The nature of geothermal resources in Slovak Republic

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Abstract: Geothermal energy in the territory of Slovak Republic is related to geothermal waters which largely occur in Triassic carbonates of Inner Western Carpathian nappes and, to a less extent in Neogene sands, sandstones and conglomerates or in Neogene andesites and related pyroclastics. The distribution of aquifers with geothermal waters and the thermal manifestation of hydrogeothermal structures have enabled the definition of 26 prospective areas and structures with potentially exploitable geothermal energy resources. These aquifers lie at depths of 200 – 5000 m (except in spring areas) and the reservoir temperatures of their geothermal waters range from 20 to 240 °C. The total amount of thermal-energy potential of geothermal waters in prospective areas represents 5538 MW_t.

Key words: hydrogeothermal structures, prospective areas, heat flow density, geothermal wells, geothermal waters, geothermal energy

Introduction

The geological structure of the Western Carpathians in Slovak territory and favourable geothermic conditions create a suitable setting for the occurrence of geothermal energy resources. The Western Carpathians are classified according to the age of development of the Alpine nappe structure as the Outer – with Neo-Alpine nappes and the Inner with Paleo-Alpine – Pre-Paleogene nappe structure. The Klippen Belt marks the boundary between them. The structure of the Western Carpathians is characterised by zoning. The Mesozoic and Tertiary formations, arrayed in a series of arcuate belts, have been tectonically transformed form qualitatively and temporally different sedimentary basins into the fold-nappe ranges, which may either be composed of sedimentary filling alone, or may include the original basement (Biely Ed., 1996).

The geological setting is favourable for the occurrence of geothermal waters with temperature higher than 20 °C only to the south of the Klippen Belt. Geothermal waters are largely associated with Triassic dolomites and limestones of the Krížna and Choč nappes (Fatricum and Hronicum), less frequently with Neogene sands, sandstones, conglomerates, andesites and related pyroclastics.

Based on results of research and investigation in 70-ties and 80-ties, which were carried out by Dionýz Štúr Institute of Geology and with respect to results of oil wells and geophysical measurements, 26 potential geothermal areas and structures were defined in the territory of Slovakia (Fig. 1).

Geothermal resources for direct use can be classified according to their temperature into three following types:

- **Low temperature** with water temperature in the range of 20 – 100 °C. They occur in Komárno high block, Danube Basin central depression, Bánovce Basin, Topoľčany embayment, Trnava embayment, Piešťany embayment, Central Slovakian Neogene volcanics (NW part), Central Slovakian Neogene volcanics (SE part), Upper Nitra Basin, Turiec Basin, Žilina Basin, Skorušina Basin, Liptov Basin, Levoča Basin (W and S parts), Horné Strháre – Trenč Graben, Rimava Basin, Trenčín Basin, Ilava Basin, Levice marginal block, Komárno marginal block, Vienna Basin, Komjatice depression, Levoča Basin (N part), Humenné ridge, Košice Basin, Beša-Čičarovce structure, Dubník depression. All determined areas have favourable conditions for low temperature geothermal waters occurrence in depths of 150 – 3500 m.
- **Medium temperature** with water temperature in the range of 100 – 150 °C. They occur in Beša Čičarovce structure, Košice Basin, Danube Basin central depression, Humenné ridge, Levoča Basin (N part), Žilina Basin, Trnava embayment, Piešťany embayment, Central Slovakian Neogene volcanics (NW part), Vienna Basin. Favourable conditions for medium temperature geothermal waters occurrence are in the depth of 2500 – 4500 m.
- **High temperature** with water temperature higher than 150 °C. They occur in Beša Čičarovce structure, Central Slovakian Neogene volcanics (NW part) and in Vienna Basin at the depth of 3500 – 5500 m.

Research, prospecting and exploration of geothermal waters has so far been carried out in 13 prospective areas (Fig. 1). In the other 13 prospective areas, geothermal waters have not been verified by wells, but 6 of them have been geologically assessed for the purpose of prospecting and exploration for geothermal waters.

Geothermic conditions

Geothermic conditions in the territory of Slovak Republic are very variable. Their regional character and spatial distribution of geothermic activity are controlled mainly by:

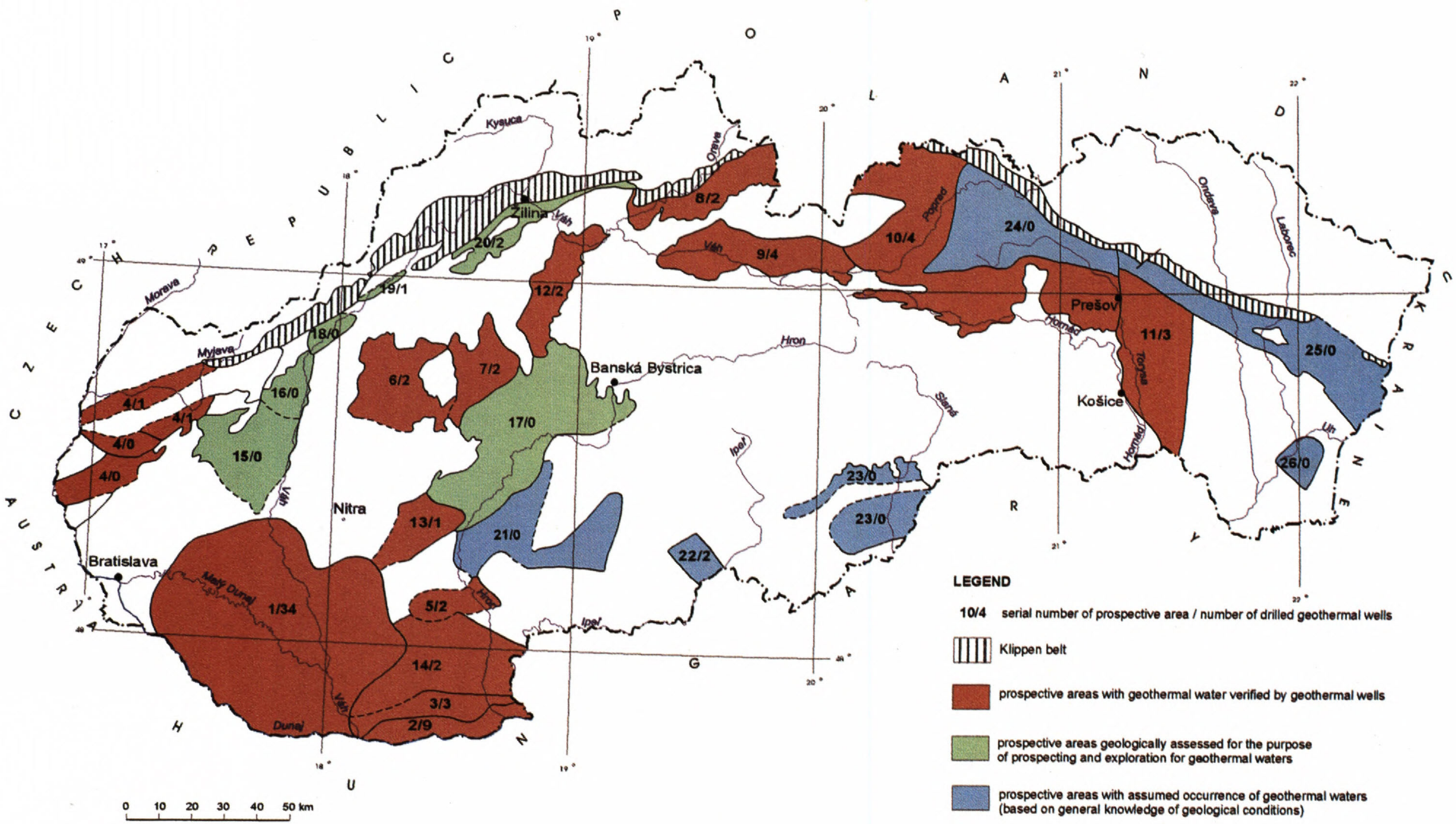

Fig. 1 Distribution of potential geothermal areas and structures in the territory of Slovak Republic
1-Danube Basin central depression, 2-Komárno high block, 3-Komárno marginal block, 4-Vienna Basin, 5-Levice marginal block, 6-Bánovce Basin and Topoľčany embayment, 7-Upper Nitra Basin, 8-Skorušina Basin, 9-Liptov Basin, 10-Levoča Basin (W and S parts), 11-Košice Basin, 12-Turiec Basin, 13-Komjatice depression, 14-Dubník depression, 15-Trnava embayment, 16-Piešťany embayment, 17-Central Slovakian Neogene volcanics (NW part), 18-Trenčín Basin, 19-Ilava Basin, 20-Žilina Basin, 21-Central Slovakian Neogene volcanics (SE part), 22-Horné Strháre – Trenč Graben, 23-Rimava Basin, 24-Levoča Basin (N part), 25-Humenné ridge, 26-Beša – Čičarovce structure

different deep structure of neotectonic blocks, mainly different thickness of the earth's crust and irregular introduction of heat from the mantle,

- course of principal discontinuities and fault lines seated deep in the earth's crust,
- spatial distribution of Neogene volcanism,
- distribution of radioactive sources in the upper sections of the earth's crust,
- hydrogeological conditions.

From the geothermic point of view, the Western Carpathians may be divided into two parts, which differ considerably in their geothermic activities and spatial distribution of earth heat. Relatively low temperatures and slide surface heat flow are characteristic of the central and northern sections of the Inner Carpathians and the western section of the Outer Carpathians. In contrast, high subsurface temperatures and high heat flow are typical of the Inner Western Carpathian Neogene basins and volcanic mountains. These two geothermically different regions are separated from one another by a zone of intensive horizontal thermal gradients, chiefly at the contact between the volcanosedimentary complex and pre-Neogene units of the Western Carpathians. Transient geothermic activity occurs in the Inner Carpathian Paleogene and eastern section of the Outer Carpathians.

Temperature conditions in Slovakia are known fairly well as available information includes results of measurements in 376 deep wells representing all essential Western Carpathian units. Vertical distribution of temperatures (Tab. 1) suggests substantial differences in temperatures in individual units, which even increase with increasing depth. Maximum differences at a depth of 1000 m are about 50 °C, but at 6000 they reach as much as 130 to 140 °C, which in such a small area can only be explained by intensive deep-seated tectonics. Regionally, the geothermic activity in the Western Carpathians decreases from the inner units towards the outer rim of the Carpathian arc.

Aside from this basic regional trend, temperature field at depths up to 3000 m is controlled by hydrogeological, geomorphologic and structural-geologic conditions. The disturbances in temperature field have various intensity and depth range. The biggest low- temperature anomalies were noted in hydrogeological structures whose thermal field is affected by infiltration of cold surface water. Hydrogeological setting is a principal phenomenon controlling the formation of thermal field in intramontane basins.

The Outer Western Carpathians mostly have a monotonous temperature field. The only major high-temperature anomaly of regional importance was noted in the eastern tract of them.

Temperature conditions in the Inner Western Carpathians vary considerably from one structural-tectonic unit to another. Low temperatures are characteristic of core mountains in central and northern Inner Carpathians and Slovenské Rudohorie Mts. A single high-temperature anomaly occurs only in the Rochovce area in the southern tract of the Slovenské Rudohorie Mts. Extremely radioactive granites cause the substantially increased geothermal activity in this area.

Tab. 1 Distribution of temperatures at different depths in essential Western Carpathian units (Franko, Remšík, Fendek Eds., 1995)

Area	Temperature (°C) in the depth of 1000 m			Temperature (°C) in the depth of 3000 m			Temperature (°C) in the depth of 6000 m		
	min.	max.	med.	min.	max.	med.	min.	max.	med.
Western Carpathians (whole)	20	74	45	69	162	107	148	282	194
Eastern Slovakian Basin	41	72	57	103	162	139	189	282	245
Outer Western Carpathians	33	51	44	82	118	101	162	193	179
Central Slovakian neovolcanics	32	72	45	86	127	105	166	210	187
Danube Basin	20	74	50	86	133	119	183	248	215
Vienna Basin	32	65	47	88	127	107	148	202	169
Slovenské Rudohorie Mts.	25	56	31	69	89	77	153	165	159
Southern Slovakian Basin	32	52	38	88	120	96	163	195	175
Intramontane basins	23	62	38	71	98	86	154	175	165

The Neogene volcanic mountains and southern tract of the Inner Western Carpathians are characterised by increased, but fairly variable geothermic activity and complex spatial distribution of temperature field. Anomalies of both local and regional importance occur and correspond to the boundaries of maximum dispersion of geothermic data.

The Western Carpathian intramontane basins are characterised by considerable dispersion of their temperature fields. Great differences of thermal activity were noted not only between individual basins, but also within a single basin between wells situated close to one another. Increased geothermal activity was noted in the Upper Nitra Basin, southern Turiec Basin and western Liptov Basin. Increased temperatures are also characteristic of the Skorušiná Basin and Central Carpathian Paleogene in the Levoča Basin. Low temperatures are typical of the Žilina and Bánovce Basins, Komárno high block and eastern tract of the Liptov Basin.

The highest geothermic activity occurs in Neogene volcanic mountains and Neogene basins. The Central Slovakian Neogene volcanics are characterised by increased geothermic activity and very variable temperature field chiefly at shallow depths, which results from their morphology. The highest temperatures were observed in the southern section of the Štiavnické vrchy Mts., Krupina Plateau and Žiar Basin. Increased temperatures are typical of the Zvolen Basin as well. In contrast, low temperatures are characteristic of the central Štiavnické vrchy Mts., Vtáčnik Mts., northeastern Kremnické vrchy Mts. and Poľana Mts. Considerable horizontal temperature gradients of regional importance occur on the northern and eastern edge of the Central Slovakian Neogene volcanics and at the contact with the Upper Nitra and Turiec Basins.

The Eastern Slovakian Basin is the most geothermal active unit in the Western Carpathians. Temperature conditions are analogous to those in the hyperthermal Panonian Basin. The highest temperatures occur in its central and southeastern tracts. Increased temperatures well correspond to the occurrences of buried igneous bodies. Lower temperatures noted in the southwestern tract of the basin in the Zemplín island area are related to an elevation pre-Neogene substratum. Decreased temperatures were noted throughout the northern and northeastern section of the basin and also at the contact with the Klippen Belt. The high geothermic activity in the Eastern Slovakian Neogene Basin is directly related to the geodynamic history and deep structure including an elevation in Mohorovičič discontinuity and an intrusion of mantle material into the earth's crust.

Heat flow density has so far been calculated in 136 wells. Results of statistical data processing for individual areas are given in Tab. 2.

Tab. 2 Distribution of heat flow density in essential Western Carpathian units (Franko, Remšík, Fendek Eds., 1995)

Area	Heat flow density q (mW/m^2)		
	q_{min}	q_{max}	q_{med}
Western Carpathians (whole)	40.6	121.6	82.1
Outer Carpathians	56.8	72.5	64.7
Slovenské Rudohorie Mts.	50.7	68.3	62.0
Core mountains	52.7	80.0	69.9
Intramontane basins	52.0	79.4	65.9
Central Slovakian Neovolcanics	74.0	109.0	94.3
Southern Slovakian Basin (eastern part)	59.9	63.4	62.2
Vienna Basin	40.6	69.0	44.0
Danube Basin	61.2	99.0	78.5
Trnava embayment	61.0	67.9	65.2
Topoľčany embayment	-	-	67.8
Eastern Slovakian Basin	82.1	121.6	110.9
Košice Basin	87.6	109.9	94.9
Eastern Slovakian Neovolcanics	-	-	73.3

The mean value calculated as an arithmetic mean of all data is 82.1 - 20.5 mW/m^2. Heat flow density in the Western Carpathians is highly variable and regionally falls from the Inner Carpathians towards the outer arc. The highest values between 82.1 and 124.6 mW/m^2 averaging 110.9 mW/m^2 have been calculated for Eastern Slovakian Basin. Heat flow density pattern corresponds to its deep structure and spatial distribution of centres of deposition characterizing its geodynamic history. This basin is regarded as a tectonically reworked basin of thermal origin formed by litospheric extension. Its geothermal activity was further increased by huge volcanism. High heat flow densities in this area occur in a place, where the earth's crust was thinned at the expense of thermally predisposed lithosphere and where more heat ascends from the upper mantle.

High values were noted in the Central Slovakian Neogene volcanics. These anomalous values are associated with Neogene volcanism whose response has probably persisted till the present day. We may realistically assume that the majority of the geothermal activity here is directly linked to thermal magmatic sources of crustal origin, the introduction of heat from the mantle being of minor importance.

Surprisingly low values were calculated for Vienna Basin. This phenomenon reflects the fact that the origin and history of the Vienna Basin differs from those of the other Western Carpathian Neogene Basins. The basin was formed at the edge of a vast sedimentary area, is of tectonic origin and, unlike the Eastern Slovakian and Danube Basins, its evolution did not include geodynamic extension with thermal manifestations in the upper mantle. On the contrary, compression at the margins of the Pannonian block resulted in lower density of surface heat flow. In remaining areas the geothermal activity copies the geothermic activity.

Hydrogeothermal characteritic of investigated areas

Hydrogeothermal characteristic of investigated areas is based on hydrogeothermal data from 76 geothermal wells and on the data from hydrogeological and geological wells as well. Each of above mentioned 13 investigated areas was assessed from the point of view of its geological and geothermal settings, hydraulic parameters and pressure conditions of aquifers, hydrogeochemical composition of geothermal waters and their thermal-energy potential.

Danube Basin central depression

The central depression of the Danube basin is enclosed by the Danube river in the southwest between the cities of Bratislava and Komárno, by the Malé Karpaty Mts. in the northwest, by the fault of Dobrá Voda (branch of Ludina) in the northeast, and approximately by the Nitra river in the southeast. A crystalline complex has been found out in the pre-Tertiary base of its northwestern and southeastern part (schists, granitoids). It can be assumed according to the geological development of the Danube Basin that the Carpathian crystalline forms the whole pre-Tertiary base of the central depression. Therefore, there are no suitable aquifers of geothermal water in the pre-Tertiary base (Franko, Remšík, Fendek Eds., 1995). The depression is filled up with the sediments of Quaternary and Ruman (gravels, sands), Dak, Pont and Panon (variation of clays or sandy clays and sands to sandstones). The depression developed between the Panon and Pliocene stages and is of a brachysynclinal shape, with the depth centre in the area of Gabčíkovo.

The upper limit of geothermal water reservoir is 1000 m below surface. At the bottom it is confined by a fairly impervious substratum – an aquitard (clays), which falls from all sides into the centre of the basin to a depth of 3400 m. The main aquifer of geothermal water is formed by sands and sandstones of Panon and Pont. In the central part of the depression, also sands to sandstones of Dak form aquifers. Clays act as an aquiclude (Remšík et al., 1990).

The maximum length of the reservoir in the depth of 1000 m is 60 km in the NE - SW direction and almost 75 km in the NW - SE direction. The maximum thickness of the reservoir in its centre is approximately 2400 m its volume is 4031 km^3, of which aquifers represent approximately 1371 km^3 (34%). The proportion of the aquifers decreases with the distance from the centre of the depression - from 40-50% to 20-30%. This corresponds with the decline of aquifers with increasing depth and/or thickness of the reservoir.

Lithologically, six hydrogeological units are distinguished in the reservoir and its overburden (Fendek et al., 1988). They represent separate complexes with various proportions of aquifers and aquicludes. Those hydrogeological complexes do not respect the stratigraphy of Neogene stages, because the layers of aquifers and aquicludes alternate irregularly in the vertical direction and nose out irregularly in the horizontal direction, which reflects the complexity of Neogene sedimentation in the depression. The thickness of particular complexes varies between 5 and 1174 m.

Geothermal activity of the Central depression is increased. The thermal gradient for the depth of 0–2500 m ranges form 34.1 to 43.7 °C/km. The heat flow density varies in the interval 60–90 mW/m^2. The highest heat flow densities have been recorded in the middle of the depression.

So far 34 geothermal wells 500 – 2800 m deep have been drilled in the depression. Their discharge (free outflow) is 0.3–25 l/s and water temperature range from 24 to 92°C. Chemical composition of geothermal waters is controlled by lithostratigraphy and depth. The waters are either marinogenic (connate waters, infiltration-degraded marinogenic waters and brines) of petrogenic. They belong to five chemical types (Franko, Remšík, Fendek Eds., 1995):

- clear Na-Cl type with T.D.S. (mineralization) over 10 g/l with the maximum value of 126.4 g/l, belonging to Badenian and Pannonian aquifers,
- clear Na-Cl type with T.D.S. of 5–10 g/l, belonging to Badenian and Panonian aquifers,
- Na-Cl type with T.D.S. of 2.7–8.8 g/l, belonging to Pontian aquifers,
- Na-HCO_3 type with T.D.S. of 1–5 g/l, characteristic for Pontian, Dacian and well „washed“ Pannonian aquifers,
- Na-HCO_3 type with T.D.S. lower than 1 g/l, characteristic of Pontian and Dacian aquifers.

Tab. 3 Chemical types of geothermal waters in the central depression of Danube Basin

No.	T.D.S. (g/l)	HCO_3/Cl ratio	Chemical type	Depth (m)	Stratigraphy
1	11.6 – 126.4	0.002 – 0.29	clear Na-Cl	1124 – 3048	Pannonian – Badenian
2	5.1 – 9.9	0.22 – 0.34	clear Na-Cl	1473 – 2460	Pontian – Pannonian
3	2.7 – 8.8	0.50 – 2.30	Na-Cl or Na-HCO_3	910 – 2474	Pontian – Pannonian
4	1.0 – 5.0	2.50 – 61.00	Na-HCO_3	904 – 2503	Dacian – Pontian
5	0.4 – 0.9	12.60 – 40.40	Na-HCO_3	276 – 800	Dacian – Pontian

In respect of chemical composition of gases, they are methane waters, nitrogenous, methano-nitrogenous waters or waters where methane is dominant. The highest methane content is characteristic of Na-Cl type of waters and ranges up to 84 vol. %. Among acid gases, CO_2 is dominant in geothermal waters. In well log profiles, it is associated with higher situated horizons or structures entirely recharged with CO_2. The gas-water phase relations revealed a surficial separation range from 0.01 – 4.98 m^3/m^3. In the dissolved gas phase in water, CO_2 is dominant, in free gas CH_4 prevails.

The aquifers were tested by short-term (3 weeks of which one week is for the recovery test), long-term (2 – 3 months) hydrodynamical controlling measurements. In the vertical sense, the beds were tested separately gradually by single segments (open by jet perforation) from the bottom to the top. The aquifers were thus tested in the depth interval 2503 – 904 m. The thickness of single tested segments in the depth interval mentioned was 87 – 592 m. The thickness of productive aquifers ranges from 34 to 192 m. After that the joined segments of the thickness of 195 – 1093 m were tested and hydraulic parameters were calculated. The transmissivity coefficient ranges from $3.6*10^{-3}$ to $4.9*10^{-6}$ m^2/s and the hydraulic conductivity ranges from $3.8*10^{-5}$ to $6.1*10^{-8}$ m/s (Fendek, 1992).

With regard to low values of piezometric gradient and average permeability of aquifers, the effective flow velocity of geothermal water averages about 0.3 to 1.8 m per year, which predicates a considerable stagnation of geothermal water under the natural conditions, as documented by drilled geothermal boreholes (Fendek, 1993).

The total yield of the boreholes is about 400 l/s, which corresponds to the thermal energy of 88.05 MW_t. The total thermal-energy potential of geothermal water of the central depression of the Danube Basin, estimated by a two-dimensional numerical model, is 150 MW_t (Fendek, 1992).

Komárno block

The Komárno block extends with the area of 513 km^2 between Komárno and Štúrovo. Its pre-Tertiary substratum consists largely of Triassic dolomites and limestones up to 1000 m in thickness, which is overburden by Paleogene, Neogene and Quaternary sediments. The block is considerably faulted and its pre-Tertiary morphology is complicated. From the hydrogeothermal point of view, the area is divided into a high and marginal block (Remšík et al., 1992). Their geothermal waters are bound to Triassic (less frequently Jurassic) dolomites and limestones.

Heat flow densities suggest that the high block has a fairly low and the marginal block medium activity. The thermal gradient for the depth of 0 – 1000 m in the high block has an average value of 14.3 °C/km and in the marginal block ranges from 32.2 to 35.8 °C/km. The average heat flow density in the high block is about 60 mW/m^2.

So far 12 geothermal wells 210-1970 m deep have been drilled in the Komárno block. Their discharge (free outflow) is 0.5 – 75 l/s and water temperature range from 20.1 to 68°C.

The Komárno block contains five chemical types of geothermal waters:

- clear Ca-Mg-HCO_3 type with T.D.S. about 0.7 g/l, locally with H_2S,
- unclear Ca-Mg-HCO_3 type with increased Ca-SO_4 content and T.D.S. about 0.7 g/l,
- transient Na-Ca-HCO_3-Cl type with T.D.S. about 0.8 g/l,
- mixed type dominated by Ca-SO_4 component with increased Na-Cl content and T.D.S. 2.2 – 3.8 g/l,
- clear Na-Cl type with T.D.S. about 90 g/l (brine).

All five types are genetically associated with Triassic dolomites and limestones of the Central Hungarian Mts., the first two of them being present in the Komárno high block and the last three types in the Komárno marginal block.

The regime of geothermal waters in the high block is directly controlled by variation in the water level of the Danube River (Remšík et al., 1992).

The transmissivity coefficient in Komárno block ranges from $1.25*10^{-1}$ to $5.07*10^{-5}$ m^2/s and the hydraulic conductivity ranges from $1.65 \cdot 10^{-4}$ to $4.41 \cdot 10^{-7}$ m/s. The highest values occur in open faults, the lowest in minor fissures.

The total amount of thermal-energy potential of geothermal waters in Komárno block represents 237.25 MW_t. This amount consists of 9.75 MW_t calculated as a natural dynamic flow through the high block and of 227.5 MW_t calculated through a volumetric method for the marginal block.

Levice block

Levice block with the higher Mesozoic nappes is confined in the east by a north-south fault running west of Levice. The Mesozoic nappes dips gently from the Santovka-Túrovce ridge and from Levice towards Pozba, from a depth of about 700 m to 1300 – 1500 m. The Mesozoic is overlaying by Neogene sediments. Geothermal water occurs mainly in Triassic dolomites, less frequently in quarzites and Badenian basal clastics.

Heat flow densities suggest that the block has an increased geothermal activity. The thermal gradient for Neogene sediments is 58.3 °C/km and for Mesozoic rocks of 28.8 °C/km. Heat flow density for Neogene sediments is of 92.1 mW/m^2 and for Mesozoic rocks of 94.2 mW/m^2.

Two wells were drilled in the structure – one exploitation Po-1 and one reinjection well GRP-1 Podhájska, creating first geothermal doublet being drilled in Slovak Republic. They are 1900 and 1470 m deep, with the discharge (free outflow) of 53.0 and 28.0 l/s and with the water temperature of 82 and 69.5 °C.

The Levice block contains only geothermal waters of clear Na-Cl type with T.D.S in the range of 12 – 20.0 g/l. They are marinogenic, original seawaters, which seeped into the bottom of the basin of deposition during the Badenian.

The transmissivity coefficient in Levice block ranges from $2.47*10^{-3}$ to $3.02*10^{-4}$ m^2/s and the hydraulic conductivity ranges from $1.17*10^{-5}$ to $2.51*10^{-6}$ m/s. The storage coefficient ranges from $1.5*10^{-4}$ – $1.1*10^{-5}$. The value of skin effect for exploitation well Po-1 is –8.903 and for reinjection well GRP-1 is 1.571.

The total thermal-energy potential of geothermal water of the Levice block, estimated by a two-dimensional numerical model, is 126 MW_t (Fendek, 1998).

Vienna Basin

Geothermal waters in Slovak tract of Vienna Basin occur in four structures – the Lakšárska Nová Ves elevation, Šaštín elevation with adjacent soutwestern and north-eastern sunken belts, Závod-Studienka sunken belt and Láb-Malacky elevation with adjacent sunken blocks (Remšík et al., 1990).

The water bearing rocks belong to Triassic dolomites and limestones of Choč and higher nappe structures as well as in Eggenburgian clastics and Karpatian sandstones and sands. The geothermal waters structures occur at the depths of 500 – 4500 m and contain waters 40–140 °C hot.

The geothermal activity of the basin is fairly low. The average value of the thermal gradient for the depth of 0 – 1000 m in Vienna Basin is 34 °C/km. Geothermal field is rather inhomogeneous with one low and one high trending roughly from north-west to south-east direction. The low of less than 45.0 mW/m^2 is associated with a southwestern sunken zone, whereas the high exceeding 65.0 mW/m^2 occurs in the Lakšárska Nová Ves elevation.

The water is of Na-Cl type with T.D.S. of 5–130 g/l. Geothermal waters of Vienna Basin are marinogenic. Although metamorphosed by the contact with surrounding rocks, the waters were either preserved, or thickened, or degraded. The evaporation of seawater in the Láb-Malacky elevation gave rise to geothermal brines with T.D.S of 90–130 g/l. They are separated from waters in higher parts of the structure by an impervious shale formation. The other structures in the Vienna Basin contain degraded seawaters. Hydrogen sulphide (H_2S) whose contents range from 100.1 to 234.0 mg/l is major component of geothermal waters in both Lakšárska Nová Ves and Šaštín elevations. It originated from biochemical reduction of sulphates contained in geothermal waters.

The total amount of thermal-energy potential of geothermal waters in Vienna basin was estimated to 511 MW_t.

Topoľčany embayment and Bánovce Basin

The Topoľčany embayment situated between the Považský Inovec and Tríbeč Mts. is an extension of the Danube Basin Central depression. The middle of the embayment is occupied by the conspicuous elongated Rišňovce depression approximately 3800 m deep. The Topoľčany embayment passes into the Bánovce and Upper Nitra Basin to the north. It is separated from them by a ridge between Prašice and Veľké Bielice, which falls to a depth of 800 – 1000 m. It is separated by faults from the Považský Inovec and Tríbeč Mts., its western slopes being very steep and eastern one very gentle. The Bánovce Basin is separated from the adjacent mountains by faults. The pre-Tertiary substratum below the embayment consists of granitoides, Mesozoic rocks of the Tatric envelope unit, as well as of Krížna and Choč nappes. The basin is filled by Neogene sediments (conglomerates, siltstones, claystones, andesites, clays, sands, acid tuffites, gravels) underlain by Paleogene formations. The Paleogene consists of a basal lithofacies (conglomerates, breccias) and overlying flyschoid facies.

Geothermal activity of the area concerned was indicated by natural thermal springs at Malé and Veľké Bielice villages. Both heat flow and temperatures fall from the south to the north and from the centre of the area towards its edges. The value of the heat flow density ranges from 65 mW/m^2 to 70 mW/m^2.

Two geothermal wells were drilled in the area. First one in Topoľčany has a depth of 2106 m, pumping rate of 2.0 l/s and the water temperature of 55 °C. The second one in Bánovce nad Bebravou has a depth of 2025 m, the pumping rate of 13.0 l/s and water temperature of 46 °C.

Two types of geothermal waters have been documented in Topoľčany embayment and Bánovce Basin. Waters of a $Ca(Mg)-HCO_3$ type are typical for carbonates of Choč nappe, their T.D.S. vary in the range of 0.6–0.8 g/l, whereas the Krížna nappe and Tatric envelope unit bear $Na-HCO_3$ and $Na-HCO_3-SO_4$ types of geothermal water with T.D.S. of 4.5–5.9 g/l.

The transmissivity coefficient in the area ranges from $6.7*10^{-4}$ to $6.7*10^{-6}$ m^2/s and the hydraulic conductivity ranges from $1.91*10^{-5}$ to $3.21*10^{-7}$ m/s.

The total amount of thermal-energy potential of geothermal waters is 17.3 MW_t.

Upper Nitra Basin

The Topoľčany embayment passes into the Upper Nitra Basin trough narrow gorge near Partizánske. The basin extends between the Žiar and Malá Magura Mts. in the north and between the Malá Magura and Suchý Mts. in the west. All these mountain ranges are separated from the basin by faults.

The pre-Tertiary substratum is created by rocks of Ipoltica Group, predominantly Choč nappe carbonates in the central part, and Krížna nappe with envelope Mesozoic in the northern tract of the Prievidza depression. The basal Paleogene (breccias, conglomerates) and flyschoid facies overlies the Mesozoic substratum. The earliest Neogene – Eggenburgian – is composed of conglomerates and sandy clays, overlain by calcareous, sandy clays interbedded with sandstones. The next sedimentation started in Badenian and was accompanied by volcanism. Thin coal beds overlie andesite tuffs near Jánova Lehora. Younger filling of the basin consists of sedimentary and volcanic rocks (andesite conglomerates, sandstones, siltstones, coal beds, clays, tuffites). The youngest component of the Neogene basinal filling is the Lelovce formation (fluvial gravels, sands, sandy clays and fresh water limestones).

Data from two geothermal wells indicate that geothermal activity of the area is considerably high. In the regional field the heat flow density values vary around 70 mW/m^2, temperature at the depth of 1000 m ranges from 35–45 °C. Surface geothermal manifestations were known in Chalmová and Bojnice Spas. The temperature of natural geothermal springs ranges from 39 °C to 45 °C.

Two geothermal wells were drilled in the basin, one of them (Š1-NB II) to the depth of 1851 m, with the free outflow of 26 l/s and temperature of 66 °C.

Geothermal waters from Choč nappe carbonates are of $Ca(Mg)-HCO_3$ type with T.D.S. below 1 g/l, and those from the Krížna nappe fall into the $Ca(Mg)-SO_4$ type with T.D.S. of 1.3 g/l.

The transmissivity coefficient estimated from the hydrodynamic tests performed on the well Š1-NB II is $4.52*10^{-3}$ m^2/s and the hydraulic conductivity has the value of $2.60*10^{-5}$ m/s. The storage coefficient has the value of $2.6*10^{-4}$ (Fendek et al., 1997).

The total amount of thermal-energy potential of geothermal waters in Upper Nitra basin is 19.6 MW_t.

Skorušina Basin

Skorušina Basin is situated between the Chočské pohorie Mts. and Klippen Belt. The basin is elongated in southwest – north direction. It is filled by Inner Carpathin Paleogene (basal conglomerates, flyschoid formation), which is underlain by Krížna nappe with outliers of Choč nappe dolomites.

Geothermal activity in the basin was indicated by the natural thermal springs 13.0–18.5 °C hot at Oravice village. Heat flow density values vary from 55 to 65 mW/m^2. Temperature at the depth of 1000 m increases from 32.5 °C in the southwest to 37.5 °C in the northeast.

Two wells were drilled in the basin: OZ-1 to the depth of 600 m and OZ-2 to the depth of 1601 m. The discharge of them was 35 l/s and 120 l/s geothermal water with the temperature of 28.5 and 54 °C.

Geothermal waters from Krížna nappe carbonates are of Ca(Mg)-SO_4 type with T.D.S. of 1.2 – 1.5 g/l.

The transmissivity coefficient estimated from the hydrodynamic tests performed on the well OZ-1 and OZ-2 is about $3.1*10^{-3}$ m^2/s and the hydraulic conductivity has the value of $3.50*10^{-5}$ m/s. The storage coefficient has the value of $2.6*10^{-4}$.

The total amount of thermal-energy potential of geothermal waters in Skorušina Basin has the value of 19.6 MW_t.

Liptov Basin

The basin extends between the massive megaanticlines of the Tatry and Nízke Tatry Mts. In the northwest it is confined by Chočské vrchy Mts. and in the east the inconspicuous Štrba Ridge fringes the basin. The basin is elongated in the east – west direction and extends with the area of 611 km^2 between Ružomberok and Štrba. The substratum of the Paleogene forms three depressions – Ivachnová, Liptovská Mara and Liptovská Kokava depressions, with the thickness of Paleogene sediments in the range of 1000 – 1625 m. Paleogene sediments consist of basal conglomerates and flyschoid formations. The Paleogene filling of the Liptov Basin is underlain by the Krížna and Choč nappes.

Geothermal activity in the Liptov Basin is intermediate. At the depth of 1000 m the temperature varies from 45 °C in Bešeňová horst to 30 °C on the periphery. Heat flow density in the regional geothermal field decreases from at least 70 mW/m^2 in the Bešeňová horst to 60 mW/m^2 in the west and less than 50 mW/m^2 in the Liptovská Kokava depression in the east. Geothermal waters flowing up from a depth of more than 1500 m to the surface heat Bešeňová horst. In contrast, the margins of the Liptov Basin are cooled by adjacent mountains and in the Liptovská Kokava area also by cold karst waters.

Evidence of geothermal activity in the area concerned comprises also natural thermal springs at Bešeňová, Liptovská Štiavnica, Liptovské Sliače, Liptovský Ján and Lúčky villages with temperatures in the range from 20 to 32 °C.

Four geothermal wells were drilled in Liptov Basin with the depth of 1987 – 2500 m, three of them had the discharge of 20 – 27 l/s, the last one had a pumping rate of 6 l/s. The temperature of geothermal waters varies from 32 to 62 °C (Remšík et al., 1994).

Geothermal waters occurring in the Choč nappe Triassic carbonates are largely of Ca(Mg)-HCO_3 type, sometime the SO_4 component is present as well. The amount of T.D.S. is 0.35 – 5.0 g/l. Geothermal waters stored in carbonatic rocks of Krížna nappe are of Ca(Mg)-HCO_3-SO_4 or Ca(Mg)- SO_4-HCO_3 type with T.D.S. of 3.0 – 5.0 g/l. Genetically, the waters are atmospherogenic with petrogenic mineralization. Aside from their chemistry, this origin is suggested also by stable isotopes contents.

The transmissivity coefficient in the area ranges from $2.3*10^{-3}$ to $3.1*10^{-5}$ m^2/s and the hydraulic conductivity ranges from $1.98*10^{-5}$ to $4.90*10^{-7}$ m/s.

The total amount of thermal-energy potential of geothermal waters in Liptov Basin was evaluated by geothermic balance method and by numerical modelling. Both methods gave approximately the same value of about 34.3 MW_t.

Levoča Basin

The Levoča Basin is separated by faults from the Klippen belt in the north and north-east, and borders the Tatry in the north-west as well as eastern tracts of the Nízke tatry, Slovenské Rudohorie and Čierna Hora Mts. in the south. The basin is filled with the Inner Carpathian Paleogene composed of a several-tens-of-meters-thick basal conglomerate formation and an overlying flyschoid formation up to 4000 m in thickness (Franko, Remšík, Fendek Eds., 1995). The geologic structure of the pre-Tertiary substratum of the Levoča Basin includes all tectonic units of the Inner Western Carpathians. Geothermal waters in this structure are bound to Choč and Krížna nappe carbonates. Their existence beneath the Paleogene was confirmed by drilling at Gánovce, Vrbov, Klčov, Plavnica, Polom, Lipany, Podskalka and Prešov.

Geothermal activity of the area is medium and the heat flow density ranges from 61.8 to 77.0 mW/m^2. Activity of geothermal field increases from the margins of adjacent mountains towards sunken sectors of the basin. Temperature field at the depth of 1000 m has a similar pattern with temperatures ranging from 30 to 45 °C (Fendek et al., 1992). Evidence of geothermal activity in the area concerned comprises also natural thermal springs at Gánovce, Baldovce, Lipovce and Vyšné Ružbachy villages with temperatures up to 23.6 °C.

Geothermal waters of Choč nappe are of Ca(Mg)-HCO_3 type with T.D.S. 2.85 – 3.29 g/l. Waters bound to Krížna nappe carbonates discharged by natural springs are of the same type with the T.D.S. of 1.85 g/l, and those from deep wells are Na-HCO_3 changing trough diverse transient and mixed types to Na-Cl type with T.D.S. of 8.67 – 11.95 g/l. Genetically, the waters are atmospherogenic with petrogenic mineralization. Aside from their chemistry, this origin is suggested also by stable isotope contents.

The transmissivity coefficient in the area ranges from $6.54*10^{-3}$ to $1.17*10^{-4}$ m^2/s and the hydraulic conductivity ranges from $7.60*10^{-5}$ to $1.59*10^{-6}$ m/s.

The total amount of thermal-energy potential of geothermal waters in Levoča Basin is 1391.4 MW_t.

Košice Basin

Košice Basin extends between the Slanské vrchy Mts. and Slovenské Rudohorie Mts. over the area of about 870 km^2. Basic information about the geologic structure, geothermal field and geothermal waters resulted from exploratory, structural geological and oil wells. Košice Basin is filled with Paleogene and Neogene sediments.

The pre-Tertiary substratum of the southern part consists of the Veporic crystalline unit and its Perm-Mesozoic envelope. The northern section is composed of the tatric crystalline and its envelope. Geothermal waters are bound to Triassic dolomites and limestones. The dolomites are from 300 m to more than 1000 m thick.

Geothermal activity of the area is considerably increased. Heat flow density increase from 75 mW/m^2 on the western edge of the basin to the maximum of 110 mW/m^2 in the southeast. Temperature field at the depth of 1000 m has a similar pattern and grows in the same direction from 45°C to 65 °C. Evidence of geothermal activity in the area includes a natural thermal spring in Košice-Ťahanovce. It was tapped by a shallow well with the discharge 4.9 l/s of geothermal water 26 °C hot.

Until now, three geothermal wells were drilled in Košice Basin. They are situated close to village Ďurkov and the results of their evaluation were not published yet.

Two different chemical types of water were identified in deep oil wells in the area. On of them is $Na\text{-}HCO_3$ type with T.D.S. of 10.9 g/l, another one is Na-Cl type with T.D.S. of 26.8 g/l – 33.4 g/l. The gases are dominated by CO_2 (Remšík, 1993).

The total amount of thermal-energy potential of geothermal waters in Košice Basin is 1276.4 MW_t.

Turiec Basin

Turiec Basin is a deep tectonic depression between the Veľká and Malá Fatra Mts. The boundaries between the basin and surrounding mountains are tectonic except on the northeastern margin. The morphology of the pre-Tertiary substratum is fairly simple – three partial depressions separated by low ridges. The biggest and largest of them is approximately 2400 m deep Martin depression in the northern sector of the basin. The Ivančiná depression in the middle of the basin is about 1000 m deep and the Horná Štubňa depression lies in the southern sector and is about 1380 m deep (Franko, Remšík, Fendek Eds., 1995). Tertiary sediments on the eastern edge of the basin are underlain by the Krížna and Choč nappes. The basin is filled by Neogene sediments (conglomerates, basal gravels, organic limestones, sands, sandy gravels, tuffites, volcanoclastics, clays and thin lignite beds).

Geothermal activity of the area is intermediate. In the regional field the heat flow density rises from 55 mW/m^2 in the north to 75 mW/m^2 in the south. Temperature field at the depth of 1000 m has a similar pattern as temperatures grow from 35 to 55 °C. Temperatures at the same time fall from the centre of the basin towards its margins. Geothermal activity in the basin is suggested by natural thermal springs at Turčianske Teplice with temperature of 45 °C and at Mošovce with temperature of 23 °C.

Two geothermal wells were drilled in Turiec Basin until now to the depth of 1458 and 2651 m. One of them is unproductive, the another one has a discharge of 12 l/s of geothermal water with the temperature of 52 °C.

Geothermal waters are bound to basal Neogene gravels, conglomerates and Triassic carbonates of the Choč and Krížna nappes.

Geothermal waters in basal Neogene clastics are of the same type ($Ca\text{-}Mg\text{-}HCO_3$) as waters in Choč nappe Triassic carbonates. The former, however, have higher T.D.S. (1.65 - 1.8 g/l) than the latter (0.98 – 1.36 g/l). Waters in Triassic carbonates of the Krížna nappe have a different chemistry. They are of $Ca(Mg)HCO_3\text{-}SO_4$ type with T.D.S. of 1.48 – 1.65 g/l.

The total amount of thermal-energy potential of geothermal waters in Turiec Basin is 22.5 MW_t.

Komjatice depression

Komjatice depression is situated between the Tríbeč and Pohronský Inovec Mts. The top of pre-Tertiary substratum composed of the Mesozoic envelope rises from the Danube basin central depression to the Klasovo area where it is 2460 m below surface.

Geothermal activity of the area is increased. Temperatures at a depth of 1000 m range from 55 to 60 °C and heat flow density from 80 to 85 mW/m^2. Geothermal waters are bounded to the Tatric envelope unit identified by oil wells (Remšík, 1989).

One geothermal well was drilled in the depression to the depth of 1830 m. Its discharge was 12 l/s of geothermal water with the temperature of 78 °C. Geothermal water is of Na-Cl type with T.D.S about 20g/l.

The total amount of thermal-energy potential of geothermal waters in the Komjatice depression is 392.64 MW_t.

Dubník depression

Dubník depression is located in the southeastern part of the Danube basin. Neogene sands, sandstones and conglomerates compose it. Geothermal waters are bound to Badenian basal clastics at the depth of 1000–2000 m. The clastics are underlain by Mesozoic carbonates.

Geothermal activity in Dubník depression is increased, close to very increased. Temperatures at a depth of 1000 m range from 45 to 70 °C and heat flow density from 75 to 92 mW/m^2. Temperatures and heat flow densities rise from the southwest to the northeast.

Two geothermal wells were drilled in the Dubník depression until now to the depth of 916–1927 m. Their pumping rates were 1.5–15.0 l/s of geothermal water with the temperature of 52–75 °C. Geothermal water is of Na-Cl type with T.D.S in the range of 10–30 g/l.

Conclusion

The geologic setting of Slovak Republic is favourable for the occurrence of geothermal energy resources. Twenty-six geothermal areas or structures have been identified as prospective areas for potential exploitable geothermal resources. They cover more than a quarter (27 %) of Slovak territory. Geothermal waters are largely bounded to Triassic dolomites and limestones of the Krížna and Choč nappes (Fatricum and Hronicum), less frequently to Neogene sands, sandstones, conglomerates, andesite and related pyroclastics.

Low temperature waters (less than 100 °C) exist in the 26 areas with 10 areas having temperatures in the range 100–150 °C and only three areas with temperature greater than 150 °C.

Research, prospecting and exploration of geothermal waters has so far been carried out in 13 prospective areas. In the other 13 prospective areas, geothermal waters have not been verified by wells, but 6 of them have been geologically assessed for the purpose of prospecting and exploration for geothermal waters.

Temperature at a depth of 1000 m vary from 20 to 74 °C with the average value of 45 °C. The average value of heat flow density is 82.1 mW/m^2 ± 20.5 mW/m^2, with the minimum value of 40.6 and maximum value of 121.6 mW/m^2.

The total amount of thermal-energy potential of geothermal waters in prospective areas (proven, prognostic and probable) represents 5538 MW$_t$.

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