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Article

Critical tectonic limits for geothermal aquifer use: Case study from the East Slovakian basin rim

Stanislav Jacko [1,*], Roman Farkovšký [1], Igor Ďuriška[1] , Barbora Ščerbáková[1] and Kristína Bátorová[1]

[1] Institute of Geosciences, Faculty BERG, Technical University of Košice, Slovakia; stanislav.jacko@tuke.sk; roman.farkasovsky@tuke.sk; igor.duriska@tuke.sk; barbora.scerbakova@tuke.sk; batorova.kristina@gmail.com

* Correspondence: stanislav.jacko@tuke.sk; Tel.: +421556023135

Abstract: The Pannonian basin major heat system in Central Europe. Their peripheral basins like the East Slovakian basin is a example of a geothermal structure with a linear directed heat flow ranging from 90 to 100 mW /m^2 from west to east. However, the use of the geothermal source is limited by several critical tectono-geologic factors: (a) tectonics, and the associated disintegration of the aquifer block by multiple deformations during the pre-Paleogene mainly Miocene period. The main discontinuities of NW-SE and N-S direction negatively affect the permeability of the environment. On the contrary, for utilization are important the secondary minor NE-SW dilatation open fractures which have developed by sinistral transtension on N–S faults and accelerated normal movements to the southeast in the present. (b) hydrogeological conditions, the geothermal structure accommodated three water types, namely Na-HCO3 with 10.9 g.l^{-1} mineralization (in the north), the Ca-Mg-HCO3 with 0.5 – 4.5 g.l^{-1} mineralization (in the west), and Na-Cl water type containing 26.8-33.4 g.l^{-1} (in the southwest) mineralization. The chemical composition is influenced by the Middle Triassic dolomites aquifer as well as by infiltration of saline solutions and meteoric waters along open fractures/faults. (c) geothermally anomalous heat 123 – 129 °C close to volcanic chain with 170 l/s total flow seems to be the perspective for heat production.

Keywords: geotherm; heat flow; permeability; structural modeling; seismic; resources; renewable; utilization; Pannonian basin; East Slovakian basin;

1. Introduction

Geothermal energy represents a very attractive, economic, and ecologic energy source. The utilization of energy for commercial purposes, which is mainly a result of the increase of world fuel prices as well as new technologies, proved to be an essential action for the realization of programs benefiting from this heat source. The necessity of the use of renewable energy resources (including geothermal energy) in Slovakia stems from both international trends, above all the countries of European communities, and from the increase of fuel prices on the world markets. The increased concern for renewable resources unfolds from the increased priority in the human environment. All these factors caused that the topic of renewable energy is an important agenda not only for scientists but also for politicians and business activities. As the socio-political pressure increases towards the transition to global low carbon and sustainable future, the role of geothermal energy usage worldwide intensifies [1]. In the year 2020, there are quantified records of direct geothermal utilization worldwide in 88 countries [2]. This is an increase in direct utilization from 82 countries reported in 2015 [3], 78 countries reported in 2010 [4], 72 countries reported in 2005 [5], and 58 countries reported in the year 2000 [6]. Around 283.58 Terawatt-hours (TWh) of geothermal heat are being used worldwide each year. An estimation of the worldwide installed thermal power at the end of 2019 is 107.7 GW which is a 52 % increase from 2015 also the thermal energy used increased from 2015 by 72.3 % to 1,020,887 TJ/yr [2]. The distribution of geothermal energy used by category is approximately 58.8 % for ground-source heat pumps, 18.0 % for bathing and

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swimming, 16.0 % for space heating (of which 91.0 % is for district heating), 3.5 % for greenhouse and open ground heating, 1.6 % for industrial process heating, 1.3 % for aquaculture pond and raceway heating, 0.4 % for agricultural drying, 0.2 % for snow melting and cooling, and 0.2 % for other applications (desalination, bottle washing, animal farming, etc.) [7]. For the last five years, the number of wells drilled was 2,647; the combined effort of professionals working on geothermal energy was 34,500 person-years and the total worth invested into projects was 22.262 billion US$ [2]. The production cost for geothermal heating is highly variable. The cost is highly dependent on the quality of the geothermal resource and the investment needed for recovery, especially the number and depth of wells required and the distance from the wells to the point of use. Geothermal heat could be transported over a considerable distance from the source to consumers. The longest single geothermal hot water pipeline in the world is located in Iceland (62 km) [8].

1.1. The geothermal sources of Slovakia

The Pannonian basin is the most significant geological structure in Central Europe. The basin evolution is related to thermal impact when crustal fragments have been directly superimposed to crustal melting in the Carpathian embayment [9]. Heat flow distribution in the Pannnoanian basin shows values ranging from 50 to 130 $mW/m^{2.}$ [9,10,11,12]. The average heat flow is considerably higher in the Carpathians especially in the Great Hungarian Plain and the East Slovakian basin [13, 14,15] with heat flow values above 100 mW/m^2 (Figure 1).

The East Slovakian Basin is part of the extensive Pannonian basin created during the Miocene. The basin is divided by the Slanské vrchy neovolcanic chain into the eastern, i.e. the Trebišov depression, and the western, the Košice depression, which is the area with the highest potential for geothermal use including generation of electricity in Slovakia. In general, geothermal sources in the Slovakia territory and their utilization are influenced by two “unknown” basic parameters: geothermal fluids and temperature.

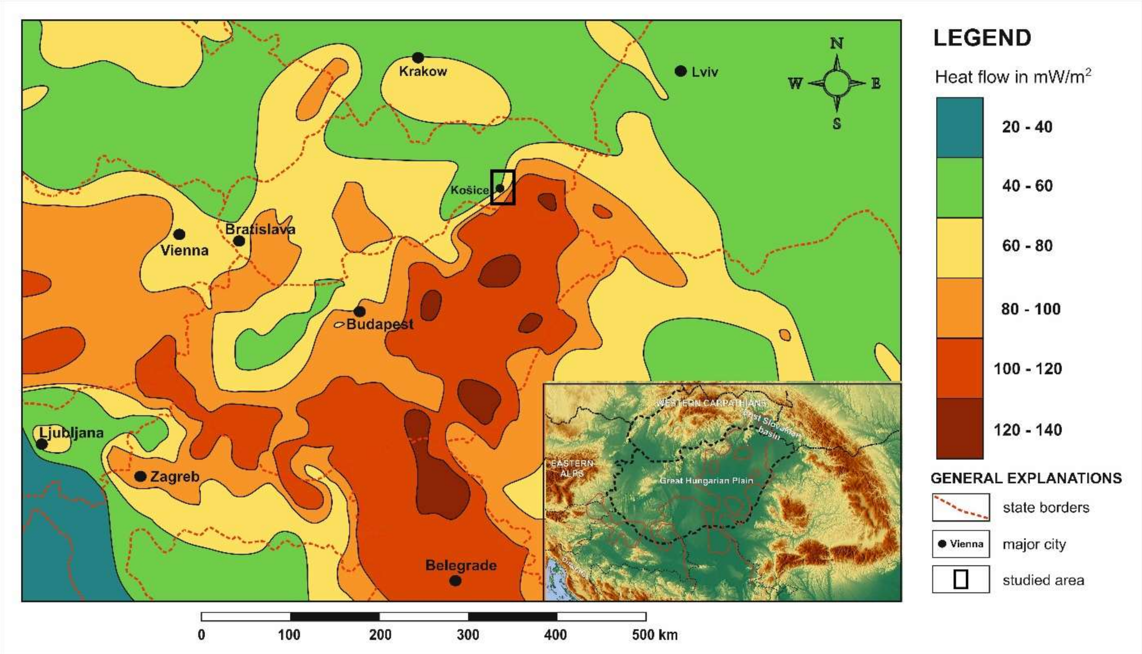

Figure1. The heat flow distribution in the Pannonian basin and their peripheral areas (values in mW/m^2). The East Slovakian basin is an integral part of the major heat flow system in Central Europe (modified after [8,9]).

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The main sources of geothermal water in the Western Carpathians are usually linked with the Middle-Upper Triassic dolomites. Geological processes during the closure of the Carpathian orogeny uplifted [16] and eroded the overlying sedimentary rocks of the Upper Triassic to Cretaceous age. They were eroded to the dolomite level. Subsequent carstification of the dolomites created the ideal aquifer in the region. The heat flow is related to the evolution of the Pannonian basin [17,18,19]. During the Miocene, basin subsiding accelerated due to the ascent of asthenolite. The result was earth crust thinning, rifting as well as the formation of the peripheral basins [20] at the northern edge of the Pannonian basin. These individualized sedimentary basins are considered to be the most important and the most suitable geothermal areas in Slovakia with a relatively high heat flow. Geothermal water in the wells was found at depths ranging from 92m to 3616m. Free outflow in the wells ranged from 0.1 up to 100 l/s. Na-HCO3-Cl, Ca-Mg-HCO3, and Na-Cl chemical type of waters with the TDS value of 0.4 – 90.0 g.l^{-1} prevail. Temperatures vary from 20 to 74 °C in 1000m depth, with an average value of 45 °C. Geothermal energy for heating is registered in 68 localities, 39 localities are useable for swimming and bathing, 11 for drying, 6 for commercial use, 4 localities for district heating, and only one locality for fish farming. Totaly in Slovakia are utilized 230,3 MW a 2000,9 TJ/yr [21].

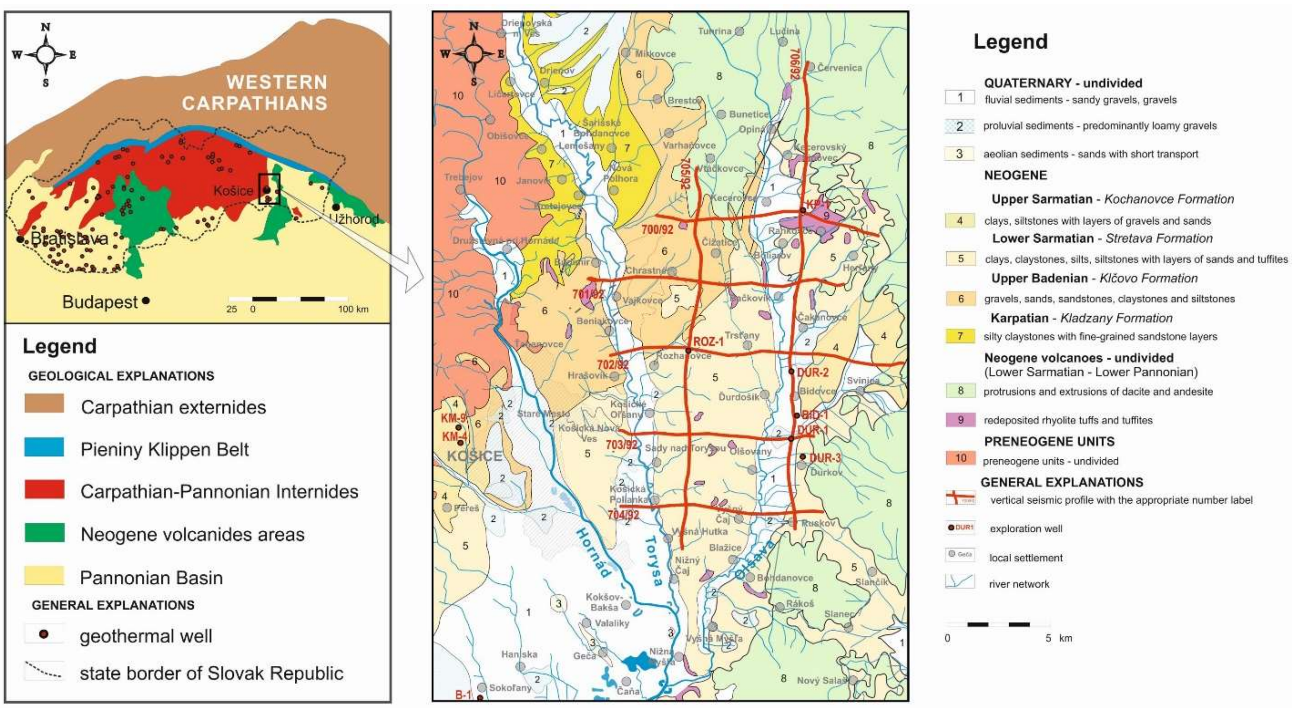

Figure 2: Simplified geological maps **(a)** Utilization of the geothermal sources in Slovakia is localized mainly on the west side of the territory. Produced wells are situated in the same aquifer as in the Košice depression. (b) Košice depression lies in the West part of the East Slovakian basin. In the geological map are important wells and deep 2D seismic cross-sections localization use in the article.

The article aims are to analyze additional parameters such as tectono-geological limits in the potentional geothermal area. The process of multiple deformations modified tectonic and sedimentary structures, had a limiting effect on aquifer spatial distribution, fluid chemistry (open dislocations), hydraulic parameters (subsidence/uplift), it can affect temperature (thermolift), lithology and wells construction. Parameters of each

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thermal resource have an impact on total initial cost and confirmation of economic and technical feasibility.

2. Geology and hydrogeological conditions

The East Slovakian basin is filled by Karpathian/Pannonian volcano-sedimentary formations and Quaternary deposits (Figure 3). They substantially differ in their basement nature which has a direct consequence on hydrogeologic conditions of the depressions [22]. The base of the Košice depression Neogene formations comprises exclusively the Inner West Carpathian rock complexes. The footwall of its northern i.e. the Prešov part is formed by Paleogene sandstone/shale formations. Pre-Tertiary rock sequences of the Čierna hora Mts. (mainly Triassic dolomites and Paleozoic cover/crystalline complexes) are elevated at the western margin of the depression(modified after [23].. They submerge below the larger part of the Neogene fill of the depression. Especially a thick dolomite layer posses very good conditions for water infiltration and groundwater circulation. Paleozoic rock complexes (mostly phyllites) of the Gemeric unit [24] form the main part of the depression footwall on the southwest. Their low water-saturation capacity is largely restricted to surface joints and weathering zone. The Triassic carbonates of the Čierna hora Mts. underlying the depression on the western border are located at the geothermally less perspective area.

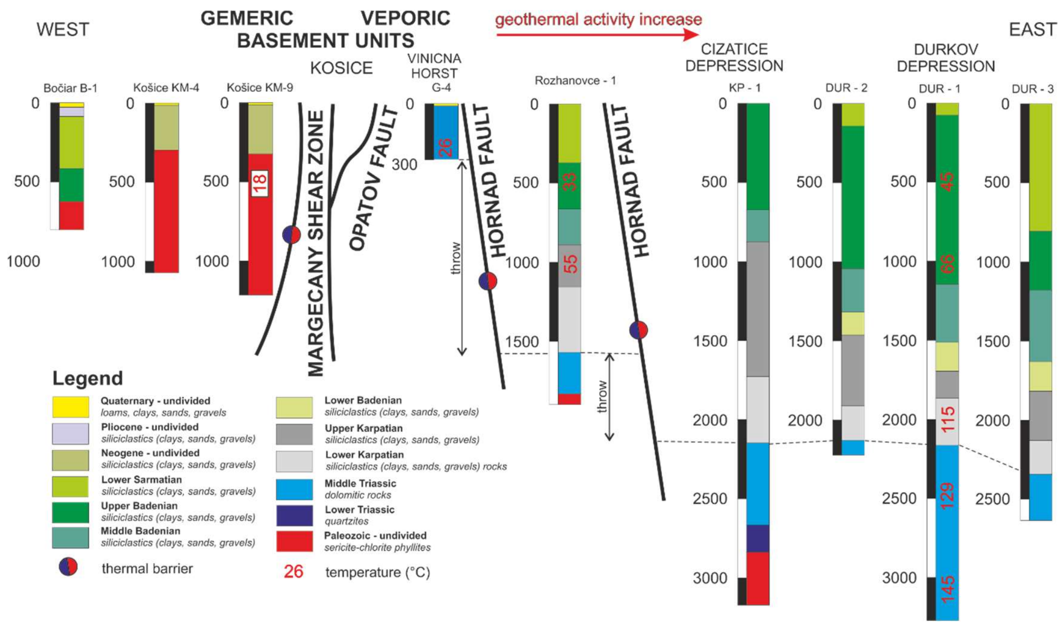

Figure 3. Structural deep wells with representative lithology and stratigraphy log in the Košice Depression. The wells are arranged from west to east. In the same direction, geothermal activity increase, and the dolomite aquifer rapidly drops down from the surface (0 m) to a depth of 2000 m. The aquifer is disintegrated into tectonic blocks on the Miocene/Quaternary Hornád fault system of N – S direction with normal fault activity.

Following actual exploration, the most promising part for the economic utilization of geothermal energy seems to be the southeastern part of the depression. In this area, 20 km distant eastward of Košice town, is the most potential Cizatice/Durkov area, where three positive geothermal wells GTD-1, GDT-2, and GTD-3 have been drilled. The wells transected reservoir rocks (e.g. the Čierna hora Mts. Triassic dolomites) at 2850 – 3150 m depths. At the GTD-1 well, the water temperature reached 125°C having 56l.s^{-1} discharge overflow. The water mineralization didn´t exceed 30gl^{-1} containing 96% of CO_2. The water of the GTD-2 well, located westwardly from the previous one, achieved 124°C

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and the discharge of 70ls^{-1}. The mineralization doesn´t exceed 28gl^{-1} and 98% CO_2 content. The water of the geothermal well GTD-3 has reached 126°C temperature and 150ls^{-1} discharge.

3. Processing methodology

Geothermal water aquifers of the area comprise Triassic karstified carbonates, mainly dolomites, their breccias, and Neogene basal clastic rocks of the Karpathian. By creating a 3D model of the southeastern part of the Kosice basin we try to show a spatial distribution of the aquifers and overlying Neogene insulators and a change in spatial thickness of the aquifers and their relations to tectonic structures. Data processing [25], correlation of 2D seismic profiles *vs.* drilling data, and results interpretation have been realized in the Petrel software (Figure 4).

Data from relevant deep wells localized around the Košice depression were used in the model. The first group of wells: structural KP-1, DUR-1, DUR -2, ROZ-1, and geothermal key wells GTD1, GTD2, GTD3 are situated in the Košice depression. The second group wells: Kosice KM-4, Kosice G5, Kosice KM-9, Drienov-2, Bankov-15, Bankov-17 are localized at the west edge of the Košice depression. The third group wells are situated in the south Gemeric unit. They are without carbonates and dolomites in the subsurface: Bociar-1, Cana-6, Komarovce-1. Structural and lithostratigraphic interpretations come out from 2D seismic cross-sections No. 700/92, 702/92, 703/92, 704/92, 705/92, and 706/92. Based on these results, it was possible to distinguish five following reliably indicative lithostratigraphic interfaces. They separate rock complexes of the different evolution stages of the area:

1, the basal plane of Mesozoic sequences.
2, the interface of Mesozoic top/ Karpatian formations
3, the interface between Karpathian/Early-Middle Badenian formations
4, Early-Middle Badenian/ Late Badenian formations boundary
5, Late Badenian/Sarmatian formations boundary

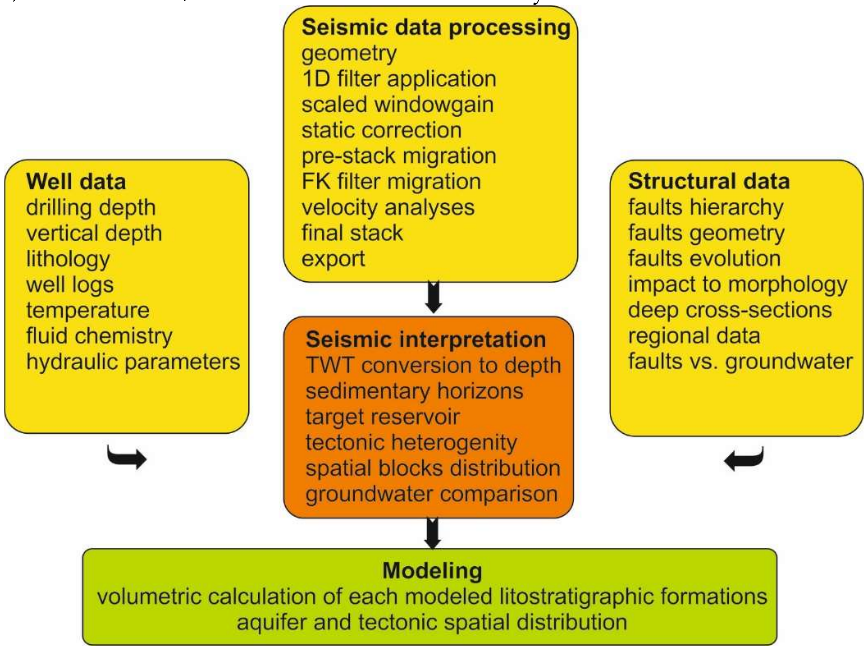

Figure 4. Integrated workflow diagram divided to three groups: data collection (yelow), interpretatiom (orange) and modeling (green).

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Fault interpretations do not fall into the important tasks of geological modeling. At this point we have to emphasize that available seismic data belongs to 2D and not to a 3D category, i.e. they provide only a limited volume for a precise 3D modeling. The problem is moreover caused by relatively large (ca, 5-7 km) distances between the 2D seismic profiles. Individual faults could change their length, depth, and direction in the profile or they could completely disappear and new faults could emerge. For the mentioned reasons the final 3D tectonic model presents a simplified structure of a lesser section of the area only. Due to the insufficient seismic data quality, fault tectonics is not included in the rest of the area. The 3D grid processed at the mentioned principles is ready for final 3D model elaboration and following interpretation steps. For the more precise demonstration of spatial distribution and changes in the thickness of the model's interior geostructural components, the model is sliced.

4. Results of structural modeling

The boundaries of the model have been delineated along seismic lines (Cizatice/Durkov structure) and partly by the west edge of the basin. Several seismic profiles provided sufficient information for interpretation purposes. North-southwardly trending the 706/92 profile (Figure 5) following the western edge of the Slanské vrchy Mts. neovolcanic chain crossed over the KP-1, DUR-1, and DUR-2 wells. The last one cut the Mesozoic successions in the depth of 2230 m. Except for the position of the mentioned five lithostratigraphical boundaries, seismic reflexes of the middle part of the profile indicate a pronounced pre-Tertiary basement elevation, reflecting probably an uplift effect of the Sarmatian neovolcanites. Steeply dipped normal faults and/or oblique-slip faults detected within the profile reduce the Miocene sequences and markedly cut the Mesozoic formations.

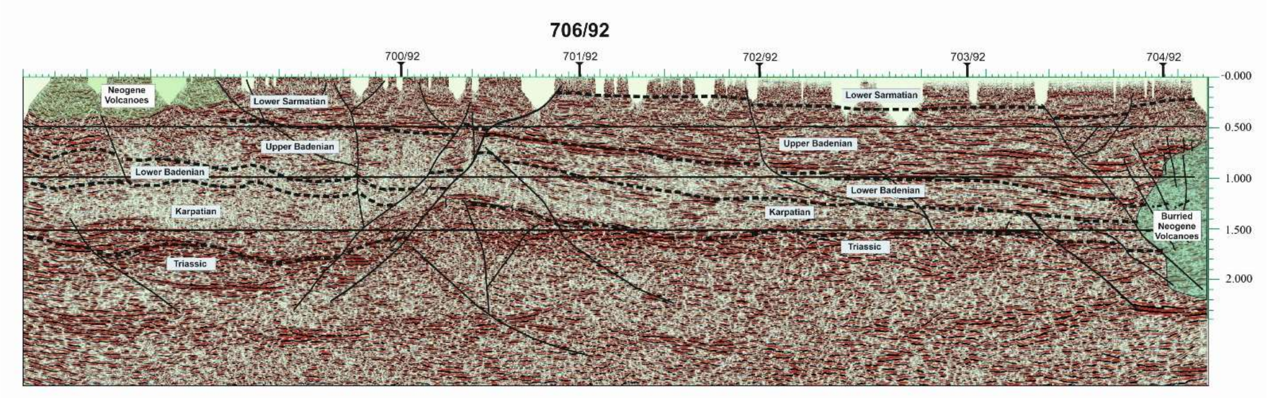

Figure 5. Deep seismic cross-section no. 706/92 oriented in a north-south direction. In the section are interpreted basic sedimentary formations and andesite volcanic rocks. A significant antiform (approximately in the middle part) represents the structural boundary between Čižatice and Durkov depressions. They are tectonically limited by NE–SW trending normal faults (modified after [26]).

More information about the Miocene basement composition and deformation nature provide the KP-1, DUR-1, and DUR-2 wells. The last well cuts heavily crushed the Middle/Late Triassic dolomites [27,28]. Penetrating of the Late/Middle Triassic carbonates in the D-1 Ďurkov well ceased at 3200m depth. The top section of the carbonates, which underlying the Neogene successions, comprises light grey compact dolomite shales containing dynamo-metamorphic exsolutions of calcite veins. Dark grey clay/shale layers among dolomites appear namely at 2682-2753 depth interval. From ca. 2750m depth dolomites containing an increased $CaCO_3$ (up to 45%) content [29].

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Kecerovské Pekľany KP-1 well, situated at the contact point of the No.700 and 706 profiles, cuts Mesozoic formations and ceased at crystalline basement rocks. The Middle Triassic section of the well consists of grey dolomites containing sporadically breccia nests, merging at the basal part to calcareous dolomites and/or to dolomitic limestones. Underlying violet - brownish to violet – reddish Verfenian shales occurs at the 2705 – 2745 m depth. The basal part of the Mesozoic succession at the 2745-2820 m depth consists of heavily sheared white grey to pinkish Lower Triassic quartzites. Variously colored shale intercalations among them form namely 2751 to 2755 depth interval [27]. Below them, at the depth of 2820 – 2940 m, violet – brownish greywackes and silicic sandstones interbedded by clay shales, probably of Permian age occur. The Triassic/ Permian boundary has been recognized at the depth of 2840 m [30] and the Permian / crystalline rocks at the depth of 2925 m have been recorded. Dark green chlorite schists and chlorite – muscovite mica schists of the Čierna hora Mts. crystalline basement rocks [31] were drilled below 2940 m.

Precise data about the presence of the faults, their spatial position and movement activity significantly influence any spatial modeling of geologic objects (Figure 6). Faults are expressed in seismic sections either as sharp edges and cut-off sequences or as reflexes of abrupt changes visible at a section. Three main i.e. NW-SE, N-S, and NE-SW fault sets deform the Neogene formations of this part of the Košice depression (Table 1).

NW – SE fault system is parallel with the direction of major tectonic units of the Western Carpathians. ***Margecany shear zone*** is a pre-Mesozoic tectonic structure that tectonically divides the Gemeric unit (phyllites/low permeability) and the Veporic unit (dolomites/high permeability). The morphology and the fault rocks of the zone are on the surface best visible between the Košice and the Margecany towns. The activity of the zone has polystage character and was formed during the Alpine Cretaceous North-South shortening of the Central Western Carpathians. The zone was reactivated several times during the Cretaceous-Neogene period. The zone is tens of meters wide on the surface. Towards the depth, the zone is lesser inclined to subhorizontal. Shear zone segments rocks of the crystalline complexes as well as the rocks of the cover formations. Typical fault rocks are mylonites of the crystalline gneisses, mylonites of the Carboniferous and Permian meta-sediments, and mylonites of the Triassic quartzites.

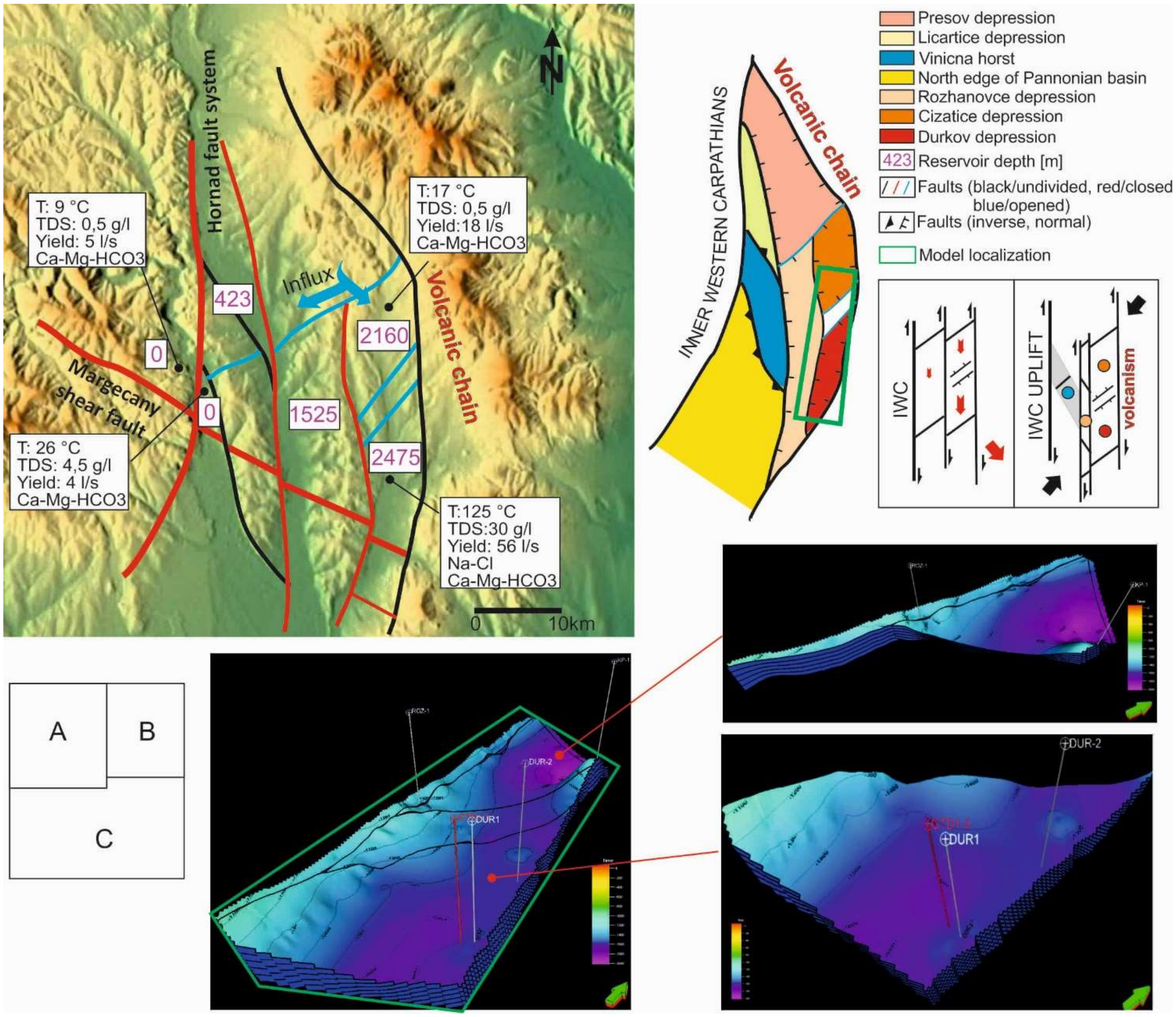

Figure 6. Block structure distribution bounded by three basic systems of NW–SE, N–S, and NE–SW directed faults in the territory of the Košice depression. (a) Interaction between morphology and tectonics is largely influenced by Miocene/Quaternary tectonics. The depth of the aquifer gradually increases from west to east to a depth of 2475 m at a distance of 20km. (b) Sketch of two important deformation stages of tectonic structure development. The period of Upper Badenian was characterized by the delimitation of crust and its disintegration on N–S trending faults, while their asymmetric subsidence caused the formation of sinistral dips with subsequent formation of individualized shear basins. The Miocene uplift of the Inner Western Carpathians (IWC) was compensated at the edge with the East Slovakian basin by the formation of asymmetric shear bends, while externally from this zone, this uplift was compensated by oblique drops on the SE. (c) Block models of the Middle Triassic dolomites underlying the Košice Basin indicate significant irregularity and very significant tectonic limitation. Tectonic boundaries have different properties from the viewpoint of permeability (modified after [26]).

Mylonites have strong foliation and penetrative subhorizontal stretching lineation of the NW - SE direction. There are also rauwackes of the Mesozoic carbonates occurring. Therefore this zone is the so-called "main limiting parameter", which tectonically delimits the potentially usable area from the south. Parallel with this shear zone the dislocations of the lower level were developed. Their multi-deformation history points out the structural diversity depending on paleo-stress conditions. The sigmoidal transpress bend of the Vinicna horst was developed at these fractures. Positive structures and local declines compensating the Miocene subsidence of the basin, e.g. subsidence of the Košice depression, rating from -285m to -310m during the post-Middle Miocene to Holocene period [22].

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The N-S trending ***Hornád fault zone*** controls geomorphology of the depression. During the Paleogene/Quaternary period, the faults of the zone divided the Košice depression into individual sub-depressions with huge tectonic subsiding from West to East. Mostly eastwards (60-85°) inclined faults, forming 3 to 5 km wide zone, practically check the shape and filling of the depression including geothermal carbonate reservoir and their underlying rock complexes. A relatively massive normal faulting represented a total rate of subsidence 2100 m at a distance of 20km [32,33,34]. The faults also substantially influence the current submersion depth of these initially slowly eastwards inclined Miocene formations. The polystage history of the fault is closely related to ESB opening during the Miocene period. According to structural research, it is possible to track deformation stages on the fault. Huge subsidence of the ESB during the Early Miocene created a system of N – S depressions. Middle Miocene core delamination has an impact on the fault too. Asymmetric subsidence and plate rotation effect [35] caused sinistral shear movements with high intensity at the west ESB rim. The basin breakdown is possibly correlated with horizons in the seismic cross-sections (Figure 4, 5) and with subdivision into blocks, horsts, and depressions. The fault is filled with cataclastic surrounding sediments (mainly shales) with limited permeability.

Moderately (45-60°) mostly to the SE dipped ***NE-SW faults***, are related with depression forming in the transtensional tectonic regime. The faults separate the depression basement into individual blocks. Tension tectonic has a positive impact on permeability and fluid flow. The same structure separates the northern Čižatice depression from the southern Ďurkov depression. Groundwater migration from the center of the basin towards the western edge at the contact with the Hornád fault system in the Košice area is likely occurring at these faults. As a result, are disproportionally high groundwater temperatures towards the western edge of the basin. Therefore, we believe that these are "key fault structures" that enabled the flow of overheated groundwater in the Košice Depression.

The modeling of evaluated seismic/well data allows specifying four lithostructural geothermal water aquifers limited by the over/underlying bedding planes. The first one forms the Mesozoic sequence of the Čierna hora Mts. Veporic unit. The deepest part of the Mesozoic pile, i. e. the basal aquifer plane (marked in violet color in Figure 7, 8) reaches depth 2000 to 2600 m., while a depth of its overlying pre-Neogene interface varies from 1250m to 1380m. The aquifer sole depth differences indicate probably topographical effects of pre-Neogene denudation and/or syn-postsedimentary tectonic processes.

At the central part of the modeled section, an outstanding (blue-colored at Figure 7) elevation extends. The elevation separates the Ďurkov area depression of the SE edge of the section from the Čižatice one developed at the section western margin. Both of the depressions reflect probably NE-SW normal faulting. The Ďurkov area depression is not as large as the previous surface but the depression in the Čižatice area is still very outstanding. It is because of the increasing activity of the Miocene N – S or NE – SW faults. These two surfaces delimitate Triassic carbonate rocks and variability in topography and thickness can be assumed.

Table 1. Basic fault parameters with different impact on permeability and surface morphology

Faults	Rank	Sense	Permeability	Morphology
NW - SE	I., III.	inverse, shear, normal	closed	asymmetric
N – S	II.	shear, normal,	closed	horst/depressions
NE - SW	III., IV.	normal	opened	-

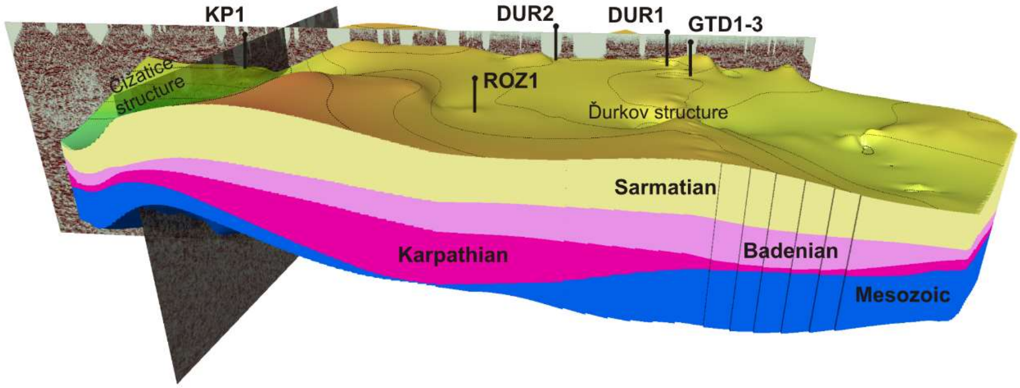

Figure 7. 3D geothermal model of the major lithological formations participated in the Košice Depression geological structure. The dolomites (blue) represent the main aquifer of the geothermal structure, which has an asymmetric shape in its N–S direction. In the model is a nice visible flexural boundary between Čizatice and Ďurkov structures (modified after [29])

Only two wells from the plotted ones, i.e. KP-1 and ROZ-1 penetrate the Mesozoic pile sole. The overlying plane of the aquifer elevation shows an uneven topography. Its deepest level reaches from 1800m to ca. 2270 m, while the highest one from 800m to 85m only. Larger altitude differences in comparison to the Mesozoic formations aquifer sole reflect probably the post-Sarmatian fault activity and distinctly higher deformation competencies of overlying Neogene formations as well.

The second aquifer body form Karpathian clastic sediments (mainly conglomerates and sandstones). This Neogene basal formation lying directly on the Mesozoic aquifer, following in this manner topography of Mesozoic formations. The Karpathian deposits are conformably overlain by Lower/Middle Badenian fine-grained clastic sediments and evaporite sediments. The topography of this lithostratigraphic interface is not as rugged as in the previously discussed cases. The variation in depth shows ca. 260ms (approx. 220 m). The surface deepest part reaches 1550ms (ca. 1850 m) and the top-level reaches 600 ms (approx. 570 m). The intensity of N-S faults decreases while NE-SW faults are still very outstanding.

The third aquifer body is sandwiched between the Lower/ Middle Badenian and Upper Badenian boundaries. It has a moderate topography, but a distinct depression in the western part of the section surface achieves 1080m amplitude (Figure 7). The maximal depth of the depression reaches ca.1530 m. while its top point is located at ca. 450m depth. Whereas an activity of the NE-SW faults fades out in the depression, normal faulting at the NW-SE faults is still progressive.

The Upper Badenian/Sarmatian bedding plane terminates *the fourth aquifer body*. It forms the top surface of the model with a moderate topography of the boundary plane or its outstanding depression reaching ca. 910m depth. The Sarmatian volcanoclastic sediments of the modeled area outcrops to the Earth's surface.

The following volumetric calculation of the individual lithostratigraphic horizons of the Košice depression forms one of the modeled outputs.

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Table 2. Results of volumetric calculation of each modeled lithostratigraphic formation.

Body	Bulk volume (km³)	Percentage
Sarmatian	73,45726	35,8
Badenian	34,67400	16,9
Karpathian	56,28562	27,5
Mesozoic	40,61837	19,8

The volumetric calculation has been performed for all lithostratigraphic formations separated in the geological model (Table 2). As it results from the cubature of the formations, the Karpathian aquifer posses the highest capacity for geothermal water accumulations. Regarding volumetrically the second aquifer, it is necessary to mention, that only Mesozoic sequences (Figure 8) comprising ca. 40,6 km³ of calculated volume, could be effective for the discussed purposes. Such volumes are not present throughout the Košice depression.

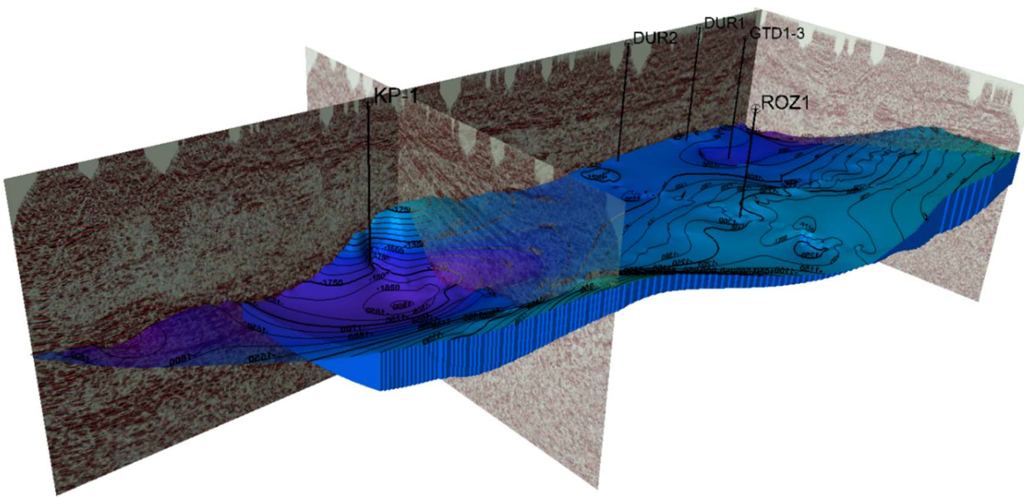

Figure 8. 3D model of the Middle Triassic buried dolomites under Košice depression. The thickness and inclination changes are influenced by fracture tectonics, which is an important structural phenomenon underlying the aquifer.

5. Discussion

The creation of economically perspective geothermal water reservoirs at geological conditions of the East Slovakian basin (ESB) closely depends on a sufficient geothermal flow and a presence of compositionally/volumetrically adequate aquifers. Both are present in the western part of the ESB, especially the southeastern section of the Košice subbasin, more precisely its Čižatice/Durkov depression.

The geothermal flow varies from 90°C at the western part of the depression to 150°C at its eastern one. An average thermal gradient of the depression sedimentary fill varies from 36,5 to 50,3 °C/km or between 25,0 – 32,3°C/km in pre–Tertiary rock formations respectively [36]. The relatively high thermal gradient in the Neogene sequences relates to their lower thermal conductivity. The geothermal gradient generally increases towards the Pannonian basin (i.e. in the South direction) due to a substantially larger overheating of the thinning Earth crust.

A tectonic crushing and a hot water inflow at the faults belong to other reasons for higher geothermal gradient raising within the Neogene sequences. At depths of 500 –

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4000m, i.e. at the depths of a presumable geothermal water aquifers location, the temperature ranges from 27 – 182 °C [13]. Analysis of the sedimentary fill in the wells also confirms a rather smaller thermal conductivity growth in the depth. While Sarmatian sediments show lower (i.e. 2, 10 W/mK) thermal conductivity, the conductivity of Badenian and Karpatian sediments is somewhat higher, i.e. 2, 09 W/mK to 2, 19 W/mK respectively. The conductivity of Paleogene sandy/clay sediments shows a characteristic value of 2,31 W/mK. An average thermal conductivity of the Tertiary rocks varies about 2,05 ± 0,25 W/mK, while constant Mesozoic carbonate rocks display 3,62 W/mK [28].

The highest thermal flow values (i.e 100 – 110 mW/m^2) of the area have been detected at the foothills of the Slanské vrchy Mts. neovolcanic territory. In the central part of the Košice depression, typical values range between 85 – 95 mW/m^2. while in its western part they vary at the 80 – 85 mW/m^2 interval. The average value of the Košice depression thermal flow reaches 94, 9 ± 10, 5 mW/m^2.

Table 3: Geothermal data summary

	Stratigraphy	Lithology	Thermal gradient °C/km	Thermal conductivity W/mK	
NEOGENE (1,6 – 20 Ma)	Sarmatian	claystones sandstones	38,1–51,4	2,10	av. 2,05 ± 0,25
	Badenian	claystones		2,10	
	Karpathian	conglomerates		2,19	
MESOZOIC (245 – 65 Ma)		dolomites limestones	22,4–30,6	3,62	

Presented values, reflecting main rock formations data collected largely from the southeastern margin of the Košice depression, could have been significantly influenced by initial compositional irregularities and the tectonic impact as well. The dolomitic aquifer of the Middle Triassic Period with underlying Verfenian shales, ± quartzites, Permian cover formation, and crystalline basement rocks (as has been confirmed by mentioned KP-1 well) belongs to the Čierna hora Veporic unit [37,38]. The dolomitic complex shows rather an uneven thickness and lengthwise development throughout the unit [23]. The Karnian sandy-shale "Lunz formation" and the Norian "Karpathian Keuper" dolomitic-shales, both of some meters in thickness at the SE part of the unit, are often missing due to an initial evolution of the Triassic formations (lc.). Analogously to other formations of the unit, some duplexes of the Triassic dolomites have also been observed. At such conditions, a vertical duplication of the dolomitic sequence, multiplying their reservoir capacity. It would be useful to add to this content, that any presence of the Križna nappe sequences at the Čierna hora Veporic unit hasn't been indicated throughout the latest complex researches of the region.

On the contrary, syn/post-Tertiary faults partially or completely segment particular formations. Following both mentioned aspects, depending on the degree of ruptured and karstified rocks, a relatively high spatial variation of aquifer, qualitative and quantitative characteristics is need to suppose.

The exploitation of geothermal energy in practice is primarily a source of possibilities. Even if a hyperthermal structure is missing slightly lower tempered geothermal water of this area is technologically utilizable for power generation and/or heating of Kosice town [39], as it is known from other world countries. For example, ORC binary power plants are designed for temperatures ranging from 45 °C (Alaska) to 225 °C (Hawaii) and are built in a variety of sizes [40,41,42]. Residual heat can be used for secondary purposes, e.g. for tourism development, agricultural or industrial production.

6. Conclusions

Geothermal waters have been saturated in the Mesozoic karstified limestones and dolomites with fissure and karstic permeability. The thickness of the Mesozoic aquifer increase from west 185 m to east 1060 m or more.

The spatial changes in thickness, permeability, and conductivity are linked with the distribution of the tectonic structures in the depression. Three major critical fault systems limit basic hydro-geothermal parameters in relatively small space and divide the Mesozoic aquifer into irregular blocs. Based on the simplified tectonic model, at least four mentioned individual blocks can be assumed in the reevaluated territory. However, they shouldn't affect the water amount and hydro-geothermal conditions of the surrounding blocks as well. Both pre-Tertiary shortenings of the basement rock sequences and Paleogene denudation processes affect the spatial distribution of Mesozoic reservoir rocks, indicated by irregular distribution of Mesozoic sequence aquifer.

The geothermal structure contains three different chemical types of water confirmed by boreholes. The Na-HCO_3 water type and 10,9 g.l^{-1} mineralization (in the North), the Ca-Mg-HCO_3 with 0,5 – 4,5 g.l^{-1} mineralization (in the West), and Na-Cl water type containing 20,4-33,1 g.l^{-1} [43] mineralization (in the Southwest). Moderate marine-genetic mineralization of the water reflecting a various degradation degree due to meteoric waters infiltration seems to be a rather positive factor for the utilization purposes. The prospective thermal – energetic potential of geothermal energy sources at the Kosice depression using an extraction – reinjection technology reaches 1276, 4 MWt [44] at an expected 40 years lifetime.

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