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Contributions to Geophysics and Geodesy Vol. 48/4, 2018 (349–363)

Lithological composition in deep geothermal source reservoirs of temperature 160 °C in the territory of Slovakia

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Abstract: Our contribution presents the geological analysis results of the lithological composition for deep geothermal sources characterized by the thermal conditions suitable for application of classic hydrothermal sources exploitation and specialized EGS technologies for the electricity production in the territory of Slovakia. The results are presented in the form of lithological characterization for the isothermal surface depths with the reservoir temperature of 160 °C. The lithological conditions of geothermal source regions were constructed using available published and archive materials. From the point of view of technically utilized depths (up to 5000 m) there are two most perspective regions – Eastern Slovakia and Danube Basin with surrounding areas. We tried to characterize supposed lithological composition also in second category of geothermal sources between 5 and 6 km.

Key words: Western Carpathians, geothermal energy, lithology of deep geothermal sources

1. Introduction

The territory of Slovakia belongs to the very perspective European areas suitable for the geothermal energy exploitation (*Hurtig et al., 1992; Geoelec, 2013, 2016; Majcin et al., 2017*). The activities related to the geothermal energy sources prospection in Slovakia were devoted to some selected localities, however, there were published also global studies of the whole area of Slovakia. The existing knowledge was concentrated and analyzed mainly in the Atlas of geothermal energy of Slovakia (*Franko et al., 1995*). This very important monographic publication presents the summary of research

doi: 10.2478/congeo-2018-0017

results in the period of more than two decades of the authors and other scientists working in this subject field as well. Among other problems it evaluates also the thermal, geological and hydrological conditions for geothermal energy, thermal capacity of sources and defines basic selection of region to separate source areas. The atlas, mentioned above, brings the data and map basis for subsequent geothermal energy studies in the Slovakia.

The prospection activities and applications were aimed mainly to hydrothermal sources (*Král et al., 1985; Franko et al., 1986; Franko et al., 1995; Remšík and Bodiš, 2010; Fendek et al., 2011* and plenty of other publications from partial geothermal localities of the Slovakia). The research activities were less focused to problems of the energy acquirement by the petrothermal approaches including the HDR (hot dry rock) and HWR (hot wet rock) ones. Beside some methodologically and technically specialized works various local analyses were accomplished. They were related mainly to the structure Beša-Čičarovce (*Franko et al., 1986; Rudinec, 1989; Franko et al., 1995; Masaryk, 2008*). In the recent years some projects of geothermal energy exploitation by EGS systems were prepared in localities of both the Danube Basin and East-Slovakian Basin, however they were not realized till now.

The publications *Majcin et al. (2016, 2017)* create the optimal geothermal base for selection of areas from region under study suitable for the deep geothermal energy utilization in the electric energy production. The mentioned papers provide, among other things, the depth distributions for deep temperature of about 160 °C which is sufficient for the reasonable economic exploitation of the geothermal energy for electricity production minimally by the binary cycle technologies. This knowledge defines basic division of perspective regions both for classic hydrothermal source types and for petrothermal sources within Slovakia.

Our contribution is aimed to precision of this division by other geothermal source parameters namely geological, economic and technical ones. For defining perspective regions in addition to available depths (optimally up to 5 km, max. up to 6 km) and terrain accessibility is another important criterion lithology in the depths involved. In this work, we have therefore mainly focused on it. We used the available information from both published and archive sources (mainly results of *Franko et al., 1995; Bezák et al., 2015*) and we use them in this work as an input data.

2. Methods

The principle of the successive separation was applied for the selection of perspective areas for deep geothermal sources exploitation within the Slovakia.

The temperature of the acquired liquid medium on the Earth's surface represents the basic determining criterion. There the reservoir temperature of 160 °C is required as the smallest one for the reasonable electric energy production minimally by binary cycles (Kalina cycle, Organic Rankine cycle or others). The starting selection model is taken from the map published in *Majcin et al. (2017)*. The second criterion for the classification of geothermal source areas has technical and economical nature. It is represented by the depth at which the required reservoir temperature is safely and effectively reachable by present day drilling methods. Nowadays the depth of 5000 m is supposed as the maximum reasonable value. The third criterion for the utilization of geothermal sources of the petrothermal type is related both to the structural and lithological conditions suitable for creation of the artificial underground heat exchanger as a part of the enhanced geothermal system (EGS). The lithological situation in the depths of determined reservoir temperature is very useful also for appraisal of the existence and quality of the geothermal energy sources.

To evaluate the territory of Slovakia in terms of its lithologic composition in the depths of the 160 °C isothermal surface, we have divided it into two categories: depth up to 5 km and depth of 5–6 km. The first depth level is the most appropriate in terms of the technological reachability (in certain areas, the mentioned temperature can be found at a 3–4 km depth), morphology (lowlands and hill country) and availability of data on the expected lithology at the said depth (boreholes, geophysical data, tectonic models). The data from the individual depth levels, which can be found in the Geothermal atlas of Slovakia (*Franko et al., 1995*), are an essential source of information for our analysis of the lithologic structure. Additional data have been acquired from the deep boreholes (*Biela, 1978*). Lithology mainly of basin filling and some other complexes was taken over project Thermes (synthesis about lithology of several authors, *Bezák et al., 2015*) and explications to the Tectonic map of Slovakia (*Bezák et al., 2004*) and other sources. The geophysical data, mainly magnetic, gravimetric and magnetotelluric (mainly *Kubeš et al., 2001; Pašteka et al., 2017*) were yet another important source of information.

The first category is divided into two areas – Eastern Slovakia and the area of the Danube Basin with the adjacent areas. Both have diverse parameters in the terms of geology. The second category (5–6 km) stretches from W to E across whole territory of Slovakia and it is least represented in Central Slovakia. The assessment of the likely lithologic composition is very ambiguous at these depths. In Western Slovakia, where the crust is thinner, we could to use also the gravimetric and magnetic results and divide the areas with predominance of granitoids and metamorphites in studied depths. Other areas are evaluated on the basis of available conceptual and factual knowledge about the tectonic structure (e.g. the Flysch Belt, Klippen Belt) or assessed as undivided crystalline complexes. An exception is the drilled Cretaceous Rochovce granite, whose impact is expected up to the required depth. The occurrence of areas with supposed subvolcanic bodies is also very interesting from the geothermic point of view.

The basic tectonic divisions of the complexes in the depths of temperature 160 °C is presented in Fig. 1. The numbers dedicate descripted areas from the second category. Two areas of first category are presented separately more in Fig. 2 and 3.

3. Results: supposed lithology of individual areas for the 160 °C isotherm

Distribution of lithological complexes for the temperature level of 160 °C is based mainly on the work of *Franko et al. (1995)*, modified after *Bezák et al. (2004)* and *Bezák et al. (2015).* The mentioned distributiom for Danube Basin is depicted in Fig. 2 and for Eastern Slovakia in Fig. 3. Lithology description for depths 5–6 km is divided into partial areas after numbers which are drawn in Fig. 1.

The Danube Basin and surrounding areas (Fig. 2)

Danube Basin is thermally extensive and it started to open up at the end of Lower and beginning of Middle Miocene. The main part of the synrift phase occurred during the Middle Miocene, and the postrift or thermal phase took

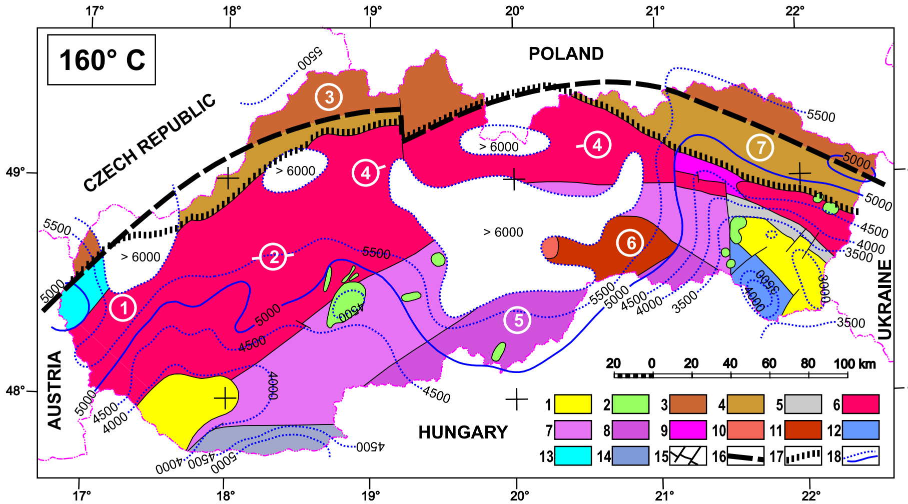

Fig. 1. Basic tectonic division of supposed rock complexes in depths demarcated by the temperature of 160 °C in the territory of Slovakia. 1 – Neogene sediments and volcanoclastics, 2 – supposed areas of subvolcanic intrusions, 3 – Flysch Belt with underlying European platform, 4 – Flysch Belt with underlying supposed Pieninic crust, 5 – Iňačevo-Kričevo unit, 6 – crystalline complexes of the Tatricum unit, 7 – crystalline complexes of the Veporicum unit, 8 – altered crystalline complexes of the Veporicum with supposed Cadomian basement, 9 – Mesozoic complexes of Fatricum, 10 – Rochovce granite, 11 – Gemericum unit with underlying Veporicum, 12 – Zemplinicum unit, 13 – Eastern Alps units, 14 – Pelsonia unit, 15 – rock complexes boundaries and faults, 16 – axis of Carpathian Conductivity Zone position, 17 – reference position of Klippen Belt, 18 – depths of the isothermal surface of 160 °C plotted with the isoline step of 500 m. Numbers in circles – described areas of second category (between 5–6 km).

place during Upper Miocene and Pliocene. The history of this basin started by arching out of the bedrock and erosion of the younger, particularly Mesozoic complexes. This was linked with the growth of asthenolite, which subsequently fused into the crust, but also resulted in subsidence, heat flow and volcanism. The biggest depression, and also thickness of sedimentary filling can be found in the central part (Gabčíkovo depression). Here, the 160 °C isotherm is usually 4 km below the surface or higher and thus in the Neogene sediments.

The sedimentation was accompanied by volcanism. Apart from the typical sedimentary rocks of pelitic and psammitic origin (mostly sandstone and claystone), the sedimentary fill of the basin is also composed of the

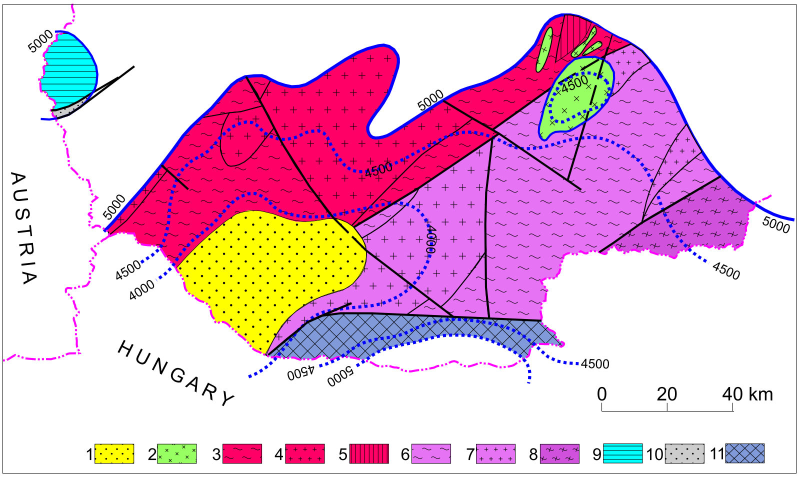

Fig. 2. Lithological complexes on the isotherm lying in the depth up to 5 km in the area of Danube Basin. 1 – Neogene sediments and volcanoclastics, 2 – supposed areas of subvolcanic intrusions, 3 – metamorphic complexes of the Tatricum unit, 4 – granitoid complexes of the Tatricum unit, 5 – Tatric mostly Mesozoic cover unit, 6 – metamorphic complexes of the Veporicum unit, 7 – granitoid complexes of the Veporicum unit, 8 – altered crystalline complexes of the Veporicum with supposed Cadomian basement, 9 – Eastern Alps Mesozoic units, 10 – Eastern Alps Palaeozoic units, 11 – Pelsonia unit.

rocks of volcanic origin (mostly volcanoslastics, but also lava flows and extrusions). Products of volcanism are concentrated mainly in the eastern and north-eastern edge of the basin, and are also buried under the younger basin fills. Their position is captured mainly by magnetic measurements and the largest occurrences are shown in the Tectonic Map of Slovakia (*Bezák et al., 2004*). The products of magmatism are shown also in the magnetic maps as positive anomalies. The Danube Basin is characterized by a relatively large number of positive anomalies (*Kubeš et al., 2010*). The sources of these anomalies are found not only in the sedimentary-volcanic complex of the Tertiary period, but also in the Pre-Tertiary basement. The anomalies in the basement can be caused by the basal differentials of granitoids (granodiorites, diorites, tonalites), amphibolites and some types of metamorphic rocks (e.g. mica schists).

In the remaining parts of the basin and neighbouring volcanic mountains, the isotherm 160 °C decreases to the bedrock at a depth of 4–5 km. In these depths, the bedrock already consists exclusively of Palaeozoic metamorphic and magmatic rocks with the exception of a small area in NE (Žiarska kotlina depression), where is a probable occurrence of Mesozoic carbonates and subvolcanic intrusions. In the area of large stratovolcanoes, such as Banská Štiavnica stratovolcano, the occurrence of intrusive volcanic rocks mostly of intermediary composition (diorites, porphyrites) is highly probable.

Metamorphic rocks of all types, ranging from phyllites to gneisses, are present. The drilling exploration and geophysical analysis indicate that relatively large areas in the Danube Basin basement are expected to include magmatic granitoid rocks of Palaeozoic age. The metamorphic and magmatic complexes belong to three tectonic units – Tatricum, Veporicum and Pelsonia. The southern part of the Veporicum is greatly altered because of the effects of volcanic and hydrothermal processes and it may have different physical properties – we therefore visualize it separately. The Pelsonia unit is located south of the Hurbanovo fault, with a possible highly-metamorphic Cadomian basement with an early Palaeozoic sedimentary cover mainly composed of carbonates. In the southernmost area, the isotherm 160 °C again falls below the depth 5 km, which is caused most likely by the occurrence of Pelsonia carbonates.

Outside the territory of Danube Basin temperatue isoline 160 °C lying in the depth smaller than 5 km also is located in small zone in the NW of the Vienna Basin. In these depths most authors expect the Mesozoic complexes of the Eastern Alps provenance. Carbonates are the prevalent lithological types here. In a small section, there are traces of metasediments of the Grauwacken zone of the Eastern Alps.

Area of the Eastern Slovakia with the isotherm 160 °C in the depth less than 5 km (Fig. 3)

The highest isotherm 160 °C in Slovakia exists in the East-Slovakian Basin, which is the center of this general area. Here the depth of the isoterm position is usually smaller than 3500 m and some times even less than 3000 m. The East-Slovakian Basin had a very specific tectonic development (e.g. *Rudinec, 1989; Bezák et al., 2004*). The bedrock of the basin is broken into blocks with uneven depth, with the deepest parts of more than 6 km in the central depression of the NW direction. The isotherm lies in the Neogene sedimentary-volcanic filling in most parts of the basin.

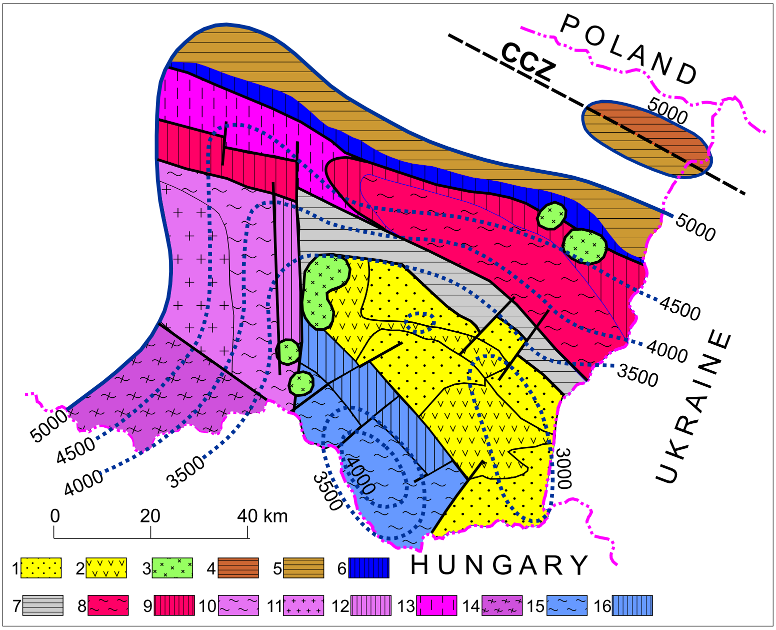

Fig. 3. Lithological complexes on the isotherm lying in depth up to 5 km in the area of the Eastern Slovakia. 1 – Neogene sediments, 2 – Neogene volcanoclastics, 3 – supposed areas of subvolcanic intrusions, 4 – Flysch Belt with underlying European platform, 5 – Flysch Belt with underlying supposed Pieninic crust, 6 – Klippen Belt, 7 – Iňačevo-Kričevo unit, 8 – crystalline complexes of the Tatricum unit, 9 – Mesozoic cover of Tatricum, 10 – metamorphic complexes of the Veporicum unit, 11 – granitoid – complexes of the Veporicum unit, 12 – Mesozoic cover of Veporicum, 13 – Mesozoic complexes of Fatricum, 14 – altered crystalline complexes of the Veporicum with supposed Cadomian basement, 15 – crystalline complexes of Zemplinicum unit, 16 – Upper Palaeozoic and Mesozoic cover of Zemplinicum.

The filling of East-Slovakian Basin consists of Neogene sediments and volcanics (from Lower Karpathian to Late Panonian and Pontian age). The sandstones, conglomerates, siltstones, claystones and different volcanoclastics are the prevailing lithological types (*Vass et al., 1991*).

Volcanic activity occurred in parallel with the sedimentation in the Miocene period not only in the neighbouring volcanic mountains but also in the potential centers in the basin. The volcanic centers within the basin fill are bound to the volcanic-tectonic zones in the NW–SE direction, which are marked on the Tectonic Map of the Slovakia (*Bezák et al., 2004*). The magnetic map (*Kubeš et al., 2001*) also shows the buried volcanoes. Therefore, the volcanic sedimentation is frequent and sometimes dominant. In the area of the volcanic centers we can assume the occurrence of subvolcanic intrusions in the depths of interest with a temperature of 160 °C.

The isotherm 160 °C falls below 4 km on the edges of the basin and it enters to the bedrock of the Neogene sediments and the Slánske vrchy Mts. volcanites. The composition of the bedrock is varied in view of the tectonically complicated interface of the Eastern and Western Carpathian units.

The geological and tectonic composition of the Pre-Tertiary bedrock in the East-Slovakian Basin is greatly affected by the deeply-established Slanská tectonic line, which was defined by *Slávik (1974)*. It stretches in a north-south direction under Slanské vrchy Mts. and it allowed the extrusion of volcanic material to the surface. It serves as a contact area for the Gemericum and Veporicum unit in the west with the Zemplín and Iňačevo-Kričevo units. The situation east of the Slanska fault system is geologically and tectonically complicated. Mesozoic complexes (mostly carbonatic) of the Fatricum is located in the northern part of the territory, it is surrounded by the southern edge of the Klippen Belt and it emerges on surface in the Humenské vrchy hills. In this part of basement we assumed also (*Franko et al., 1995*) crystalline complexes of the Tatricum. We expect that the Iňačevo-Kričevo unit is located to the South of Fatricum and Tatricum in the Neogene sedimentary bedrock, and composed of very weakly metamorphic fine sandstones and schists with pockets of limestones.

The Zemplinicum tectonic unit is located in the southern part of this territory (*Slávik, 1976*). Zemplinicum is a structural-tectonic unit composed of highly metamorphic crystalline core (mostly gneisses and amphibolites) and their Carboniferous-Permian and Mesozoic cover. The tectonic structure of the Zemplinicum rock complexes is not entirely clear to this day. The western part of the said territory is composed of crystalline complexes of the Veporicum with a significant presence of granitoids. Numerous authors (e.g. *Franko et al., 1995*) expect the occurrence of Mesozoic carbonates in the cover of crystalline complexes.

The isotherm 160 °C reaches the outer flysch sediments (sandstone, claystone) in the northernmost part of the area in question. We assume that these flysch sediments are situated on the boundary of supposed Pieninic crust and European platform.

The territory of Slovakia with the isotherm 160 °C in a depth of 5–6 km

This territory stretches across the whole Slovakia from west to east. It occupies various geological and geomorphological units, which will be described sequentially from the west as presented and numbered in Fig. 1. The smallest area is located in Central Slovakia where the isothem falls below 6 km mostly under the higher mountains. Supposed lithology is described after smaller regions marked by numbers which are shown in Fig. 1.

1. Area of the SE part of the Vienna Basin and the Malé Karpaty Mts.

In the said depth, the basement of Vienna Basin also includes the Mesozoic East Alpine complexes in the north, while in the southern part and in the area of the Malé Karpaty Mts. we can already see the complexes of the Tatricum represented by Hercynian metamorphites (paragneisses, amphibolites, phyllites). The occurrence of granitoids is likely to be the case in these depths mostly SE of the Malé Karpaty Mts. which means that this area is more favourable in terms of lithology and morphology. The occurrence of flysch sediments is possible even at a depth of more than 5 km in the northern part up to the CCZ axis. The flysch sediments in the northernmost part of Vienna Basin basement are thrusted onto the Brunia crystalline structures and/or their Palaeozoic cover, which mainly consists of carbonates.

2. Area of the northern protrusions from the Danube Basin, including the Piešťany and Horná Nitra depressions and the surrounding mountains of Považský Inovec and Tribeč

At a depth of 5–6 km, we mainly expect the Tatricum crystalline rocks in this area. Due to the reduced crust thickness in this area as a result of asthenolite, the gravimetric data allow us to distinguish the position of the predominantly heavier Palaeozoic metamorphic rocks (gneisses, micaschists, less phyllites and amphibolites) in the mountains area from the lighter granitoids in the depressed areas – basins, coupled also with the effects of overlying Tertiary sediments. In some tectonically exposed areas, for example along the Považie fault or near the Klippen Belt, we can consider the possibility of Mesozoic and Upper Palaeozoic rocks being tectonically sucked into these depths (see *Franko et al., 1995*). The Mesozoic rocks are mainly represented by the carbonates of the cover of crystalline complexes and Fatricum units.

3. Outer Carpathian Flysch Belt in the north-western Slovakia

This is a Flysch Belt where the flysch sediments may be assumed to have reached a thickness of more than 5 km mainly in the southern part, near the Klippen Belt zone. These lighter sediments overshadow the weight effect of the European platform in the bedrock. In these areas, the European platform is represented by the Brunia unit consisting of granitoids, gneisses and amphibolites and their Lower Palaeozoic cover. The span and mainly the extent of particular Klippen Belt rocks (carbonates, marbles, schists, sandstones etc.) in the depth is difficult to assess, but their occurrence is likely in the narrow zone at the foreland of the Tatricum. Some authors even consider a larger presence of Mesozoic rocks of the oceanic type. In the areas where the Klippen Belt zone passes south of the Carpathian Conductivity Zone (CCZ), we assume the presence of the segment of Pieninic crust in the bedrock of flysch sediments, which has a rock composition similar to Brunia.

4. Northern Slovakia: area of core mountains from Strážovské vrchy Mts. to Branisko Mts. and the adjacent basins or hills with a predominant Tertiary sediments

In this areas the isotherm 160 °C lies in the depth more than 5500 m, thats why these areas only contain Palaeozoic crystalline rocks, mostly of Tatricum, less of Veporicum tectonic unit. However, since this area belongs to the Carpathian gravity low, we are lacking the distinctive features for the determination of the position of granitoids and metamorphic rocks. The geological development on the surface indicates that granodiorites and granites prevail along with orthogneisses and paragneisses with smaller content of amphibolites.

5. Wider area of the Lučenská kotlina depression

In the mentioned depth range, the Veporicum crystalline rocks prevail in the northern part, and due to the Hercynian tectonic superposition, we expect this area to contain mainly Palaeozoic mica-schist rocks with supposed Cadomian basement in the southern part. According to the magnetotelluric measurements, the southern part exhibits anomalous conductivity along the entire cross-section of the crust. This is due to the fact that it is substantially altered by intensive tectonic movements in the regional faults and also by young volcanic activity accompanied by hydrothermal alterations. Therefore, this block is visualized separately in the Fig. 1. The occurrence of subvolcanic intrusions mostly of basaltic character is also very likely in this area.

6. Area of Gemeric unit

The occurrence of Veporicum crystalline rocks is very likely in these depths over 5500 m although the occurrence of Palaeozoic low metamorphic phyllites, metasandstones and metavolcanites of the Gemericum is also possible. The presence of a Mesozoic cover from the Veporicum is less likely. Further north, only the crystalline Veporicum is present (granitoids and metamorphites), which is tectonically separated from the Tatricum. *Franko et al. (1995)* again expects the possible presence of carbonate complexes of the Tatricum cover in the areas adjacent to Klippen Belt, as well as Fatricum complexes. Relatively small intrusion of the Cretaceous Rochovce granite on the western edge of Gemericum is very interesting in terms of lithology.

7. Outer Carpathian Flysch Belt in the north-eastern Slovakia

This area of Outer Flysch Belt has a completely different gravimetric but also magnetotelluric features than the western flysch area. Lithology of flysch sediments is same (alternation of sandstones and claystones). We assume that this is caused by a different crust type in the bedrock of the flysch sediments (tectonically disturbed platform, e.g. *Bezák et al., 1997*, segment of Pieninic crust, e.g. *Grad et al., 2006*) and especially by a much larger influence of the volcanic activity (intrusions into the flysch are also expected, see *Kucharič et al., 2012, 2013*), including the protrusions of partial asthenolites into the flysch strata. Therefore, this area is interesting and promising in terms of geothermal use.

4. Conclusion

The contribution finalizes the primary selection of the perspective areas for deep geothermal sources exploitation within the studied region of Slovakia.

We utilized the principle of the successive separation on the geothermal base (*Majcin et al. 2017*) which provides the depth distributions for deep temperature of about 160 °C. This temperature is sufficient for the reasonable economic exploitation of the geothermal energy for electricity production minimally by the binary cycle technologies. Applied were additional geological, economic and technical parameters of geothermal sources.

In this paper we described the supposed lithological composition in depths technically applicable for utilization of the heat of rock complexes. The studied territory of Slovakia is divided to two categories according depths – first one up to 5 km and the second one between 5 and 6 km. The results were constructed from various accessible geoscientific sources enhancing the basic knowledge presented in Geothermal atlas (*Franko et al., 1995*). The rock complexes are presented only schematically because of better lucidity. Our results create the base for both starting decisions of regions suitable for electricity production by binary cycles and further selection requires more precise exploratory development works (analysis of geological profiles, boreholes, additional geophysical works and others) in concrete localities. According the basic parameters (temperatures, depth, accessibility, lithology) application by geothermal sources evaluation we determined the central parts of both basins (East-Slovakian and Danube) as the most favourable. The suitability is increased mainly in the case if the sedimentary filling containes volcanic bodies. Further we incorporate the border parts of mentioned basins including the volcanic mountains, from intramountains basins Žiarska kotlina depression is favourable, further NE part of Outher Carpathians Flysch zone and a part of Vienna Basin to the perspective geothermal areas of Slovakia for electricity production.

Acknowledgements. The authors are grateful for partial support of the work by the APVV agency by means of project APVV-0724-11 and the Slovak Grant Agency VEGA by means of projects 2/0091/15, 2/0042/15 and 1/0141/15.

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