STATE GEOLOGICAL INSTITUTE OF DIONÝZ ŠTÚR

EVALUATION OF THE ENERGY POTENTIAL OF GEOTHERMAL BOREHOLES AND RESERVOIR ENVIRONMENT AT THE PARTIZÁNSKE SITE FOR THE PURPOSE OF CENTRAL HEAT SUPPLY SYSTEMS

(GEOLOGICAL STUDY)

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1 DEFINITION OF THE TASK AND SCOPE OF THE WORK TO BE CARRIED OUT

The energy and reservoir engineering evaluation of the existing geothermal wells and reservoir environment at the Partizánske site results from the economic contract, where:

- commissioned by Friends of the Earth - CEPA in cooperation with the city of Partizánske
- contractor: the State Geological Institute of Dionýz Štúr (Bratislava)

based on personal and written communication, have arrived at the following definition of the work:

- evaluation of hydrogeological, hydraulic and thermal-energetic potentials of existing boreholes
- Evaluation and sensitivity analysis of the installed capacity of geothermal wells as a function of the yield and temperature at the outlet of the exchanger schemes
- balance assessment of the balanced heat flow in the area of Partizánske
- evaluation of possible thermal outputs in relation to the sustainable reservoir capacity of the Banská basin
- evaluation of thermal-energy parameters and reservoir geometry in the relevant surroundings of the site
- Determination of the steps necessary to carry out hydrodynamic tests at the site (workplan).

The present assessment is built to form a relevant basis for the preparation of the project geological task and project documentation in relation to the necessary formalities of the application for NFP from the Fund for fair transformation, the subject of which is to be the design and implementation of low-temperature central heating systems in the city of Partizánske using geothermal energy sources.

2 BRIEF OVERVIEW OF HYDROGEOTHERMAL EXPLORATION

The Partizánske locality is situated in the south-eastern part of the Bánovská basin geothermal water formation, which as a northern outcrop of the Danube Basin was subjected to systematic hydrocarbon prospecting in the first stage, mainly using deep structural drilling or geophysics, for example:

- gravimetric measurements
- radiometry and aeromagnetic measurements
- reflection and refraction seismics
- geoelectrical measurements
- thermometric measurements on structural geological boreholes (FRANKO - GAZDA, 1969; BRESTENSKÁ ET AL., 1975)

Exploration of the entire area for the purpose of verifying and capturing geothermal water or harnessing geothermal energy has been stagnant for a long time. The existence of mineral and thermo-mineral springs in the Banovská basin was documented at the localities of Malé and Veľké Bielice and Chalmová, respectively (TKÁČIK ET AL., 1969), which formed the basis for the first comprehensive study on the possibilities of using geothermal waters and their parameters in the area by assessing shallow hydrogeological boreholes and springs (FRANKO ET AL., 1983). In particular, boreholes **MB-3 Malé Bielice**, **MB-4 Malé Bielice** and **VB-3 Veľké Bielice** verified geothermal waters with temperatures $_{Twh}$ = 39 - 40 °C, and a total verified yield of currently Q = 18.8 $l.s^{-1}$ (MARCIN ET AL., 2020).

The first hydrogeothermal borehole constructed for the purpose of verification and capture of geothermal water was the borehole **BnB-1 Bánovce nad Bebravou** at the Biskupice site (ČERMÁK - BONDARENKOVÁ, 1984), which detected Mesozoic carbonates at a depth of 1,877 - 2,050 m assigned to the Choč escarpment and verified geothermal waters with a temperature of $_{Twh}$ = 35 - 40 °C with an overflow capacity of 3 $l.s.^{-1}$. Subsequently, a hydrodynamic test (BONDARENKOVÁ ET AL., 1990) was carried out on the borehole, which recommended geothermal water abstraction rates of Q = 9 - 11 $l.s^{-1}$, while pumping increased the geothermal water temperature to the level of $_{Twh}$ = 45 - 49 °C (JEZNÝ, 2013). The currently approved geothermal water quantities for the BnB-1 borehole assume a productivity of Q = 17 $l.s^{-1}$ (e.g. MARCIN ET AL., 2016).

The first comprehensive idea of the energy potential from the period 1984-1985 (FENDEK ET AL., 1985, 1986) formulated the idea of segmentation of the pre-Tertiary basement of the Bánov Basin or Topoľčany Bay with regard to the possibility of formation of circulating hydrogeothermal structures, within which they were delineated in the north-south direction:

- Banovská basin (own) with central depression Ruskovce
- zone of partial morphostructural elevations and depressions of the pre-Neogene substrate on the Prašice - Partizánske line
- Topoľčany Bay with central depression Veľké Ripňany
- the northern edge of the Gabčíkovo-Rišňovská depression;

with an expected average reservoir temperature of T_{res} = 75 °C and a reference temperature of T_{ref} = 15 °C, the study estimated geothermal energy reserves of 17.5 MWt if the forecast geothermal water resource is 66.6 l.s .$^{-1}$

The deep borehole **FGTz-1 Topoľčany** (FENDEK ET AL., 1986) was originally drilled to test the Mesozoic strata of the Choc and Križňan Formations within the Topoľčany Bay. However, the borehole intercepted Middle Triassic carbonates of the envelope unit of the Tatrik, which verified geothermal waters producible by pumping with a yield of Q = 3 - 5 l.s^{-1} and a temperature at the mouth of T_{wh} = 41 - 54 °C, which is itself a significant dissipation.

The HGTP-1 Partizánske borehole (MÉRYOVÁ, 2000) verified geothermal waters with temperature T_{wh} = 20 °C and yield Q = 12.8 l.s^{-1} bound to the Middle Triassic carbonates of the Chocká escarpment, which was a follow-up to a study focused on the possibilities of obtaining and using geothermal waters in the vicinity of Partizánske.

The last realized hydrogeothermal borehole in the area is **FGTz-2 Partizánske** (REMŠÍK ET AL., 2007), who verified geothermal waters with temperature T_{wh} = 33 °C and yield Q = 12.5 l.s .$^{-1}$

Extensive geothermal research of the Topolčany Bay or the Bánov Basin (REMŠÍK ET AL., 2007) has identified two basic structures of hydrogeothermal waters bound to the carbonates of the Choč escarpment:

- Bánov hydrogeothermal structure in the northern part of the territory
- the Zavada-Belich hydrogeothermal structure in the southern part of the area.

The hydrogeothermal assessment included a review of geothermal energy quantities and reserves for the prospective area defined at that time, with the following resolution:

- for the area of occurrence of geothermal aquifers outside the allocated structures: based on the energy balance method (e.g. FENDEK ET AL., 2005), the 'geothermal energy quantity' is set at 15,167 MWt , corresponding to a 'geothermal water quantity' of 191,97 $l.s^{-1}$ at an average temperature of 34 °C at the mouth of the production wells and a reference temperature of 15 °C
- for a dedicated banking structure:
  - The balance method (e.g. FENDEK ET AL., 2005) determined a "geothermal water quantity" of 63.99 $l.s^{-1}$, corresponding to a "geothermal energy quantity" of 6.65 MWt
  - USGS volumetric method (e.g. MUFFLER - CATALDI, 1978) determined an "exploitable amount of geothermal energy" of 32.7 MWt, corresponding to "geothermal water quantity" at 324.98 $l.s^{-1}$
- for the separated závadic-white structure:
  - The balance method (e.g. FENDEK ET AL., 2005) determined a "geothermal water quantity" of 77.69 $l.s^{-1}$, corresponding to a "geothermal energy quantity" of 5.8 MWt
  - USGS volumetric method (e.g. MUFFLER - CATALDI, 1978) determined "an 'exploitable amount of geothermal energy' of 30,85 MWt, corresponding to "geothermal water quantity" at 412.07 l.s .$^{-1}$

The present hydrogeothermal assessment (REMŠÍK ET AL., 2007) was based on the assumption of reservoir production for a period of $_{tprod}$ = 30 years and a reference temperature of $_{Tref}$ = 15 °C, with an availability coefficient of R0 = 0.1 when using the USGS bulk method.

3 GEOLOGICAL AND HYDROGEOTHERMAL CONDITIONS OF THE AREA

3.1 Delimitation of the territory

The Partizánske site is part of the more broadly defined Bánovská kotlina geothermal water body with the identifier SK300090FK (MARCIN ET AL., 2016, 2020) with a total area of $_{AUGV}$ = 557.964 km^2 (Figure 3.1). Within the geothermal water body itself, the reservoir medium has been verified (i.e. documented by geological/hydrogeothermal boreholes) in Mesozoic carbonates (Middle and Middle-Upper Triassic):

- Hronika / Chocsky escarpment (Figure 3.1), $_{ACHP}$ = 397 km^2
- of the envelope of the Tatrik unit (only the FGTz-1 Topoľčany borehole; FENDEK ET AL., 1986); while according to the estimates of the tectonic map of the pre-Tertiary bedrock, it is possible to assume the extension of Mesozoic geothermal waters in the entire geothermal water body, except for the SW margin.

Fatrik Formation (syn. Križňanský příkrov) in the underlying chronik systems.

The Partizánske locality as the subject area (Figure 3.1) was defined by the spatial extent of the Middle Triassic carbonates of the hronik from the south and east, and by tectonic delineation on the line Chynorany - Rybany - Nedašovce, with a total area of $_{APTZ}$ = 55 km .^{2}

3.2 Brief overview of the geological structure

The geological structure of the geothermal water formation and therefore also the area in question is idealized vertical sequence:

- Quaternary sedimentary formations
- sedimentary Neogene
- Inner Carpathian Palaeogene
- tectonic unit hronika (chočský příkrov)

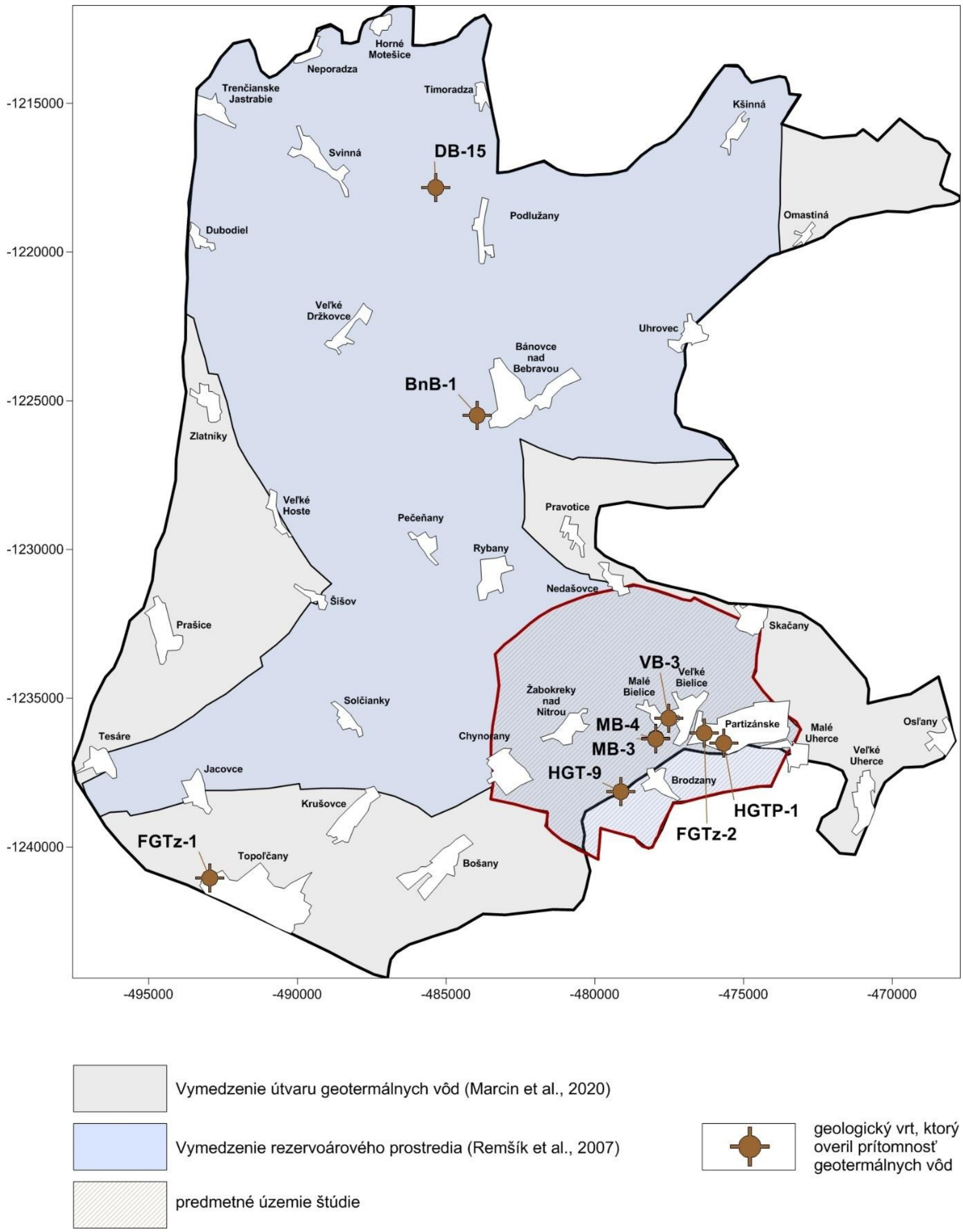

Figure 3.1: Delineation of the study area at the Partizánskké site in relation to the total area of the geothermal water body and the area of the expected extension of the reservoir environment in the Mesozoic carbonates of the hronik

- tectonic unit Fatrika (Križňanský příkrov)
- packaging unit tatrika
- crystallinicum tatrika.

The Cenozoic profile is formed by Neogene formations with typical siliciclastic fill, in which pelitic fractions predominate, in the bedrock with succession of the Inner Carpathian Paleogene (Banská basin), which in the base-ceiling direction is represented by the basal pine layer of conglomerates and breccias with a transition to the Hutian layer with a predominance of claystones, and then to the Zuberecky, flyschoidal layer.

Views differ on the spatial structure of **the pre-Tertiary basement** (Figure 3.2). While in the southwestern part the formations of the envelope unit of the Tatrik were verified by the FGTz-1 Topoľčany borehole, the carbonates of the Fatrik in the direct Paleogene or Neogene bedrock have not been confirmed by drilling, therefore the regional hydrogeothermal assessment (REMŠÍK ET AL., 2007) assumes the extension of the carbonates of the Chronik from the Tesáre - Bošany line to the northeast to the Kšinná - Omastiná junction.

The HGTP-1 and FGTz-2 boreholes directly at the Partizánske site verified the assumed, steady-state vertical profile. The stratigraphic and lithological profiles of the individual boreholes in the relevant area are shown in Table 3.1.

Table 3.1: Vertical geological profiles of boreholes in the relevant surroundings of the Partizánské site

VB-1 Veľké Bielice 0 - 8.5 m ; Quaternary 8.5 - 15.0 m ; Neogene	**VB-2 Veľké Bielice** 0 - 13.0 m ; Quaternary 13.0 - 96.0 m ; Neogene 96.0 - 166 m ; Palaeogene 166 - 241 m ; Middle / Upper Triassic (Chronicle)
MB-1 Malé Bielice 0 - 11.2 m ; Quaternary 11.2 - 15.5 m ; Neogene	**MB-3 Malé Bielice** 0 - 8.2 m ; Quaternary 8.2 - 100 m ; Neogene
FGTz-2 Partizánske 0 - 12.0 m ; Quaternary 12.0 - 97.0 m ; Neogene 97.0 - 165 m ; Palaeogene 165 - 961 m ; Middle / Upper Triassic (Chronology) 961 - 998 m ; Lower Triassic (Chronology)	**HGTP-1 Partizánske** 0 - 7.5 m ; Quaternary 7.5 - 13.1 m ; Neogene 13.1 - 196 m ; Palaeogene 196 - 500 m ; Middle / Upper Triassic (Chronicle)

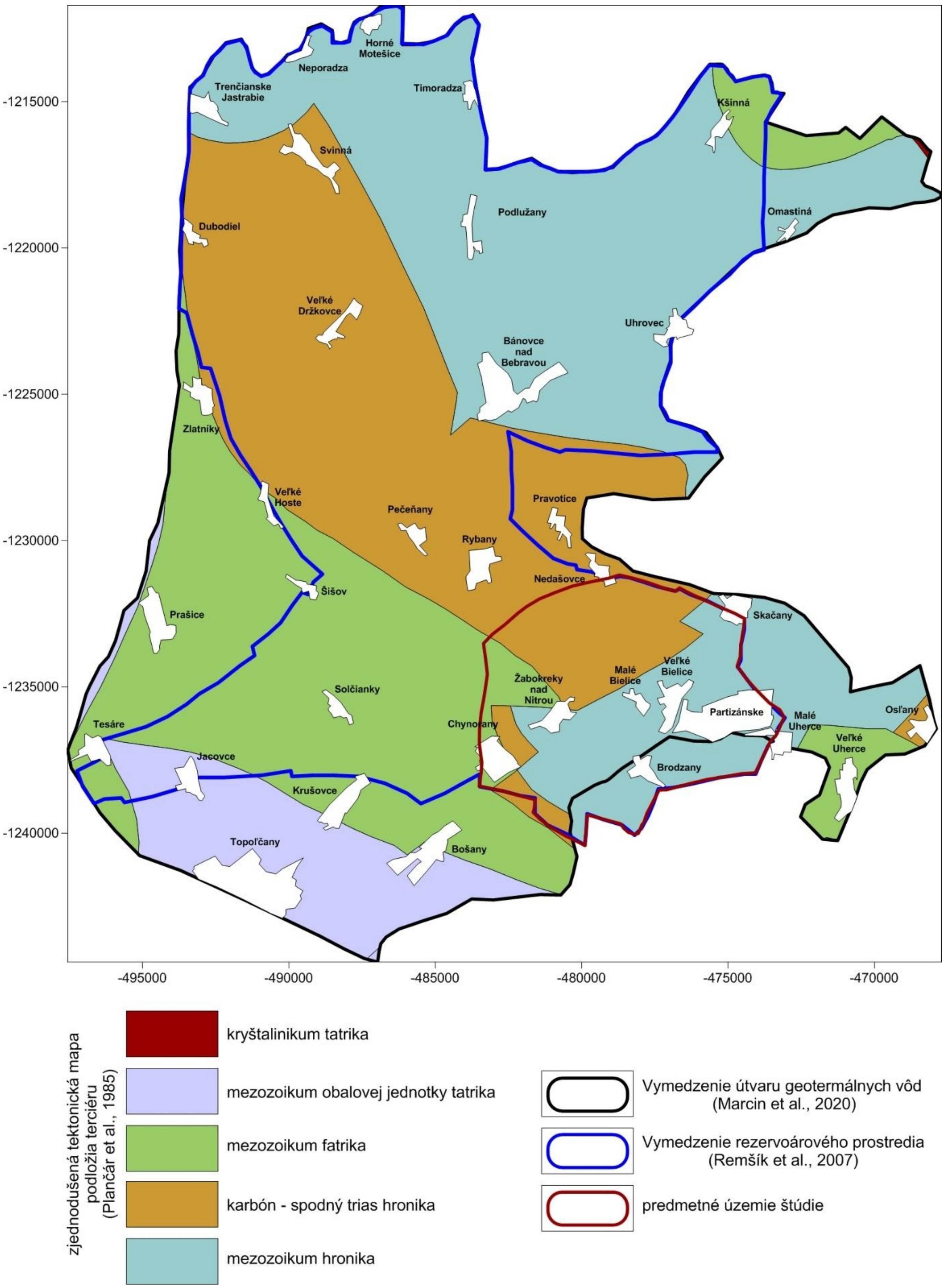

Figure 3.2: Schematic of the inferred pre-Tertiary bedrock. Modified after: Plančár et al. (1985; Remšík et al., 2007)

For the purposes of this study, the term **"reservoir environment"** refers to the **Mesozoic, mid-Triassic to Upper Triassic profile of the Chronik / Choc¸a escarpment**, which represents the direct bedrock of the sedimentary fill of the Bansko Basin.

According to the geological model, which was constructed for the Banovská basin within the geological task "Analysis of the possibilities of sustainable use and exploitation of geothermal energy resources in Slovakia - Part I" (FRIČOVSKÝ ET AL., 2024), the Mesozoic carbonate ceiling decreases in the SE-NW direction on fault systems, which makes the immediate surroundings of the Partizánske site an elevated cover, where the total thickness of the Cenozoic is up to 500 m (Fig.3 and 3.4), while other covers with a SW - NE axis fall in the direction to the NW, at the contact with the morphostructure where the inferred Mesozoic ceiling is 1000 - 1200 m, which represents the outcrop of the Topoľčany Gulf. At the Oslany - Uherce line, the Mesozoic rises directly to the surface. The dominant structure is the so-called Ruskovská / Držkovská depression, with estimated reservoir ceiling depths of up to 3000-3200 m, which have not yet been reliably verified b y drilling and thus represent a significant uncertainty. In the direction of the Strážov Hills (N) and the Hornonitrian Basin (NE), the reservoir environment re-emerges on fault systems to depths of no more than 200-500 m at the margins of the entire basin.

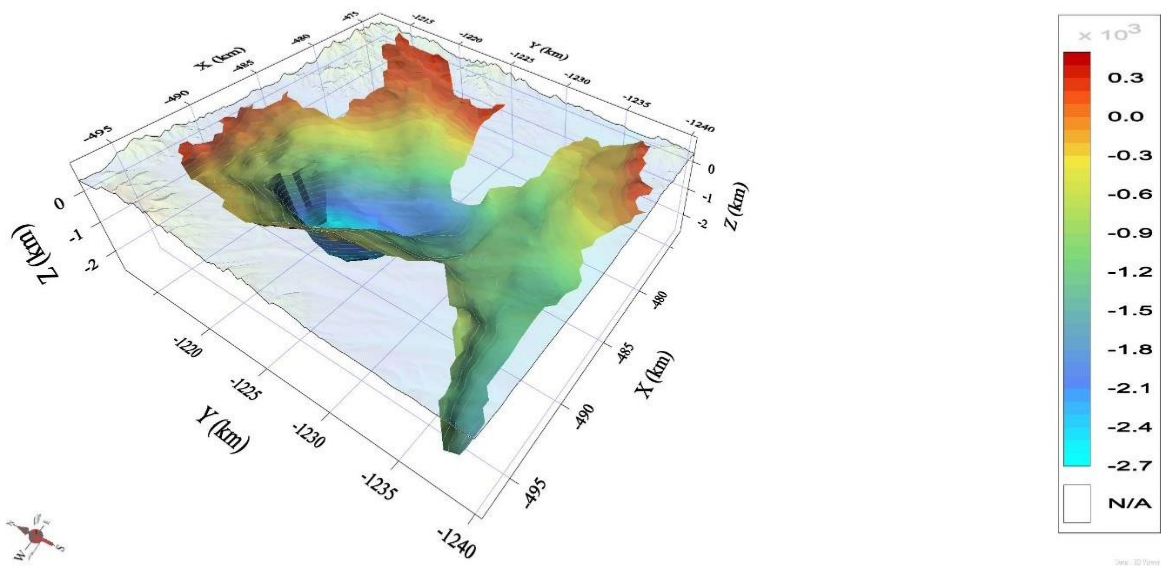

Figure 3.3: 3D view of the ceiling of Mesozoic carbonates in the Banova basin - view from the SW (elevation in km). Modified after Fričovský et al. (2024)

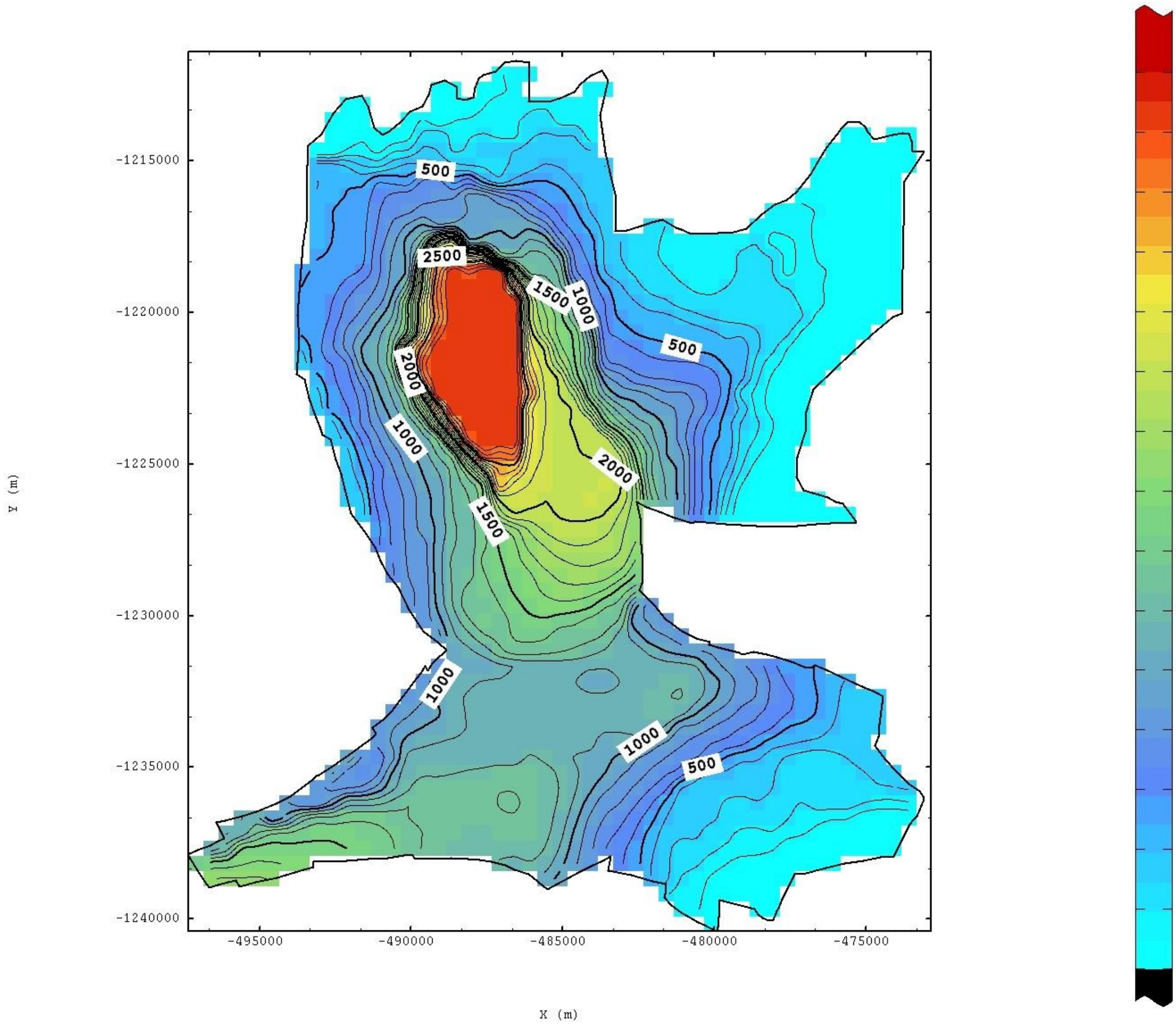

Figure 3.4: Tertiary overburden thickness map in m, representing the vertical depth of the Mesozoic ceiling. Modified from Fričovský et al. (2024)

The thickness of the reservoir environment is the second feature of its geometry. According to the model solution for the Banova Basin (FRIČOVSKÝ ET AL., 2024), the estimated thickness of carbonates decreases generically towards the depocentre of the geothermal water body in the SE-NW and NE-SW directions, including a general decrease from the western boundary, with the total interval of the modelled thickness reaching 1-900 m, while it is at the Partizánské site in the direction of Brodzany and Partizánské that the model solution predicts local maxima (Figures 3.5 and 3.6). At the same time, the modelled values were directly verified by the FGTz-2 Partizánské borehole (REMŠÍK ET AL., 2007), in which the thickness of carbonates, i.e. reservoir rocks, reached 800 m and represents a complete profile, as the borehole intercepted Lower Triassic lithotypes at its base; and also by the HGTP-1 (MÉRYOVÁ, 2000); which verified the Middle Upper Triassic Lunzian strata on the basis of carbonates up to 350 m thick, i.e. another profile of the carbonates beneath them is still available.

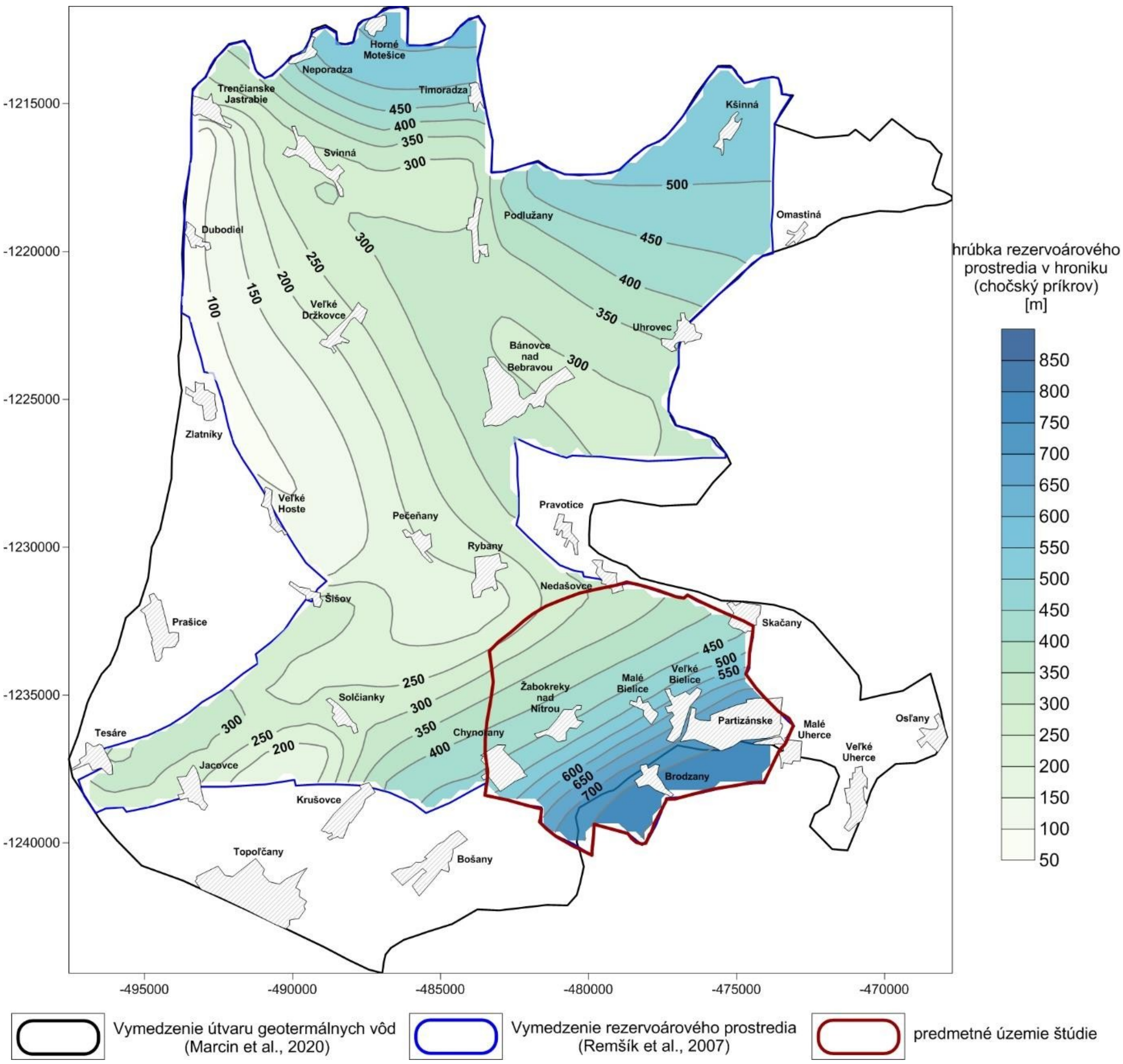

Figure 3.5: Model of the thickness distribution of the reservoir environment - carbonate chronite. Modified after Fričovský et al. (2024).

From the distribution of the atectonic thickness model, it is recommended to design more extensive drilling at the Partizánské site, especially in the vicinity of the vent area (Veľké and Malé Bielice) to depths corresponding to the HGTP-1 well, as the distribution of carbonates, their geometry, and the nature of the environment (see 3.4) may yield knowledge of distinct, or only partially coupled, circulatory systems that could, in turn, both support the total quantities of geothermal water produced and, in an assumed, pure-conductive environment, increase the temperature of the geothermal water produced as a function of depth.

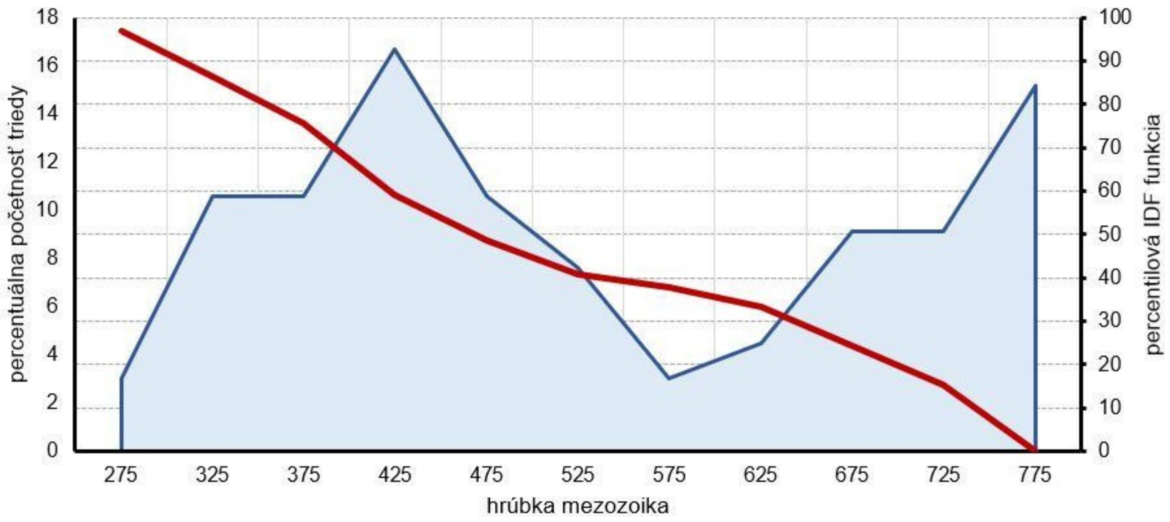

Figure 3.6: Histogram and IDF distribution curve of the reservoir thickness model at the Partizánské site.

3.3 Hydrogeological conditions

3.3.1 Hydrogeological function of the rock environment

The reservoir/reservoir rocks in the Banovo Basin are:

- Upper Triassic carbonates (so called main dolomite) chronite (karst - fissure secondary permeability)
- Middle Triassic carbonates (karst - fissure secondary permeability)
- Middle Triassic carbonates fatrika (karst - fissure secondary permeability)
- Middle Triassic carbonates of the Tatrik envelope unit (karst - fissure secondary permeability)
- conglomerates, breccias and carbonate sandstones of the Borovian Paleogene of the Banská basin (primary intergranular permeability, secondary fracture permeability).

Although the presence of fatrik was excluded SW of the Tesáre - Bošany line by the FGTz-1 Topoľčany borehole (FENDEK ET AL., 1986), there is no reason to ignore their possible presence in the subsoil of the Middle Triassic carbonates of the chronite, or its Upper Carboniferous - Lower Triassic sequence both in the central part of the basin and at the **Partizánské locality** (REMŠÍK ET AL., 2007).

This means that if deep geological/geothermal exploration is undertaken, there is reason to assume the presence of at least one deep reservoir environment beneath the currently proven environment associated with the carbonate sequence of the chronology. The hydraulic continuity of the reservoir environments associated with the two tectonic units has not yet been conclusively demonstrated.

The Cenozoic profile of the Neogene and Paleogene formations can be considered as a **hydrogeological insulator**, as well as the Lunzian strata, which were verified by the HGTP-1 well (MÉRYOVÁ, 2000), or the profile of the Lower Triassic sequences of the chronology, for example in the FGTz-2 Partizánske well (REMŠÍK ET AL., 2007). Possible Upper Triassic and Lower Triassic sequences of the fatric and envelope units of the tatric, respectively, will be very similar.

An unconfirmed, but presumed **semi-insulator** to **insulator** in the circulation systems of the Banská basin is also the Upper Triassic - Cretaceous Fatrika profile, which is expected to occur beneath the tectonic unit of the Chronicle.

An important function in the filtration regime of groundwater/geothermal waters is played by fault systems defining tectonic cover in the immediate vicinity of the Partizánské site. Repeatedly (FRANKO ET AL., 1983; FRANKO - GAZDA, 1969; MÉRYOVÁ, 2000; REMŠÍK ET AL., 2007) their function as transit descent as well as transit exit routes was confirmed - in the case of the Partizánske site on the W foothills of the Tríbeč Mountains, which may influence the conceptual classification of circulation/accumulation systems in the Bánov Basin, respectively in the relevant surroundings of the site (see 3.3.2).

3.3.2 Hydraulic parameters of the rock environment

Hydraulic parameters of the rock environment were verified in four hydrogeothermal boreholes (Table 3.2) - while comprehensive overviews of all relevant parameters are lacking in the available literature. According to the summary report of the Banova Basin research, the absolute flow coefficient of the reservoir environment ranges from $2.98\ .10^{-13}$ to $2.78\ .10^{-10}$ m^3 ; the flow coefficient ranges from 6.7 .10-6 to 7.82 .10-3 $m^2\ .s^{-1}$, a permeability coefficient ranging from $1.42\ .10^{-14}$ to $1.76\ .10^{-11}$ m^2 , and a filtration coefficient reaches values of $3.19\ .10^{-7}$ to $2.25\ .10^{-4}$ $m.s^{-1}$. (REMŠÍK ET AL., 2007).

Since the reservoir environment is defined by karst - fissure permeability, the hydraulic parameters are mainly controlled (which is also true for the Partizánské site):

- the extent of paleo-crustal phenomena with a naturally higher permeability than the fissure (discontinuity) component
- the degree of tectonic faulting of the carbonate rock complex, and it is naturally to be expected that around major tectonic lines where more significant tectonic (vertical) displacements have occurred, the primary tectonic line is supported by concomitant tectonic fault zones, which increases the permeability in the fracture component
- the influence of the compaction rate is questionable - Table 3.2 shows a significant decrease of the absolute flow coefficient in the coronal zone between the wells in the vicinity of Parizánské and the well BnB-1 Bánovce nad Bebravou (ČERMÁK - BONDARENKOVÁ, 1984), which corresponds with the increase of the depth of the reservoir environment occurrence

Table 3.2: Hydraulic parameters of the reservoir environment in the Banova basin. Modified after Remšík et al. (2008)

parameter	absolute flow coefficient	flow coefficient	coefficient of permeability	filtration coefficient
label	Tp	T	kp	kf
unit	m^3	$m^2.s^{-1}$	m^2	$m.s^{-1}$
FGTz-1	$2,98\ .10^{-13}$	$6,7\ .10^{-6}$	$1,42\ .10^{-14}$	$3,19\ .10^{-7}$
FGTz-2	$2,78\ .10^{-10}$	$3,55\ .10^{-3}$	$1,76\ .10^{-11}$	$2,25\ .10^{-4}$
HGTP-1	-	$7,82\ .10^{-3}$	-	-
BnB-1	$4,3\ .10^{-12}$	$6,38\ .10^{-5}$	-	$2,55\ .10^{-6}$

3.3.3 Conceptual characteristics of circulation systems

In terms of the classical classification of the hydrogeological regime of geothermal energy sources, two basic circulation structures are identified within the Bánovská basin geothermal water body (REMŠÍK ET AL., 2007):

- Bánov hydrogeothermal structure defined as semi-open, with infiltration area on the southern slopes of the Strážov Hills, from the south by fault systems on the line Velušovce - Prašice - Šišov - Pečeňany, where the general trend of groundwater / geothermal water flow is in the direction N - S or SSW - SE
- the Race-Bielica hydrogeothermal structure defined as open, tectonically defined to the north in relation to the Banská structure, bounded to the south by the Tríbča massif,

or tectonically to the Rišňovská depression in the vicinity of Topoľčany at the contact of the chronik / fatrik and the enveloping unit of the tatrik; with the infiltration area in the southernmost slopes of the Strážovské Hills, but especially on the W boundary of the Tríbeč Mountains, with the vent area in the vicinity of Malé Bielice and Veľké Bielice.

CONCEPTUAL CLASSIFICATION OF THE PARTISAN LOCALITY

The Partizánske locality is spatially part of the Závadsko-Bielica hydrogeothermal structure. A closer specification of the hydrogeological regime at the site (MÉRYOVÁ, 2000) shows a combined hydrogeological function of the fault systems on a relatively small area, where probably:

- downward flow trend within the transit-ascending filtration branch south of Partizánske
- the outflow trend within the transit-ascending filter branch and the outlet area NE of Partizánske in the vicinity of Malé Bielice and Veľké Bielice.

In terms of conceptual classification (MOECK, 2014), the Partizánske site - including the entire Bánov Basin - is classified as a predominantly-conductive CD concept of forearc basins and orogenic zones (CD2). From the regional point of view (FRIČOVSKÝ ET AL., 2024), the Bielice - Partizánske area can be considered as a hydrogeothermal conceptual subtype CD2a

: Inner mountain basins, the basic features of which are:

- the presence of both circulating and storage hydrogeothermal systems
    - in the case of accumulation systems, there is no sensu-stricto accumulation of geothermal waters and long residence time in the reservoir environment, while the filtration of geothermal waters can be stable in the long term and influenced only by the hydrological regime and precipitation subsidy; the possibility of reduction of hydrogeothermal systems to the so-called circulating structures based on fault lines is also supported by the different function of the faults on a relatively small area and the Ca-Mg-HCO3 type of the verified geothermal waters in Maly Bielice,
      Veľké Bielice, also Partizánske
    - circulating systems are extremely susceptible to rapid (units of years) progression of the hydraulic/temperature front in the event of reservoir energy depletion

due to the fast filtration rate of the reservoir medium and the short residence time
- classical cation geothermometry fails in circulating systems due to fast flow and short residence time, therefore it is necessary to apply complex silicate geothermometry and multicomponent geothermometry for the purpose of monitoring reservoir response manifestations
- Classical indicators of cold front penetration (e.g. Mg^{2+}, SiO_2) are strongly suppressed by the natural chemistry of geothermal waters, and cannot be applied reliably without geothermometric methods of analysis

- possible flow regimes in the case of reservoir systems are mainly represented by **lateral transition structures** (step down and upward directions between the reservoir tectonic sub-crusts) or **basin segmentation structures** (multiple vertical descents and ascents between the reservoir tectonic sub-crusts prior to the outlet)
  - Lateral transgressions structures often manifest themselves in a mismatch between the hydrogeological and hydrological balance of the area and the hydraulic sustainability of the reservoir environment, with relatively little variability in the temperature of the produced reservoir medium
  - Basin segmentation structures are manifested in the case of long-term production by relatively more pronounced oscillations of reservoir temperature during long-term production without a pronounced trend (until the onset of the cold front penetration phase), while the correlation between hydraulic sustainability and the hydrogeological / hydrological balance of the area is not so significantly broken in the long term
  - relatively low mineralisation up to 2 $g.l^{-1}$ of the reservoir medium
  - a reliable indicator of reservoir dynamics are the so-called thermochemical methods (thermochemical mapping of mixing indicators and vertical reservoir dynamics) in combination with silicate-chalcedony and opal geothermometry, and the application of multicomponent geothermometry

Within the hydrogeothermal exploration of the Partizánske site these methods of research, analysis and interpretation of the dynamics of geothermal energy sources were not used.

The possibilities of the presence of geothermal energy sources bound to the underlying mid-Triassic carbonates of the Fatrika are described as uncertain or debatable in the available literature (MÉRYOVÁ, 2000; REMŠÍK ET AL., 2007). Meanwhile, hydrogeothermal boreholes have verified the Ca-Mg-HCO3 type geothermal water, which is mainly typical for:

- circulating stable filtration systems in carbonates
- geothermal energy sources tied to a tectonic unit of a mountain; or
- stratified reservoir systems:
    - without hydraulic continuity (fatrika geothermal waters have standard Ca-SO4, Ca- Mg-SO4 or Ca-Mg-HCO3-SO4 to Ca-Mg-SO4-HCO3 type)
    - minimum hydraulic continuity, where the ratio of geothermal water input from the fatric to the graveyard should be practically negligible based on the chemical composition of the trapped geothermal waters in the graveyard.

From the above "macrochemical" indication it follows that within the locality of Partizánske:

- the reservoir environments in the hippocampus and the fatric probably do not communicate with each other
- the implementation of deeper geothermal boreholes could lead to the capture of a hydraulically independent reservoir environment, probably with different filtration parameters and a different conceptual model of geothermal waters, but probably at higher temperatures
- A comprehensive answer to the question of hydraulic continuity must be addressed within the next exploration tasks at the site or within the geothermal water body with regard to the possibilities of long-term sustainable production of geothermal energy resources.

At the same time, however, the above analysis does not answer the question of whether the reservoir environment of the hronik subsidizes a potential reservoir environment in the fatrik tectonic unit, or whether indeed both reservoir environments may share the same infiltration or common downward transit area. Clarification of this is only possible if there is verification of the geothermal energy sources tied to the underlying fatrikum, and subsequent modelling and analysis of the thermochemical and dynamic conceptual relationships between the two trapped units. If a portion of the geothermal waters filtering through, or subsidizing, the mid-Triassic carbonates of the hronica were to simultaneously subsidize the deeper downward pathways of the transit zone of hydrogeothermal structures bound to the carbonates of the fatricum, this would also be one of the risks to the hydraulic sustainability of the long-term production of geothermal energy resources from the verified of the reservoir environment in the fatrik, according to which it should be consequently necessary to optimize production strategies, as the potential induction of pressure depression in the open section of the fatrik could affect the rate of natural replenishment of the reservoir environment in the higher tectonic unit.

3.4 Geothermal environment

3.4.1 Geothermal field

The geothermal field over the entire geothermal water body (Figure 3.7) can be considered as significantly monotonic based on the surface heat flux density, with a general increase of geothermal activity in the west-east direction, which may be a reflection of the thermal activity of the northern outcrops (basins) of the Danube Plain and their periphery compared to the relatively monotonic geothermal field in the vicinity of the core mountains (e.g., the Tribeč Mountains on the eastern boundary of the basin).

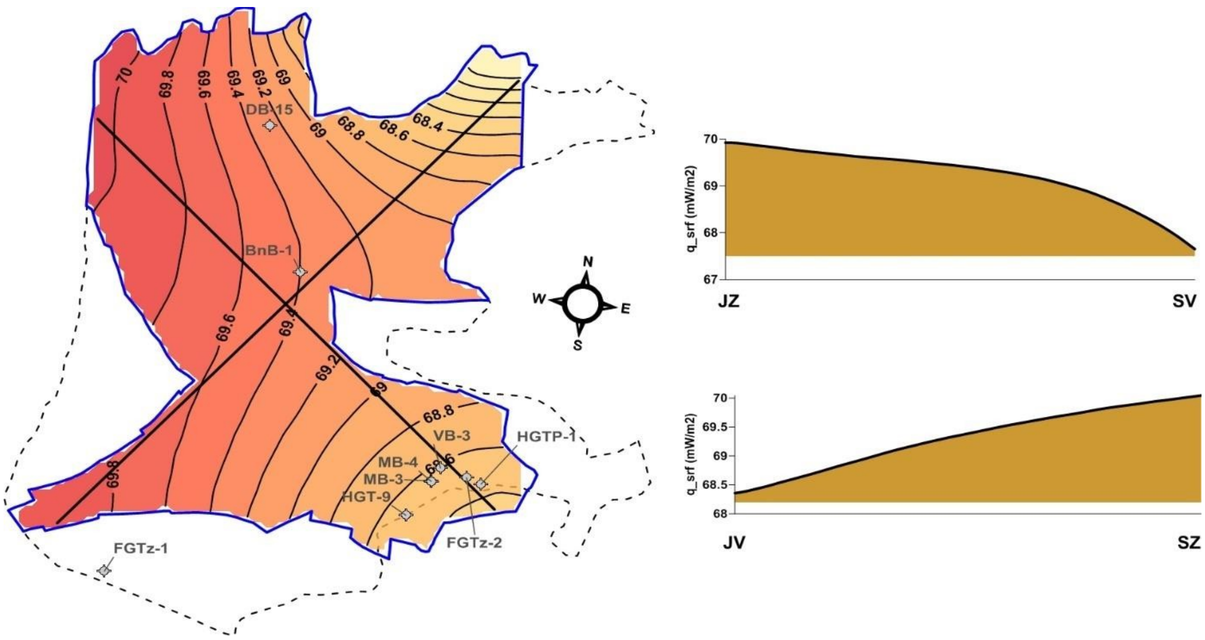

Figure 3.7: Surface heat flux density averaged over the defined reservoir environment of the Banská basin

Within the framework of the construction of a stationary geothermal model for the environment of the Banova Basin (FRIČOVSKÝ ET AL., 2024), the estimate of the range of heat flux density is 67 - 70.1 $mW.m^{-2}$, which is valid for the defined cover of the carbonate extension of the chronite, with a mean value of 68.7 $mW.m^{-2}$. However, it should be emphasized at this point that this is the **surface heat flux density**, i.e. the amount of heat transferred per 1 m^2 area within the area, and within the entire vertical rock profile.

From the point of view of the heat flux density expressed **on the surface of the carbonate hronites** (FRIČOVSKÝ ET AL., 2024), which in the stationary geothermal model was derived from the surface heat flux density map by subtracting the radiogenic component, a change in the qualitative (spatial) distribution of the heat flux and an absolute violation of the trends of its orientation on the surface is evident (Figure 3.8). Several trends are visible from the map:

- the removal of the Tertiary sedimentary cover, which due to its lithological composition and hydrogeological function represents a "thermal cap", results in a significant concentric trend (anomaly) of a sharp decrease in heat flux density in the direction of the central part of the Banovská depression with a range of values of 65 - 67 $mW.m^{-2}$
- a zone of decreasing geothermal activity NE of the Timoradza - Uhrovec junction in the direction of the Hornonitrian Basin, with values of 66 - 68 $mW.m^{-2}$, i.e. with a decreasing trend despite the decrease in the thickness of the overlying tertiary

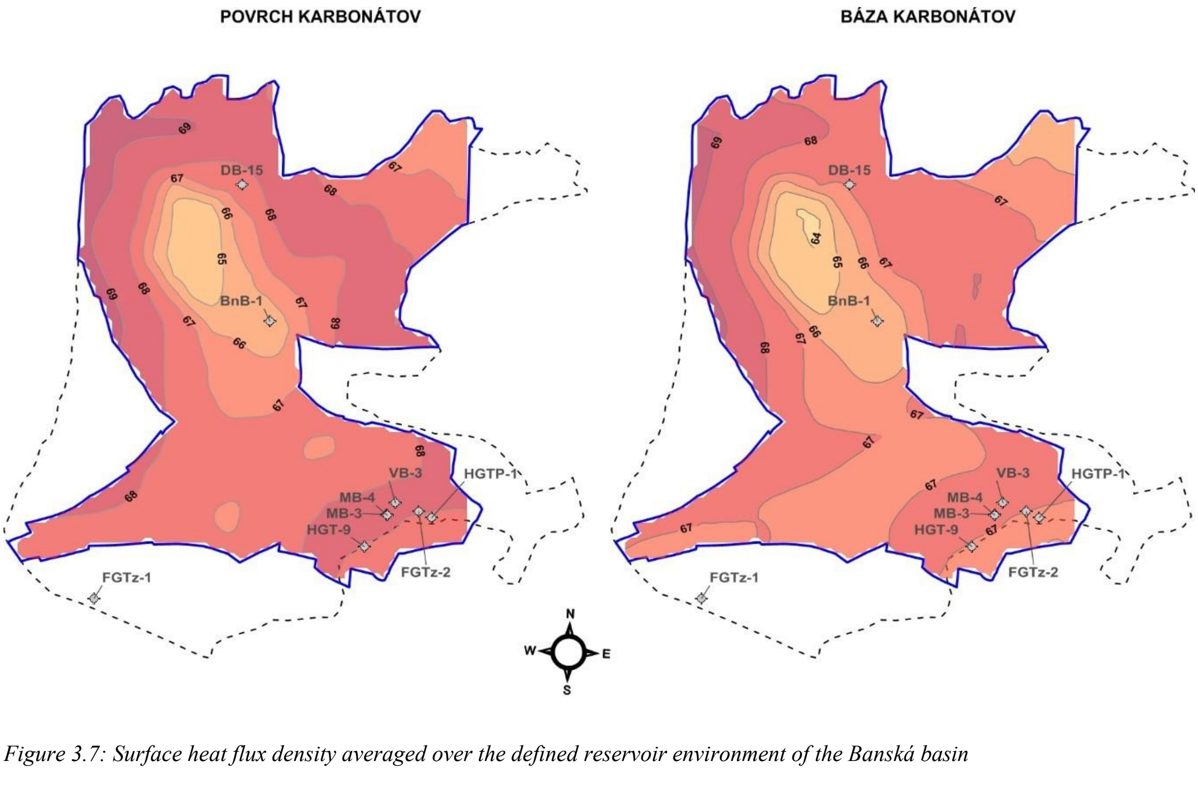

Figure 3.7: Surface heat flux density averaged over the defined reservoir environment of the Banská basin

- monotonic zone of the southern part of the Bánov Basin, with a steady heat flux density south of the Veľké Hoste - Pravotice junction with values of 67-68 $mW.m^{-2}$, which continues to the Topoľčany Bay and to Partizánské
- a zone of local threshold - linear anomaly in the form of an island of geothermal activity in the polygon Chynorany - Skačany - Partizánske - Brodzany with a relatively stable value of heat flux density of about 68 mW.m $.^{-2}$

GEOTHERMAL FIELD IMPLICATIONS FOR THE PARTISAN

In the regional hydrogeothermal assessment of the Topoľčany Bay and the Bánov Basin (REMŠÍK ET AL., 2007) for the relevant area of the town of Partizánske it is stated that "*a heat flux above 70 mW/m2 was also detected in the borehole FGTz-2 Partizánske (74.2 mW/m2). This value is probably related to the increased heat yield along the tectonic lines in the vicinity of the geothermal water vent area at Maly and Veliki Bielice*", whereas the geothermal activity analysis itself states that the heat flux values for the FGTz-2 borehole were calculated from a temperature-unsteady profile and only from the depth interval corresponding to the carbonates, while the analysis refers to the complete vertical profile, i.e. Mesozoic + Tertiary. **It should be stressed that this is an incorrect procedure in terms of implementation methodology** (the so-called Fourier heat flux density calculation should be performed with complete and steady-state temperature curves, or from the intervals of the curves corresponding to the target intervals).

The comparison of the heat flux density on the surface and on the ceiling of Mesozoic carbonates shows the following for the locality of Partizánske and its surroundings:

- A central, concentric heat flux density anomaly that becomes uncorrelated towards the periphery in relation to the thickness of the Tertiary basin fill may indicate the potential for the formation of limited reservoir convection, as modelling (FRIČOVSKÝ ET AL., 2024) predicts an increase in graveyard temperatures in this part of the reservoir in the interval 80-115 °C
- in the case of the formation of more convective cells in the area of the defined anomaly, the manifestations of uneven reservoir overheating can be expected, especially in the NE and SE directions, where the disproportions between the geometry of the impermeable overburden and the heat flux density distribution are most pronounced, if the surface heat flux density is used as a comparison plane

- in the case of uneven reservoir heating, it is possible that the Partizánske site may be influenced by reservoir dynamics from the north, either thermally or hydraulically, while the expected processes in a similar situation are:
    - support for unforced vertical filtering
    - temperature distribution of the stationary and dynamic thermal field; consequently:
    - the influence of reservoir dynamics can influence - decrease - reservoir temperatures also at the Partizánske site in the long term without direct hydraulic combination, while this process does not have to be bidirectional, i.e. the influence of the stationary field by cooling at the Partizánske site does not necessarily have to be manifested in the centre of the local heat flux anomaly, but it can change the geometry and orientation of convection cells bound (if they exist) to the periphery of the anomalous area.
- by combining the reduction of the radiogenic heat component from the surface heat flux density, it is also evident that the local, linear heat flux anomaly may be valid for a given overburden geometry also in the Partizánske area - with a uniform emergence from the Chynorany - Skačany - Partizánske - Brodzany polygon to the NW and SE.
    - the fact that there are no significant contrasts in either of the defined directions may imply that the rate of vertical percolation of geothermal waters in the reservoir environment is rather related to the deeper reservoir positions (possibly under the influence of uneven superheating and the decay of uneven superheating from the north) - the anomaly is not reflected proportionally in the heat flux density at the surface
    - synchronous structures of linear anomalies are more typical of fast, predominantly-circulating systems with limited accumulation area
    - In the case of geothermal water intrusion into shallow positions, or into Paleogene basal formations, the rate of dilution is intense - which should be reflected in terms of long-term monitoring by trend features Mg^{2+} , i.e, that there may be a significant risk to the reservoir environment of rapid penetration of the hydraulic (cold) front from the overburden in the event of intense changes in the reservoir pressure regime, or effective filtration regime, if the circulating nature of the hydrogeothermal system is verified/confirmed.

3.4.2 Vertical temperature distribution

Temperature conditions in the reservoir environment were solved for stationary, predominantly conductive environment within the geothermal model serving as a basis for the conditional probabilistic model for estimation of geothermal energy resources and reserves and sustainable reservoir potential within the task "*Analysis of options for sustainable use and exploitation of geothermal energy resources in Slovakia - Part I*" (FRIČOVSKÝ ET AL., 2024). The obtained results must therefore be seen from the following perspectives:

- temperatures represent the modelled distribution of temperatures in the reservoir environment that are not affected by any flow
- represent a model-based estimate of temperatures based on geothermal and geophysical parameters of the rock environment
- Differences between model and measured temperatures, if they exceed standardized estimation errors (10%), can be indicators of reservoir dynamics and geothermal flow processes, and thus represent one proxy indicator of the interpretation of a conceptual flow model - by default in conjunction with geochemical and thermochemical models.

As we state above, the reservoir environment of the Bánov basin can be considered as predominantly conductive, i.e. the key mode of vertical heat transfer in the basin, or to its base and subsequently to the ceiling, is conduction - this would be true even if spatially isolated convection cells were to form, especially in the central part of the basin. Hence the modelled temperature:

- a function of the projection of geothermal activity (heat flux density) on the surface
- a function of the modelled/calculated reservoir ceiling depth (depending on the thickness of the overlying Cenozoic insulator, i.e. Palaeogene + Neogene) and the reservoir base (depending on the thickness of the overburden + reservoir thickness)
- a function of the geothermal parameters of the rock environments, which were dynamically recalculated as a function of geometry (surface, ceiling), hydraulics (porosity), and depth of the model points using mathematical global models standardized in geothermal practice, using reference values obtained from the analysis of solid samples (Table 3.3).

Table 3.3: Geothermal parameters used in the construction of the stationary geothermal model of the Bánov Basin and the Partizánske site. Modified after Remšík et al. (2008)

Litostratigraphy	bulk density	porosity	thermal conductivity
	$kg.m^{-3}$	-	$W.m^{-1}.K^{-1}$
Cenozoic sedimentary basin fill			
sands, sandstones (Ng)	2 070	0,139	2,6
clays, claystones (Ng)			1,77
conglomerates (Pg)	2 370	0,127	2,73
Mesozoic			
carbonates	2 750	0,03	3,36
clayey shales	2 670	0,05	2,45

In the Bánov Basin area, temperatures at the ceiling of the Mesozoic Choctaw Trench range from T = 18 - 106 °C (Figure 3.8), as a characteristic function of the depth of carbonate surface deposition, i.e. the thickness of the overlying Tertiary; only at the NE margin of the basin, from the Timoradza-Uhrovec junction, can a combination of Palaeogene and Neogene thicknesses be assumed, with a relatively more intense decrease in surface heat flux densities. Temperatures at the base of the Mesozoic reach a range of T = 25 - 112 °C (Figure 3.8), as a result of the thickness distribution of carbonates and the presence of lunar layers in their complex. Temperatures above 100 °C, if the distribution of reservoir depth and thickness matches or approaches the model solution, can be expected at the Veľké Držkovce - Svinná junction, at depths below 2000 m.a.s.l. This is a significant, and spatially constrained anomaly, which is just caused by local and spatially limited depression.

TEMPERATURE DISTRIBUTION AND IMPLICATIONS AT THE PARTISAN SITE

Under the influence of a relatively monotonic distribution of heat flux density on the surface, which also corresponds to the projection of heat flux density on the ceiling of the carbonate chronite in the area of the defined Partizanske polygon, the spatial distribution of the stationary reservoir temperature corresponds to the geometry of the reservoir environment.

Under the influence of the geometry of the overburden, the estimated temperature on the ceiling of the reservoir varies in the interval T = 18 - 52 °C, while relatively continuous minima of stationary temperatures can be assumed on the so-called Bielica line, i.e. in the zone of reduction of the overlying Cenozoic to the N and SW of Partizánské, while in the southern part of the territory the stationary temperatures reach up to 35 °C on the ceiling, while towards the northern boundary of the defined polygon they reach up to 50 °C.

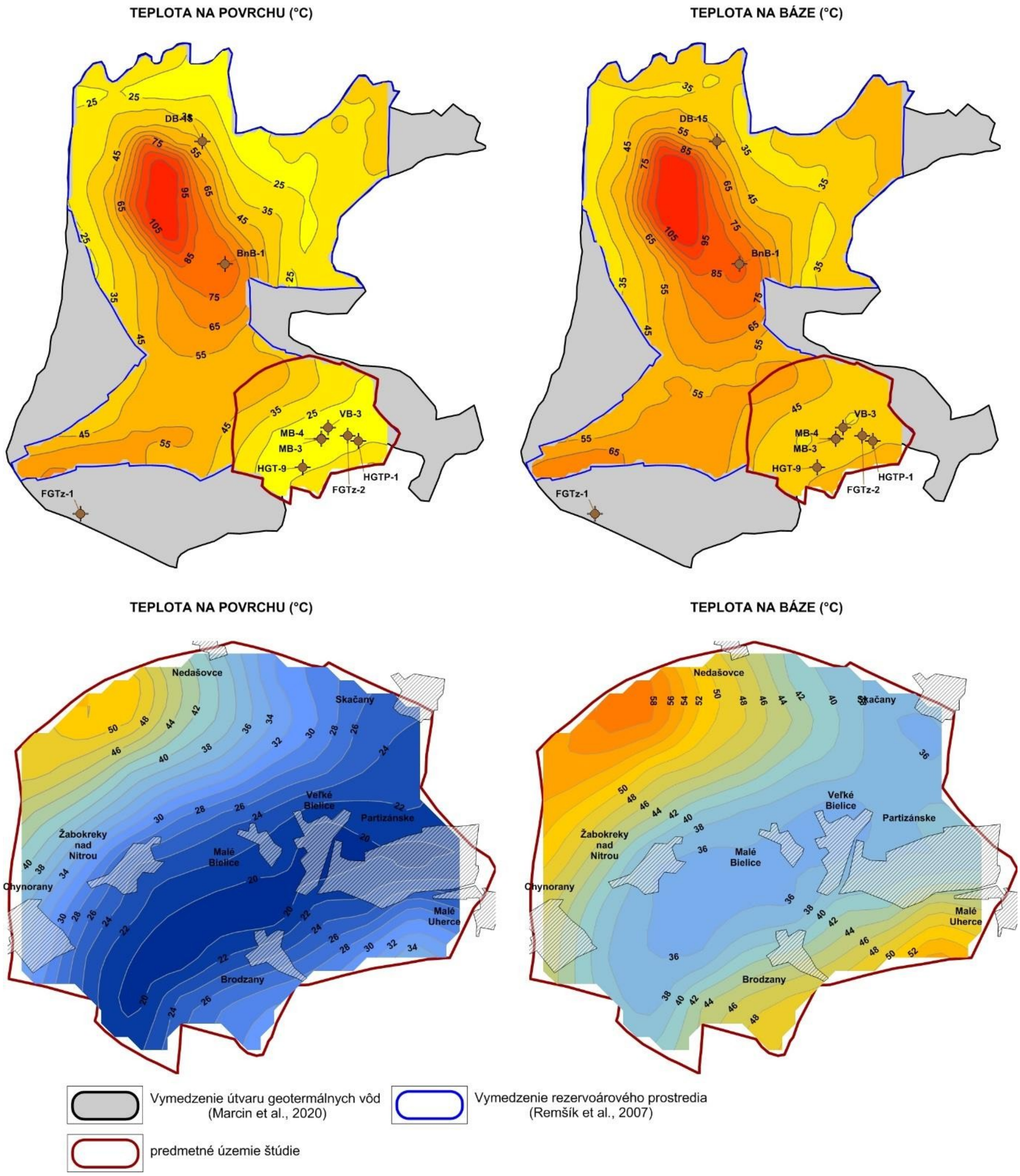

Figure 3.8: Distribution of temperature maps based on the stationary geological and geothermal model.

Under the influence of the geometry of the carbonates themselves and their varying thickness, with a significant upward trend towards the SE boundary of the defined polygon, temperatures at the base of the reservoir are modelled in the range T = 34-59 °C, with maxima flattening out between the northern and southern edges of the study area, as it is the thickness of the carbonates that increases significantly towards the SE. An overview of the basic reservoir temperature statistics is given in Table 3.4.

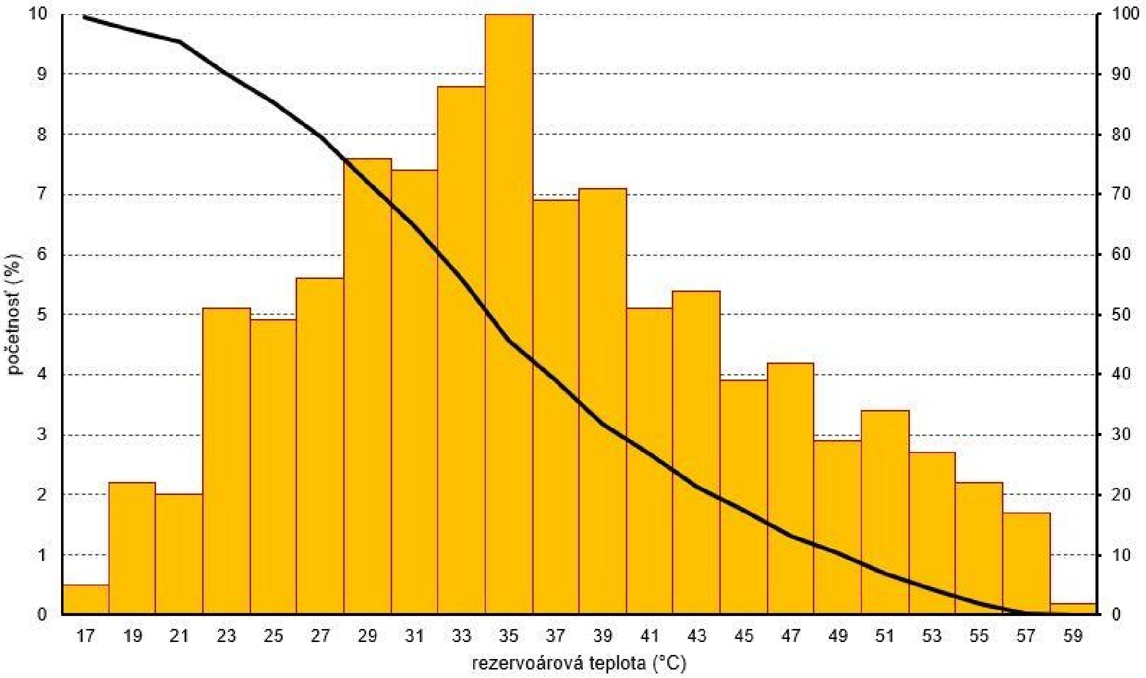

Figure 3.9: Functional histogram of the stationary temperature distribution in the vertical profile of the reservoir environment at the Partizánske site.

Table 3.3: Geothermal parameters used in the construction of the stationary geothermal model of the Bánov Basin and the Partizánske site. Modified after Remšík et al. (2008)

parameter	carbonate ceiling	carbonate base	polygon model
minimum	18	34	18
maximum	52	59	59
average	30	43	41
median	27	42	34
No. deviation	10	7	9

Based on the geometry of the geological setting and the geothermal parameters of the area (Table 3.2), the conductive gradient of the Cenozoic (Neogene and Paleogene profiles together) - i.e. the overlying reservoir environment $\Gamma_{CD\text{-}Ng}$ = 34 - 38 °C.km^{-1} throughout the delineated polygon, with $\Gamma_{CD\text{-}Ng}$ = 35.8 °C.km^{-1} in the 1 x 1 km vicinity of well FGTz-2 and $\Gamma_{CD\text{-}Ng}$ = 36.1 °C.km^{-1} in the vicinity of well HGTP-1, which may represent the state of the unaffected environment. Conductive gradient values in the Mesozoic reach $\Gamma_{CD\text{-}Mz}$ = 23 - 27 °C.km^{-1} in the defined polygon of the wider surroundings of the city of Partizánske, while in the area 1 x 1 km from the FGTz-2 borehole $\Gamma_{CD\text{-}Mz}$ = 25.9 °C.km^{-1} , and in the vicinity of the HGTP-1 $\Gamma_{CD\text{-}Mz}$ = 25.5 °C.km^{-1} (Figures 3.11 and 3.12).

If we proceed from the analogy of the FGTz-2 borehole-verified lunar layers separating the upper and lower carbonate complexes in a 70 m thick chronology (REMŠÍK ET AL., 2007), and assume the validity of the model estimate of the Mesozoic thickness in the immediate vicinity of the HGTP-1 borehole, then the stationary temperature of the environment at the base of the Mesozoic complex can reach T = 37-39 °C using the Mesozoic temperature gradient. This is a reasonably good agreement with the assumption of 41 °C in the model solution for the delineated site.

Interpretation of vertical temperature profiles of boreholes at the Partizánske site is questionable due to the conditions of their construction. Thermally stable profile is available only from the borehole HGTP-
1 Partizánske (Figure 3.10). By comparing the model curve of the conductive environment and the vertical temperature profile in the borehole body (MÉRYOVÁ, 2000) it is possible to interpret:

- The more pronounced temperature anomalies were initially interpreted at depths of 131 m (Paleogene), 145 m (Paleogene), 200-205 m (Paleogene-Mesozoic interface), with the main tributary interval identified in Mesozoic dolomites at 285-315 m depth; and thus:
- identified Paleogene temperature anomaly, i .e. The difference between the measured temperature and the modelled profile temperature reaches $\Delta T \approx 1$ °C, is probably significantly deeper than the original interpretation, approximately 160 m deep, and shows a temperature pulse relative to the stabilised profile; Thus, one possible explanation is that the inflowing geothermal waters that cause the temperature anomaly originate from the underlying Mesozoic (hydraulic continuity between the Paleogene and Mesozoic is quite common in the interior basins and depressions of the Western Carpathians); either by flowing directly into the borehole or by flowing into the reservoir, where it is heated
- the temperature anomaly in the Mesozoic below 280 m depth is manifested by an increase in temperature relative to the stationary environment of $\Delta T \approx 1$ - 2 °C, while the measured temperature profile retains higher values than those of the stationary environment; one solution may be both an estimation error within the model and the possibility of vertical communication of the lower and upper carbonate complex through the borehole-identified lunar layers, e.g. by filtering along fault systems
- The above options represent the simplest solutions to the conceptual model of flow in and around the HGTP-1 well, but there is insufficient data, particularly from geothermal water analyses, to confirm or reinterpret them and to model reservoir dynamics and mixing,

or the determination of a conceptual history of the samples that is capable of identifying the depths and temperatures of the last thermodynamic equilibration.

Interpretation of the vertical temperature profile in borehole FGTz-2 is more difficult based on the single temperature profile obtained (Figure 3.11), as the measured values do not represent a stabilized geothermal environment. Prior to conducting the vertical temperature profiling, the borehole was run for an approximately 30-minute free-flow. Thus, the obtained temperature distribution curve provides a record influenced by the movement of geothermal water within the borehole, primarily from the open (perforated) section of the borehole (400 - 900 m), with subsequent conductive cooling still within the borehole due to slow movement. The reference hydrogeothermal assessment considers the section below 900 m as a thermally stable profile (REMŠÍK ET AL., 2007), which would imply a tributary zone at the base of Mesozoic dolomites. Interestingly, even at the assumed steady state, the measured temperature is lower than the modelled temperature gradient based on the geometry and geothermal parameters of the reservoir environment and its overburden. The temperature difference is ΔT ≈ 2 - 2,5 °C. The model solution assumes, based on the Mesozoic profile, temperatures in the interval T = 38 - 39 °C, the modelled temperature directly in the borehole is 37 °C, the measured temperature in the borehole is T = 34 °C (Figure 3.11 and 3.12).

According to the tectonic map of the bedrock, the FGTz-2 well is located on the edge of the tectonic cover of the local stationary minimum of the Bielica Elevated Cover. Lower measured temperatures than the temperature of the stationary environment may indicate the effect of short residence time of geothermal water in the reservoir environment, viz:

- preferential binding of circulatory pathways to nearby fault lines
- the absence of a sensu-stricto accumulation area, which would in turn confirm one of the possible scenarios of the so-called circulation system
- repeated mixing of geothermal waters and their vertical or horizontal percolation within the tectonic blocks in the vicinity of the borehole.

These processes, which significantly influence the reservoir response mode for long-term geothermal energy production, can only be interpreted from comprehensive hydrogeochemical monitoring or chemical composition data, which are not currently available.

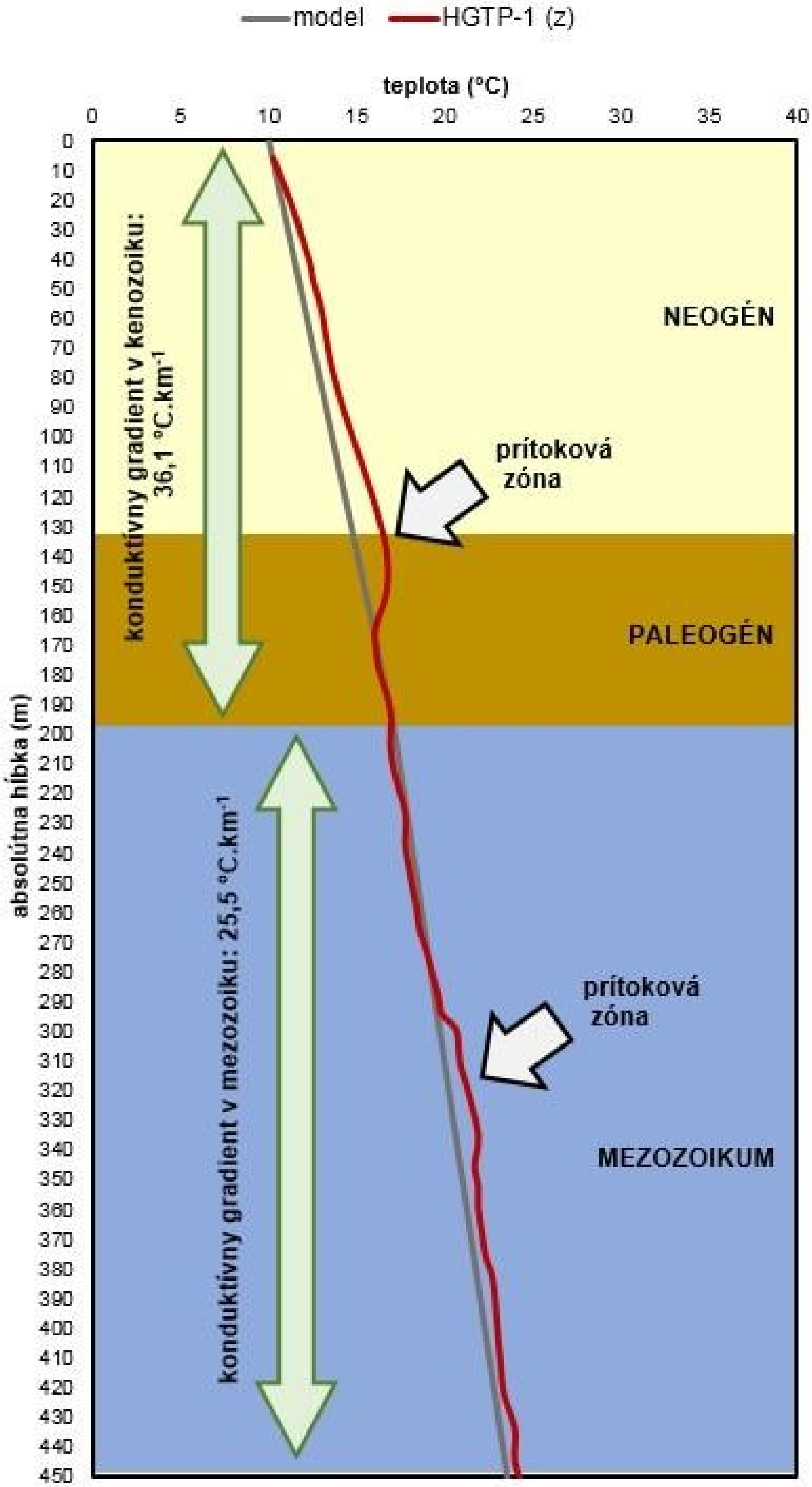

Figure 3.10: Interpretation of the vertical temperature profile in borehole HGTP-1 (Méryová, 2000) in relation to the local temperature gradient

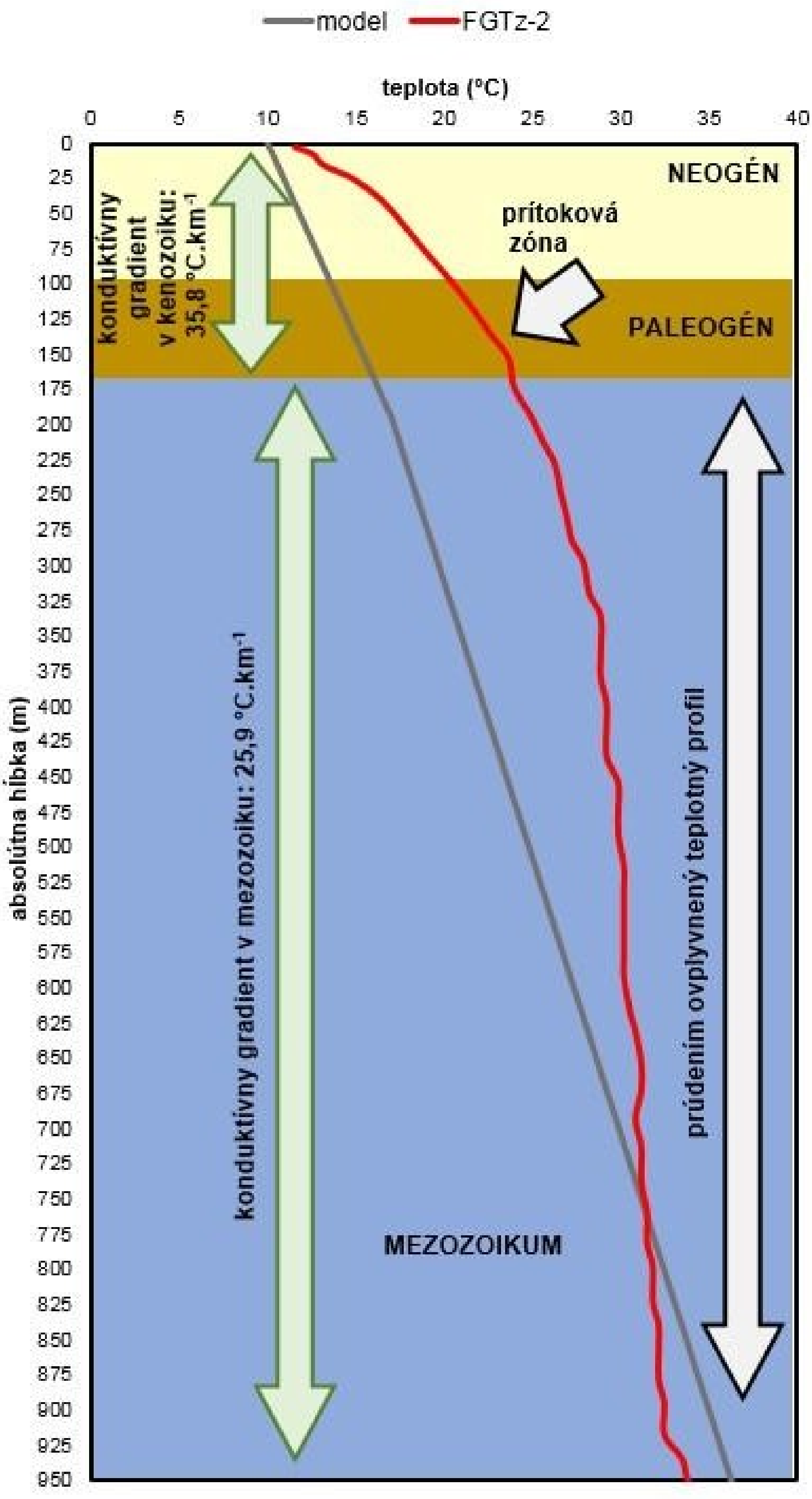

Figure 3.11: Interpretation of the vertical temperature profile in borehole FGTz-2 (Remšík et al., 2007) in relation to the local temperature gradient

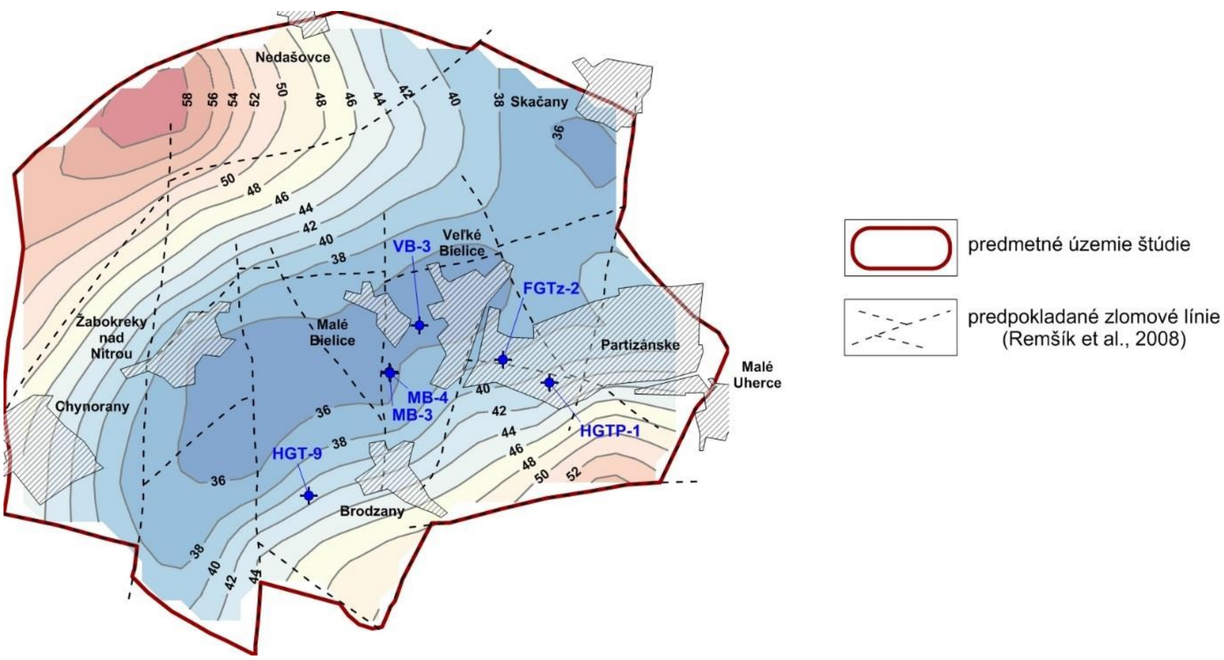

Figure 3.12: Projection of the reservoir-based temperature map (°C) onto the assumed fault systems of the Partizánske site polygon

DYNAMIC MANIFESTATIONS OF TEMPERATURE DURING HYDRODYNAMIC TESTS AND THEIR IMPLICATIONS TO THE ENVIRONMENT

Hydrodynamic tests of at least the baseline 21-day duration were conducted on wells HGTP-1 (Figure 3.12) and FGTz-2 (Figure 3.13). Practically from both hydrodynamic tests, there is a visible increase in temperature with pumping time, which is typical especially if it is the formation of a pumping-induced pressure depression during a step increase in production, or in connection with a continuous pressure drop while maintaining a constant yield, thus activating inflows from deeper open horizons (if present). These activations of the inflow horizons level off over time, depending on their filtration parameters. In a hydrogeologically confined environment, or one that is situated in a lithological/stratigraphic trap with no functional communication with the surrounding environment, these temperature trends are less pronounced, and rather there is a gradual increase in temperature as the reservoir environment is progressively depleted and inflows from the base of the reservoir are the last to be activated. During pumping interruptions (technical failures or drawdown tests), shallow inflow horizons are gradually activated (pressure between the well body and the underlying horizons equilibrates and inflows cease), and at the same time the wells undergo a conductive cooling of the geothermal water, which is usually manifested by a short-term drop in temperature to (quasi) initial values. Also for this reason, according to the results of the hydrodynamic tests, it can be assumed that the reservoir environment is obviously open.

In borehole HGTP-1 (Figure 3.13), the temperature increase is evident during the first, short section of the step-up test, which is manifested by step-ups in productivity (20.04.2000 - 24.04.2000). Rather, the constant withdrawal between 27.04.2000 and 06.05.2000 can be considered as the relevant section. It is here that a gradual temperature increase of ΔT ≈ 2 °C is visible at constant production, with minimal oscillation, which equally implies the possibility of activation of deeper inflow horizons into the borehole. However, this trend needs to be verified by long-term pumping.

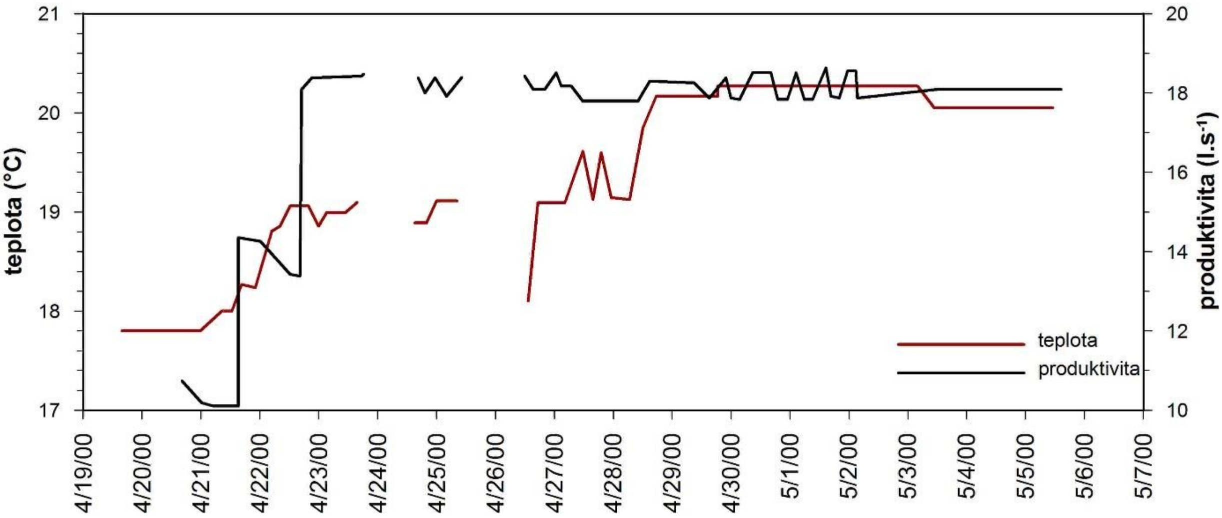

Figure 3.13: Record of hydrodynamic test on well HGTP-1 Partizánske. Modified after: Méryová (2000).

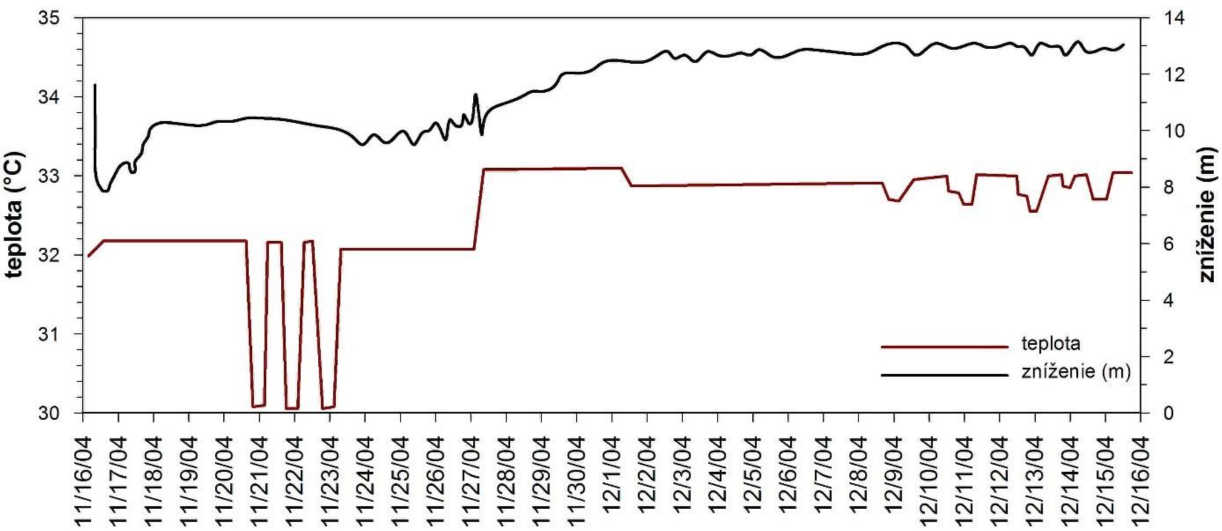

Figure 3.14: Record of hydrodynamic test on the well FGTz-2 Partizánske. Modified after Remšík et al. (2008).

A similar situation can be seen in the FGTz-2 Partizánske well (Figure 3.14), where the pumping test was carried out with a constant production strategy. Long-term pumping, which corresponds to a gradual increase in drawdown (groundwater level), resulted in a temperature increase of ΔT ≈ 1 °C. This reactivates a probably deeper inflow horizon in the boreholes, possibly deeper inflows or warmer inflows from the surrounding area. However, the hydrodynamic test is unrepresentative in the long term.

Based on the distribution of the stationary geothermal field, and also on the results of short hydrodynamic tests, it is not entirely possible to determine the mode of geothermal energy sources and communication between the Partizánske and Bielice sites. Therefore, the temperature oscillations observed towards the end of both pumping stages may indicate several scenarios:

- long-term pumping will stabilize the produced temperature with an increase of ΔT ≈ 1 - 2 °C when there is no penetration of the cold front, which in turn can be supported by communication with the southeastern part of the polygon in the direction of Partizánske, where higher temperatures are expected
- long-term pumping will stabilize the produced temperature at a level similar to the initial stage, or oscillate the temperature around the initial (initial) temperature, which means maintaining stable, current inflow profiles
- long-term pumping will lead to a decrease in the produced temperature, which would mean the activation of preferential shallow tributary horizons, or communication with the Bielice elevation and structure, even if there would be no change in the qualitative and quantitative parameters of the produced geothermal waters at the Bielice site

The influence of the lunz layers on the reservoir hydraulic parameters is insignificant in the FGTz-2 well. However, in the HGTP-1 well, there was no significant temperature increase, at least from the temperature record, during the 21 days drilled to indicate inflow from the underlying carbonate complex in their subsurface.

Nevertheless, based on the evaluation of the hydrodynamic test, we believe that the observed, measured vertical temperature profiles and the temperature record from the hydrodynamic test may indicate that both complexly and partially in the upper and lower carbonate horizons of the carbonate horizons, vertical filtration of geothermal water may occur prior to inflow to the well or during production, corresponding to multiple inflow horizons subsequently.

4 ENERGY POTENTIAL OF HYDRO-GEOTHERMAL WELLS AT THE SITE PARTIZÁNSKE

The energy potential of hydrogeothermal boreholes at the Partizánske site was calculated in relation to the reference temperature of the regional hydrogeothermal assessment in a probabilistic model and balance assessment of dynamic quantities of geothermal energy according to Table 4.1, using the balance equation /4.1/

$$P_{th} = Q_{wh} \cdot c_{wh} \cdot (T_{wh} - T_{ref}) \qquad /4.1/$$

Where: P_{th} - thermal energy output (MWt), Q_{wh} - yield ($l.s^{-1}$ / $kg.s^{-1}$), c_{wh} - specific heat capacity ($J.kg^{-1}.K^{-1}$), T_{wh} - temperature at the mouth of the production well (°C), T_{ref} - reference temperature (°C)

Table 4.1: Geothermal parameters used in the construction of the stationary geothermal model of the Bánov Basin and the Partizánske site. Modified according to: Marcin et al. (2016, 2020)

parameter	symbol	unit	HGTP-1	FGTz-2
proven productivity	Q_{pv}	$l.s^{-1}$	12,8	12,5
proven productivity	Q_{pv}	$kg.s^{-1}$	12,5	12,2
heat capacity	c_{wh}	$J.kg^{-1}.K^{-1}$	4119	4109
temperature of the GT water produced	°C	MWt	20	33
reference temperature	°C	MWt	15	15

Maintaining the temperatures included in the underlying geothermal energy resource databases for Slovakia (MARCIN ET AL., 2016, 2020), then the installed capacity of the HGTP-1 geothermal well would correspond to **$P_{th,inst}$ = 0.3 MWt**, and the installed capacity of the FGTz-2 geothermal well would reach **$P_{th,inst}$ = 1.0 MWt** (Figure 4.1 and 4.2). The combined capacity of the two wells on the inlet side of the exchanger cycle would therefore be **$P_{th,IN}$ = 1.3 MWt**.

The presented expression of the heat-energy outputs thus represents the net energy potential of the geothermal energy sources at the input of the heating cycle, and does not take into account the thermodynamic and thermal efficiency of the heat exchange itself, while still being referenced to the balance ambient temperature T_{ref} = 15 °C.

The problem with this expression of heat output is:

- The hydrodynamic tests (Figure 3.13 and 3.14) on the HGTP-1 and FGTz-2 wells cannot really be considered representative, and it is questionable how stable the temperature profile recorded by the tests is
- In view of the long-term production of geothermal energy resources and the not fully understood spatial relationships of the circulation system in the southeastern part of the Bansko Basin, it is questionable how the inflow rates to geothermal wells, and thus the potential temperatures at the mouths of the production wells before entering the energy cycle, will change with n-year production
- Based on the 21-day/30-day hydrodynamic test, even the long-term parameters of productivity/capacity alone are not sufficiently verified.

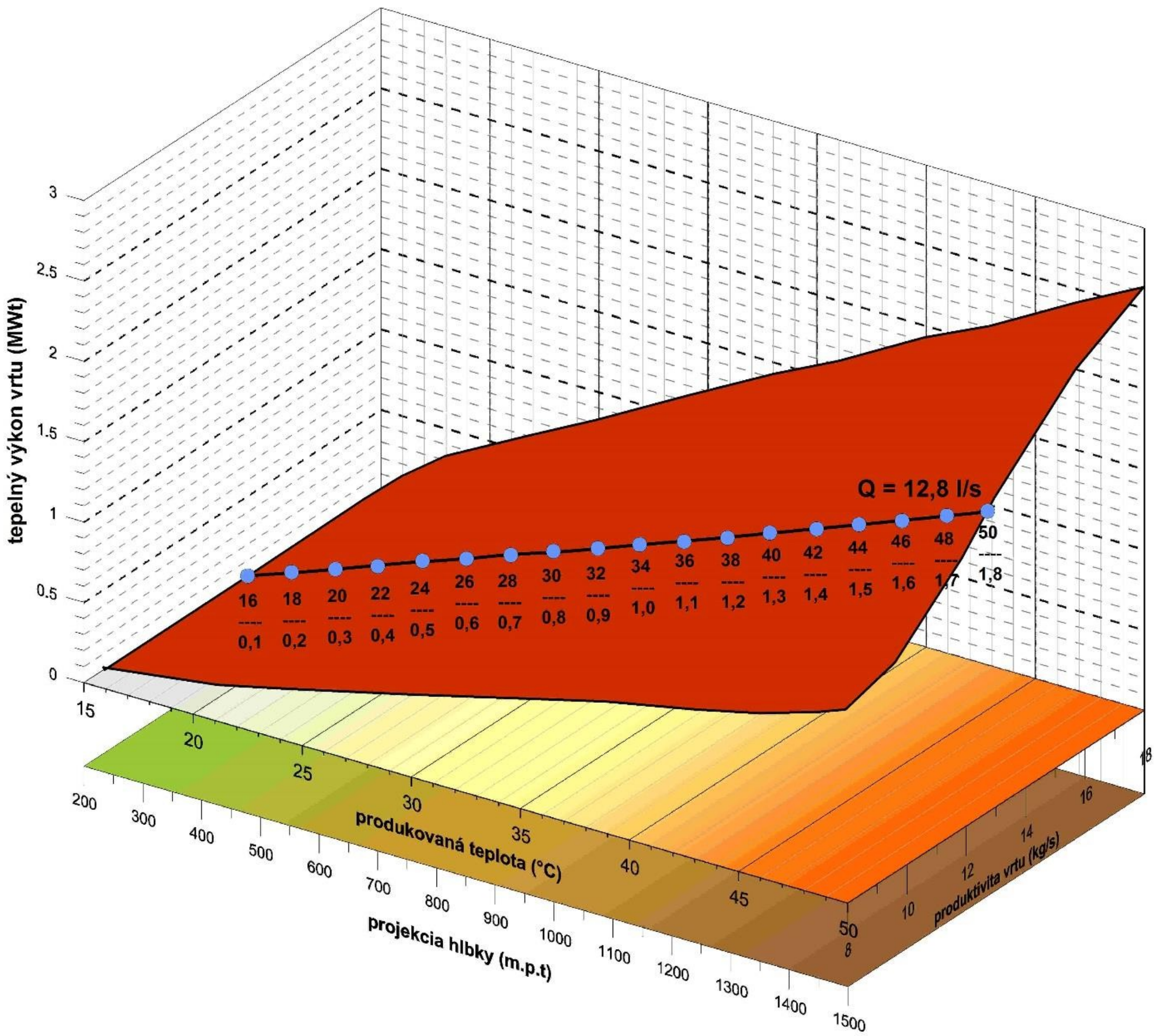

Figure 4.1: Sensitivity analysis of the thermal-energy output of the HGTP-1 Partizánské borehole according to the changes of the produced temperature and the produced quantities of geothermal water

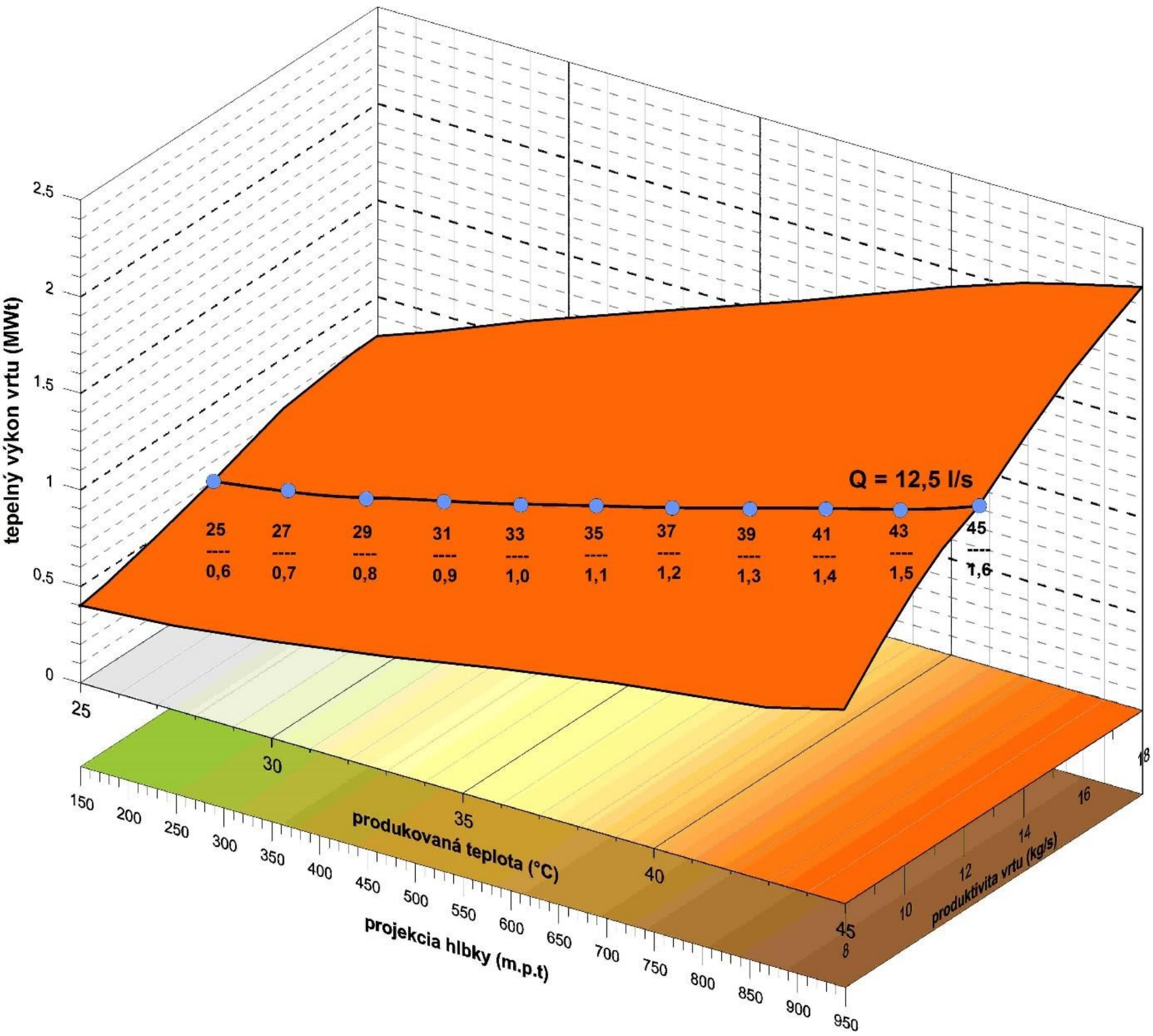

Figure 4.2: Sensitivity analysis of the thermal-energy output of the FGTz-2 Partizánske borehole according to the changes of the produced temperature and the produced quantities of geothermal water

For the HGTP-1 and FGTz-2 geothermal wells, sensitivity maps of thermal-energy output development were constructed (Figure 4.1 and 4.2; Table 4.2 and 4.3) to determine gross installed capacity as a function of variation in productivity and temperature produced. The selected temperature ranges represent estimates of the temperature achievable in the reservoir environment of the depth interval and reservoir base, respectively, based on the geothermal model, while maintaining the likely temperature loss during inflow to the well (vertical transients) and the temperature loss directly in the wells. In the case of a graphical sensitivity scheme, the level

both the "depth projection" and the approximate depth interval over which the modelled geothermal water temperature can be expected in a stationary environment.

Table 4.2: Calculation of the thermal energy output of the HGTP-1 borehole in relation to the reference temperature T_{ref} = 15 °C.

temperature (°C)	Productivity (l.s)$^{-1}$										
	8	9	10	11	12	13	14	15	16	17	18
16	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
17	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2
18	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3
19	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3
20	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4
21	0.2	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.5	0.5
22	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.5	0.5	0.5	0.6
23	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.6	0.6	0.6
24	0.3	0.4	0.4	0.4	0.5	0.5	0.6	0.6	0.6	0.7	0.7
25	0.4	0.4	0.5	0.5	0.5	0.6	0.6	0.7	0.7	0.7	0.8
26	0.4	0.4	0.5	0.5	0.6	0.6	0.7	0.7	0.8	0.8	0.8
27	0.4	0.5	0.5	0.6	0.6	0.7	0.7	0.8	0.8	0.9	0.9
28	0.5	0.5	0.6	0.6	0.7	0.7	0.8	0.8	0.9	0.9	1
29	0.5	0.6	0.6	0.7	0.7	0.8	0.8	0.9	1	1	1.1
30	0.5	0.6	0.7	0.7	0.8	0.8	0.9	1	1	1.1	1.1
31	0.6	0.6	0.7	0.8	0.8	0.9	1	1	1.1	1.1	1.2
32	0.6	0.7	0.7	0.8	0.9	0.9	1	1.1	1.1	1.2	1.3
33	0.6	0.7	0.8	0.8	0.9	1	1.1	1.1	1.2	1.3	1.4
34	0.7	0.7	0.8	0.9	1	1	1.1	1.2	1.3	1.3	1.4
35	0.7	0.8	0.9	0.9	1	1.1	1.2	1.3	1.3	1.4	1.5
36	0.7	0.8	0.9	1	1.1	1.1	1.2	1.3	1.4	1.5	1.6
37	0.8	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.6
38	0.8	0.9	1	1.1	1.2	1.2	1.3	1.4	1.5	1.6	1.7
39	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8
40	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9
41	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9
42	0.9	1	1.1	1.2	1.3	1.5	1.6	1.7	1.8	1.9	2
43	0.9	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	2	2.1
44	1	1.1	1.2	1.3	1.4	1.6	1.7	1.8	1.9	2	2.1
45	1	1.1	1.2	1.4	1.5	1.6	1.7	1.9	2	2.1	2.2
46	1	1.2	1.3	1.4	1.5	1.7	1.8	1.9	2	2.2	2.3
47	1.1	1.2	1.3	1.5	1.6	1.7	1.8	2	2.1	2.2	2.4
48	1.1	1.2	1.4	1.5	1.6	1.8	1.9	2	2.2	2.3	2.4
49	1.1	1.3	1.4	1.5	1.7	1.8	2	2.1	2.2	2.4	2.5
50	1.2	1.3	1.4	1.6	1.7	1.9	2	2.1	2.3	2.4	2.6

Table 4.3: Calculation of the thermal energy output of the FGTz-2 borehole in relation to the reference temperature T_{ref} = 15 °C.

temperature (°C)	Productivity (l.s)^-1										
	8	9	10	11	12	13	14	15	16	17	18
25	0.4	0.4	0.5	0.5	0.5	0.6	0.6	0.7	0.7	0.7	0.8
26	0.4	0.4	0.5	0.5	0.6	0.6	0.7	0.7	0.8	0.8	0.8
27	0.4	0.5	0.5	0.6	0.6	0.7	0.7	0.8	0.8	0.9	0.9
28	0.5	0.5	0.6	0.6	0.7	0.7	0.8	0.8	0.9	0.9	1
29	0.5	0.6	0.6	0.7	0.7	0.8	0.8	0.9	1	1	1.1
30	0.5	0.6	0.7	0.7	0.8	0.8	0.9	1	1	1.1	1.1
31	0.6	0.6	0.7	0.8	0.8	0.9	1	1	1.1	1.1	1.2
32	0.6	0.7	0.7	0.8	0.9	0.9	1	1.1	1.1	1.2	1.3
33	0.6	0.7	0.8	0.8	0.9	1	1.1	1.1	1.2	1.3	1.4
34	0.7	0.7	0.8	0.9	1	1	1.1	1.2	1.3	1.3	1.4
35	0.7	0.8	0.9	0.9	1	1.1	1.2	1.3	1.3	1.4	1.5
36	0.7	0.8	0.9	1	1.1	1.1	1.2	1.3	1.4	1.5	1.6
37	0.8	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.6
38	0.8	0.9	1	1.1	1.2	1.2	1.3	1.4	1.5	1.6	1.7
39	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8
40	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9
41	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9
42	0.9	1	1.1	1.2	1.3	1.5	1.6	1.7	1.8	1.9	2
43	0.9	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	2	2.1
44	1	1.1	1.2	1.3	1.4	1.6	1.7	1.8	1.9	2	2.1
45	1	1.1	1.2	1.4	1.5	1.6	1.7	1.9	2	2.1	2.2

A very important fact in the whole calculation of the energy potential of the geothermal wells is also the fact that **the productivity of both wells has not yet been verified by a joint hydrodynamic test assuming their simultaneous production**, i.e. there has been no verification of their real possibility to produce the long-term predicted/verified yields; and that **the productivity of both wells has not yet been verified by a joint hydrodynamic test with the currently used well MB-3 Malé Bielice**, even in relation to the preservation of the natural springs on the site. For this reason, it is necessary to treat the results of the energy balance and energy sensitivity balance of the HGTP-1 and FGTz-2 wells as indicative until verification, operational hydrodynamic testing and production monitoring with the necessary interaction and reservoir response modelling has been carried out.

5 ENERGY POTENTIAL OF THE RESERVOIR ENVIRONMENT

5.1 Energy balance of the reservoir environment

The estimation of the total energy potential of the reservoir environment, i.e. the Upper Triassic (main dolomite) and Lower Triassic carbonates of the hronik was solved within the geological task "*Analysis of the possibilities of sustainable use and exploitation of geothermal energy resources in Slovakia - Part I*" (FRIČOVSKÝ ET AL., 2024) at two parallel levels: in terms of the energy balance of the reservoir (total energy potential vs. sustainable energy potential); and in terms of the time component of the reservoir production (long-term - 100 years vs. short-term - 40 years of geothermal energy production).

5.1.1 Total heat-energy potential

According to the global model for estimating the total and sustainable energy potential of geothermal energy resources in Slovakia (FRIČOVSKÝ ET AL., 2024), the USGS volumetric method (MUFFLER - CATALDI, 1978; GRANT, 2014; GARG - COMBS, 2015) subjected to Monte Carlo probabilistic simulation /5.1/ was used to determine the total amount of energy stored in the reservoir environment:

$$E_T = E_M + E_W + E_V \quad \begin{cases} E_M = A_t.\Delta z.[\rho_m.c_m.(1-\phi).(T_{res}-T_{ref})] \\ E_W = A_t.\Delta z.\rho_W.c_W.\phi.(T_{res}-T_{ref}).S_W \\ E_S = A_t.\Delta z.\rho_S.c_S.\phi.(h_{res}-h_{ref}).(1-S_W) \\ T_{ref} \in \langle T_{ref};T_{inj}\rangle \\ S_W \in \langle 0;1\rangle \end{cases} \qquad /5.1/$$

where: variables **in bold** are conditional probabilistic simulations in the model according to functional distribution histograms based on a stationary geothermal model, and underlined constants, the remaining parameters represent functional relationships to the simulated quantities;

and at the same time where: E - amount of energy (J), symbols Mm, Ww and Vv - denote the rock environment, water component and vapour phase (if in thermodynamically separated form), **At** - reservoir area (m^2), **Δz** - thickness of the reservoir environment corrected by the simulated estimation of the thickness of the effective profile (m), ρ - specific bulk density ($kg.m^{-3}$), c - specific heat capacity ($J.kg^{-1}.K^{-1}$), ϕ - porosity (-), **Tres** - reservoir temperature, Tref - reference temperature, **hres** - specific enthalpy of the vapor fraction ($kJ.kg^{-1}$), href - specific enthalpy of the aqueous component at the reference temperature ($kJ.kg^{-1}$), **sw** - saturation of the pores with the aqueous component (-);

and where: ϕ is a functional relation to the depth of the definition point **z(DP)** at the centre of the reservoir environment, which is a simulation of the carbonate ceiling depth and carbonate thickness; ρw is a functional relation to Tres, ρm is a functional relation to ϕ, cw is a functional relation to temperature, and cm is a functional relation to ρm.

The result of the simulation according to /5.1/ is the definition of the total amount of heat in the reservoir system, which represents the so-called energy base. This is the modelled distribution of heat in the reservoir environment, which is hypothetically accumulated in relation to a given reference temperature. Consequently, the available heat / available geothermal energy quantity E0 /5.2/ expresses the amount of heat technically and technologically recoverable from the reservoir environment (MUFFLER - CATALDI, 1978; GRANT, 2014; GARG - COMBS, 2015):

$$E_0 = E_T \cdot R0 \qquad /5.2/.$$

The available amount of geothermal energy has long been (incorrectly) referred to in the domestic literature as the "renewable amount of geothermal energy", as it is a function of the geothermal energy availability coefficient R0, which has been (equally incorrectly) referred to as the renewability coefficient (FRIČOVSKÝ ET AL, 2024); while, however, it has nothing to do with the renewability and recovery of the energy component of the reservoir environment, but expresses the degree of possibility of obtaining geothermal energy from the reservoir environment under given geological, geothermal, hydrogeological and hydraulic conditions (e.g. GRANT - BIXLEY, 2011; GRANT, 2014; GARG - COMBS, 2010, 2011, 2015; CIRIACO ET AL., 2020).

The geothermal energy availability factor R0 is a critical part of the application of the USGS volumetric method. In reference hydrogeothermal evaluations, the constant R0 = 0.1 has been used (FENDEK ET AL., 1985; FENDEK ET AL., 2005; REMŠÍK ET AL., 2007); however

without broader explanation, at based on convection exploitation R0in regional hydrogeothermal assessments of Slovakia (FRANKO ET AL., 1995; FENDEK ET AL., 2005), but without real conceptual basis.

The probabilistic model (FRIČOVSKÝ ET AL., 2024) limits the risks arising from the constants, and by applying conditional probabilistic Monte Carlo simulation, uses a dynamic estimation of R0 based on the parameters of a specific geothermal water body. In the case of the Banova Basin, the effective reservoir volume method was used (SANYAL - BUTTLER, 2005; TESTER ET AL., 2006; WILLIAMS ET AL., 2008; FOX ET AL., 2014; FRIČOVSKÝ ET AL., 2023, 2024) /5.3/ expressing the amount of geothermal energy available in the energy prospective portion of the reservoir:

$$R0 = \frac{A_e.\Delta z_e.\boldsymbol{\Phi}_e}{A.\Delta z.\boldsymbol{\Phi}_e}.\frac{0,9Tres_{,ini}}{\left(Tres_{,ini} - T_{ref}\right)} = \frac{A_e.\Delta z_e.\boldsymbol{\Phi}_e}{A.\Delta z.\boldsymbol{\Phi}_e}.\frac{T_{cool}}{\left(Tres_{,ini} - T_{ref}\right)} \qquad /5.3/$$

where: variables **in bold** are the variables in the model conditional on probabilistic simulation according to functional distribution histograms based on a stationary geothermal model, and underlined constants, the remaining parameters represent functional relationships to the simulated quantities;

and where the symbol "e" represents the effective/prospective area of the formation, A - area of the reservoir environment (m^2), **A_e** - area of the effective or prospective area (m^2), **Δz** - thickness of the reservoir environment corrected for the effective profile (m), ϕ - porosity (-), **$Tres_{,ini}$** - stationary reservoir temperature (°C), T_{cool} - tolerated cooling temperature (°C), t.10 % with respect to the initial conditions, T_{ref} - reference temperature (°C).

The last step is the conversion of the heat quantity to the energy balance of the environment according to relation /5.4/ (MUFFLER - CATALDI, 1978):

$$H_0 = \frac{E_T \, . \, R0}{t_{prod}} = \frac{E_0}{t_{prod}}$$

where: t_{prod} represents the balance production time for which the energy capacity of the reservoir environment is evaluated (s, years).

In terms of the construction of probabilistic models for the estimation of geothermal energy resources and reserves in global reservoir engineering practice, the obtained IDF distribution curves of the H_0 energy balance (Figures 5.1 and 5.2) are then used for the determination of the geological certainty classes and the McKelvey scheme, respectively, according to Tables 5.1 and 5.2 (SANYAL - SARMIENTO, 2005; WILLIAMS ET AL., 2010; CIRIACO ET AL., 2020).

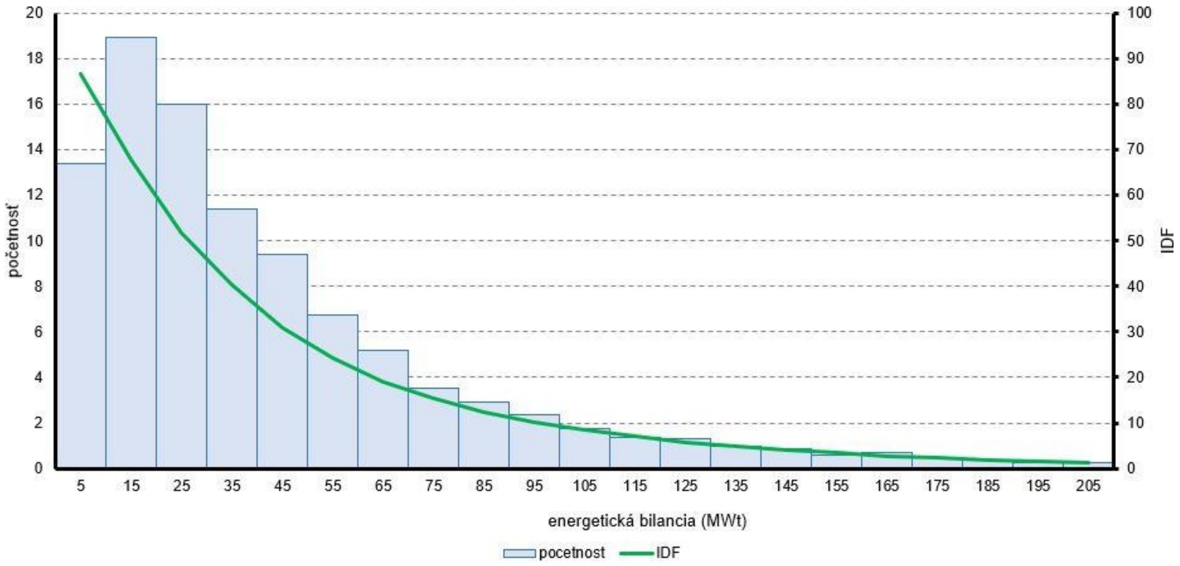

Figure 5.1: Probabilistic model of the energy balance of the reservoir environment of the Banova Basin for a production time of 40 years. Modified after Fričovský et al. (2024)

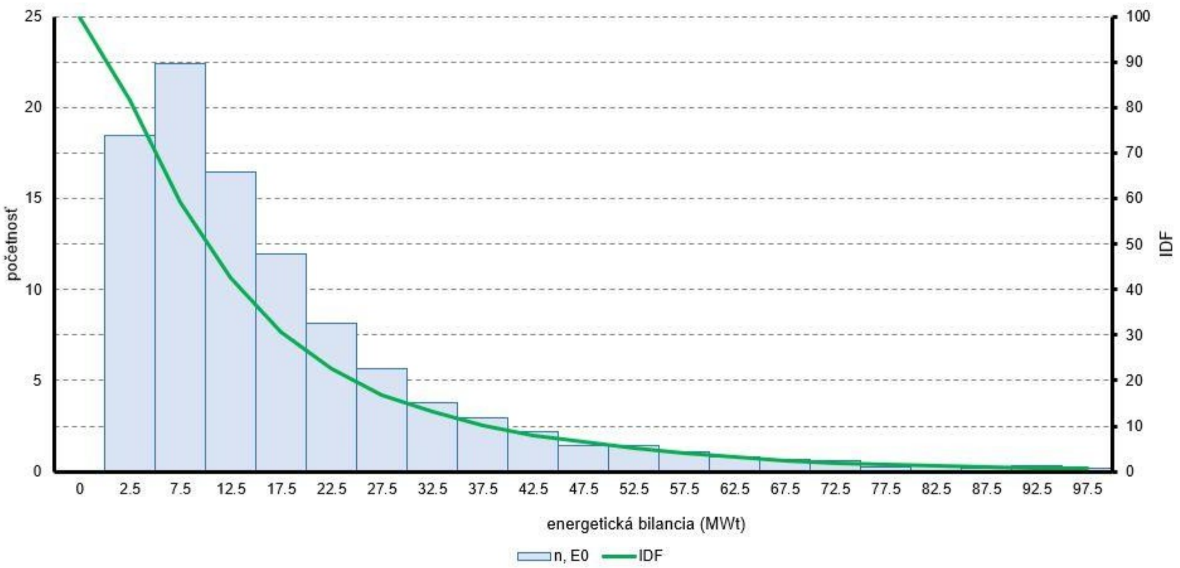

Figure 5.2: Probabilistic model of the energy balance of the reservoir environment of the Banova Basin for a production time of 100 years. Modified after Fričovský et al. (2024)

The probabilistic model estimation of the thermal-energy potential for the Bánov Basin reservoir shows a significant bias in both cases, which is mainly due to temperature anomalies in the central depression of the Bánov Basin, affecting both the energy balance of the reservoir and the simulated distribution of the geothermal energy availability coefficient R0 (FRICOVSKÝ ET AL., 2024).

Table 5.1: Energy balance of the reservoir environment of the Banovská basin. Modified after Fričovský et al. (2024)

McKelvey scheme category	unit	symbol	40 years	100 years
verified stocks	MWt	Rpv	5,6	5,6
probable stocks	MWt	Rpb	23	9
estimated stocks	MWt	Rinf	70	28
geothermal energy reserves	MWt	RET	98	43
geothermal energy sources	MWt	RST	1389	552
Technical TEP	MWt	TTP	29	15
probable TEP	MWt	$TPP_{(p)}$	31	13

Table 5.2: Principles of construction of the probabilistic model of the McKelvey scheme. Modified from: Sanyal - Sarmiento (2005), Grant (2014)

Category	geological-geothermal characteristics	probabilistic characteristic
geothermal energy sources	- energy stored in the system - limited technical and technological availability - lowest probability class	$RS_T < \mathrm{P10}(E)$
Indicated/derived stocks	- without drilling demonstration - solid indications by analogy with proven systems and structures - thermal, geophysical, geochemical indications or manifestations - high likelihood of reassessment when drilling or upgrading input parameters	$R_{\inf} = \mathrm{P10}(E) \boxtimes \mathrm{Md}(E)$ if $\mathrm{Md}(E) < \mathrm{P50}(E)$ $R_{\inf} = \mathrm{P10}(E) \boxtimes \mathrm{P50}(E)$ if $\mathrm{Md}(E) > \mathrm{P50}(E)$
probable stocks	- demonstrated by defensible numerical, geophysical and geochemical modelling results - indicated by direct or indirect surface and subsurface symptoms - proximity to geothermal wells	$R_{pb} = \mathrm{Md}(E) \boxtimes \mathrm{P90}(E)$ if $\mathrm{Md}(E) < \mathrm{P50}(E)$ $R_{pb} = \mathrm{P50}(E) \boxtimes \mathrm{P90}(E)$ if $\mathrm{Md}(E) > \mathrm{P50}(E)$
verified stocks	- part of the geothermal energy reserves successfully verified by drilling and sufficient monitoring - drilling, monitoring and testing activities will not have a significant impact on the recalibration of the estimated quantity of proven reserves - practically represent the installed capacity of a geothermal borehole , or the sum of the installed capacity of geothermal boreholes within the evaluated GT field	$R_{pv} > \mathrm{P90}(E)$

According to Table 5.2, the **probable thermal energy potential TTP(p)** defined at the estimation level E = $_{H0}$ (according to /5.4/) represents the maximum amount of geothermal energy bound to the reservoir environment that can be verified with a probability of 50 %, which also corresponds to the critical limit of tolerable risk /5.5/

$$TTP_{(P)} = R_{pb} + P90(H)_0 \qquad /5.5/.$$

The likely thermal energy potential is then used in the model to estimate the sustainable reservoir capacity.

5.1.2 Sustainable reservoir capacity estimation model

According to the Sustainable Reservoir Management Concept (AXELSSON ET AL., 2001), sustainable reservoir capacity represents the amount of geothermal energy present in the reservoir environment that can be produced for a given period of time so as to minimize the risk of its quantitative and qualitative depletion.

The model for estimating sustainable reservoir capacity is based on the storage capacity factor method /5.6/, which in the original version (BJARNADOTTIR, 2010) expresses a measure of the amount of energy used against a discrete amount of geothermal energy in the reservoir:

$$r_{cap} = \overline{R_{pb} ⊠ R_{pv} R_{pb}} \qquad /5.6/$$

where: r_{cap} - reserve capacity factor (-), R_{pb} - amount of geothermal energy in the reservoir (MWt), R_{pv} - verified / produced amount of geothermal energy (MWt).

The original method was subsequently modified into the form of a general notation /5.7/ (FRIČOVSKÝ ET AL., 2020, 2024; MARCIN ET AL., 2020), which takes into account the results of the probabilistic model in relation to the amount of geothermal energy that can be extracted from the system:

$$r_{cap(U)} = \frac{TTP_{(p)} - P_{th,ref}}{TTP_{(p)}} = \frac{TTP_{(p)} - \sum_{i=1}^{n} Pth_{,ref(i)}}{TTP_{(p)}} = \frac{P50(H_0/t_{prod}) - \sum_{i=1}^{n} Pth_{,ref(i)}}{TTP\,P50(H_0/t_{prod})} \qquad /5.7/$$

where: $Pth_{,ref}$ represents the amount of geothermal energy extracted from the system at the T_{ref} reference temperature (MWt); the symbol (U) denotes the referencing of the storage capacity factor to the actual use.

In both modifications of the storage capacity factor method, the critical sustainable reservoir capacity $Pth_{(S)}$ /5.8/ is equal to the storage capacity factor $r_{cap} = 0.5$ (BJARNADOTTIR, 2010; FRIČOVSKÝ ET AL., 2024); and thus represents a maximum of 50% of the probable thermal-energy potential:

$$P_{th(S)} = 0,5.TTP_{(p)} = 0,5.\left[\frac{(P50(H_0)).R0}{t_{prod}}\right] = 0,5.P50\left(\frac{H_0}{t_{prod}}\right) \qquad /5.8/.$$

By fitting the estimation results to $TTP_{(p)}$, it is then possible to estimate:

- for a production period of 40 years: $Pth_{(S,40)} = 15$ MWt
- for a production period of 100 years: $Pth_{(S,100)} = 7$ MWt

Consequently, the amount of geothermal energy available for use at its current production can be expressed through the sustainable development potential of current geothermal energy production $Pth_{(D)}$ /5.9/, which by definition means the amount of geothermal energy that is available in the reservoir environment at its current level of use without compromising its sustainable energy capacity $Pth_{(S)}$:

$$Pth_{(D)} = Pth_{,(S)} - Pth_{,ref} = 0,5.TTP_{(P)} - Pth_{,ref} = 0,5.\left[P50\left(\frac{H_0}{t_{prod}}\right)\right] - \left[Q_{act}.c_{wh}.(T_{wh} - T_{ref})\right] \qquad /5.9/.$$

5.1.3 Current status of the use and exploitation of geothermal energy resources in the Bánov Basin

According to current long-term data, geothermal energy resources in the Bánov Basin (FRIČOVSKÝ ET AL., 2023) are exploited at 3 locations for recreational purposes (Malé Bielice, Partizánske, Bánovce nad Bebravou). Since $Pth_{(D)}$ is a function of the so-called thermal reference power (i.e. the amount of geothermal energy extracted from the reservoir relative to the reference temperature) $Pth_{,ref}$ /5.10/ data from the 2011-2022 monitoring period (MARCIN ET AL., 2016, 2020; FRIČOVSKÝ ET AL., 2024) on the amounts of extracted geothermal water were used:

$$Pth_{,ref} = Q_{act} \cdot c_{wh} \cdot (T_{wh} - T_{ref}) \qquad T_{ref} = 15°C \qquad Q_{act} \in \langle 0; Q_{pv} \rangle \qquad /5.10/$$

Where: q_{act} - actual monthly geothermal water produced (kg.s^{-1}), c_{wh} - specific heat energy capacity of geothermal water at the production wellhead (J.kg^{-1} .K^{-1}), T_{wh} - temperature of geothermal water at the wellhead (°C), T_{ref} - reference ambient temperature (°C)

Cumulative geothermal water quantities during the study period ranged from Q = 0.21 - 0.23 .10^{6} m^{3} , corresponding to annual cumulative averages of Q = 6.9 - 9.6 l.s^{-1} . The detailed production of geothermal water quantities is given in Figure 5.3.

For a reference temperature of T_{ref} = 15 °C, the reference heat outputs, thus corresponding to the amount of geothermal energy extracted from the reservoir relative to the same reference temperature, amounted to the same reference temperature as the basin-wide ambient energy capacity $Pth_{,ref}$ = 0.3 - 1.1 MWt (Figure 5.4).

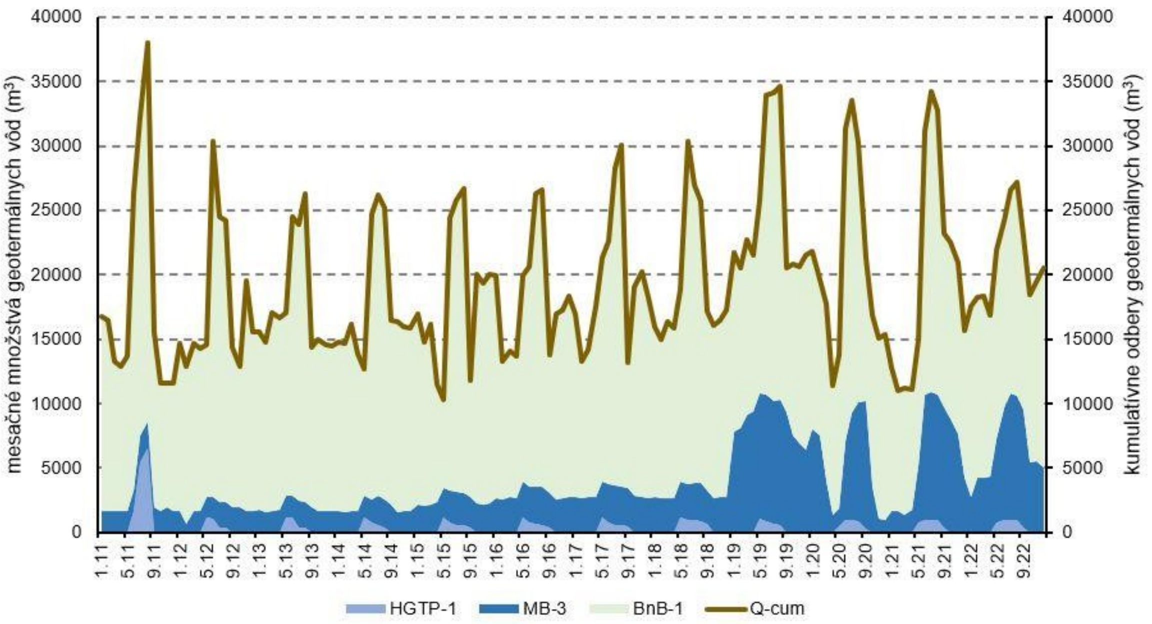

Figure 5.3: Geothermal water abstraction in the Banovská basin for the period 01/2011 to 12/2022

5.1.4 Potential for the development of geothermal energy production in Bánovská basins

With an average monthly variability of the reference thermal output $Pth_{,ref}$ = 0.3 - 1.1 MWt (Figure 5.4), in the period 01/2011 to 12/2022, it can be expected that it was available at all times after plugging into the expression /5.9/:

- $Pth_{(D)}$ = 13.9 - 14.8 MWt for the short-term production horizon, respectively
- $Pth_{(D)}$ = 5.9 - 6.7 MWt for the long-term production horizon;

which means that 92-98% of sustainable energy capacity was still available for the short-term production horizon, or 40-45% of sustainable energy capacity for the long-term production horizon.

Both of the above models for the short-term and long-term production horizons show that **from the point of view of the energy balance of the reservoir environment, it is possible to continue the development of geothermal energy production from the carbonates of the hronik, including the Partizánske site**. However, the amount of geothermal energy available at the Partizánske site is conditional on its hydrogeological balance if production is not based on the use of doublets.

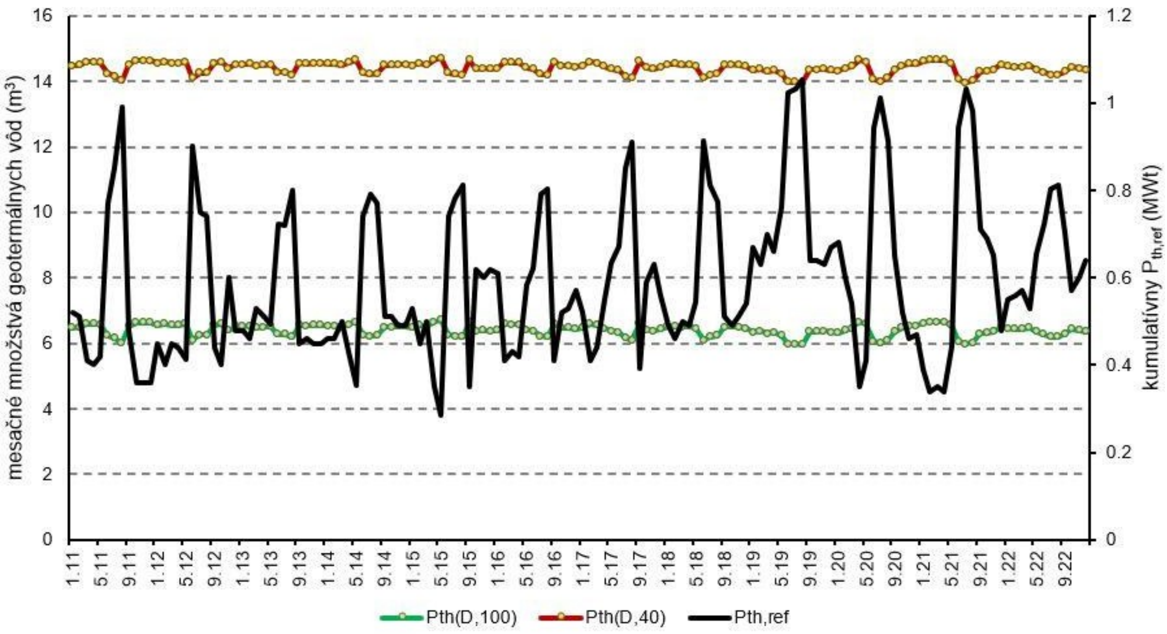

Figure 5.4: Evolution of cumulative quantities of geothermal energy withdrawals in relation to the sustainable development potential in the Banov Basin for the period 01/2011 to 12/2022

5.2 Hydrogeothermal balance of the defined polygon of the Partizánske locality

The hydrogeothermal balance method is used to determine the quantities of geothermal water whose production should be in accordance with the amount of heat passing through the reservoir system so that its geothermal equilibrium is not disturbed; however, its use for determining "forecast quantities" or "dynamic quantities" of geothermal energy is questionable, as it is based on parametric and conceptual models of convective, volcanic systems (WHITE - WILLIAMS, 1975; FENDEK ET AL., 2005; FRICOVSKY ET AL., 2024).

$$Q_{dyn} = \sum_{i=1}^{n} \frac{A.q_0}{(T_{res} - T_S).c_w.\rho_w} \qquad /5.11/$$

Where: q_{dyn} - dynamic, equilibrium quantities of geothermal water ($m^3.s^{-1}$), A - area of the respective heat flux density level (m^2), q_{top} - heat flux density at the surface of the horizon of interest ($mW.m^{-2}$), T_{res} - average temperature of the stationary model at a given horizon (°C), T_S - surface temperature (°C), c_w - specific heat capacity of the reservoir medium at a given temperature ($J.kg^{-1}.K^{-1}$), ρ_w - specific bulk density of the reservoir medium at a given temperature ($kg.m)^{-3}$

A standard and common error in the use of this method in Slovak conditions is its reference to the surface heat flux density, which probably results from the adoption of the method in hydrothermal systems where convective flows repeatedly reach the surface, or the convective additions to the total heat flux density from the reservoir environment overlap the radiogenic component of heat production in the overburden. In the predominantly-conductive environment of hydrogeothermal systems in Slovakia, this procedure must be corrected for the **heat flux density at the surface of the target reservoir environment**, in this case the carbonates of the graben.

The second recurring error is the use of the average value of the heat flux density and the average temperature over the whole structure. In both cases, this is a significant error as this approach neglects the distribution of potential anomalies of geothermal activity and the different reservoir geometry, which in a predominantly-conductive environment also affects the distribution of geothermally stable (stationary) reservoir temperature.

The balance was applied for comparison both in the area of the defined carbonate cover of the hronik (REMŠÍK ET AL., 2007) and for the defined polygon surrounding the Partizánske site. By substituting the values from Table 5.3 into relation /5.11/ the following results can be obtained (Figure 5.5):

- Q_{dyn} = 237 $kg.s^{-1}$ and Q_{dyn} = 250 $l.s^{-1}$ respectively for the defined reservoir environment of the carbonate chronite throughout the Banská basin
- Q_{dyn} = 30 $kg.s^{-1}$ and **Q_{dyn} = 32 $l.s^{-1}$** for the defined reservoir environment of the Partizánske site polygon, respectively.

Table 5.3A: Representative parameters used in the hydrogeothermal balance of the reservoir environment of the Banovská basin

$q_{top,min}$	$q_{top,max}$	$A_{(q,i)}$	T_{res}	β_{vw}	ρ_w	c_w	$Q_{dyn,i}$	$Q_{dyn,i}$	$Q_{dyn,i}$
$mW.m^{-2}$	$mW.m^{-2}$	km^2	°C	$1.K^{-1}$	$kg.m^{-3}$	$J.kg^{-1}.K^{-1}$	$m^3.s^{-1}$	$kg.s^{-1}$	$l.s^{-1}$
69	70	21,1	29	0,0003	954,4	4215	0,027	25	27
68	69	126,1	34	0,0003	951,4	4218	0,113	107	113
67	68	169,1	48	0,0005	945,9	4212	0,086	82	86
66	67	46,2	62	0,0006	944,2	4192	0,016	16	16
65	66	22,2	86	0,0008	949,6	4125	0,005	5	5
64	65	12,5	108	0,001	964,1	4026	0,002	2	2

Table 5.3B: Representative parameters used in the hydrogeothermal balance of the reservoir environment of the Partizánske site polygon

$q_{top,min}$	$q_{top,max}$	$A_{(q,i)}$	Tres	βvw	ρw	cw	$Qdyn_{,i}$	$Qdyn_{,i}$	$Qdyn_{,i}$
$mW.m^{-2}$	$mW.m^{-2}$	km^2	°C	$1.K^{-1}$	$kg.m^{-3}$	$J.kg^{-1}.K^{-1}$	$m^3.s^{-1}$	$kg.s^{-1}$	$l.s^{-1}$
67	68	169,1	29	0,0003	954,1	4216	0,003	3	3
66	67	46,2	40	0,0004	948,6	4217	0,019	18	19
65	66	22,2	55	0,0005	944,6	4205	0,011	10	11

The input parameters are obtained from the stationary geothermal model of the Banova basin within the construction of its probabilistic model. It should be emphasized that the obtained **dynamic quantities of geothermal waters are related to the defined polygon of the Partizánske site, and these quantities vary as a function of area and heat flux density, therefore they should be seen as indicative, and subsequently verified by hydrodynamic tests**.

For correction of the equilibrium quantities, which theoretically are taken into account in the increase of the central heat supply systems of the town of Partizánske, it is necessary to deduct from the energy balance the verified productivity of geothermal waters in the borehole MB-3, which is currently the only one in use /5.12/

$$Q_{ball} = Q_{dyn} - Q_{MB\text{-}3,pv} = 32 - 8,5 = 23,5 \; [l.s^{-1}] \qquad /5.12/.$$

Equilibrium quantities should ensure energy balance in case of simultaneous production at the Malé Bielice site and the Partizánske site. **However, these quantities do not represent the hydraulic equilibrium between the two sites, which must be verified by regime measurements, hydrodynamic tests and continuous monitoring**. According to the energy balance, the agreement between **Q_{bal} = 23.5 $l.s^{-1}$** and $Qpv_{,FGTz\text{-}2}$ = 12.5 $l.s^{-1}$, respectively $Qpv_{,HGTP\text{-}1}$ = 12.8 $l.s^{-1}$, which have been verified at both wells (REMŠÍK ET AL., 2007). If the average temperature of the stationary reservoir environment in the Partizánske polygon is T_{res} = 41 °C according to the stationary geothermal model and as a representative productivity under ideal condition, the modelled equilibrium geothermal water quantities Q_{bal} will be substituted into the relation for the calculation of the heat and power output /5.13/, then assuming their verification:

$$Pth_{,BAL} = Q_{bal} \cdot c_{wh} \cdot (T_{wh} - T_{ref})$$
$$\Rightarrow Pth_{,BAL} = 23,5 \times 4102 \times (41-15)$$
$$\Rightarrow Pth_{,BAL} = 2,5 \; [MWt] \qquad /5.13/.$$

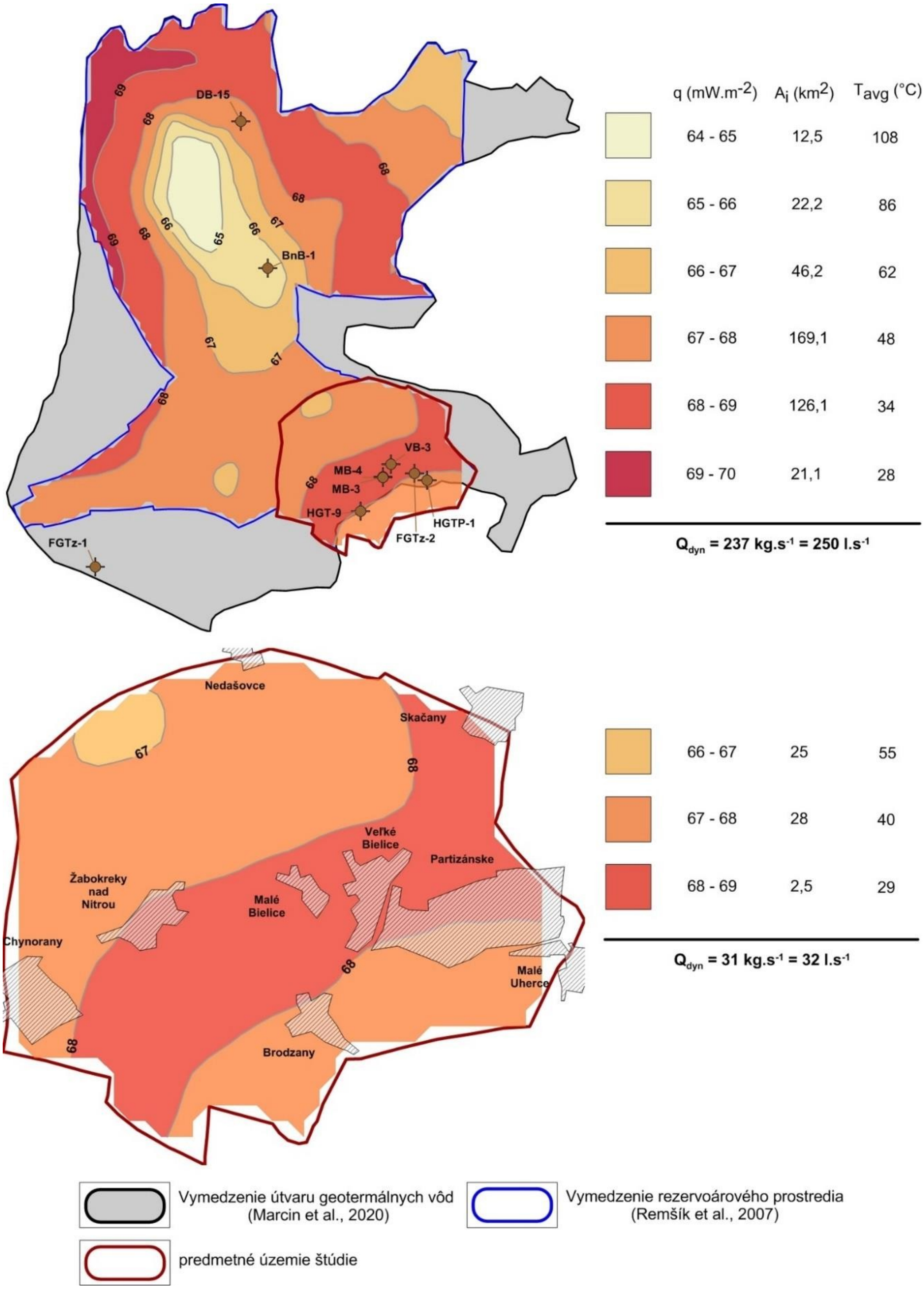

Figure 5.5: Calculation parameters for the hydrogeothermal balance of the reservoir environment of the tectonic unit hronika (top) and the defined polygon of the Partizánske site (bottom)

As a result, then, if the hydrogeological regime is constrained by the distribution of fault systems separating the eastern part of the Bielica hydrogeothermal structure as defined by Remšík et al. (2008) - which needs to be verified by hydrodynamic tests - then the maximum balance heat capacity may be **$Pth_{,BAL}$ = 2.5 MWt, which** would correspond, given the verified amounts of geothermal energy, to approximately their maximum productivity at simultaneous pumping.

At the current state of knowledge of the geothermal, hydrogeological and hydraulic conditions of the reservoir, where a common hydrodynamic (operational, semi-operational) long term scale is missing, it is recommended in the energy calculations to calculate the maximum geothermal water production at the level of **Q_{bal} = 23.5 $l.s^{-1}$** , which corresponds **to a balance heat capacity of $Pth_{,BAL}$ = 2.5 MWt**, which is unlikely to be exceeded. As a result then:

- If the long-term hydrodynamic test re-verifies the geothermal waters at their current level, i.e. with a summary result of Q_{pv} = 25.3 $l.s^{-1}$, it will be necessary to update the monitoring plan between the boreholes operating within the Partizánske project and Mali Bielice, including the intercepted springs in the local spring field, so that:
    - increased certainty that the quantities of geothermal water produced do not affect their surroundings hydraulically (pressure regime changes)
    - the certainty that a defined polygon defined on tectonic lines does not communicate with its surroundings is increased
    - the production system of the low-temperature central heat supply will be stable in terms of geothermal water productivity
    - the possibility of early identification of adverse reservoir response manifestations is increased in the event of long-term changes in the circulation, filtration, chemical or thermal parameters of the reservoir environment and reservoir medium
- If the long-term hydrodynamic test fails to re-verify the geothermal waters at wells HGTP-1 and FGTz-2 at Q_{pv} = 25.3 $l.s^{-1}$ (independently verified) and Q_{bal} = 23.5 $l.s^{-1}$ (balance), respectively; but with the reason for non-verification being insufficient yield, then the choice of actions to consider are:
    - implementation of additional drilling in the reservoir environment of the reservoir in order to achieve at least balance, equilibrium quantities of geothermal water
    - implementation of additional drilling in the reservoir environment of fatrik with different balance, filtration and circulation properties

- If the long-term hydrodynamic test does not re-verify the geothermal waters and their productivity at wells HGTP-1 and FGTz-2 at Q_{pv} = 25.3 $l.s^{-1}$ and Q_{bal} = 23.5 $l.s^{-1}$, respectively; with the reason being the impact on the source and discharge rates and the groundwater/thermal water quality at the Malé Bielice site, then the following is for consideration:
  - to verify the productivity at the Partizánské site by a long-term hydrodynamic test, which would maintain the quantitative and qualitative state of the waters at the Bieleška site, at the cost of reducing the productivity at the Partizánské site (which will be necessary)
  - to carry out tracer tests to verify the production and communication status of the geothermal waters of the lower part of the reservoir in the underlying lunz aquifer, or to verify directly in the lower horizon of the reservoir the possibilities of hydraulic communication between the two horizons by managing long-term pumping even with extreme drawdown
  - in the case of positive results that would verify the hydraulic independence of the lower horizon of the Choc fault, to carry out additional drilling or deepening of the existing borehole to the level of the lower horizon
  - Consider exploratory deep drilling to identify the reservoir environment in the underlying tectonic unit - the Križňan fault (fatrikum).

5.3 Discussion on the potential of the geological environment in the Križňany fault (fatrik)

One of the solutions to the situation at the Partizánske site is the possibility of a comprehensive hydrogeothermal survey of the site in order to identify or verify the **reservoir environment of the lower tectonic unit bound to the Križňany escarpment - the fatrikum**. The map of the pre-Tertiary bedrock (FUSÁN ET AL., 1985; REMŠÍK ET AL. 2007) assumes the distribution of fatrik sequences directly in the bedrock of the Cenozoic profile between the Žabokreky nad Nitrou - Zlatníky and Bošany - Tesáre lines, respectively north of the Kšinná - Omastiná line on the NE margin of the Bánov Basin. Analogies between the Bánov Basin and other inland basins, such as the Levoča Basin (DANIEL ET AL., 1998), the Liptov Basin (REMŠÍK ET AL., 1998) or the neighbouring Hornonitrian Basin (FENDEK ET AL., 2004), but

We assume that fatric sequences are present in most of the basin area also under the profile of the chronite, which represents both the Middle - Upper Triassic carbonate complex and the extension of the so-called ipolitic group, i.e. siliciclastic sediments (quartzites, shales, claystones) of the Lower Triassic and Permian melaphyric series. It must be emphasised at the outset that **the Křižňan fault has not yet been verified by boreholes** in the area defined for the Partizánske site**, as in the rest of the basin**.

If we assume the preservation of the profile verified by the boreholes at the Partizánske site (Quaternary to Lower Carboniferous complex of the chronology), and subsequently the layered sequences observed in the inland basins, then the idealized overall profile would look as follows:

- Quaternary sediments (negligible due to thickness)
- Neogene sediments (typically clays to claystones with a predominance of sands and sandstones)
- Paleogene sediments (carbonate-based conglomerates and breccias passing to contact with Neogene sediments into predominantly claystone layers)
- Upper Carboniferous complex of the Upper Triassic (dolomites)
- Lunzian layers of the Chronozoic - Middle/Upper Triassic (claystones, clayey shales)
- lower carbonate complex of the chronology - Middle Triassic (dolomites, calcareous dolomites, limestones, dolomitic limestones)
- ipolitic chronology group - Permian to Lower Triassic (claystones, shales, clayey shales, quartzites, melaphyry series)
- Upper Triassic to Cretaceous development of the fatric (claystones, clayey limestones, organogenic limestones, detrital limestones, slieven limestones, slickensides)
- Middle Triassic fatric development (limestones, dolomitic limestones, dolomites, calcareous dolomites; carbonate complex with a pronounced predominance of limestones)
- spodotriassic development of fatrikas (claystones, clayey shales, shales, quartzites, rarely sandstones).

It follows that there are two significant uncertainties in terms of the geology of the area that are key to the exploration to verify the reservoir environment in the Fatrika carbonate complex:

- the thickness of the iolitic group exposed beneath the carbonates of the chronite
- Thickness of Upper Triassic to Cretaceous fatric development in the overlying fatric carbonates.

The following procedure is used to provide an overall picture of the risks that verification of the reservoir environment in the Cross Creek would need to consider in terms of pricing or planning a deep hydrogeothermal well:

1) DETERMINATION OF THE PROFILE LOCATION

The location of the hypothetical profile is determined according to the FGTz-2 Partizánske borehole (REMŠÍK ET AL., 2007), as the borehole was able to verify the complete profile of the Cenozoic and the lower and upper carbonate complex, while the interception of the spodotriassic sequence at the base of the borehole also confirms the assumption of the development of the iolithic group in the bedrock of the lower carbonate complex of the chronite. This profile will also be used to calculate the idealized depth as well as the temperature of the subsurface.

From the geological task "*Analysis of the possibilities of sustainable use and exploitation of geothermal energy resources in Slovakia - Part I*" (FRIČOVSKÝ ET AL., 2024) the structural histograms of the thickness of the Ipolitic Group and the Upper Triassic-Cretaceous evolution of the Fatrik were used for the construction of the model profile. These histograms were generated by modelling both horizons in geothermal water bodies where data of relevant quality were available for their extension. Similarly, for the next steps of the analysis of deep drilling feasibility, we used statistical/distribution functions to determine the stationary geothermal gradient in the profile of the ipolitic group and the underlying Upper Triassic - Cretaceous complex of the Krzannan escarpment (syn. fatrik).

Consequently, throughout the study, we use specific percentile cases of the analogous distribution of the two complexes, which we consider to be more representative than expressions of discrete values. Still, these are idealized profiles, and the reality may differ significantly from the modeled situation.

2) VERTICAL DEFINITION OF THE IPOLTIC GROUP

The verified position of the ipolitic group in the carbonate bedrock of the chronology allows us to assume its thickness on the basis of the analogous principle from the Western Carpathian environment. According to its probability distribution (Figure 5.6), it is strongly negatively (left) skewed. Based on the geological profile of the FGTz-2 borehole, then, the base of the ipolitic group for selected values of $\Delta z_{(IPO)}$ in the interval $P25(\Delta z_{(IPO)})$ - $P75(\Delta z_{(IPO)})$ (Table 5.4) ranges probably in the interval $zIPO_{,b}$ = 1243 - 1452 m according to the percentile range of simulated profile thicknesses:

$$zIPO_{,b} = z_{CHP,b} + \Delta z_{(IPO)}$$

$$= 961 + \Delta z_{(IPO)} \left| \begin{array}{ll} \Delta z_{(IPO)} & = 282m \left(P75\left(\Delta z_{(IPO)}\right)\right) \\ \Delta z_{(IPO)} & = 397m \left(P50\left(\Delta z_{(IPO)}\right)\right) \\ \Delta z_{(IPO)} & = 491m \left(P25\left(\Delta z_{(IPO)}\right)\right) \end{array} \right.$$

$$= \langle 1243;1452 \rangle m$$

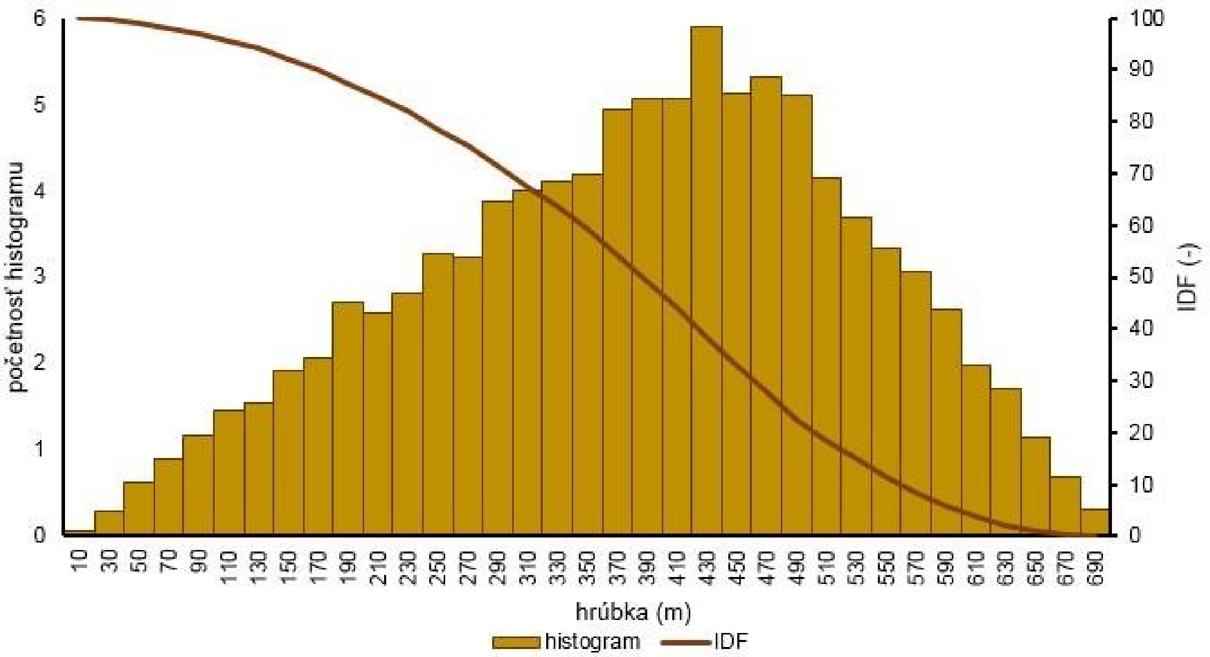

Figure 5.6: Structural histogram of the thickness of the so-called ipolithic group of the chronology (Permian to Lower Triassic evolution) in the underlying carbonates of the chronology based on the so-called global geological model of the ipolithic group. Modified after Fričovský et al. (2024).

3) TEMPERATURE GRADIENT AND TEMPERATURE INCREMENT IN THE IPOLITAN GROUP

The next step is to determine the temperature increment in the profile of the ipolytic group. This is calculated from the temperature of the stationary, conductive environment in the carbonates of the chronite, localized at their base (Figure 3.6), i.e., $TCHP_{,b}$ = 37 °C. The increment is calculated as a function of the temperature gradient on the vertical profile of the ipolytic group (Figure 5.7, Table 5.4). This has a strongly bimodal character under Slovak conditions, probably in the interval $\Gamma CD_{,IPO}$ = 24 - 35 °C.km^{-1} (in the range of the 25th to 75th percentile).

In the result, the predicted temperature is then expressed in the scale $TIPO_{,b}$ = 43 - 53 °C, according to Eq:

$$TIPO_{,b} = {}_{TCHP,b} + \left(\Delta z_{(IPO)} \cdot \Gamma_{CD,IPO}\right)$$

$$= 36 + \Delta z_{(IPO)} \left| \begin{matrix} \Delta z_{(IPO)} = 282m \left(\text{P75}\left(\Delta z_{(IPO)}\right)\right) \\ \Delta z_{(IPO)} = 397m \left(\text{P50}\left(\Delta z_{(IPO)}\right)\right) \\ \Delta z_{(IPO)} = 491m \left(\text{P25}\left(\Delta z_{(IPO)}\right)\right) \end{matrix} \right. . \Gamma_{CD,IPO} \left| \begin{matrix} \Gamma_{CD,IPO} = 24°C.km^{-1} \left(\text{P75}\left(\Gamma_{CD,IPO}\right)\right) \\ \Gamma_{CD,IPO} = 30°C.km^{-1} \left(\text{P50}\left(\Gamma_{CD,IPO}\right)\right) \\ \Gamma_{CD,IPO} = 35°C.km^{-1} \left(\text{P25}\left(\Gamma_{CD,IPO}\right)\right) \end{matrix} \right.$$

$$= \langle 43;53\rangle °C$$

However, due to the bimodality of the expansion and for clarity of the combinations that arise by decomposing the probabilistic simulation based on percentile fractions, we use only the mean value of the simulated ipolitan group gradient ensemble, i.e., $\Gamma CD_{,IPO}$ = 30 °C.km^{-1} ; and the resulting temperatures on the assumed ipolitan group base scale as $TIPO_{,b}$ = 45 - 51 °C, for the following calculations. As a result, we thus assume that the temperature difference can reach ΔT = 9 - 15 °C at the base of the entire chronite complex relative to the base of the chronite carbonates.

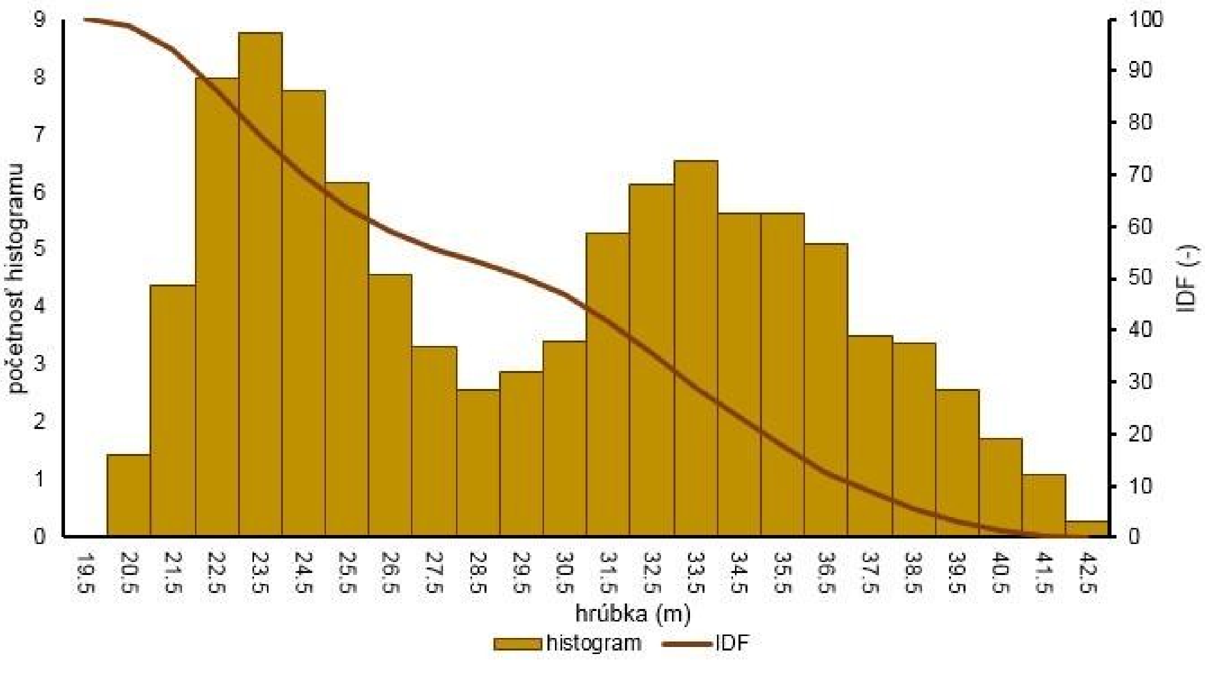

Figure 5.7: Structural histogram of the conductive gradient of the so-called ipolitic group of the Hippodrome (Permian to Lower Triassic evolution) in the underlying carbonates of the Hippodrome based on the so-called global geological model of the ipolitic group. Modified after Fričovský et al. (2024).

4) VERTICAL DELINEATION OF THE FATRIK INSULATOR

For the sake of simplicity and based on the analogous hydraulic parameters of the Upper Triassic to Cretaceous Fatrik complex, we will use the designation **"fatrik isolator"**, as the whole complex is normally extremely unproductive or unproductive in Slovakia and is generally considered to be of regional importance, and may be involved in the transport of groundwater or geothermal water in case of significant tectonic or other structural disturbances. In the interior basins, this profile reaches a thickness of $\Delta zKN_{,iso}$ = 33 - 2100 m (Figure 5.8), and within the P25 to P75 distribution, a thickness of $\Delta zKN_{,iso}$ = 446 - 784 m. This means that, maintaining the 25th to 75th percentile, the base of the Fatrika insulator can be expected to be at a depth of $zKNizo_{,b}$ = 1689 - 2236 m according to Eq:

$$zKNizo_{,b} = z_{CHP,b} + \Delta z_{(IPO)} + \Delta z_{(KN,iso)}$$

$$= 961 + \Delta z_{(IPO)} \left| \begin{array}{l} \Delta z_{(IPO)} = 282m \left(\text{P75}\left(\Delta z_{(IPO)}\right)\right) \\ \Delta z_{(IPO)} = 397m \left(\text{P50}\left(\Delta z_{(IPO)}\right)\right) \\ \Delta z_{(IPO)} = 491m \left(\text{P25}\left(\Delta z_{(IPO)}\right)\right) \end{array} \right. + \Delta z_{(IPO)} \left| \begin{array}{l} \Delta z_{(CN,iso)} = 282m \left(\text{P75}\left(\Delta z_{(CN,iso)}\right)\right) \\ \Delta z_{(KN,iso)} = 397m \left(\text{P50}\left(\Delta z_{(KN,iso)}\right)\right) \\ \Delta z_{(CN,iso)} = 491m \left(\text{P25}\left(\Delta z_{(CN,iso)}\right)\right) \end{array} \right.$$

$$= \langle 1689;\ 2236 \rangle\, m$$

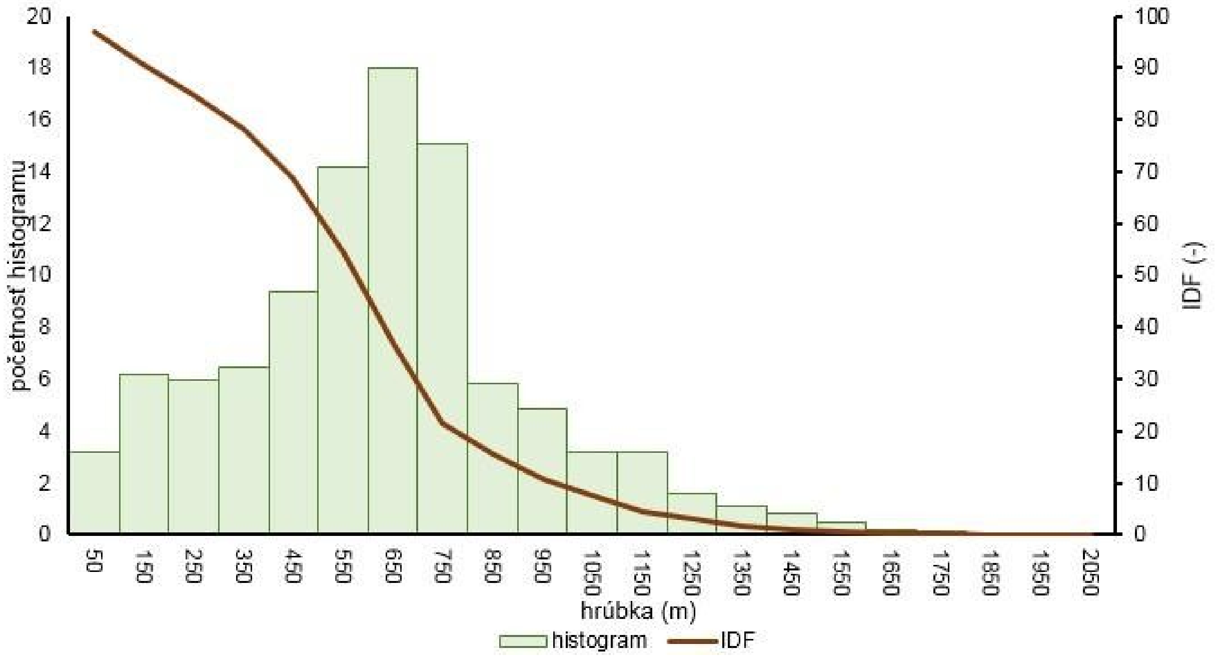

Figure 5.8: Structural histogram of the thickness of the fatric insulator in the underlying carbonates of the Chronozoic and Iolitic Group based on the so-called global geological model of Upper Triassic to Cretaceous fatric evolution. Modified from: Fričovský et al. (2024).

5) TEMPERATURE GRADIENT AND TEMPERATURE INCREMENT IN THE FATRIK INSULATOR

A global model of the conductive gradient in the fatrik insulator profile constructed in geothermal water bodies with its known occurrence shows its strongly lognormal distribution (Figure 5.9) in the interval $\Gamma CD_{(KN,iso)}$ = 20 - 48 °C.km^{-1} , while in the standard percentile range P25 - P75 it takes values $\Gamma CD_{(KN,iso)}$ = 20 - 48 °C.km^{-1} . Since the gradient is strongly lognormal, its modal value $\Gamma CD_{(KN,iso)}$ is used for further estimates
= 25.5 °C.km^{-1} , so that the temperature increment expressed as a function of gradient per vertical step (thickness) with the modal value of the gradient is estimated to be in the range $T_{(KN,iso)}$ = 10 - 18 °C. Thus, the temperature at the base of the fatrik insulator is the sum of the temperature at the base of the ipolytic group and the temperature increment, so that the estimated temperature is **$T_{KN,iso,b}$ = 56 - 70 °C** according to Eq:

$$T_{KN,iso,b} = T_{CHP,b} + \left(\Delta z_{(IPO)} \cdot \Gamma_{CD,IPO}\right) + \left(\Delta z_{(KN,iso)} \cdot \Gamma_{CD(KN,iso)}\right)$$

$$= 36 + T_{IPO,b} + \Delta z_{(IPO)} \left| \begin{array}{l} \Delta z_{(CN,iso)} = 282m \left(\mathrm{P75}\left(\Delta z_{(CN,iso)}\right)\right) \\ \Delta z_{(KN,iso)} = 397m \left(\mathrm{P50}\left(\Delta z_{(KN,iso)}\right)\right) \\ \Delta z_{(CN,iso)} = 491m \left(\mathrm{P25}\left(\Delta z_{(CN,iso)}\right)\right) \end{array} \right. . \Gamma_{CD(CN,iso)} \left| \Gamma_{CD(CN,iso)} = 25,5 °C.km^{-1} \right.$$

$$= \langle 56;80 \rangle °C$$

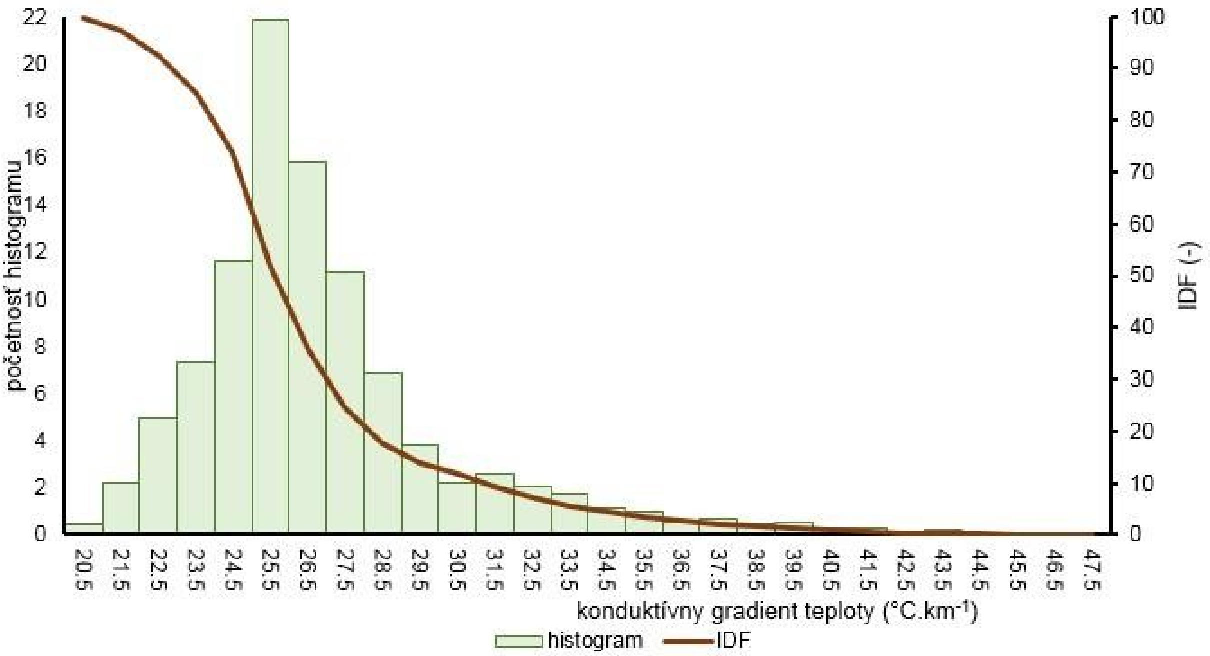

Figure 5.9: Structural histogram of the fatric insulator conductive gradient in the underlying carbonates of the Chronozoic and Ipolitic Group based on the so-called global geological model of Upper Triassic to Cretaceous fatric evolution. Modified from: Fričovský et al. (2024).

The above increment ΔT = 20 - 35 °C represents the temperature increase between the base of the carbonates of the graben, which can be considered as a shallow or upper reservoir, and the ceiling of the mid-Triassic carbonates of the Fatrik, which can be considered as a deep or lower reservoir, at the modelled depth $zKNizo_{,b}$ = 1689 - 2236 m.

Table 5.4: Representative parameters of the global model of the ipoltic group and the fatrik insulator used in the simulation of the temperature estimation on the carbonate surface around the city of Partizánske. Modified from Fričovský et al. (2024)

parameter	thickness of the ipolytic group	conductive gradient of the ipolar group	Fatrika insulator thickness	conductive gradient in the fatrik insulator
minimum	8	20	33	20
maximum	698	43	2122	48
average	384	30	628	27
median	397	30	630	26
P25	491	35	784	28
P50	397	30	630	26
P75	282	24	446	25

6) DISCUSSION ON THE CEILING OF THE RESERVOIR IN FATRIK

From the above example, it is possible to draw tentative, and for the purposes of the economic study, conclusions on the ranges of depth required for the drilling to be carried out in order to verify the ceiling of the mid-Triassic carbonates of the Fatrika if the relevant options are considered. The modelled depth of the base of the mid-Triassic fatric carbonates is based on model solutions, while the deviation of reality from the model can vary equally favourably (an optimistic scenario would be realistically verified lower thicknesses of the overburden of the lower reservoir with higher temperatures, if the actual temperature gradients in the ipoltic group and fatric insulator were higher than the chosen mean and modal value) as well as unfavourably (a negative scenario would be realistically verified larger overburden thicknesses of the lower reservoir with lower temperatures if the actual temperature gradients in the ipoltic group and fatric insulator were lower than the chosen mean and modal value). However, the uncertainties mentioned above are a standard part of deep hydrogeothermal exploration and cannot be excluded. The only way to reduce risk in this case is to choose appropriate surface geophysical exploration methods (in particular resistivity profiling or seismic) - as discussed in Chapter 6.

The results of the modelled estimate of the ceiling of the expected Lower Triassic can be summarised in Tables 5.5 and 5.6.

Table 5.5: Model estimation of the ceiling of the lower reservoir (mid-Triassic carbonates of the Fatrik = Krusnanskian escarpment). The highlighted values in the table are subsequently used to determine the from-to range of temperatures in the fatrik.

<table>
<tr><td colspan="5">constant surface level = 0 m</td></tr>
<tr><td colspan="5">constant thickness of Cenozoic overburden = 165 m according to FGTz-2</td></tr>
<tr><td colspan="5">constant thickness of the mid-Triassic to Upper Triassic profile of the chron = 796 m according to FGTz-2</td></tr>
<tr><td colspan="2" rowspan="2">indicative model for estimating the ceiling of the lower reservoir (m)</td><td colspan="3">simulated fatric insulator thickness (Upper Triassic to Cretaceous fatric evolution)</td></tr>
<tr><td>P25($\Delta zKN_{,iso}$) = 784 m</td><td>P50($\Delta zKN_{,iso}$) = 630 m</td><td>P75($\Delta zKN_{,iso}$) = 446 m</td></tr>
<tr><td rowspan="3">simulated thickness of the ipolytic group</td><td>P25($_{\Delta zIPO}$) = 491 m</td><td>2236</td><td>2082</td><td>1898</td></tr>
<tr><td>P50($_{\Delta zIPO}$) = 397 m</td><td>2142</td><td>1988</td><td>1804</td></tr>
<tr><td>P75($_{\Delta zIPO}$) = 282 m</td><td>2027</td><td>1873</td><td>1689</td></tr>
</table>

Table 5.6: Reservoir ceiling temperature estimation model (mid-Triassic carbonates of the Fatrik = Cross Range). The highlighted values in the table are subsequently used to determine the from-to range of temperatures in the fatrik.

<table>
<tr><td colspan="5">constant surface temperature = 10 °C</td></tr>
<tr><td colspan="5">constant temperature on the basis of carbonate chronite (FGTz-2 conductive well profile) = 36 °C</td></tr>
<tr><td colspan="2" rowspan="2">indicative model for estimating the temperature at the ceiling of the lower reservoir (°C)</td><td colspan="3">simulated fatric insulator thickness (upper Triassic to Cretaceous fatric evolution); temperature expression with temperature gradient in the fatrika insulator complex 25.5 °C.km^{-1}</td></tr>
<tr><td>P25($\Delta zKN_{,iso}$) = 784 m</td><td>P50($\Delta zKN_{,iso}$) = 630 m</td><td>P75($\Delta zKN_{,iso}$) = 446 m</td></tr>
<tr><td rowspan="3">simulated temperature based on the ipolar group with a temperature gradient of 30 °C.km^{-1}</td><td>P25($TIPO_{,b}$) = 51 °C</td><td>71</td><td>67</td><td>62</td></tr>
<tr><td>P50($TIPO_{,b}$) = 48 °C</td><td>68</td><td>64</td><td>59</td></tr>
<tr><td>P75($TIPO_{,b}$) = 45 °C</td><td>64</td><td>61</td><td>56</td></tr>
</table>

7) DEFINITIONS OF SELECTED SCENARIOS

It follows from point 6 that, keeping constant the values that have been verified at the site by the FGTz-2 Partizánske well, it is possible to determine from the model at the corresponding probability level the so-called:

- minimum scenario corresponding to $zKN_{,iso,b}$ = 1 689 m and $T_{KN,iso,b}$ = 56 °C, with overburden thicknesses greater than the modelled 75% probability

- Maximumscenario corresponding to $_{,iso,b}$ = 2 236 m and $T_{KN,iso,b}$ = 71 °C with a probability that overburden thicknesses are greater than the modelled 25%;

while the steady-state model accounts for the expressed patterns of the conductive gradient in the reservoir overburden according to the mean value in the ipolytic group and the modal value in the fatrik isolator.

8) REFERENCE VERTICAL DISTRIBUTION TEMPERATURE IN CARBONATE FATRIK FOR CONDUCTIVE (UNAFFECTED) ENVIRONMENTS

To estimate the vertical temperature distribution in the lower reservoir, we use the same principles for calculating the vertical step and increment as for determining its ceiling. A global model of the Middle Triassic carbonates of the Fatrik/Crizňan escarpment, which represents a possible deep reservoir environment at the site (FRIČOVSKÝ ET AL. 2024), shows its quasi-sloping to the right, with carbonates reaching thicknesses in the model solution of $\Delta zKN_{,res}$ = 35 - 860 m (Figure 5.10; Table 5.7). We therefore use a thickness interval of up to 500 m with a step thickness of 100 m to model the minimum and maximum scenarios.

Conductive gradient values in the mid-Triassic carbonate environment (Figure 5.11; Table 5.7) range from $\Gamma CD_{,KN,res}$ = 12 - 46 °C.km^{-1} , with a very similar, skewed distribution to that of their thickness distribution in the global Cross-Crucian model for the reservoir environment of the Western Carpathians. In contrast to previous calculations, since this is an estimate of the possible temperature range in the lower reservoir, the values corresponding to P25($\Gamma CD_{,KN,res}$) = 27 °C.km^{-1} and P75($\Gamma CD_{,KN,res}$) = 22 °C.km^{-1} will be used.

The minimum scenario, based on the variation of the environmental conductive gradient, predicts that the resulting temperatures in the carbonates of the fatrik could range from T_{res} = 58-59 °C for the 100 m depth level of the carbonate profile (z_{res} = 1689 + 100 = 1789 m) to T_{res} = 69-70 °C for the 500 m depth level of the carbonate profile (z_{res} = 1689 + 500 = 2189 m). **The maximum scenario** expects temperatures for the conductive environment of T_{res} = 73 - 74 °C for the 100 m depth level of the carbonate profile (z_{res} = 2236 + 100 = 2336 m) and up to T_{res} = 82 - 85 °C for the depth level 500 m (z_{res} = 2236 + 500 = 2736 m). Thus, the resulting difference from the conductive profile of the shallow reservoir carbuncles in the corona would be ΔT = 33 - 49 °C. The results are presented in Table 5.8. The tentative, idealized geological profiles and the vertical profiles of the stationary field temperature made to them are subsequently presented in Figures 5.12 and 5.13. It is essential to stress that this is a **model solution**, and also that it is an **estimate of temperatures within a conductive environment**, including previous approximations.

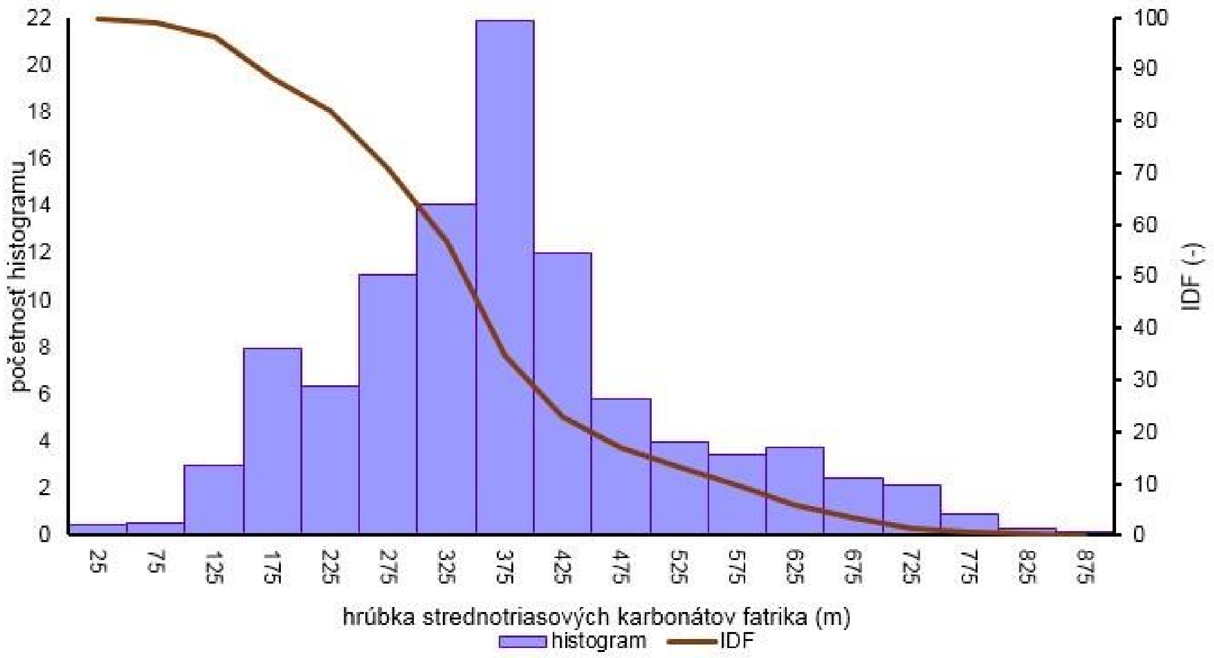

Figure 5.10: Structure histogram of the thickness of the Middle Triassic carbonates of the Fatrik based on the so-called global geological model of the Middle Triassic evolution of the Fatrik in the intra-mountain basins of the Western Carpathians. Modified after Fričovský et al. (2024).

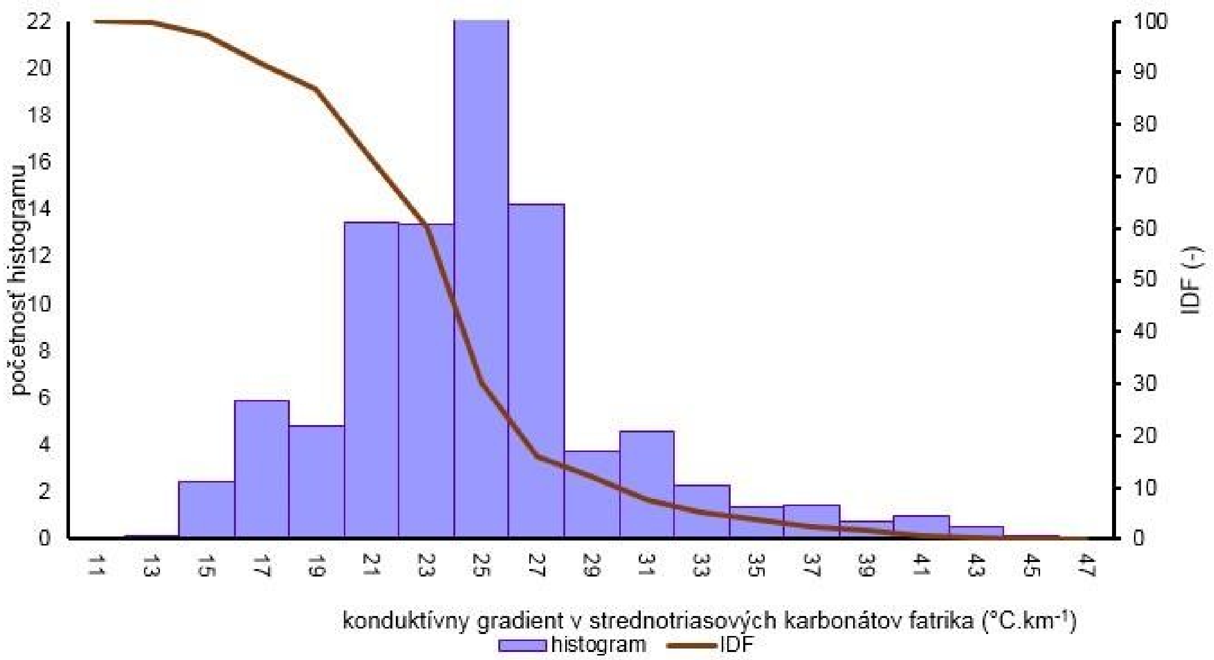

Figure 5.11: Structural histogram of the conductive gradient in the Middle Triassic carbonates of the Fatrik based on the so-called global geological model of the Middle Triassic evolution of the Fatrik in the interior basins of the Western Carpathians. Modified after Fričovský et al. (2024).

Table 5.7: Parameters of Middle Triassic carbonates of the Fatrik Formation based on a global geological model of Middle Triassic Fatrik evolution in the intra-mountain basins of the Western Carpathians. Modified after Fričovský et al. (2024).

parameter	Thickness of mid-Triassic carbonates of Fatrika	Conductive gradient of mid-Triassic carbonates of fatrica
minimum	36	12
maximum	860	46
average	376	25
median	367	25
P25	436	27
P50	367	25
P75	286	22

The above profiles of boreholes and vertical distribution of individual lithostratigraphic horizons, or vertical temperature distribution, must be seen as model or indicative. The actual borehole profile is influenced by local conditions, in particular:

- proximity of the town of Partizánske to the hydrogeological massif of the Tríbeč Mountains, which is related to the significant segmentation of the bedrock, significant tectonics, often with vertical jumps in the order of 10s or 100s of metres
- the possibility of reduction of geological units and individual strata within the graben or basement fracture, which models are unable to capture as there is no deep geological/structural/exploration/hydrogeothermal well in the relevant vicinity in the same situation
- the model still represents the distribution of a stationary, flow-intact geothermal field, meaning that it does not account for the presence of groundwater or geothermal water, with the site still close to the predicted infiltration area
    - in the case of reservoir environment in the subsurface, its hydraulic / hydrogeological communication along fault systems with the surface or with the infiltration area and the resulting, also intense, distortion of temperature conditions in the reservoir cannot be completely excluded, especially with a negative trend (temperatures of the dynamic reservoir environment tend to be lower by percentages or tens of percentages relative to the distribution of the intact temperature field as they approach the down-dip transition and infiltration areas); all these facts need to be verified.

Table 5.8: Model of the so-called minimum and maximum scenarios of the depth of the fatric computational nodes and the vertical temperature distribution in the fatric for a conductive environment.

surface temperature $_{TS}$ = 10 °C						
base of Cenozoic insulator $_{zIZO}$ = 165 m according to FGTz-2						
thickness of Cenozoic insulator $_{\Delta zIZO}$ = 165 m according to FGTz-2						
Gradient in the Cenozoic insulator $_{\Gamma IZO}$ = 35.8 °C.km^{-1} (conductive profile of borehole FGTz-2)						
temperature at the ceiling of the TIZO chronology$_{,b}$ = 16 °C (conductive profile of the FGTz-2 borehole)						
carbonate thickness of the chron $_{\Delta zCHP}$ = 796 m according to FGTz-2						
carbonate base of the chronology zCHP$_{,b}$ = 961 m according to FGTz-2						
Conductive gradient in the carbonates of the $\Gamma CD_{,CHP}$ = 25.9 °C.km^{-1} (FGTz-2 conductive profile)						
TCHP$_{,b}$ = 36 °C (FGTz-2 well conductivity profile)						
Conductive gradient of the ipolar group $\Gamma CD_{,IPO}$ = 30 °C.km^{-1}						
Conductive gradient of the fatrik insulator $\Gamma CD_{,KN,iso}$ = 25.5 °C.km^{-1}						
Scenario	minimum			Maximum		
	thickness of the ipoltic group $_{\Delta zIPO}$ = 282 m			thickness of the ipolytic group $_{\Delta zIPO}$ = 491 m		
	base of the ipoltic group zIPO$_{,b}$ = 1243 m			base of the ipolytic group zIPO$_{,b}$ = 1452 m		
	temperature based on the ipolytic group TIPO$_{,b}$ = 45 °C			temperature based on the ipolytic group TIPO$_{,b}$ = 51 °C		
	Fatrika insulator thickness ΔzKN$_{,iso}$ = 446 m			Fatrik insulator thickness ΔzKN,iso = 784 m		
	fatrika insulator base zKN$_{,iso,b}$ = 1689 m			fatrika insulator base zKN$_{,iso,b}$ = 2 236 m		
	temperature at the ceiling of the fatrika reservoir $_{TKN,iso,b}$ = 56 °C			temperature at the ceiling of the fatrika reservoir $_{TKN,iso,b}$ = 71 °C		
depth (m)	z (m.p.t)	P25($\Gamma CD_{,KN,res}$) = 27 °C.km^{-1}	P75($\Gamma CD_{,KN,res}$) = 22 °C.km^{-1}	z (m.p.t)	P25($\Gamma CD_{,KN,res}$) = 27 °C.km^{-1}	P75($\Gamma CD_{,KN,res}$) = 22 °C.km^{-1}
100	1 789	59	58	2 336	74	73
200	1 889	61	61	2 436	76	75
300	1 989	64	64	2 536	79	78
400	2 089	67	66	2 636	82	80
500	2 189	70	69	2 736	85	82

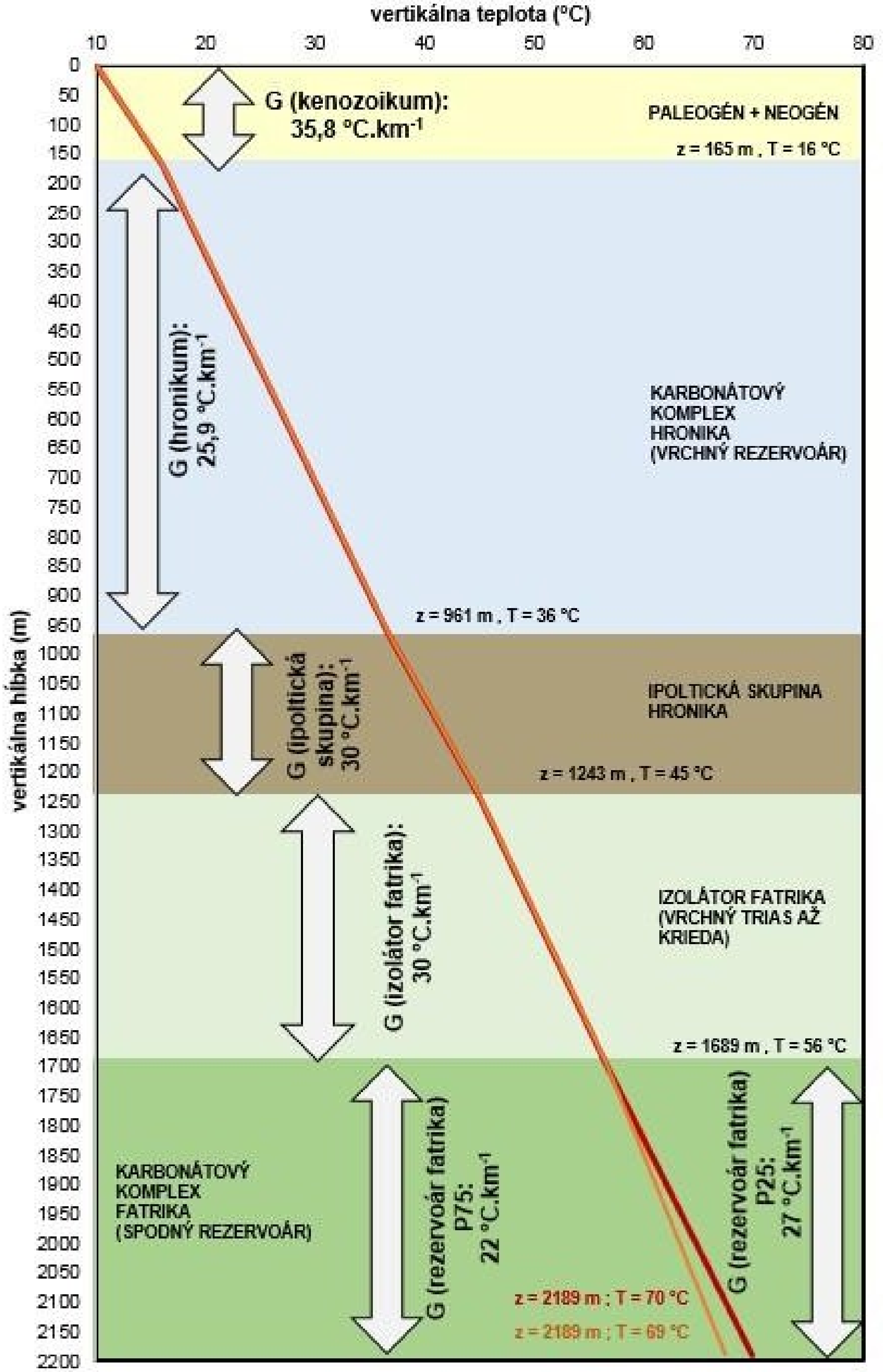

Figure 5.12: Idealised geological and stationary-geothermal profile of a deep borehole for reservoir verification in the Kriznjan fault - results of the so-called minimalist scenario.

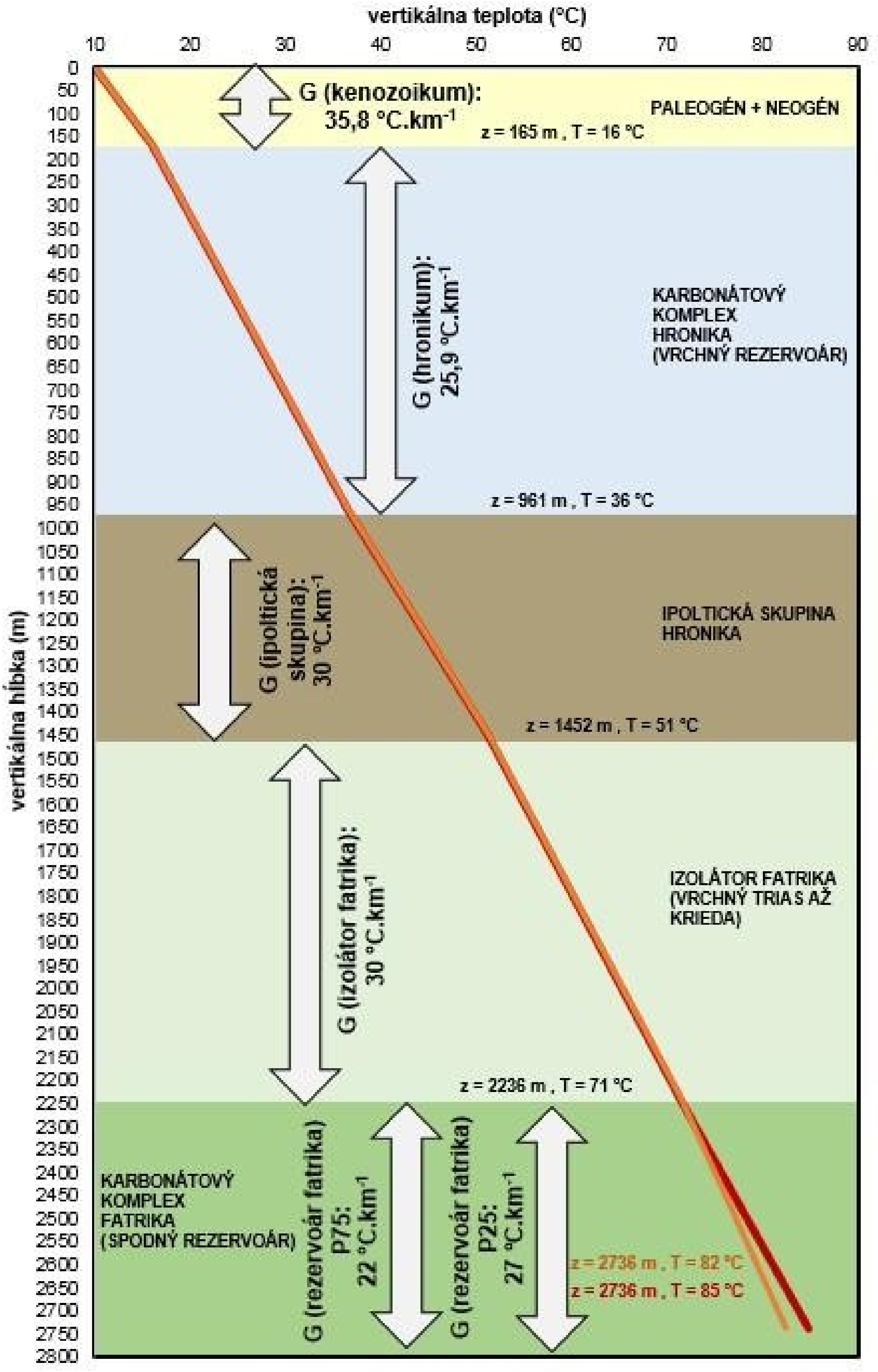

Figure 5.13: Idealised geological and stationary-geothermal profile of a deep borehole for reservoir verification in the Kriznjan fault - results of the so-called maximalist scenario.

6 PROPOSALS FOR FURTHER STEPS IN THE DEVELOPMENT OF THE PARTIZÁNSKE LOCALITY

From the analysis of the existing data on the reservoir environment, and taking into account the underlying geological, geothermal and probabilistic models in relation to both the Bánov Basin and the defined locality of Partizánske itself, i.e. the town and its relevant surroundings, it can be stated:

- the state of hydrogeological and hydraulic continuity between the reservoir environment in the tectonic blocks around the town of Partizánske, in which the hydrogeothermal wells HGTP-1 and FGTz-2 are located, and the Bielice outcrop area of the Bielice structure, has not yet been reliably demonstrated by long-term (semi-operational or operational) hydrodynamic tests; while **the solution to the uncertainty of the hydraulic and hydrogeological connection** is in relation to the potential long-term geothermal energy production in Partizánsko:
    - implementation of a joint hydrodynamic test of wells HGTP-1 and FGTz-2 during continuous monitoring of wells and spring seeps in Bielice
    - implementation of a supplementary tracing test
- the conceptual model of the site can also be considered uncertain, especially in terms of geothermal water flow (spatial and vertical) and the circulation-accumulation character of hydrogeothermal structures - in relation to vertical or horizontal transitions, simple or repeated mixing, the function of fault systems and the actual geothermal water transitions from the surrounding area; while **the solution to the uncertainty of the conceptual model** is in relation to the possible long-term geothermal energy production in Partizánko:
    - intensive geochemical and thermochemical monitoring of geothermal waters before and after the implementation of hydrodynamic tests, as well as periodically during the long-term production of geothermal energy resources; both at the Partizánske site and at the Bielice site
    - targeted geophysical surveys, especially with a focus on resistivity or magnetotelluric monitoring (head-on, schlumberger)
- the question of the possibility of increasing the production of geothermal energy resources at the site is also linked to the possibility of capturing and verifying geothermal energy resources in the so-called lower reservoir, which is associated with the Middle Triassic carbonates of the Križňany

near surface, but which have not been verified in the relevant area; while the risk of non-verification must be seen in relation to the possibility of expanding both the quantities of geothermal water produced and the energy potential at which higher temperatures can be achieved, with a relatively low risk of hydraulic influence on the Bielica vent area; and **the uncertainty of the quantitative and qualitative parameters of the underlying reservoir** can be partially reduced:

- geophysical survey - geoelectrical profiling combined with seismic profiling in selected polygons
- by implementing an exploratory/research deep geothermal borehole.

6.1 Proposals for further geological works at the Partizánske site

We consider the following to be the key geological work that must be carried out at the Partizánske site in order to minimize (not eliminate) the qualitative and quantitative risks associated with the long-term production of geothermal energy resources:

1) HYDRODYNAMIC TESTS

Hydrodynamic tests have been carried out so far only separately for wells HGTP-1 and FGTz-2, with the wells within the Bielice site and the spring outlets chosen as observation objects, however, as the wells were drilled at different times, no joint hydrodynamic test has been carried out. The obtained results cannot be objectively considered as representative, since:

- The 21-day HDS between Partizansky and Bielice in a dynamic circulation system may not show significant influences outside the normal range of fluctuations in the geothermal water flow regime
- we do not consider the mode / possibility of hydraulic communication between Bielice and Partizánský to be clarified
- We do not consider that the hydraulic communication mode of the effective filter profiles between the HGTP-1 and FGTz-2 wells itself, which should form the basis of a low-temperature centralized heat supply system, has been clarified.

We therefore propose:

- Conduct a joint hydrodynamic test on the HGTP-1 and FGTz-2 wells for at least 90 days in the first phase, testing the quantities of geothermal water verified to date, including:
    - **constant pumping of previously verified quantities for 60 days** (objective of the hydrodynamic test: to verify the existing verified quantities of geothermal energy from short-term hydrodynamic tests and the communication between wells during joint production, as well as the communication between the Partizánske site and the Bielice site); or to a d a p t and optimize the quantities extracted in relation to the actual results
    - **step-up production tests for 30 days**, which should simulate a possible step-up reservoir management strategy; and this should be possible if the results of the previous stage indicate that this would be feasible
    - geochemical monitoring and sampling of geothermal water samples at least once a week at produced wells, spring vents and produced well MB-3 Malé Bielice
    - thermometric and barometric monitoring with continuous recording of temperature, pressure, and productivity twice a day on all monitoring objects
    - if technically possible, vertical thermometric and barometric profiles once a week (optimally) or once every two weeks

2) TRACING TESTS

Tracer tests are a relatively unused method in the research and exploration of geothermal energy resources in Slovakia, mainly due to the large distance between the borehole and the relevant observation points in the vicinity. In this case, the distance between wells HGTP-1 and FGTz-2 is approximately 800-900 m as the crow flies, or a similar distance can be estimated for the relationship between wells FGTZ-2 and MB-3. This means that the potential to capture tracers prior to their decomposition, even given the assumed filtration parameters of the rock environment, would support the implementation of a tracer test. In this case, tracer tests should be performed with at least 2 individual tracers, specifically for FGTz-2 and specifically for HGTP-1, which would avoid overlapping results. The aim of the assay should be results refuting, confirming or quantifying the rate of hydraulic communication between Partizánský and Bielice, Partizánský and the surrounding area, or within the reservoir environment itself within vertical flows along fault systems. Another possibility of tracer tests would be their application to shallow hydrogeological boreholes south of Partizánský in order to verify the filter channels, or the downward and upward flows along open fault lines in the direction to the two investigated sites, and thus to verify the degree of contribution of the nearby infiltration area to the formation of the hydrogeothermal circulation system.

3) HYDROGEOCHEMICAL AND THERMOCHEMICAL MONITORING

If additional hydrodynamic tests are carried out, it is necessary, according to the established practice, to take samples of the produced geothermal water at each building of the pressure depression (targeted increase of production) or at least 3 samples during the whole course of the hydrodynamic test. These requirements are totally inadequate given the complexity of hydrogeothermal systems, and fall well short of the principles of monitoring and regime tracking of geothermal energy resources in global practice. At the same time, monitoring work is rarely continued after the hydrodynamic test and before the actual production is opened, which may be a framework of weeks or months or years. Despite the fact that increasing the frequency of monitoring, the monitoring objectives and the monitoring methods implemented increases the economic cost of the project, the implementation of comprehensive and representative monitoring is crucial in interpreting conceptual models of geothermal water flow systems in the reservoir environment and the wider site surroundings, identifies possible changes in reservoir dynamics and reservoir processes, and allows for the interpretation of processes related to the penetration of a hydraulic (pressure) or cold front in advance. At the same time, the monitoring and its interpretation reliably answers questions about the processes of superheating, mixing, thinning, heating, etc. For the proposed hydrodynamic test, we therefore recommend to consider:

- Sampling once a week at all monitoring sites for extended analysis; while monitoring pH, EC, TDS, Ca, Mg, Na, K, HCO_3, Cl, SO_4, Al, Fe, H_2SiO_4/SiO_2, B, F, Li, free CO_2; rare elements and other metals with frequency as per law; including gas analysis
- monitoring should include periodic assessment of trends, changes, time series and dependencies with evaluation:

- so-called hydrochemical facies diagrams: the Stiffler, Schoeller, Piper, ΔCFB diagram (Cl-F-B)
- so-called geochemical equilibrium diagrams: ΔCFB diagram (Cl-F-B), ΔCSH (Cl-SO4-HCO3), ΔBCL diagram (B-Cl-Li), Giggenbach diagram, Na-K-Mg-Ca geoindicator, MI-geoindicator, K-Mg-Ca geoindicator,
- so-called dynamic mapping models of dilution, mixing, reservoir adiabatic boiling, superheating: the X-Sh model (SiO_2 vs enthalpy), the X-SC model (SiO_2 vs free CO_2), the X-HC model (HCO_3 vs Cl), the X-Ch model (Cl vs enthalpy)
- Conventional silicate and cation geothermometry, including dynamic/system diagrams (Na-K, K-Mg, Na-K-Ca)
- multicomponent geothermometry: the CEQ method (complex balance temperature), the TSI method (total balance temperature), the TSI/TCA method (type curve analysis) and the RMED method (cluster median multicomponent geothermometry), the TCLM method (three-phase system mixing method)

- sampling at the beginning and at the end of the hydrodynamic test for isotopic analysis

Despite the certainly increased economic demands, we consider a consistent system monitoring and its interpretation, including the boreholes at the Bielice site and natural springs,
considered necessary, in the development of the conceptual site model, and in the setting up of the initial, and subsequently calibrated, reservoir response models.

4) ORIENTED SEISMIC SURVEY

Seismic survey - reflection, is objectively one of the most expensive surface geophysical methods. Nevertheless, due to the necessity of specifying the geological structure of the relevant surroundings of the town of Partizánske, or the Bieleczka vent zone, as well as due to the proximity of the so-called hydrogeological massifs (Tríbeč) representing infiltration zones, and the assumed importance of fault systems in the transport and flow of geothermal waters, we consider it necessary to carry out a number of seismic profiles on the whole area (Figure 6.1), whose proposed position (Table 6.1) reflects their expected importance:

- **the profile line with L1** with a length of 7.65 km is located south of the FGTz-2 and HGTP-1 wells, approaching the edge of the basin and the northern outcrops of the Tríbeč Mountains - the target of the proposed line is to verify the tectonic structure and the presence of mainly J-S or N-S oriented fault systems in the direction of the assumed downward trends of groundwater flow; and at the same time the deep geological structure east of Brozdian, where under the influence of the increase in the thickness of the Cenozoic sedimentary basin fill we assume increased temperatures of the stationary geothermal field, and at the same time an increase in the thickness of the carbonates of the Chronozoic (upper / shallow) reservoir.

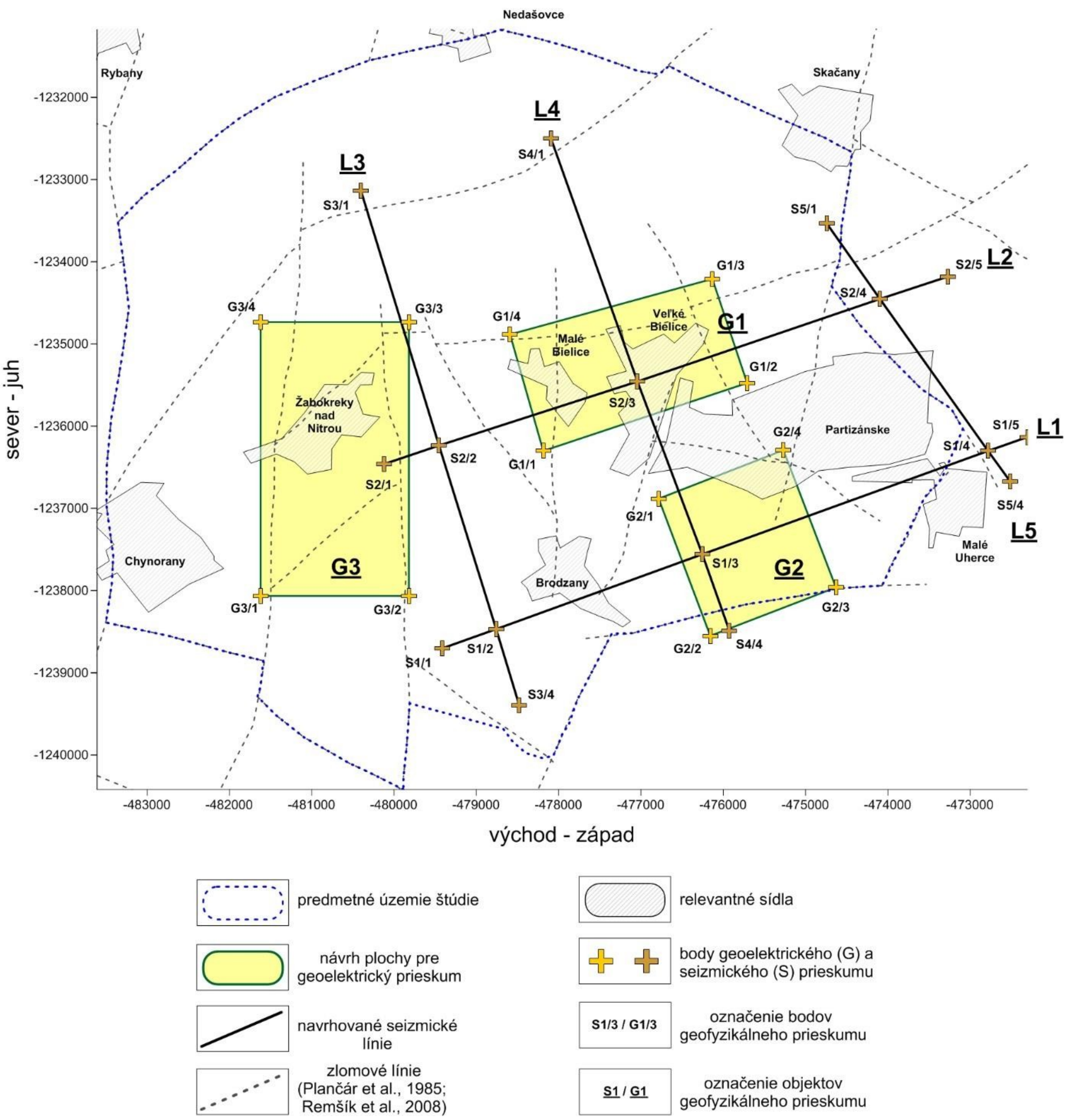

Figure 6.1: Situation and spatial orientation of the proposed surface geophysical exploration objects within the development of geothermal energy production at the Partizánsske site.

- The 7.2 km long **profile line L2** crosses the interpreted Bielica fault zone and within its delineation intercepts several inferred fault systems of suitable N-S or S-S orientation, which, especially when intersected with faults in the general E-W and W-E directions, may represent significant geothermal water filtering routes; the aim of the proposed profile is both to verify and identify significant tectonic lines, whose role is assumed within the groundwater/geothermal water flow systems, as well as the deep geological structure in the vicinity of the vent zone, spatially in relation to the southern part of the Bánov Basin, and also to the Partizánske locality
- The 6.6 km long **profile line L3** passes west of Brodzian and is designed to intersect lines L1 and L2, and maintains its position in one of the assumed segmented tectonic crusts W of Partizánské and SW of the Bielecka vent zone, which is assumed to be a descending transit area for groundwater/geothermal water of very shallow circulation; the aim of the line is to verify both the deep geological structure and the tectonic conditions at the western edge of the study area, and to support interpretations of the relationship between the hydrogeological massif of the northern/northwestern edge of the Tríbč, and the Bielica/Partizánská circulation structure
- **profile line L4** with a length of 6.4 km passes in the NW-SE direction through the Bielica vent area and its course covers both the area connecting this zone with the hydrogeothermal structures of the Bánov basin and the NW edge of the hydrogeological massif of the Tríbč massif; whereas the seismic profile is intended to verify the presence of tectonic lines that could serve as communication routes between the two sites and their wider surroundings, as well as the deep geological structure in the direction of the foothills of Tríbč, also in relation to the geological structure of the assumed transport or infiltration paths supporting local flow regimes and sub-modes of flow
- **profile line L5** with a length of 3.9 km is located west of the town of Partizánske and designed so that together with lines L4, L1 and L2 form an orthogonal network of seismic lines bounding the town of Partizánke and likely locations where it would be possible to locate, if necessary or possible, a deep exploratory geothermal borehole aimed at intercepting and verifying the underlying reservoir in the Križňanské fault, while, in line with the previous lines, the primary task of the seismic profile is to verify the course or continuation of the tectonic lines, and at the same time to contribute to the picture of the deep geological structure underlying the carbonates of the chronology, or its Permo-Spodnotriasian evolution (i.e. the ipoltic group).

Table 6.1: Coordinate system of seismic and geoelectric/magnetotelluric survey points in the vicinity of Partizánske

point designation	X-rail (S-JTSK03)	Y-junction (S-JTSK03)
L1/1	-479416.554	-1238703.38
L1/2	-478759.766	-1238468.82
L1/3	-476254.57	-1237558.693
L1/4	-472782.955	-1236301.401
L1/5	-472304.449	-1236132.503
L2/1	-480120.261	-1236460.905
L2/2	-479454.095	-1236235.716
L2/3	-477042.722	-1235456.936
L2/4	-474096.532	-1234452.99
L2/5	-473270.868	-1234180.88
L3/1	-480401.758	-1233139.406
L3/4	-478478.283	-1239397.711
L4/1	-478093.586	-1232501.367
L4/4	-475926.169	-1238487.584
L5/1	-474743.956	-1233533.47
L5/4	-472510.85	-1236676.701
G1/1	-478187.423	-1236301.401
G1/2	-475710.361	-1235475.7
G1/3	-476132.585	-1234209.037
G1/4	-478590.876	-1234884.604
G2/1	-476785.148	-1236882.262
G2/2	-476157.911	-1238550.987
G2/3	-474631.363	-1237962.15
G2/4	-475269.381	-1236292.008
G3/1	-481621.511	-1238065.363
G3/2	-479820.022	-1238065.363
G3/3	-479820.022	-1234734.471
G3/4	-481621.511	-1234734.471

5) ORIENTED GEOELECTRICAL SURVEY

In combination with the seismic survey, we propose to further explore and develop the production Resources geothermal Energy also application of linear, or area geoelectric or magnetotelluric survey. Its advantage is the possibility of a good correlation with seismicity in relation to the deep geological structure of the environment, and also the possibility of identifying different groundwater/thermal temperatures, which within a "unit" geological environment show different resistivity/conductivity characteristics under the influence of different temperatures. To support research on natural groundwater/geothermal flow regimes, or forced flow due to forced infiltration or reinjection, geoelectric surveying is one of the most commonly chosen surface methods or exploration or monitoring. The location of the survey polygons in Figure 6.1 is then supported by their spatial coordinates in Table 6.1:

- Polygon G1 (6km^2) is proposed to be targeted west of the seismic lines at its eastern edge, in the vicinity of the village of Žabokreky nad Nitrou, where, in addition to a targeted investigation of the deep geological structure, an attempt is made to interpret significant differences in the temperature of the reservoir medium (groundwater/geothermal) relative to its surroundings, which can contribute significantly to the conceptual modelling of the whole area, including the identification of possible transit zones and filtration profiles, especially in the shallow reservoir interbedded medium of the mountain (lower and upper carbonate complex)
- Polygon G2 (2.9 km^2) is proposed in the Bielica vent area as one way to support research on the flow and communication of the entire Bielica hydrogeothermal structure with its surroundings, in this case the southern margin of the Bansko Basin hydrogeothermal structures, whereby the application of point or line surveys at the location of the vent area may contribute to interpretations of the modes of vertical or lateral transitions of geothermal and groundwater of different temperatures prior to their presumed mixing and the vent itself
- Polygon G3 (6.0 km^2), on the other hand, is located on the southwestern outskirts of the town of Partizánske, on the line between the FGTz-2 / HGTP-1 wells and the foreland of the Tríbča hydrogeological massif, where it is repeatedly assumed that descending transit roads will be located, which should influence the stationary geothermal field of the shallow reservoir environment, while the obtained interpretations may provide grounds for interpretation of the orientation and intensity of possible vertical or lateral transitions within the reservoir environment of the reservoir in its lower and upper carbonate complex, and in case of fault lines intercepted, also contribute to the verification/exclusion of specific fault systems on the subsidence of the Partizánske locality, or the so called Partizánske fault. Bieleczka outcrop area.

6) SUGGESTIONS FOR OTHER SUITABLE METHODS OF EXPLORATION AROUND THE TOWN OF PARTISAN

The above methods are among the most used in practice methods of surface verification of tectonic structure or deep geological structure before the start of the actual drilling exploration. Geoelectrics, with adequate correlation from sampling or long-term observations and hydrogeothermal or shallow hydrogeological survey data, is also suitable for monitoring or estimating the spatial flow of groundwater/geothermal water with different densities, for example, also influenced by temperature or total mineralization, which reflects the length or depth of circulation or residence time of the geothermal/groundwater in the geological environment. In addition to the above, other methods of surface exploration are also under consideration, which may be less economically challenging to implement:

- **shallow thermometry** is usually carried out with probes up to 1-2 m, in which the temperature distribution and its deviations from normal due to local temperature/thermal anomalies are measured; therefore it is of particular importance at the interface between the assumed vent area and its surroundings, as it can provide indications of the spatial extension of the geothermal water output to the surface - for this reason it is significant N and NW of Partizánské in the direction of the Bielica structure vent area.
- **soil CO_2 flux probing** is performed by standard 10 - 50 cm soil probes - in this case it can be used to monitor the extension of soil CO_2 anomalies due to geothermal water outflow into shallow reservoir positions both within the Bielica structure and in linear profiles in the direction of the FGTz-2 and HGTP-1 wells, respectively; or in the vicinity of selected fault lines, which should serve as filtration routes for groundwater/geothermal water, especially in the phase of its ascent to the surface, when CO_2 release occurs due to pressure loss.

7) MODELLING WORK

Modelling work is an integral part of the practice of reservoir engineering, and its contribution is primarily to increase knowledge of the hydrogeothermal structure or its response to short-term or, more specifically, long-term production. The main feature of the modelling work is its continuity and calibration, each time from the results of previous stages of exploration. For the long-term production of geothermal energy resources at the Partizánske site, due to its

The sensitive surroundings of the hydrogeological massif of Tríbča and the proximity of the Bielica structure's vent area are therefore recommended to be considered for long-term production:

- continuously reviewed hydrodynamic numerical spatial modelling (for its representativeness it is necessary to carry out local hydrogeological mapping in order to determine the hydrogeological balance of the area) based on long-term and frequent monitoring
- Dynamic lumpfite or pseudo-lumpfite reservoir response modelling (historical part) and reservoir response prediction (near-future modelling) based on temperature and pressure monitoring of produced wells and monitoring objects
- Dynamic lumpfite or pseudo-lumpfite modelling of reservoir temperature response (historical part) and reservoir response prediction (near-future modelling) in functional relation to the results of hydraulic lumpfite models or calibrated numerical spatial models, considering reservoir dynamics (transfers, inflows, outflows of geothermal water into and out of the reservoir environment)
- continuous geothermometric and thermochemical modelling;
- while modelling numerical indicators of so-called spontaneous or forced reservoir convection and non-uniform reservoir overheating, the results of which can support/calibrate thermal response models, clearly defining the mode and variability of heat transport in the reservoir system; and/or
- continuous geological modelling based on existing data, or targeted geological modelling from data of the currently implemented geophysical survey.

As we repeatedly state above, the implementation of additional exploration work, comprehensive and frequency stable monitoring, as well as modelling of the obtained results, especially in their calibration against the "archive" data, can significantly contribute to the reduction of the risks of hydraulic (geothermal water quantities) but especially thermal-energy depletion of the reservoir environment and reservoir medium, in the sense of the global practice. As a result, especially thanks to long-term and comprehensive monitoring, which is then supported by updated and calibrated modelling, it is often possible to predict the future development of the reservoir response and to optimise the production strategy and reservoir management so that in the event of unfavourable developments, production and the project do not have to be terminated.

6.2 Proposals and delineation of potential exploration areas

All the above mentioned works, which are related to the implementation of geothermal exploration or drilling works, must be implemented within the exploration area in accordance with the applicable legislation. The exploration area is linked to the delimitation of a spatially well-defined area in which, once approved, interventions in the geological environment may be carried out, while at the same time, in accordance with the legislative framework, exploration areas for the same purposes may not overlap.

From all the above conclusions it follows that we consider, given the knowledge of geological, hydrogeological, hydraulic, and geothermal conditions, the implementation of a comprehensive and complementary hydrogeothermal survey both directly on the site Partizánske, as well as in its relevant surroundings. For this purpose, two exploration areas are tentatively defined for the time being, significantly different in area (Figure 6.2 and Table 6.2), which reflect a specific intention and are based on different assumptions.

The first variant of the exploration area PÚ1 practically corresponds with the whole polygon of Partizánské as it was evaluated in the whole study. Its size and delimitation allow for the full implementation of the proposed geophysical survey methods, or drilling if necessary or discretionary, as well as hydrodynamic tests on all boreholes. At the same time, the extent of the exploration area also creates additional possibilities for monitoring the relationship of both the Bielica outcrop zone and the reservoir environment in the vicinity of Partizánské with the surrounding area - whether the hydrogeological massif of Tríbč or the structures in the Bánov Basin itself. In connection with its size, there are also possibilities of research of hydrogeological communication on the border of the defined area, where it is assumed a change in the granularity of the pre-Tertiary bedrock and its relief, especially the gradual increase of the Cenozoic basin fill.

The second variant of the exploration area PÚ2 is spatially limited and covers the immediate surroundings of Partizánské, the existing hydrogeothermal wells FGTz-2 and HGTP-1, and with lower economic costs for its management it allows the implementation of hydrodynamic tests, including research and exploration of the relation to the Bielica vent zone, as well as spatially (comparing Fig.1 and 6.2) overlaps with the lines of the seismic profiles and the proposed areas for the implementation of geoelectric (line or area -

point) survey, but with significantly spatially limited information. However, the exploration area also extends into an area where the geological model constructed for the Bánov Basin as a whole, as a geothermal water body, predicts both an increase in the thickness of the Tertiary in the southward direction from the system of tectonic crusts in the vicinity of Bielice, and an increase in the thickness of the carbonates of the Chronozoic, still with an underlying ipolitic group.

However, the choice of the exploration area is still up for consideration and should also reflect the real economic possibilities of the project, and therefore the two proposals presented can only be seen as indicative and for further discussion.

Table 6.2: Coordinate system of exploration areas around the town of Partizánske

point designation	X-rail (S-JTSK03)	Y-junction (S-JTSK03)
PU1/1	-479886,851	-1240418,56
PU1/2	-478066,882	-1240011,869
PU1/3	-474070,241	-1237939,133
PU1/4	-472510,85	-1236676,701
PU1/5	-472304,449	-1236132,503
PU1/6	-473270,868	-1234180,88
PU1/7	-474400,133	-1232637,632
PU1/8	-476660,34	-1231618,466
PU1/9	-478713,088	-1231178,39
PU1/10	-480304,039	-1231552,028
PU1/11	-481446,35	-1231996,115
PU1/12	-483354,535	-1233518,539
PU1/13	-483608,312	-1236519,523
PU1/14	-483502,406	-1238389,046
PU1/15	-480859,164	-1240113,132
PU2/1	-476157,911	-1238550,987
PU2/2	-475926,169	-1238487,584
PU2/3	-474631,363	-1237962,15
PU2/4	-476132,585	-1234209,037
PU2/5	-478590,876	-1234884,604
PU2/6	-478187,423	-1236301,401

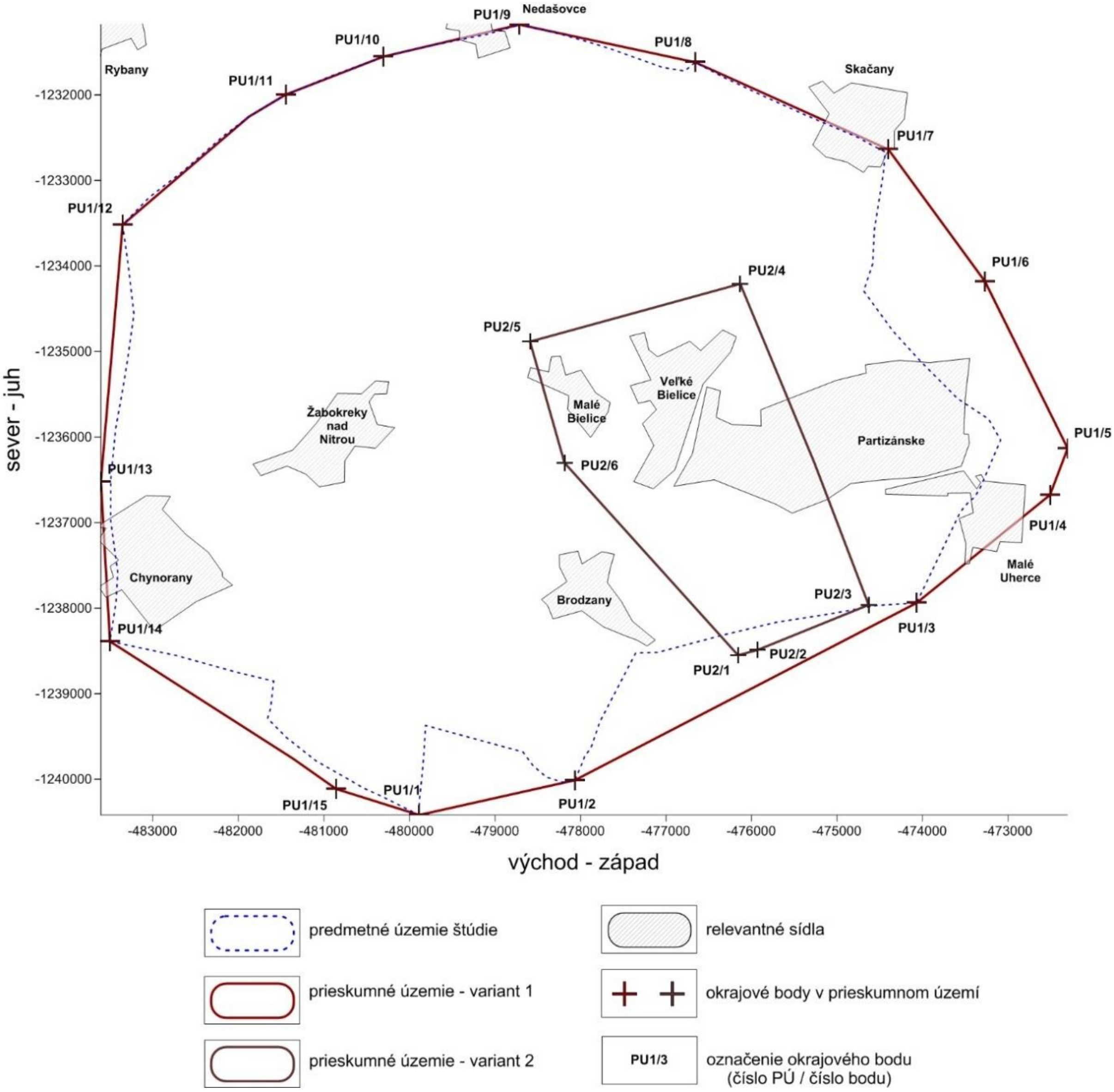

Figure 6.2: Situation and spatial orientation of the proposed surface geophysical exploration objects within the development of geothermal energy production at the Partizánsske site.

7 SUMMARY

From the results of the study, which aims to assess the suitability of the site for long-term production of geothermal energy resources in low-energy / low-temperature centralized heat supply systems, according to the observed or modeled facts, it follows:

- geothermal energy sources are tied - their proven part - to the reservoir environment of a probably shallow reservoir in the mid-Triassic complex (lower part) and the Upper Triassic complex (upper part) of the Mountainous
- probabilistic model of estimation of geothermal energy resources and reserves for the Bánovská basin geothermal water body gives the probable total thermal-energy potential - i.e. with a probability of verification and real energy-generating capacity of the reservoir environment of 50% - the level of estimation $TTP_{(p)}$ = 31 MWt for a production period of 40 years and $TTP_{(p)}$ = 13 MWt for a production period of 100 years in the sense of the concept of sustainable reservoir management.
- using the balance of reserves capacity factor method, the critical sustainable reservoir capacity of the pylon is $Pth_{(S)}$ = 15 MWt and $Pth_{(S)}$ = 7 MWt for the short-term and long-term production horizons, respectively.
- the current state of the total geothermal energy production from the reservoir environment of the Banovská basin reaches $_{Pth}$ = 0.3 - 1.1 MWt, which means that **in relation to the total sustainable capacity of the reservoir environment it is still possible to develop geothermal energy production both in the long and short term**
- if the potential for sustainable development of geothermal energy production is the difference between the sustainable capacity and the level of current geothermal energy withdrawals, i.e. the heat output of active wells, then for the short-term production horizon $Pth_{(D)}$ = 13.9 - 14.8 MWt and for the long-term production horizon $Pth_{(D)}$ is still available
  = 5,9 - 6,7 MWt within the reservoir environment in the Banovská basin, which represents also from the point of view of the Partizánske locality an interesting potential
- within the defined polygon, the calculation of the balance dynamic quantities gives
  Q_{dyn} = 32 $l.s^{-1}$
- The equilibrium quantities of geothermal water, corrected for the productivity at Bielice, are **Q_{bal} = 23.5 $l.s^{-1}$** , which at an average temperature of 44 °C represents a thermal

an energy output of **$Pth_{,bal}$ = 2,5 MWt** with a reference temperature of 15 °C; these quantities of geothermal water and geothermal energy should be verified as a first priority in hydrodynamic tests

- The quantities of geothermal water already verified separately are Q_{pv} = 25,3 $l.s^{-1}$ for the FGTz-2 and HGTP-1 wells, which must be verified by a joint hydrodynamic test
- short-term hydrodynamic tests carried out at different time periods on the wells HGTP-1 Partizánske and FGTz-2 Partizánke do not assume hydraulic communication between their immediate surroundings and the vent area in the vicinity of Bielice, however, it should be stressed that:
  - the tests carried out took place at different time intervals
  - the results obtained cannot be considered conclusive due to their duration
  - neither a joint hydrodynamic test nor a joint hydrodynamic test has been carried out in relation to the Bielica outcrop area
- as a possible solution to the situation due to the relatively low energy outputs of the existing hydrogeothermal wells, and also due to the possibility of hydraulic communication of the site with the Bielecka vent area or the hydrogeological massif of the Tríbča comes into consideration:
  - **Deepening of the existing HGTP-1 well** to the level of the lower carbonate complex of the Chronozoic (Middle Triassic Chronozoic), which would thus be common to the FGTz-2 and HGTP-1 wells
  - **Undertaking deep exploration/hydrogeothermal drilling** to identify and validate the reservoir environment and source of geothermal energy in the mid-Triassic carbonates of the lower tectonic unit, the Fatrike; while understanding the inherent uncertainties associated with such situations (in particular the enormous lack of data from the area) is essential
- **The model of the idealized vertical well profile** referenced to the vicinity of the FGTz-2 Partizánke well assumes a distribution of the reservoir ceiling in the mid-Triassic carbonates of the Fatrika at a depth of 1600-2200 m with a ceiling temperature of T = 56-71 °C for the conductive, stationary environment, and a temperature of T = 65-89 °C for the subsequent depth step of 500 m in the reservoir environment; Whereas the results of the analyses of the existing wells to date imply that the two reservoir environments do not communicate with each other

- within the planned development of geothermal energy resource production**, we strongly recommend to carry out oriented geophysical surveys**, and **within the hydrodynamic tests to carry out their comprehensive and frequency-intensive monitoring**, which would be able to take into account and capture the possible dynamics of the reservoir environment in relation to the nearby infiltration and transit-descent area, with subsequent periodic modeling and evaluation of the reservoir response **in order to minimize the risks to the long-term sustainable reservoir production**.

Also based on the results obtained, we believe that **the Partizánske site has the potential for the development of long-term production of geothermal energy resources for low-temperature / low-energy district heating and it is necessary to continue its systematic research and subsequent monitoring in order to minimize the risks to the potential long-term sustainability of production**.

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