buried in soil. The registration time of 120 seconds was chosen to register the entire AMT frequency range (0.5 Hz–8192 Hz) with a sufficient number of stacking. Transmitter and receivers were full synchronized using GPS time provided by GPS receivers used for positioning at the same time.

Registered vector components of electric and magnetic field were transformed to resistivity time/depth sounding profiles followed by 1D and finally 2D inversion. The inversion and modelling was controlled using existing data from parametric test measurements at borehole sites. Inversion and modelling results were presented in the form of a 2D resistivity section and resistivity block model. The inversion results were assisting to determine the thickness of Palaeogene clay-sandstone sediments, depth to pre-Cainozoic basement and also lithology-structural units within the pre-Cainozoic basement.

The final integrated geological geophysical interpretation was made considering all available geological data from surface mapping and boreholes, CSAMT survey (Fig. 2) and archive geophysical data including DC current electric sounding (VES, Fig. 2), regional airborne magnetic survey and regional ground gravity survey. The outcome of the integrated interpretation was a geological cross section showing both, the principal lithology-structural units and tectonic pattern.

Geothermometry

The method was used for estimation of the depth at which the reservoir waters are formed. Geothermometers, empirical equilibrium functions between water and solutes implying provenance zone temperature take advantage in slowness of initial conditions re-equilibration at cooler temperatures. Silica geothermometers and conventional cation geothermometers were used in the study to compare reservoir conditions at Bešeňová and Lúčky. Fričovský et al. (2015) showed that the conventional cation geothermometers overestimated the temperatures of geothermal waters in the Bešeňová area by 2–4 times. The use of cation geothermometers showed the immaturity of the system, reflected in rapid variations of Na/K, K/Mg, and Na/Mg rations through the system. This could be well seen on a Na–K–Mg geoindicator (Giggenbach 1988), which proved most of the cations geothermometer invalid.

Silica geothermometry is based on the solubility of all silica polymorphs at particular temperature and pressure conditions. The SiO_2 concentration in thermal fluids is measured. Silica geothermometers reflect the temperature-controlled solubility of quartz and its polymorphs (chalcedony, cristobalite, and amorphous silica), assuming equilibrium at the rock-water-solute contact (Giggenbach 1988). Quartz is the most stable and least soluble solid silica form in conditions of 120 (mature systems) or 180 (mature, immature systems) –330 °C

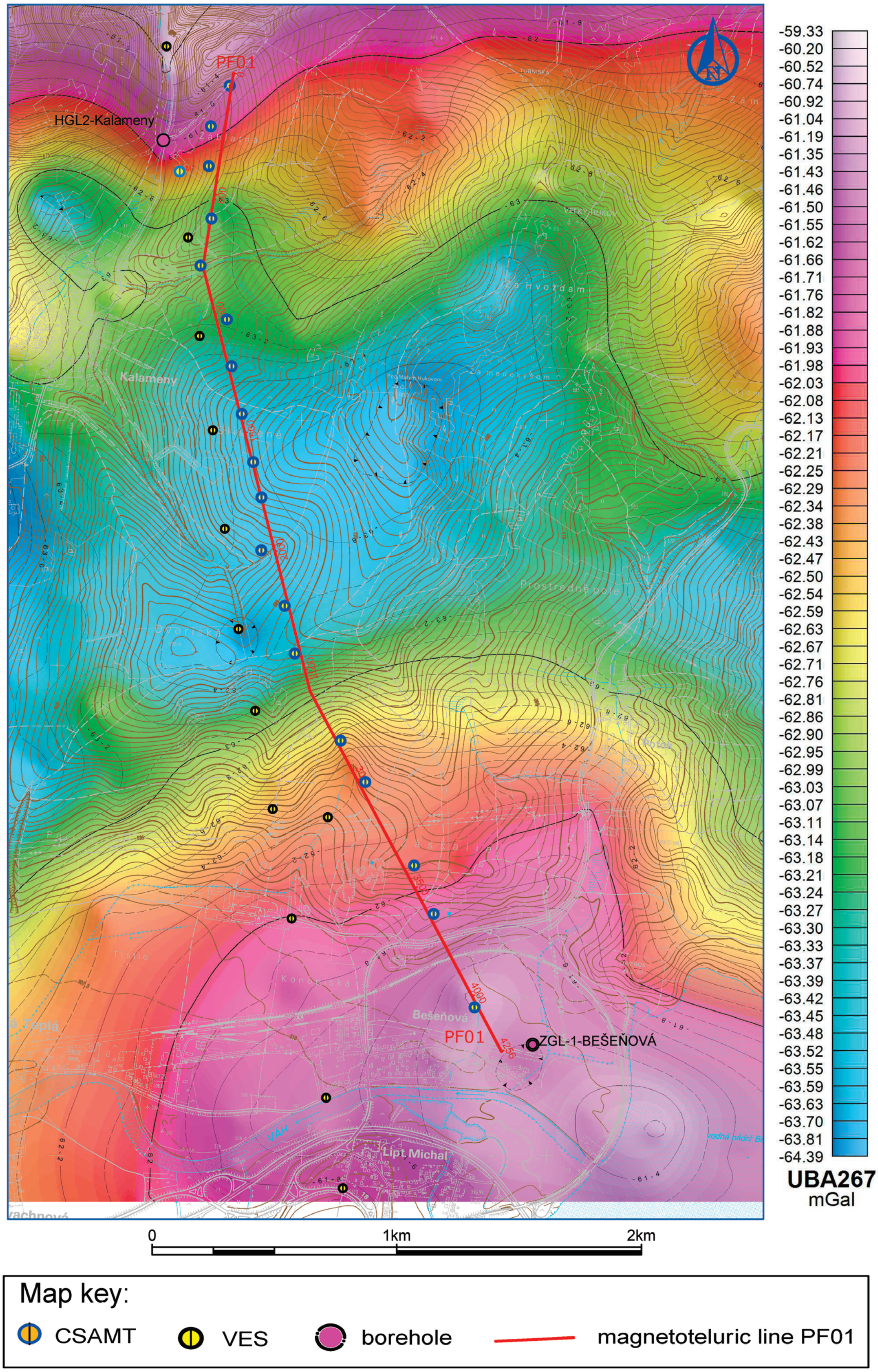

Fig. 2. Location of geophysical surveys along Profile PF01 imposed on the Bouger anomaly gravity map (Grand et al. 2001).

(Fournier & Rowe 1966), controlling SiO_2 concentration within the range. Ambiguity appears at the 120 – 180 °C interval, as chalcedony becomes metastable and more soluble. Thereafter, below 120 °C it is possible that chalcedony controls the SiO_2 content preferentially.

A large set of geothermometers was used for reservoir temperature estimation in both areas. The best agreement between values measured at the depth of screen placement and theoretical values for the Bešeňová borehole was obtained using the Arnórsson et al. (1983) equation for chalcedony (adiabatic boiling model):

$$T\,[°C] = \frac{1264}{(5.31 - \log C)} - 273.15, \qquad (1)$$

where C is silica oxide content.

The best agreement between measured and theoretical temperature values for the Lúčky borehole was obtained using the equation for the K–Mg geothermometer (Giggenbach 1988):

$$T\,[°C] = \frac{4410}{14.0 + \log\left(\frac{K^2}{Mg}\right)} - 273.5, \qquad (2)$$

where K and Mg are potassium and magnesium contents, respectively.

The K–Mg geothermometers of Giggenbach (1988) refer to the situation where the dissolved sodium and calcium cations are not in equilibrium state between the water and rock environment. The critical problem of the K–Mg geothermometer is that it reacts with the geothermal water much faster than other geothermometers do, and it is more sensitive to carbonate environments at low enthalpies.

Results

The results (Fig. 3) indicate an upper low-resistivity (50 Ω·m) layer outcropping to the surface.

Based on the results of Gluch et al. (2009) this layer is interpreted as Palaeogene sediments with higher content of clay components representing together the strata of the Zuberec and Huty formations. The thickness of Palaeogene sediments along the survey line is variable in average about 500 m with a general tendency towards thinning out to the south in the direction of borehole ZGL-1.

The resistivity model shows an obvious anomaly standing out from the general picture described above. It is semi vertical 600–800 m wide zone of low-resistivity (50–100 Ω·m), which is dipping down to a depth of over 1500 m below surface. The zone was registered by CSAMT measurements undertaken at 5 stations and starts about 800 m south of borehole HGL-2 measured along the survey line. This anomaly zone is interpreted as increased thickness of Palaeogene sediments (1500–2000 m). Such an interpretation is also supported by gravity low anomaly (Fig. 2) placed at the same location which is indicating obvious depression in pre-Cainozoic basement.

The Palaeogene low resistivity layer is under-bedded by a half space of higher resistivity interpreted as pre-Cainozoic basement of variable resistivity layers and segments (300–3000 Ω·m) reflecting various Mesozoic rocks and strata. Palaeogene sediments are under-bedded by marls and marly limestones of the Lower Jurassic and Cretaceous. They also contain a high proportion of clayey compound, which may reflect interpreted low resistivity in the Pre-Cainozoic basement within the low resistivity anomaly zone.

The low resistivity anomaly isolates the Triassic carbonates of the Fatricum occurring at Kaľameny–Lúčky area from the carbonates occurring in Bešeňová pre-Cainozoic basement elevation hit by the borehole ZGL-1 and confirmed by CSAMT and gravity survey (Fig. 2). Mesozoic rocks, mostly dolomites appear underneath the Palaeogene sediments in the western part of the Liptovská Kotlina Depression as indicated by boreholes ZGL-1 and FGTB-1 and geophysical interpretations as well. These carbonates tectonically belong to the Hronicum. Dolomites have higher apparent resistivity than the marls, marly limestones, or shales and anhydrites of the Fatricum. Considering the results of CSAMT inversion, we may assume that compact dolomites and limestones are characterized by higher apparent resistivity from 400 Ω·m up to couple thousands Ω·m, while the marls and marly limestones of the Fatricum have lower resistivity (100–300 Ω·m).

Differentiation of Middle Triassic dolomites from shale and dolomites of the Carpathian Keuper appears to be difficult in most cases based on resistivity. On the other hand, existing resistivity contrast appears to be sufficient to distinguish the dolomites from marls and marly limestones.

The high-resistivity layer (2960 Ω·m), occurring at the larger depths at the beginning of the resistivity section (HGL-2 borehole), could represent either compact Triassic dolomites, of which disintegration degree decreases with the depth, or Lower Triassic quartzites of the Lužná sequence, which were hit by geothermal boreholes ZGL-3 in Liptovská Kokava and FGL-1 in Pavčina Lehota (Fig. 1b). The pre-Cainozoic basement has a obviously disturbed (eroded) and tectonically fragmented relief, as can be seen from the measured resistivity values of Mesozoic rocks (Fig. 3).

The geological interpretation (Fig. 4) shows that the Hronicum is not extended continuously in the Bešeňová elevation. Hence, the Hronicum system represents the top aquifer of the stratified Bešeňová elevation hydrogeothermal system.

The interpretation of data proves former assumptions and expectations (e.g. Remšík & Fendek 2005) on spatial limitation of the Hronicum which have further consequences for the hydrogeological and thermal regime of the structure.

The same is also valid for shales of the Carpathian Keuper, which are in the central part of the profile isolated by Palaeogene sediments from the north and by marls and marly limestone of the Lower Jurassic–Lower Cretaceous from the south.

The continuation of the Middle Triassic dolomites from the Bešeňová elevation towards the Kaľameny–Lúčky is disrupted by Palaeogene sediments and in the deeper part also by

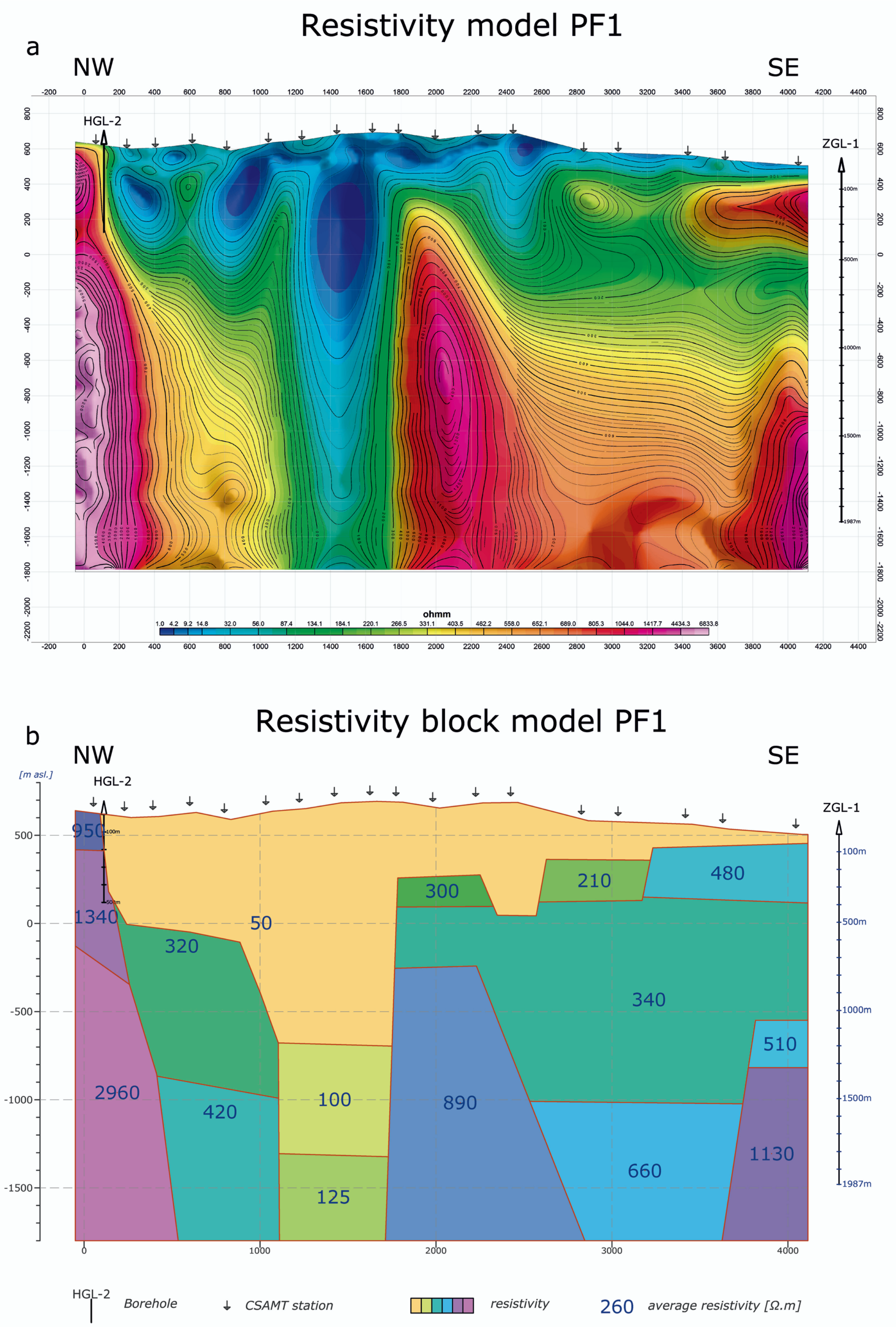

Fig. 3. a — 2D resistivity section; **b** — Resistivity block model along profile PF01.

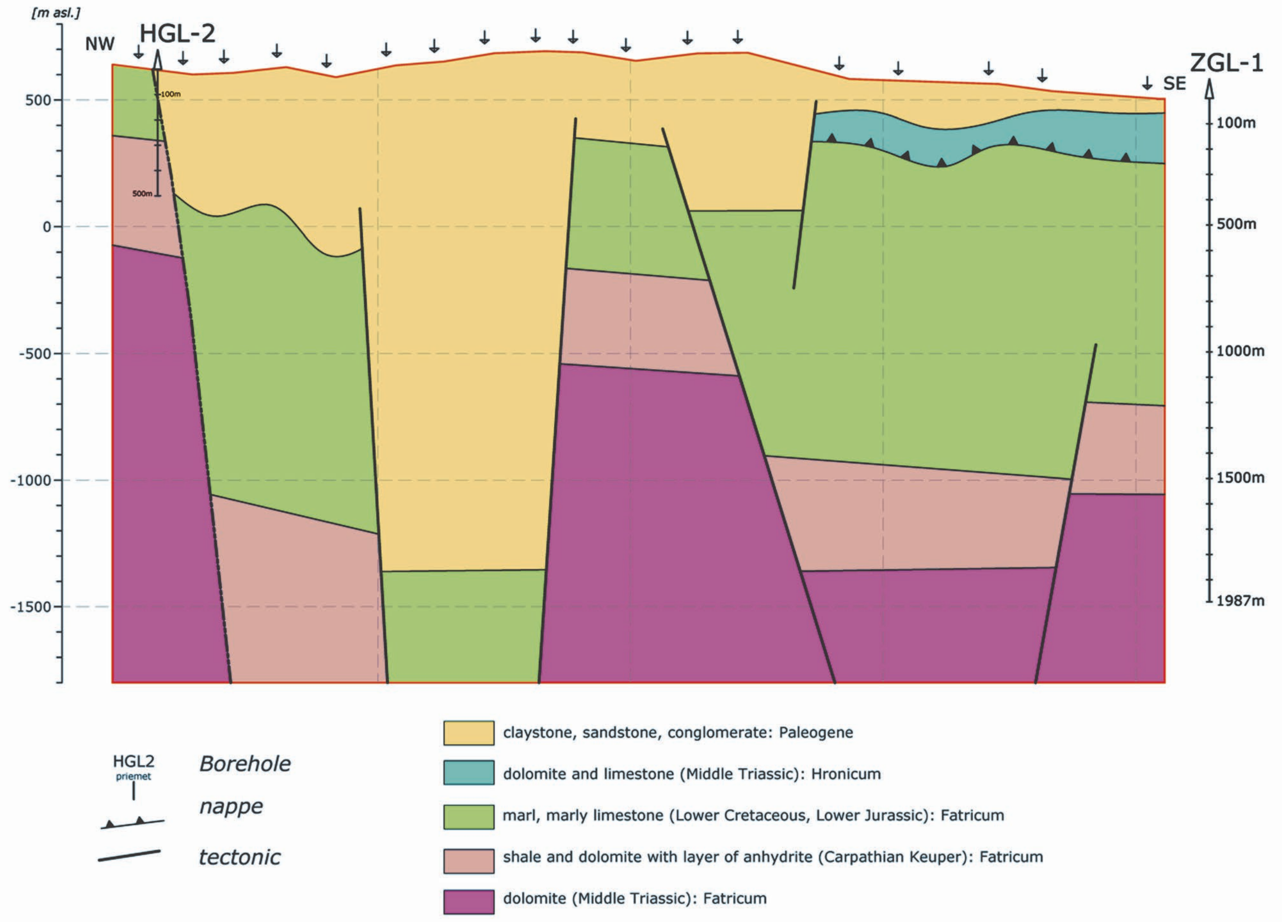

Fig. 4. Integrated geological-geophysical interpretation — geological section of the profile PF01.

marls and marly limestones of the Jurassic–Cretaceous age, which, in the regional view, are considered as hydrogeological isolators. From the regional point of view it is worth mentioning that the thickness of Palaeogene sediments increases significantly in the Ivachnová depression and the Liptovská Mara depression which are extending to the west and the east from the Bešeňová elevation.

Discussion

The extent of the marls and marly limestone in the pre-Cainozoic basement is also confirmed by the stripped gravity map of the Liptovská Kotlina Depression published by Szalaiová et al. (2008). This map represents the corrected Bouguer anomaly gravity map by the 3D gravitational effect of the Palaeogene infill. Therefore it reflects the anomalies that resources are located within the pre-Cainozoic basement. As the studied area is characterized by the relative gravitational low it can be suggested that its source could be with the most likely the Jurassic-Cretaceous marls and marly limestones, as they have not only lower resistivity but also lower density in comparison with the Triassic dolomites (Eliáš & Uhmann 1968).

Geothermometry applied to mineral waters at Lúčky (HGL-2 borehole) and geothermal waters at Bešeňová (ZGL-1 borehole) showed the following results. The chalcedony (adiabatic boiling model) geothermometer after Arnórsson et al. (1983) gave the value of 65.2 °C for Bešeňová what satisfies the circulation depth of 1580 m (see Table 1). The same geothermometer used for Lúčky gave the result of 42.3 °C which satisfies the circulation depth of 900 m (Table 1). The same temperature of 42.3 °C was estimated for Lúčky also by K–Mg geothermometer (Giggenbach, 1988). However, the use of K–Mg geothermometers did not give acceptable results for Bešeňová, where the temperature estimated by K–Mg geothermometer was only 35.3 °C. The free outflow temperature at the well head in Bešeňová is 62 °C therefore the 35.3 °C is a highly underestimated result. It means that the mineral water in Lúčky is formed at a much shallower depth than the geothermal water in Bešeňová.

The former radiocarbon analysis allows us to estimate the age of groundwater appearing in the Liptovská Kotlina Depression. The estimated age of geothermal water of the Bešeňová area (ZGL-1 borehole) is 27,000 years (Franko 2002) corresponding to the infiltration time during the Paudorf interstadial (Wurm 2–3 glaciations), whereas the estimated age of mineral waters in Lúčky and Kaľameny is 23,000 and

18,300 years respectively, corresponding to the colder time period in the Wurm 3 glaciation. Franko (2002) provided a suggestion on preferential infiltration zone for Bešeňová hydrogeothermal structure to the south and basically countered an idea of connectivity of the Bešeňová elevation and Lúčky mineral water structure.

The isotopic composition of oxygen $\delta^{18}O$ in geothermal water from boreholes ZGL-1 Bešeňová, ZGL-2A Liptovský Trnovec and in mineral water in LSH-1 borehole in Liptovská Štiavnička is also different from the isotope composition of oxygen in BJ-101 and HGL-3 sources in Lúčky, HGL-2 in Kaľameny and in the main inflow to the borehole ZGL-3 Liptovská Kokava.

Another argument confirming the existence of two separated structures is that there was no observed influence on discharges in the Lúčky area caused by long-term hydrodynamic testing on the borehole FGTB-1 in 2012.

Conclusions

The CSAMT method was successfully applied in the western part of the Liptovská Kotlina Depression. Utilization of the method enabled us to delineate the relief of the pre-Cainozoic basement and to segment it into lithostratigraphic units. The geological interpretation of the results showed that the Hronicum does not extend continuously in the Bešeňová elevation. The same also applies the to shales of the Carpathian Keuper, which are isolated in the central part of the profile by Palaeogene sediments from the north and by marls and marly limestone of the Lower Jurassic–Lower Cretaceous from the south. The interpretation of geophysical data available for the western part of the Liptovská Kotlina Depression, together with the interpretation of the CSAMT method have confirmed, that there is no interconnection between the Lúčky mineral water structure and the Bešeňová geothermal water structure. The two structures are separated by a huge thickness of Palaeogene sediments in the shallow part and also by marls and marly limestones of the Fatricum in the deeper part, which are considered to be hydrogeological isolators on regional scale. In our opinion it was proven that the continual interconnection of geothermal aquifers in the area between the Bešeňová and Lúčky–Kaľameny does not exist. This study has proven that there exist neither structural nor hydraulic conectivity between the two structures as well. This was also confirmed by the results of geothermometry application and by comparison of the radiocarbon ages of groundwater in water bearing structures. Disproving a structural and hydraulic connectivity between the Lúčky and Bešeňová structures is a major addition to our knowledge of the Liptov Basin geothermal field and definitely supports assumptions and suggestions given since detailed studies of these two systems began.

Finally, the study as presented in this paper is the first application of the CSAMT method to geothermal exploration in the territory of the Slovak Republic.

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