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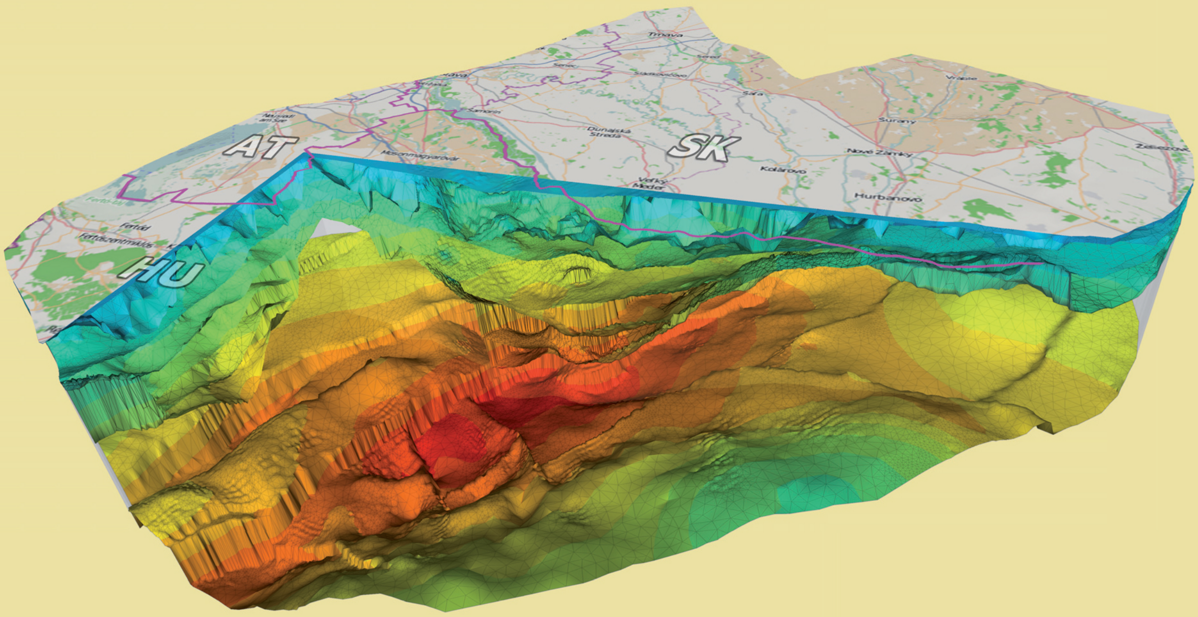
Towards Sustainable Cross-Border Geothermal Energy Utilization

TRANSENERGY – Transboundary Geothermal Energy Resources of Slovenia, Austria, Hungary and Slovakia



State Geological Institute of Dionýz Štúr, Bratislava

2/2014

SLOVAK GEOLOGICAL MAGAZINE

Periodical journal of the State Geological Institute of Dionýz Štúr is a biyearly presenting the results of investigation and researches in wide range of topics:

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The journal is thematically focused in the issues of the Alpine-Carpathian region.

Bratislava, December 2014

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Cover: Danube Basin pilot area investigated by the TRANSENERGY project. Temperature at the boundaries of the hydrostratigraphic units, data exported from steady-state hydrogeothermal model, vertical exaggeration 5x (J. Švasta).

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Preface

A comprehensive and systematic research of geothermal energy together with drilling of geothermal wells in Slovakia started in 1971, by the implementation of the project „Geothermal Energy" (responsible researcher O. Franko). The organization responsible for implementation of the task was Geological Institute of Dionýz Štúr (GIDŠ) in Bratislava (since 1996 Geological Survey of the Slovak Republic - GS SR, since 2000 State Geological Institute of Dionýz Štúr - SGIDŠ).

Results of complex and systematic research in the early 90s enabled to implement the project, which summarized the knowledge about the geothermal waters and their quantitative and qualitative parameters in relation to the geological environment and geothermal conditions in our country. The effort resulted in comprehensive work, the first of its kind in Slovakia - Atlas of Geothermal Energy of Slovakia (eds. Franko, Remšík and Fendek), which GÚDŠ issued in 1995. The basis of the Atlas were results from research; in particular the knowledge of the Tertiary filling of the basins, Pre-Tertiary basement of the Inner Western Carpathians, temperature distribution, thermal field and hydrogeothermal conditions.

In terms of research and exploration of geothermal energy significant attenuation in the implementation of geothermal wells occurred after socio-economic change in 1989. The research in this period was focused mainly on the projects and tasks that did not require the drilling of geothermal wells (given their significantly increased financial costs). The implementation of geothermal wells gradually started in the second half of the 90s, covered from private sources and the character of the work performed by SGIDŠ (at that time GS SR) had to adapt to new circumstances.

In the research and prospection of geothermal energy, international cooperation played and currently still plays an important role, not only in terms of fund-raising for research and exploration. Thus, ŠGÚDŠ participated in the international project "Atlas of Geothermal Resources of Europe" published in 2002 (edited by Hurter and Haenel, for Slovakia compiled by authors Remšík, Fendek, Král and Mello). As a result of trilateral cooperation among Austria - Slovakia – Hungary, international transboundary project DANREG was implemented. The output - the Geothermal Potential Map (in scale 1:200,000) of the Danube region in the Vienna-Bratislava-Budapest triangle was compiled and published in 1998.

Since Slovakia has joined the European Union in 2004, the issues related to European cohesion policy have came to forefront, along with protecting the quantity and quality of geothermal waters in the transboundary areas and sustainable development of European regions. In terms of these requirements the international cooperation project TRANSENERGY - Transboundary Geothermal Energy Resources of Slovenia, Austria, Hungary and Slovakia, was implemented under the number CE126P3. The outcomes of the project are results of the cooperation of geological institutes and geological services of Slovenia, Austria, Hungary and Slovakia The project was carried out under the Operational Programme Central Europe, co-financed by the ERDF.

This issue of Slovak Geological Magazine includes an overview of basic information and general conclusions drawn from the current review of geothermal water prospection and utilization in Slovakia. The monograph also presents selected results of geological, hydrogeological and geothermal models of the Danube Basin and adjacent areas as the outcome of TRANSENERGY project that was carried out by the State Geological Institute of Dionýz Štúr, Geological and Geophysical Institute of Hungary, Geological Survey of Slovenia and Geological Survey of Austria.

Radovan Černák and *Anton Remšík*

LIST OF ACRONYMS

AAGTW	Average Amount of Geothermal Water Abstraction
AGTW	Amount of Geothermal Wells
ALCAPA	Alps, (Northern) Carpathians and Pannonia
ANE	Amount of Non-renewable Energy
ARE	Amount of Renewable Energy
DANREG	Danube Region Environmental Geology Programme
DEM	Digital Elevation Model
DRBD	Danube River Basin District
DRBMP	Danube River Basin Management Plan
DRPC	Danube River Protection Convention
EEB	External Evaluation Board
ENWAT	Environmental State and Sustainable Management of Hungarian-Slovak Transboundary Groundwater Bodies
ERDF	European Regional Development Fund
FEFLOW	Finite Element subsurface FLOW simulation system (software)
GBA	Geological Survey of Austria
Geo-ZS	Geological Survey of Slovenia
GSLIB	Geostatistical Software Library
GTWU	Amount of Utilized Geothermal Wells
ICPDR	International Commission for the Protection of the Danube River
MÁFI	Geological Institute of Hungary
MFGI	Geological and Geophysical Institute of Hungary
NASA	National Aeronautics and Space Agency
NGA	National Geospatial-Intelligence Agency
NREAP	National Renewable Energy Action Plan
OEWAV	Guidelines for Utilization and Protection of Thermal Water in Austria
RMSE	Root Mean Square Error
SGIDŠ	State Geological Institute of Dionýz Štúr
SHMI	Slovak Hydrometeorological Institute
SRTM	Shuttle Radar Topography Mission
SRTM	Slovak Republic
TDS	Total Dissolved Solids
TEP	Thermal Energy Potential
TRANSENERGY	Transboundary Geothermal Energy Resources of Slovenia, Austria, Hungary and Slovakia
UTM	Universal Transverse Mercator
WFD	Water Framework Directive
WGS	World Geodetic System
WP	Water Abstraction Permit
WPW	Water Abstraction Permit for Well

1. Geothermal Energy Research in Slovakia and Cooperation on Geothermal Transboundary Project TRANSENERGY

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Abstract. The paper presents a brief overview of 40 years of research in geothermal energy sector in Slovakia and its current geothermal resources bound to 27 delineated areas with documented 141 boreholes on Slovak territory. In the light of merging European policy the transboundary resources (in this case water and geothermal energy) are in future focus. However few projects focused on transboundary geothermal resources were implemented in Central European region so far. The need for complex evaluation of geothermal energy sector was identified by geological surveys and institutions of four countries in the western part of the Pannonian Basin. The project TRANSENERGY - Transboundary Geothermal Energy Resources of Slovenia, Austria, Hungary and Slovakia was focused on harmonized geoscientific evaluation of the geological environment, coupled by geothermic and hydraulic models. The project was rather complex including issues of utilization of geothermal water, the analysis of legislative and management differences along with proposal for future harmonized evaluation of management in project partner countries. The results and the outputs were summarized in relevant reports that are accessible on the project web site (http://transenergy-eu.geologie.ac.at). Results of the project covered stakeholder needs as well, by relevant information accessible through web map application (http://www.arcgis.com/home/webmap).

Keywords: Slovakia, transnational cooperation, transboundary aquifer, geothermal energy, thermal water, groundwater

1.1. Introduction

The EU aims to get 20% of its energy from renewable sources by 2020 (2009/28/EC Directive on the promotion of the use of energy from renewable sources). Renewables include biomass, solar, geothermal energy, wind, as well as hydro-electric generation of energy. More renewable energy will enable the EU to cut greenhouse emissions and make it less dependent on imported energy, which nowadays becomes very important task for future. On the other hand boosting the renewables industry encourages technological innovations and employment. To fulfil the EU aims 20-20-20, the cooperation of European countries is needed on transnational level through common understanding the different attitudes applied in neighbouring countries, knowledge transfer, coordinated evaluation of the technology applied, and the best possible solution to be implemented.

Geothermal energy, as one of the renewable sources, is thermal energy generated and stored in the Earth that originates from the original formation of the planet (20%) and from radioactive decay of minerals (80%) (Turcotte & Schubert, 2002). The adjective geothermal originates from the Greek roots γη (ge), meaning earth, and θερμος (thermos), meaning hot. Geothermal gradient is the rate of increasing temperature with respect to increasing depth in the Earth's interior. Away from tectonic plate boundaries, it is about 25 °C per km of depth in most of the world (Fridleifsson et al., 2008). In comparison thermal gradient in Slovak part of the Danube Basin is documented in the range 35.6-43.7 $°C.km^{-1}$ (calculated for depth interval 0-2,500, Franko et al., 1989) and in Hungarian part of the Pannonian Basin more than 50 $°C.km^{-1}$ (Tulinius et al., 2010). This gives the great potential for renewable source utilization.

The Earth's internal thermal energy flows to the surface by conduction at a rate of 44.2 terawatts (TW), (Pollack et al., 1993) and is replenished by radioactive decay of minerals at a rate of 30 TW (Rybach, 2007). These power rates are more than double humanity's current energy consumption from all primary sources, but most of this energy flow is not recoverable. In addition to the internal heat flows, the top layer of the surface to a depth of 10 meters is heated by solar energy during the summer, and releases that energy and cools during the winter.

From hot springs, geothermal energy has been used for bathing since Paleolithic times and for space heating since ancient Roman times, but it is now better known for electricity generation. Worldwide, 12,013 MWe of geothermal power was online in 24 countries in 2014 (Matek, 2014).

An estimate of the installed thermal power for direct utilization at the end of 2009 in 78 countries was up to 50 GWt. The distribution of thermal energy used by category is approximately 47.2% for ground-source heat pumps, 25.8% for bathing and swimming (including balneology), 14.9% for space heating (of which 85% is for district heating), 5.5% for greenhouses and open ground heating, 2.8% for industrial process heating, 2.7% for aquaculture pond and raceway heating, 0.4% for agricultural drying, 0.5% for snow melting and cooling, and 0.2% for other uses (Lund et al., 2010).

Systematic exploration of geothermal energy in Slovakia began in the early 70s of last century and lasts until today. Within the geothermal research and exploration in the Slovak territory research and exploratory geothermal wells were drilled. After fulfilment of research and geological targets they have become sources of geothermal water for various types of use.

1.2. Overview of geothermal resources in Slovakia

Nappe-folded Mesozoic strata setting, existence of the Tertiary basin, Neogene volcanism, Alpine-type and German-type tectonics along with favourable hydrogeological and geothermal conditions created suitable conditions for the presence and distribution of geothermal water in Slovakia. Geothermal water is connected mostly to the Triassic limestones and dolomites of Carpathian nappe systems, to a smaller extent the Paleogene clastic rocks, Neogene sands, sandstones, conglomerates and the Neogene andesites and pyroclastic. These rocks represent collectors of geothermal water and are found at depths of about 200-5,000 m (excluding spring areas). Reservoir temperature of geothermal water was documented in the range 20-240 °C.

Spatial distribution of hydrogeothermal structures allowed to define 26 prospective areas with potentially available resources of geothermal energy. Recently part of Lučenská kotlina Basin was delineated by Dzúrik et al. (2007). As a more appropriate name of this structure Remšík (2012) proposed the name "Rapovce structure", since according to current knowledge, not the entire basin (Lučenská kotlina Basin) is suitable in terms of geothermal water occurrence, but only a part delineated by authors.

Source of geothermal energy in the Slovak Republic is mostly geothermal water, which was tapped during the geothermal research by prospection or exploratory geothermal wells.

The first overview report summarizing the basic results of 37 research and exploratory geothermal wells was compiled by Franko (1986). The overview of geothermal wells and basic data about them including the utilization, ownership (at that time) is given in "Inventory of geothermal resources and their potential utilization in Slovakia" (Franko et al., 1993). It was the first inventory of geothermal resources.

Summary of the results of the geothermal wells drilled in the years 1971-1994 in Slovakia is delivered by works of Remšík & Fendek (1995) and Fendek et al. (1995). Comprehensive list of geothermal wells with geothermal installations is given in the Atlas of Geothermal Energy of Slovakia (Franko et al., 1995). In this publication was comprehensively evaluated and summarized knowledge gained during more than two decades of geothermal review investigations along with maps and description of geothermal structures. Occurrence of geothermal water in Slovakia in cartographic form is given in map of Geothermal Resources and Mineral Water published in The Landscape Atlas of the Slovak Republic (Fendek et al., 2002).

The list of geothermal energy resources, which are used in different regions of the Slovak Republic, is described in work of Fendek et al. (1999). Overview of geothermal wells taking into account the current state of geothermal water exploration in Slovakia until 2004 work is delivered by work of Fendek et al. (2004). The latest overview of geothermal wells as geothermal water sources in Slovakia along with selected characteristics and parameters is given in Remšík et al. (2011) and Remšík (2012).

The distribution of sources of geothermal water along with the type of geothermal structure is shown on Fig. 1.1. In the course of further geothermal research and exploration new geothermal wells will be added and therefore there is need of ongoing update. Table 1.1 shows a summary data on the geothermal water in Slovakia. Following text gives the basic information of research results (Remšík, 2012):

- wells as sources of geothermal water were drilled in the years 1956-2011, particularly in 1971 to 2011, the wells were research or exploratory geothermal boreholes, hydrogeological or geological boreholes, which tapped the geothermal water to use. Currently there are 141 wells that are exploited for geothermal water utilization (excluding wells used in spas and for medical purposes registered at Ministry of Health;
- depth of the wells is in interval between 64 and 3,616 m;
- screening interval in the borehole that yields geothermal water is located in the depth interval from 11 to 3,390 m under surface;
- geothermal water collectors are the Mesozoic rocks, mainly Triassic limestones and dolomites; and Paleogene clastic rocks (breccias, conglomerates and sandstones) and Neogene sands or gravels, sandstones and conglomerates, in less extent andesites and pyroclastics;
- yield of wells, mainly in case of overflow, is in the range of 1.5 to 100 $l.s^{-1}$; total cumulative yield of geothermal water is 2,084 $l.s^{-1}$;
- geothermal water temperature at the wellhead (on surface) is 18-129 °C;
- heat output from wells is between 0.05 and 29.0 MWt; cumulative amount of geothermal energy thermal power represents 345 MWt;
- TDS of geothermal water ranges from 0.4 to 90.0 $g.l^{-1}$; most values are in the interval of 0.7 to 12.0 $g.l^{-1}$; small part of TDS values reach 20-30 $g.l^{-1}$;
- chemical composition of geothermal water was documented with following types: Ca-Mg-HCO_3, Ca-Mg-HCO_3-SO_4, Ca-Mg-SO_4, Na-HCO_3, Na-HCO_3-Cl and Na-Cl type.

The assessment of geothermal areas also shows that the calculated amount of geothermal power in prospective geothermal areas of Slovakia is approximately 6.2 GWt. In contrast to that the quantity of geothermal power verified by wells (345 MWt) represents only 5.53%. The comparison of the total amount of geothermal power and verified heat power shows that in the area of Slovakia there is still appoximately 5.9 GWt to be verified (Remšík et al., 2011).

1.3. Transboundary geothermal areas in Slovakia

The EU Framework Water Directive is a general legal act oriented towards the sustainable utilization, protection and improvement of the water resources state, sets common approaches and goals for water management in 27

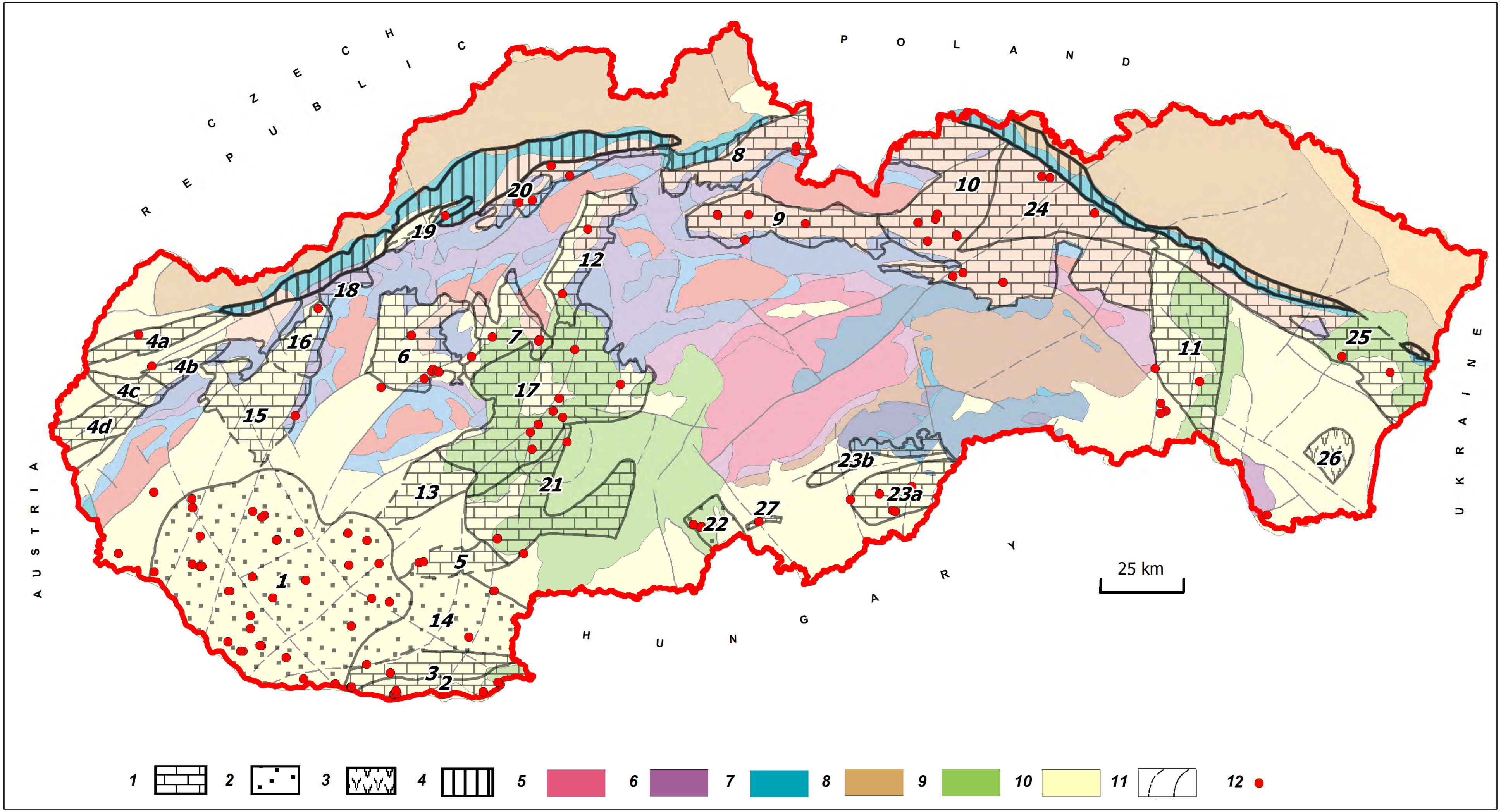

Figure 1.1 Geothermal prospective areas according to Remšík et al., 2011, based on Fendek, et al., 2002, and on geological map Biely et al., 1996
Explanation: (1 - 3 main aquifers of geothermal water) 1 - Triassic carbonates, 2 - Neogene sands, sandstones and conglomerates, 3 - Neogene andesites and related pyroclastics, 4 - Klippen belt, (5-10 geological structures) 5 - Early Paleozoic metapsamites, metapelites, predominantly acid metavolcanic and volcanoclastic rocks, 6 - Late Paleozoic (Crystalline) granitoids and metamorphic rocks, 7 - Mesozoic predominantly carbonate rocks (limestones and dolomites), minor sandstones, claystones, quartzite, 8 - Paleogene sandstones and claystones, 9 - Neogenic volcanic and volcano-clastic rocks, predominantly andesites, 10 - Neogene sandstones and claystones, 11 - main faults,12 - geothermal wells. Numbers of geothermal prospective areas are listed in Table 1.1

Table 1.1 Overview of the geothermal prospective areas and wells in Slovakia (based on Remšík, 2012)

Area nr.	Name of geothermal prospective areas	Code of geothermal water body	Amount of geothermal wells	Depth of wells (m)	Age and lithology of the collectors	Temperature on wellhead (°C)	Total yield of geothermal area ($l.s^{-1}$)	Total thermal power of geothermal area (MW_t)	TDS ($l.s^{-1}$)	Chemical type of geothermal water
1	Danube Basin Central Depression	SK300240PF	45	290-2,800	Dacian - Badenian, sand, sandstone, basal clastic sediments, andesites	18-91	479.7	99.17	0.5-20.1	$Na-HCO_3$, $Na-HCO_3-Cl$, $Na-Cl-HCO_3$, Na-Cl
2	Komárno High Block	SK300010FK	10	125-1,021	Lias - Triassic, limestones, dolomites	20-40	265.0	17.42	0.7-0.8	$Ca-Mg-HCO_3$,$Ca-Mg-HCO_3-SO_4$
3	Komárno Marginal Block	SK300020FK	4	1,184-1,970	Neogene -Triassic, conglomerates, limestones, dolomites	42-64	15.9	2.62	2.2-90.0	mixed type, Na-Cl
4	Vienna Basin (Šaštín, Lakšár, Láb-Malacky elevation, with adjacent sunken belt and Závod-Studienska sunken belt)	SK300030FK	2	2,100-2,605	Eggenburgian, Triassic, clastic sediments, limestones, dolomites	73-78	37.0	9.50	6.8-10.9	$Na-Ca-Cl-SO_4$, Na-Cl
5	Levice Marginal Block	SK300210FK	2	1,470-1,900	Badenian, Triassic, clastic sediments, limestones, dolomites	69-80	81.0	20.74	19.2-19.6	Na-Cl
6	Topoľčany embayment and Bánovce Basin	SK300090FK	7	102-2,106	Paleogene, Triassic, breccias, carbonates	20-55	68.8	5.26	0.7-5.9	$Ca-Mg-HCO_3$, $Ca-Mg-HCO_3$- SO_4, resp. Cl
7	Upper Nitra Basin	SK300100FK	5	150-1,851	Paleogene, Triassic - Permian, breccias, carbonates, sandstones	19-59	57.9	7.05	0.4-1.9	$Ca-Mg-HCO_3$, $Ca-Mg-SO_4-HCO_3$
8	Skorušina Basin	SK300120FK	2	600-1,601	Triassic, dolomites	28-56	135.0	18.29	0.8-1.3	$Ca-HCO_3$,$Ca-Mg-HCO_3$
9	Liptov Basin	SK300130FK	6	400-2,500	Triassic, carbonates	25-66	121.4	20.36	0.5-4.7	$Mg-Ca-HCO_3$, prevailing $Ca-Mg-HCO_3-SO_4$
10	Levoča Basin W and S parts	SK300140FK	9	607-3,616	Mesozoic, dolomites, limestones	25-62	226.3	34.24	0.6-4.0	$Ca-Mg-HCO_3-SO_4$,$Ca-Mg-HCO_3$
11	Košice Basin	SK300170FK	7	160-3,210	Neogene, Triassic, gravel, sand, dolomites	18-129	207.4	78.88	0.7-31.0	prevailing Na-Cl, $Na-Ca-Cl-HCO_3$
12	Turiec Basin	SK300110FK	2	1,503-2,461	Triassic, carbonates	54	12.2	2.02	2.5	$Ca-Mg-HCO_3-SO_4$
13	Komjatice Depression	SK300250FK	0	-	-	-	-	-	-	-
14	Dubník Depression	SK300180PF	4	350-1927	Neogene, sand, sandstones, clastic sediments	18-75	36.0	3.7	1.6-30.0	Na-Cl, $Na-Ca-HCO_3$,$Na-SO_4-Cl$
15	Trnava embayment	SK300040FK	1	118	Triassic, dolomites	24			2.52	$Ca-Mg-HCO_3-SO_4$
16	Piešťany embayment	SK300050FK	1	1206	Mesozoic, carbonates	19,4			1.41	$Mg-Ca-SO_4$
17	Central Slovakian Neogene volcanics NW part	SK300190FK	10	64-2500	Neogene, Mesozoic, porphyres, limestones, dolomites	27-57	80.6	9.47	0.4-5.0	$Ca-Mg-SO_4-HCO_3$, $Ca-Mg-SO_4$,$Ca-Mg-HCO_3$
18	Trenčín Basin	SK300060FK	0	-	-	-	-	-	-	-
19	Ilava Basin	SK300070FK	1	1761	-	-	-	-	-	-
20	Žilina Basin	SK300080FK	4	600-2,258	Paleogene, Triassic, sandstones, carbonates	24-41	57.4	2.95	0.4-0.5	$Ca-Mg-HCO_3$, $Ca-Mg-HCO_3-SO_4$
21	Central Slovakian Neogene volcanics SE part	SK300200FK	4	65-910	Neogene, Triassic, andesites, sandstones, limestones	25-46	64.1	3.84	1.0-5.7	$Ca-Mg-HCO_3-SO_4$, $Na-Ca-SO_4-HCO_3$
22	Horné Strháre – Trenč graben	SK300260FK	4	320-625	Neogene, sand	21-38	16.0	1.04	0.4-3.1	$Na-HCO_3$
23	Rimava Basin	SK300220FK	5	158-1,050	Triassic, carbonates	18-33	61.3	1.76	1.7-5.9	$Ca-Mg-HCO_3$, $Ca-HCO_3$
24	Levoča Basin NE part	SK300150FK	3	3,400-3,500	Paleogene, Triassic, sandstones, carbonates	53-85	19.0	4.55	9.4-12.3	Na-Cl, $Na-HCO_3-Cl-SO_4$
25	Humenné ridge	SK300160FK	2	600-823	Neogene, Mesozoic, sand, sandstones dolomites, limestones	29-34	6.0	0.41	4.4-11.9	$Ca-Na-Cl-SO_4$, $Na-Cl-SO_4-HCO_3$
26	Beša – Čičarovce structure	SK300230FP	0	-	-	-	-	-	-	-
27	Lučenec basin (Rapovce structure)		1	1,501	Triassic, carbonates	38			12.6	$Na-HCO_3$
Summary of delined geothermal areas			**141**	**64-3616**	**Neogene-Mesozoic, sand, sandstones, breccias, andesites, carbonates**	**18-129**	**2,083,9**	**345,04**	**0.4-90.0**	**$NaHCO_3$ - NaCl, CaMg SO_4HCO_3, mixed type**

countries. In line with the WFD and following EU guidelines for classifying groundwater bodies (EC Horizontal Guidelines), with regard to long-term information database in the assessment of groundwater in Slovakia and national specifics three independent levels of groundwater bodies were identified: (1) Quaternary groundwater bodies, (2) Pre-quaternary groundwater bodies and (3) geothermal groundwater bodies. Delineation of the geothermal groundwater bodies respects the delineation of geothermal areas as shown on Fig. 1.1 and Tab. 1.1. As seen on the map there are several geothermal structures of anticipated or verified transboundary character, though on level of geothermal groundwater bodies only Komárno High Block (SK300010FK) and Komárno Marginal Block (SK300020FK) were identified and mutually agreed (with Hungary) as transboundary groundwater bodies. Skorušinská panva Basin (SK300120FK) was not internationally agreed with Poland as cross-border structure and will be evaluated at the national level with respect to confirm or reject the presumed mutual transfer of groundwater across the border area (Report of the Slovak Republic on the status of implementation of the Water Framework Directive, Kollár et al., 2005). Based on aforementioned report more attention is recommended to geothermal waters, mainly completing the database of geothermal resources and their exploitation, processing of geothermal water balance monitoring and implementation of geothermal groundwater bodies. Particular attention is recommended as well, to the selected transboundary water bodies, their evaluation and higher demands on the quantity and quality of the data.

Apart from the WFD, in the Danube River Basin there is the overall legal instrument for co-operation on transboundary water management - the Danube River Protection Convention (DRPC). The convention was signed in 1994 by eleven states from the Danube River Basin and came into force in 1998. The International Commission for the Protection of the Danube River (ICPDR, www.icpdr.org) is a transnational body, which has been established to implement the Danube River Protection Convention. In 2000, the ICPDR contracting parties nominated the ICPDR as the platform for the implementation of all transboundary aspects of the WFD in the Danube River Basin District (DRBD). In the Danube River Basin Management Plan (DRBMP) (ICPDR, 2009) the transboundary thermal water body Komárno High Block "Komárňanská vysoká kryha/ Dunántúli-khgs. északi r." was nominated as transboundary groundwater body of basinwide importance in the DRBD and marked as GWB-11.

Besides the international declarations and conventions regulating the transboundary water bodies, bilateral agreements between Slovakia and neighbouring countries exist though not exclusively specifying groundwater or geothermal water management issues.

Bilateral agreement between Slovakia and Hungary on transboundary water management came into force by the Decision of Council of Ministers 55/1978. (XII. 10.). The agreement focuses on surface waters, but also encompasses groundwater aquifers divided by the state border. A permanent Czechoslovakian-Hungarian Water Management Committee is set up, which holds a meeting once a year. The update of the agreement is ongoing. In addition to this bilateral agreement, Governmental Decision 2093/1999. (V.5.) on the general cooperation between the Republics of Hungary and Slovakia on environmental and nature protection, discusses general aspects of protecting the environment and its elements (such including water), but no specific water or groundwater relate points are included.

Bilateral agreement between Slovakia and Austria on the water management is based on the treaty between the Czechoslovak Socialist Republic and the Republic of Austria with the subject of border waters and transboundary water management, which was signed on December the 7, 1967 in Vienna. The permanent Slovak – Austrian commission for these Waters (water route March /Morava) was founded (BGBl. Nr. 106/1970; „Vertrag zwischen der Republik Österreich und der Tschechoslowakischen Sozialistischen Republik über die Regelung von wasserwirtschaftlichen Fragen an den Grenzgewässern"). This agreement concerns issues and measures for the preservation of watercourses along the state border as well as border crossing and neighbouring waters that may have an adverse effect on the other party. The treaty focuses on surface waters excluding fishing and any water utilization of energy-economic importance.

1.4. Transboundary groundwater structures under the scope of international cooperation

There have been couple of international projects implemented that were focused on geoscientific information sharing knowledge (eWater and OneGeology projects). Within the frame of international cooperation, the project DANREG was implemented by Austria, Slovakia and Hungary (1987-1997) (Tkáčová et al., 1998). The aim of the project was to develop a set of geological, geophysical and geo-environmental maps and explanatory notes, as well as the development of a separate study on the quality of water, geothermal energy and environmental aspects. Substantial part on the Slovak territory of the project DANREG was the Danubian Basin. From geothermal point of view Geothermal Potential Map was compiled in scale 1:200,000 (Kollmann, Rótar-Szalkai, Remšík in Tkáčová et al., 1998) displaying temperature of expected aquifer, basement surface and location of wells.

Other project that was designed for common evaluation of transboundary aquifers was project ENWAT (Environmental state and sustainable management of Hungarian-Slovak transboundary groundwater bodies), implemented within the frame of the European Union INTERREG IIIA during the years 2006-2008. In this project three transboundary groundwater bodies were investigated in the Hungarian-Slovakian border region: Ipoly/Ipeľ Valley, Bodrog region (both of them with

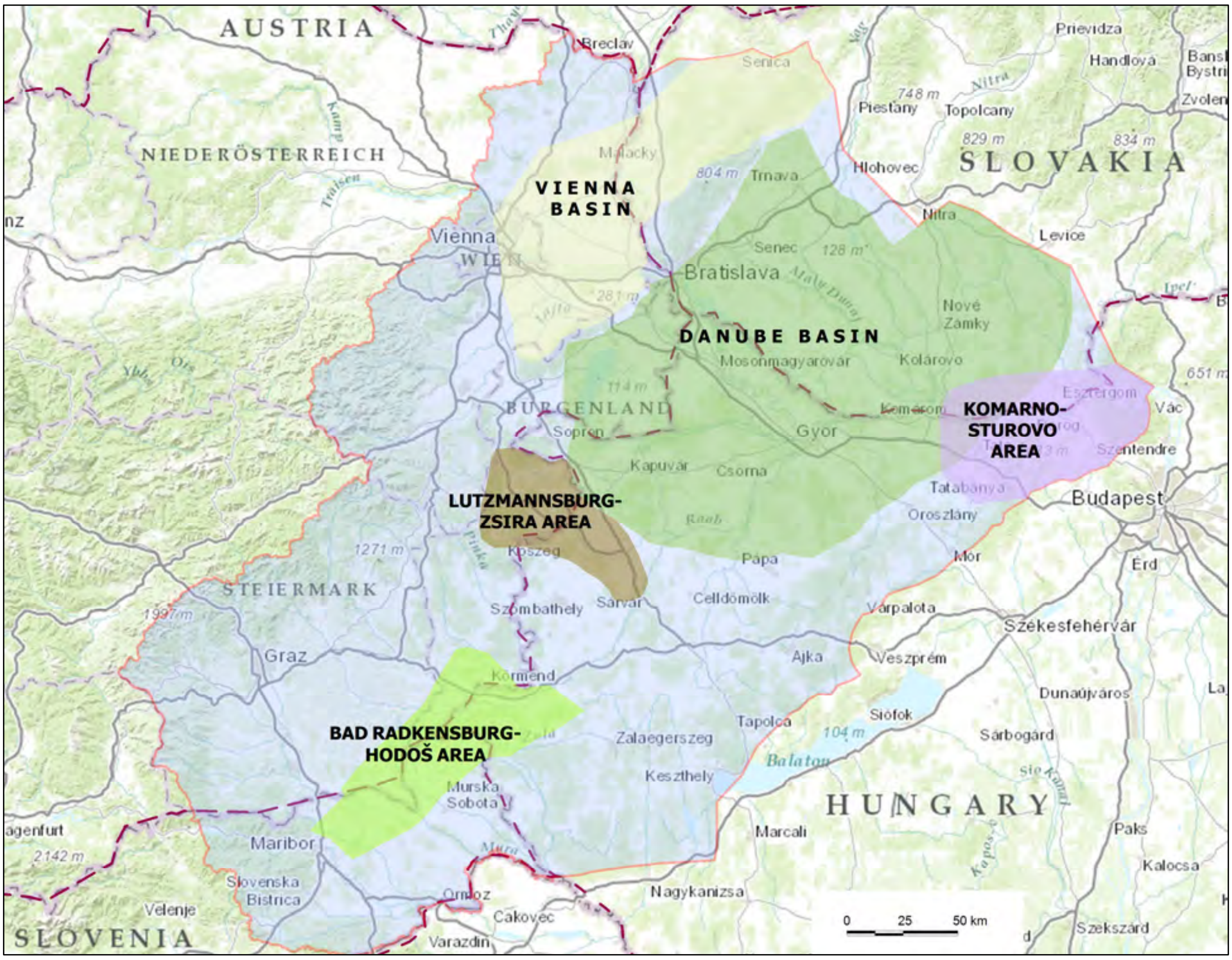

Figure 1.2 The supra regional and pilot model areas of the TRANSENERGY project

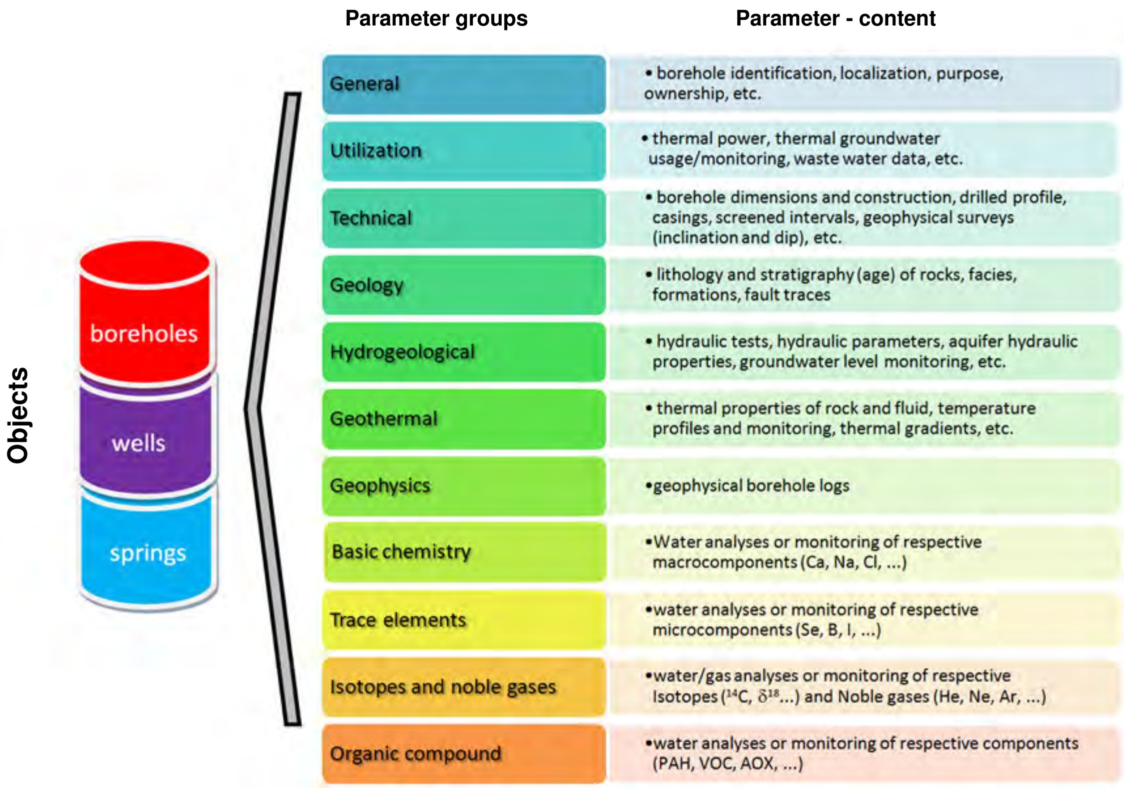

Figure 1.3 Parameters of the TRANSENERGY borehole database

porous aquifers) and Aggtelek-Slovak Karst region, with dominating karstic type of permeability. Despite the focus of this project only on "cold" transboundary groundwater aquifers, the project has shown the effective cooperation with partnership geological survey - Geological Institute of Hungary, MÁFI (Magyar Állami Földtani Intézet).

As mentioned above, no comprehensive study focused on transboundary geothermal resources has been done till 2010. The need for joint transboundary evaluation of the geothermal resources, along with the utilization evaluation, creation of geoscientific models and management aspects was recognized by four Central European countries (Hungary, Slovenia, Austria and Slovakia) that share transboundary geothermal energy resources in the western part of the Pannonian Basin. The project TRANSENERGY - Transboundary Geothermal Energy Resources of Slovenia, Austria, Hungary and Slovakia therefore addressed the key problem of using geothermal energy resources in cross-border regions in a sustainable way. The project was implemented through the Central Europe Program, Area of Intervention 3.1. (Developing a high quality environment by managing and protecting natural resources) and co-financed by ERDF with duration from April 2010 till September 2013. Partners in TRANSENERGY project were four national geological surveys: MFGI – Geological and Geophysical Institute of Hungary, Geo-ZS – Geological Survey of Slovenia, GBA – Geological Survey of Austria and SGIDŠ – State Geological Institute of Dionýz Štúr (Slovakia), that have long experience in cross-border co-operation in Central Europe and as governmental institutions guaranteed an independent assessment.

1.5. International cooperation on geothermal energy project TRANSENERGY

The aim of TRANSENERGY project was to summarize the relevant data, compile transboundary geoscientific models that were inputs for geothermal energy evaluation in project area and ***provide recommendations for a sustainable and efficient utilization of transboundary hydrogeothermal resources*** on regional level, respecting the natural boundaries of geothermal reservoirs that exceed national level of evaluation. These recommendations were based on the main project outcomes: a complex assessment of the present production and wide-range utilization of thermal groundwater, as well as the results of integrated evaluation of geological, hydrogeological and geothermal models at various scales. Appraisals were carried out by more than 80 experts of the four national geological surveys of the partner counties, providing an impartial assessment and common understanding of the hydrogeothermal systems of the western part of the Pannonian Basin. The developed problem-oriented approach of TRANSENERGY focused on the needs of decision-makers and might be applied in other regions in Europe, thus helping the countries to reach their National Renewable Energy Action Plans (NREAP) targets without threatening the environmental targets and/or interests of their neighbouring regions.

The TRANSENERGY project is complex in terms of the topics that were evaluated and studied throughout its implementation. Thus the matter of this chapter is rather an overview of the project focus and the areas covered by the project than its tangible results. These are accessible on the project website in the form of work package reports (http://transenergy-eu.geologie.ac.at/) or in following articles of this Slovak Geological Magazine volume that are focused on the Danube Basin modelling outcomes and the utilization of the geothermal energy.

The project area covered 47,750 km^2 with geological, hydrogeological and geothermal models in "supra regional scale" (covering the whole project area) and models studied in more detail in 5 pilot areas (Figure 1.2): (1) Danube Basin (A-SK-HU); (2) Vienna Basin (SK-A); (3) Komárno-Štúrovo area (HU-SK); (4) Bad Radkersburg - Hodoš area (A-SLO-HU); (5) Lutzmannsburg - Zsira area (A-HU).

The implementation of the project reflected the needs of complex evaluation of geothermal energy aspects and included:

- Transnational data management
- Geothermal water utilization aspects
- Cross-border geoscientific models
- Implementation tools for transboundary geothermal resource management and interactive map server

Three types of databases were elaborated incorporating geothermal sources (with thermal water at least 20 °C), their managers and users:

- Database of authorities (http://akvamarin.geo-zs.si/authorities/) holds information about 40 institutions active in the management of geothermal resources in the project area and presents their view on the regulatory regime of research and utilization of geothermal energy and thermal water.
- Database of thermal water users (http://akvamarin.geo-zs.si/users/) comprises 149 active and 65 potential users in the project area, as well as data about 403 geothermal wells and thermal springs, the temperature and use of water, and wastewater management. In Slovakia alone there were 23 active and 21 potential users identified in research area.
- Database used as a source of geological data for further evaluation and modelling purposes. Compiling this database was done in couple of steps. Data showed low uniformity as they were of different origin and from various sources - different formats, scales, projections, various types of geological maps and cross-sections, geophysical profiles, as well as borehole data. The final database contained 1,686 objects involving 242,811 records represented in 453 individual parameters. Parameters were grouped in 11 different groups (Fig. 1.3). The spatial distribution of the data is on Fig. 1.4.

Chosen information is available for public and is published on the official site of TRANSENERGY project (http://transenergy-eu.geologie.ac.at).

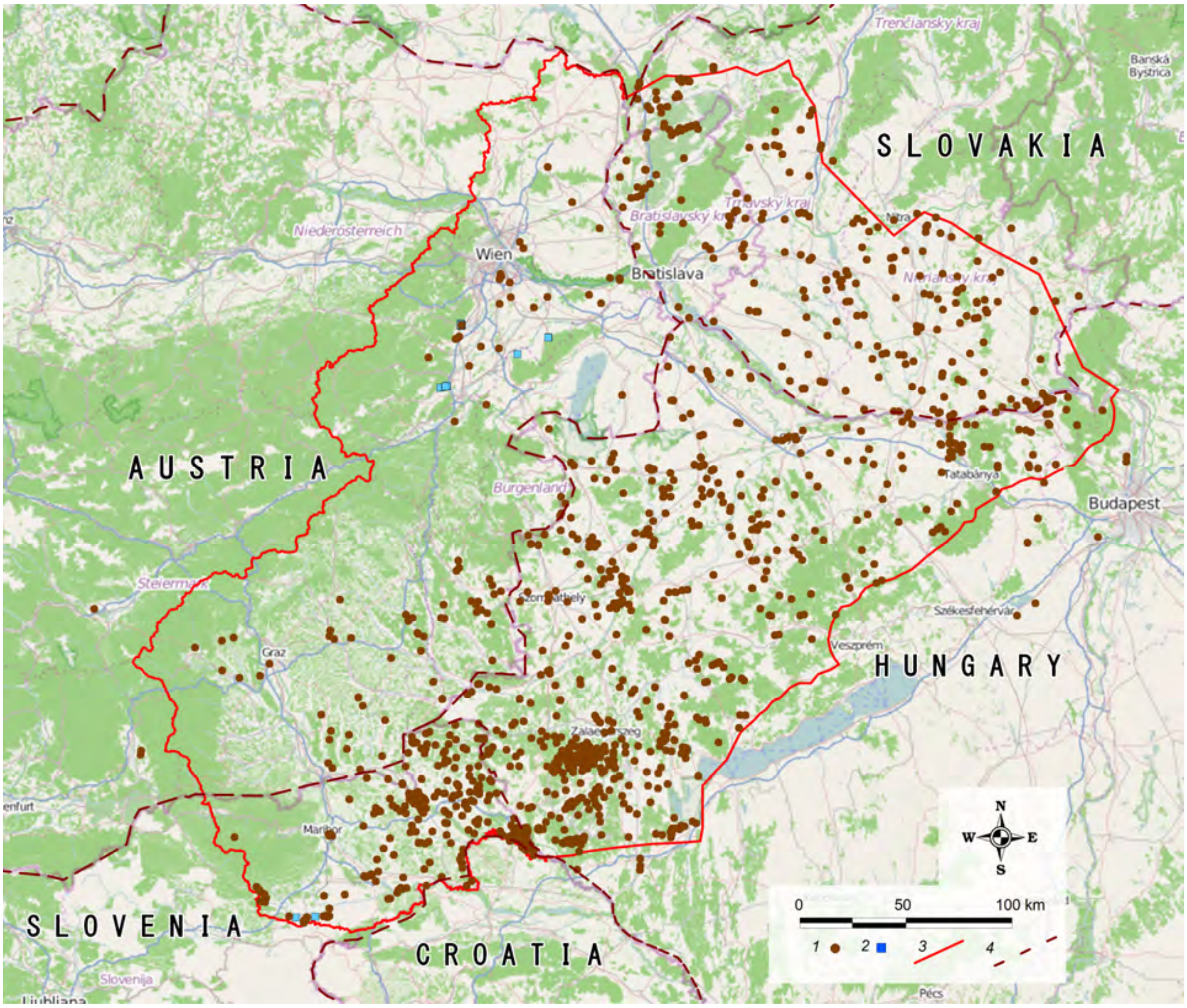

Figure 1.4 Spatial distribution of the source data objects (modified Mikita et al., 2011). Explanations: 1 - boreholes (including petroleum boreholes that show only location though data are confidential), 2 - springs, 3 - supraregional area, 4 - state boundaries

Overview of ***geothermal energy utilization*** was one of the main outputs of the project. Based on information of 214 geothermal energy users, the utilization maps were compiled. The geothermal water is utilized in 17 different ways in the project area, of which bathing and swimming (incl. balneology) is the most frequent way of utilization in all 4 countries. Drinking water use is applied mainly in Hungary, while space and water heating in Slovenia and Slovakia. Hydrodynamic changes in geothermal aquifers due to thermal water exploitation have been noticed in 303 wells from all 4 project countries.

Geoscientific models represent the simplified version of the existing hydrogeothermal systems (which are complex in reality) and by the interpretation and extrapolation of input data, they provide a continuous information in space (e.g. about the geological build-up, rock parameters, hydraulic heads that direct groundwater flow, temperature distributions in the subsurface, etc.) also for those areas, where measured data are not available. By quantifying the different parameters, the models also simulate the relevant interactions of the real systems and may provide information about their future responses (Rotár-Szalkai et al., 2010).

The ***geological*** models outlined rock geometry, determined the main geological units with similar hydrogeological characteristics (i.e. hydrostratigraphical units), which were important input data for the hydrogeological and geothermal models. The ***hydrogeological-hydrogeochemical*** models described the thermal water flow system, while the ***geothermal*** models expressed the 3D temperature distribution in the subsurface.

Modelling activity was performed at two scales and successive phases: first models (geological, hydrogeological and geothermal) were performed at 1:500,000 scale for the entire project area ("***supraregional models***"). The aim of these models was to handle the project area in a uniform system approach, to determine the main geological structures and flow systems and the relation between them, to describe distant hydrogeological processes, to describe the geothermal potential and quantify the hydrogeothermal resources, and to provide boundary conditions for the pilot models. The ***models*** developed for ***pilot areas*** at a scale of 1:100,000 to 1:200,000 focused on special transboundary problems which were varied accross areas. On the pilot areas both ***steady state*** (expected changes in the system under present utilization practice) and ***scenario*** models (responses of the system to different predicted/hypothetical utilization schemes in the future) were developed.

The web-based geothermal information system as one of the outputs of the project incorporated geological, hydraulic and geothermal conditions with the utilization characteristics of the geothermal resources. A web viewer was created for a spatial presentation of the collected data, helping the user at his orientation in space and giving the desired information about wells and way of their utilization. On the interactive map (Fig. 1.5), accessible on the website http://transenergy-eu.geologie.ac.at/, any desired combination of data in studied region can be displayed. Data are arranged into six groups: geology, geological cross-sections, geothermal potential, utilization maps, maps of potential reservoirs, and the database. A series of geological maps was created for the entire project area. In addition to the surface geological map in the scale of 1:200,000, 9 geological maps at the scale of 1:500,000 are available, showing geological composition beneath the selected younger rocks as given in the title of the map. In this way maps of the basement rocks of the Quaternary, Upper Pannonian, Lower Pannonian, Sarmatian, Badenian, Lower Miocene, Paleogene and Senonian sequences, as well as the map of the Pre-Cainozoic basement rocks beneath the sedimentary basins were created. Three geological cross-sections were made in the direction NW-SE through the entire project area, and 12 detailed cross-sections through the five pilot areas. The interactive maps show depths of the isotherms 50, 100, and 150 °C, maps of the surface heat flux density, and maps of the temperatures at depths of 1,000, 2,500 and 5,000 m. Thirteen utilization maps show the activity of thermal wells, tapped aquifers, monitoring set-up of the extracted thermal water and waste water, and its utilization purpose. The database is linked to individual wells, and by clicking on it, the user can obtain data about its location, drilling, geological composition, aquifers, and the chemical composition of thermal water.

In the evaluation and application of the data it has to be considered that numerous local phenomena are not shown due to the small scale and consequent generalizations. Therefore, an additional and more detailed study of local hydrogeological and geothermal conditions is still required to perform a high-quality project for any new implementations of geothermal energy use in the project area.

Apart from evaluation of the data, comparison of the utilization and geoscientific modelling special attention was dedicated to comparison of the ***legislation and management of the geothermal water***. Based on comparison of four Central European countries, different policies and attitudes in utilization, reporting, responsibilities, monitoring policies and delineation of geothermal water bodies were identified. The comparison of the legislation was very complicated task to do, as different schemes are applied, though common attitude on certain transnational level in geothermal water management is desirable in transboundary policies. For more detailed overview of the legal aspects, administrative procedures and conditions for licensing geothermal water utilization have been summarized in manuscript Lapanje & Prestor (2011). In legislation the threshold temperature for thermal water (at the point of seepage) is defined in Slovakia (Geological Act 569/2007) over 20 °C and in Hungary (Act LVII of 1995 on water management) over 30 °C. In Slovenia it is accepted in practice that thermal water is groundwater with temperature over 20°C, though without the legislation definition in the relevant Acts. The similar situation applies for Austria, where OEWAV-Regelwerk 215 (Guidelines for Utilization and Protection of thermal water in Austria) is applied for the definition of thermal water with minimum outflow temperature 20 °C.

Monitoring, as integral part of groundwater and geothermal energy management has been overviewed and analysed by several TRANSENERGY studies (Prestor et al., 2012, Rotár-Szalkai et al., 2013).

As a result of the different attitudes in geothermal water and geothermal energy sector on level of legislation, quantitative and qualitative monitoring, disposal of the used geothermal water the new methodology was proposed to evaluate the geothermal water management in project partner countries. The methodology is following guidelines for the protection of Lake Léman (Lachavanne & Juge, 2009) identified 10 crucial indicators that were used for evaluation of pilot areas of TRANSENERGY project (Prestor et al., 2012).

The project was designed from its beginning as ***stakeholder needs oriented***. All the relevant information, reports and outputs are accessible for wide public on web page http://transenergy-eu.geologie.ac.at/. As authorities dealing with everyday management, licensing, etc. of thermal groundwater/geothermal energy were among the main targeted stakeholders, a special attention was paid to identify them. Based on a questionnaire survey, altogether 40 authorities' data (10-Austria, 15-Hungary, 7-Slovakia, 8-Slovenia; information on organization, contacts, role, etc.) were organized into a database (http://akvamarin.geo-zs.si/authorities) (Prestor & Lapanje, 2010).

The final project results also target the ***decision/policy makers*** at international level, aiming to provide them scientifically based recommendations and evaluations supporting the performance of EU policies and elaboration of various strategies.

Nevertheless, ***other stakeholder groups*** can also largely benefit from TRANSENERGY results. The outlined potential geothermal reservoirs (Rotár-Szalkai, 2012) provide an excellent overview for ***project developers*** on the prospective areas for further possible explorations, while feasibility studies demonstrated for ***future investors*** that on the basis of project data and models tangible projects can be planned. The overview of current legislation (Lapanje & Prestor, 2011) and financial incentives (Nádor et al., 2013) deliver useful information on the non-technical issues. The elaborated geoscientific models (Rotár-Szalkai et al., 2013) can be also used in further

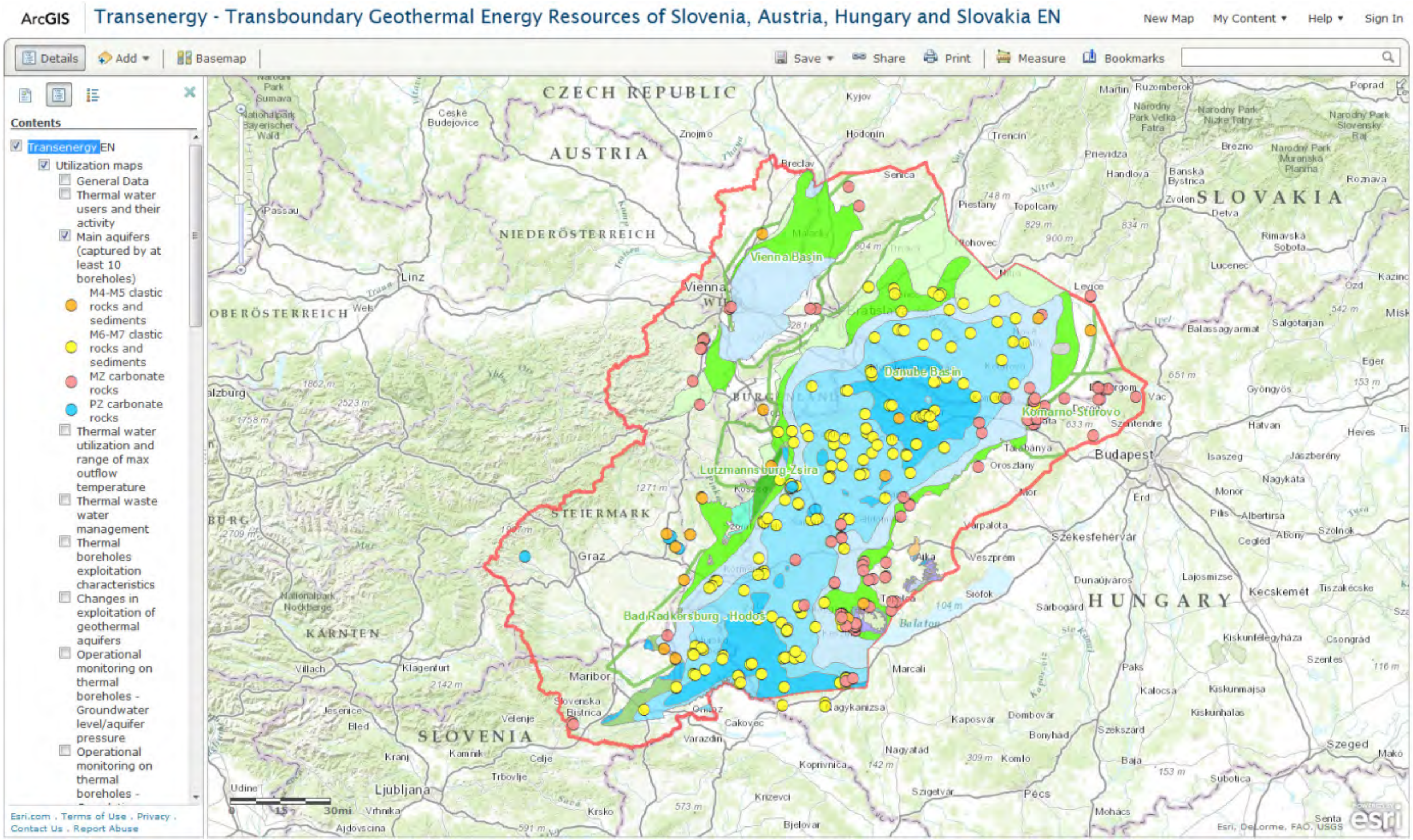

Figure 1.5 Example of an interactive web map, composed of a geological map of the Late Miocene clastic rocks and sediments and a map of captured geothermal aquifers, created from the users database http://transenergy-eu.geologie.ac.at)

academic research, while some results of pilot area models provide detailed information on reservoir properties for present and potential ***users***.

Besides the stakeholders approached through questionnaires, publishing activities and by project organized conferences and seminars, of the project directly involved stakeholders. From very beginning of the project proposal, the establishment of the External Evaluation Board (EEB) was designed. EEB members consisted of each country stakeholders, including one national and one local governmental representative, one current and one potential user, as well as 3 people from international agencies. The EEB members were providing an independent appraisal of the project results and were actively participating by implementing their needs and ideas into the project work and results.

1.6. Conclusions

The paper presents a brief overview of research results in geothermal energy sector in Slovakia and its current geothermal resources bound to 27 delineated areas with documented 141 boreholes on the Slovak territory. Though in the light of merging Europe policy the transboundary resources (in this case water and geothermal energy) are in future focus. The project "TRANSENERGY–Transboundary Geothermal Energy Resources of Slovenia, Austria, Hungary and Slovakia" addresses the key problem of using natural resources that are shared by different countries in a sustainable way. Natural resources, such as geothermal energy whose main carrying medium is groundwater is strongly linked to transboundary geological structures.

The project delivers multilingual web-portal for facilitating a sustainable use of the thermal water in the western Pannonian region that includes:

- Geological, hydrogeological and geothermal maps, cross sections, models;
- A multilingual borehole database;
- Thermal water utilization maps;
- Geothermal potential maps;
- A database of authorities dealing with management and licensing of transboundary geothermal aquifers;
- A summary of actual legal and funding framework in the participating countries with emphasis on cross-border geothermal facilities;

A strategy paper evaluating existing exploitation, future possibilities and recommendations for a sustainable and efficient geothermal energy production at the project area.

The web service (www.transenergy-eu.geologie.ac.at) as one of the main outputs of the project is public and can be used by the involved authorities (water management, mining, land use), by consultants and investors.

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2. Geological Model of the Danube Basin; Transboundary Correlation of Geological and Geophysical Data

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Abstract. The presented paper comprises the first successful attempt towards compiling the full 3D horizontal and cellular model of the Danube Basin created in the frame of the international TRANSENERGY project. In this article we are presenting only one of the five pilot areas of the TRANSENERGY project – the Danube Basin.

The 3D model is built on a large amount of geological (mapping, stratigraphic, wells) and geophysical (seismic, geomagnetic, gravitational) data, completed by structural and geodynamic studies in all participating countries (Slovenia, Austria, Hungary and Slovakia). After gathering and processing all available data a unified stratigraphical framework was compiled for all participating countries, followed by defining the main structural features and finally creating the model.

Our 3D model contains 8 horizons (Quaternary, Upper and Lower Pannonian, Sarmatian, Badenian, Neogene volcanites, Lower Miocene and Paleogene and the Pre-aienozoic basement) subdivided into 37 formations. The structural pattern of the area was simplified after several consultations into a scheme of 7 approximately SW-NE and 4 roughly NW-SE to W-E faults.

The 3D model is also the first attempt to visualize the Neogene volcanic bodies buried below younger sediments, including hypothetical Gabčíkovo volcano.

Keywords: Danube Basin, international cooperation, cross-border geology, 3D geological model, structural model, buried volcanoes

2.1. Introduction

The aim of the TRANSENERGY project was to support the harmonized geothermal water and geothermal energy utilization in the western part of the Pannonian Basin and its adjacent basins (e.g. Vienna Basin), which are situated in the transboundary zone of Austria, Hungary, Slovak Republic and Slovenia. The so called supraregional model includes the entire project area of the NW Pannonian Basin and the adjacent areas, encompasses the main geothermal reservoirs and manages the complete area in a uniform system approach. The supraregional model area was further divided into several subregions of enhanced hydrogeothermal utilization potential, designated as pilot areas, usually forming geological or hydrogeological units which have been identified and investigated in a more detailed way. In the Supra regional area five pilot areas were chosen, where local models had been developed. They focused on the local transboundary problems, and the detailed geological characteristics of the areas. The areas were the following: Vienna Basin, Danube Basin, Komárno-Štúrovo area, Lutzmannsburg-Zsira area and the Bad Radkersburg-Hódos area (Fig. 2.1).

As a starting step we collected all available seismic (160 sections) and well data (1672 wells). After this step it was necessary to define the technical framework for the project (file exchange formats, scale of maps etc.). Finally the WGS1984 UTM Zone 33N as the common coordinate system and Transverse Mercator as the common projection were chosen.

The next step was the harmonization of stratigraphic data, e.g. the time-consuming process of correlation of different formations. These formations describe sometimes the same lithologic and temporal geological units of a partner country with different synonyms, but more often the different names can cover slightly different rock lithologies as well. The most problematic question was the harmonization of the Post-Oligocene formations of the Paratethys. The most valuable sources for this task were the Geological Map of Western Carpathians and adjacent areas (Lexa et al. eds., 2000), the DANREG project maps and explanatory notes (Császár et al., 2000) and the T-JAM project (Fodor et al., 2011). The complete harmonized stratigraphical chart is published in Maros et al. (2012).

The 3D geological models for each one of the pilot areas were made separately: the Vienna Basin in Austria, the Danube Basin in Slovakia, the Komárno-Štúrovo and Lutzmannsburg-Zsira areas in Hungary and the Bad Radkersburg-Hódos area in Slovenia.

The final products scales of the Supra regional and Pilot areas models are the following:

- Supra regional area 1:500 000, Surface geology 1: 200 000
- Pilot areas:
  - Danube Basin 1:200,000;
  - Vienna Basin 1:200,000;
  - Lutzmannsburg-Zsira 1:100,000;
  - Bad Radkersburg-Hódos 1:200,000;
  - Komárno-Štúrovo 1:200,000.

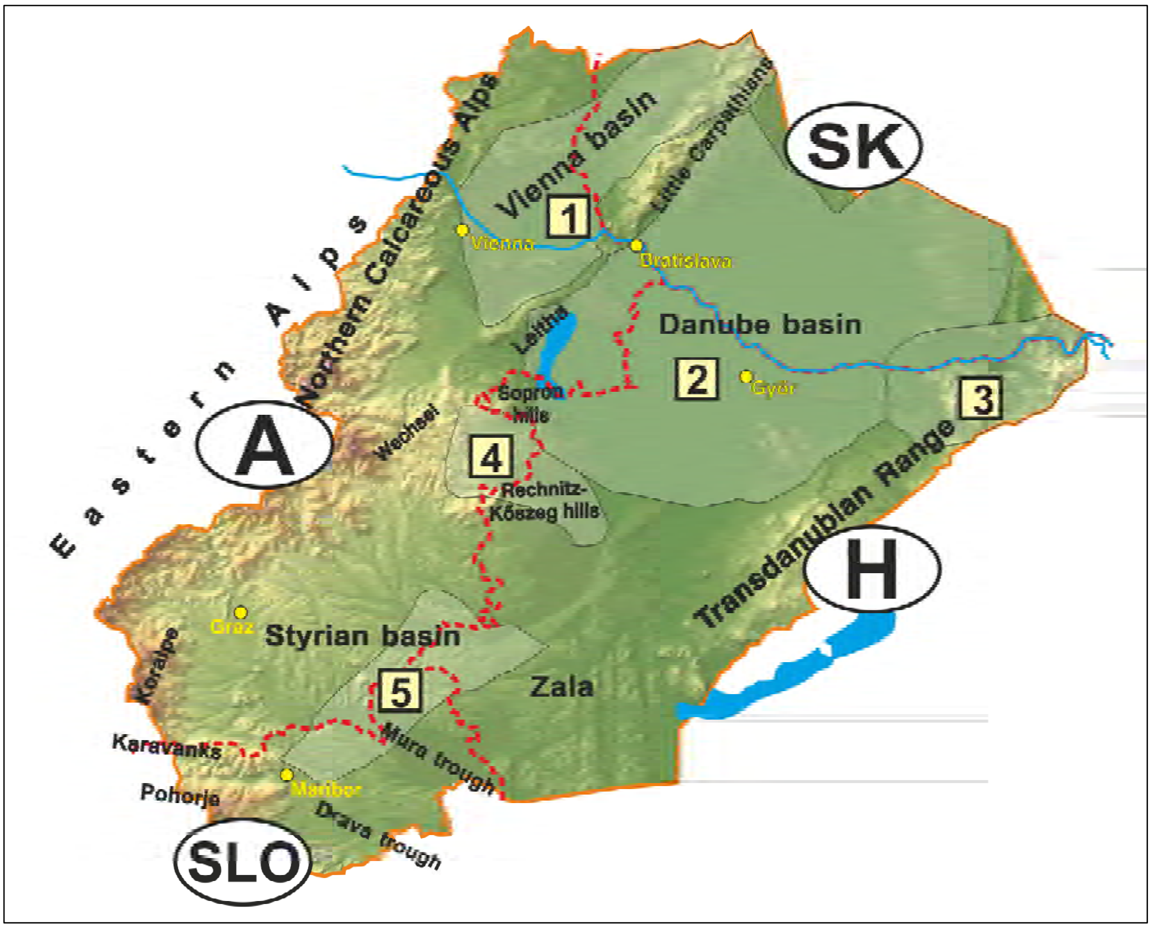

Fig. 2.1 Localization of the supraregional (orange line) and the pilot areas: 1 - Vienna Basin; 2 - Danube Basin; 3 - Komárno-Štúrovo area; 4 - Lutzmannsburg-Zsira area; 5 - Bad Radkersburg-Hódos area (modified after Maros et al., 2012)

2.2. Methodology

The primary aim of the geological model of the Danube Basin pilot area was to create a 3D geological framework accurate enough for hydraulic modelling, however we realized, that such a model itself would be valuable for further research. The model is based on seismic and borehole data, partially on other sources (published results, maps). The Danube Basin pilot area is located in three countries (Slovakia, Hungary and Austria) and was modelled in the frame of geological horizon models of the TRANSENERGY territory (Maros et al., 2012). The pilot area covers 1,2340 km^2, has a slightly elongated shape with length ca. 140 km in SW-NE and width ca. 110 km in NW-SE direction.

The steps of creating the model we can be summarized as follows:

1. *Creation of the common framework for all participants:* since the TRANSENERGY Supra area covers parts of four states, the work on the model started with unifying the different local stratigraphic charts for all four states (Slovakia, Hungary, Austria and Slovenia). In this phase we also needed to agree on horizons to be modelled, coordinate system and projection, scale of outputs, exchange formats to be used etc.

2. *Data compilation and processing*: collecting the existing seismic and well data (Tab. 2.1, Figs. 2.2 and 2.3), as well as other published works. In this phase we had consulted concepts as well as details with experts due to the optimization (simplification in fact) of the later fault model and stratigraphy.

3. *Pre-modelling data processing*:
   - calculation of time-to-depth for the seismic profiles;
   - redefinition of the borehole data according to the unified stratigraphic legend;
   - converting and entering the data into the 3D modelling software.

4. *Creation of the 3D model in main steps*:
   - creation of non-faulted horizons;
   - creation of the fault model;
   - combining non-faulted surfaces with fault model into a faulted 3D model;
   - input and refining lithological and stratigraphic content of 3D "space" between horizons (zones).

5. *Creation of outputs*: visual (maps, sections) as well as text outputs, presentations.

During the work we used common text and tabular editing tools (MS Office, OpenOffice), vector and bitmap-based graphical software (Corel, Inkscape, GIMP), MapInfo and partly also ArcGIS for map and GIS based tasks. The 3D modelling itself was realized with software Petrel 2008.

Table 2.1 Overview of input data

	Number of wells	Deepest well [m]	Medium depth of wells [m]	Number of seismic profiles
Slovakia	146	3,303	1,139	19
Hungary	189	4,517	1,084	63
Austria	74	1,860	243	–

2.3. Overview of the geological history of the Danube Basin

The Neogene Danube Basin is the largest subunit of the Western Carpathian basin system. In the Slovakian territory it corresponds to the Danube Lowland and in the area of Hungary it is called Little Hungarian Plain. It`s western margin is bordered by the Eastern Alps with Leitha Mts., and northernmore by the Western Carpathian Malé Karpaty Mts. In the North, the basin is laterally finger-like protruding among the Malé Karpaty, Považský Inovec and Tribeč Mts.

Structural evolution of the basin comprises several temporal phases, depending closely on the evolution of the mountain chain. The major part of the basin started its evolution in the Badenian time. Structurally, this was an episode of the finalizing phase of the pull-apart type depocentres collapse, gradually changing into extensional grabens of the basin rifting. The extension started along NNE-SSW trending normal faults which could be rejuvenated displacements along previously reverse faults in the basement and a very complex reverse–strike slip–normal fault deformation history has to be supposed along Rába and Hurbanovo tectonic zones. The later (Sarmatian and Pannonian) history is characterized like a back-arc basin, with the depocentres functioning as extensional grabens and half-grabens. The wide rifting at the Sarmatian/Pannonian boundary was followed by deep thermal postrift subsidence phase (Royden et al., 1983, Kováč, 2000).

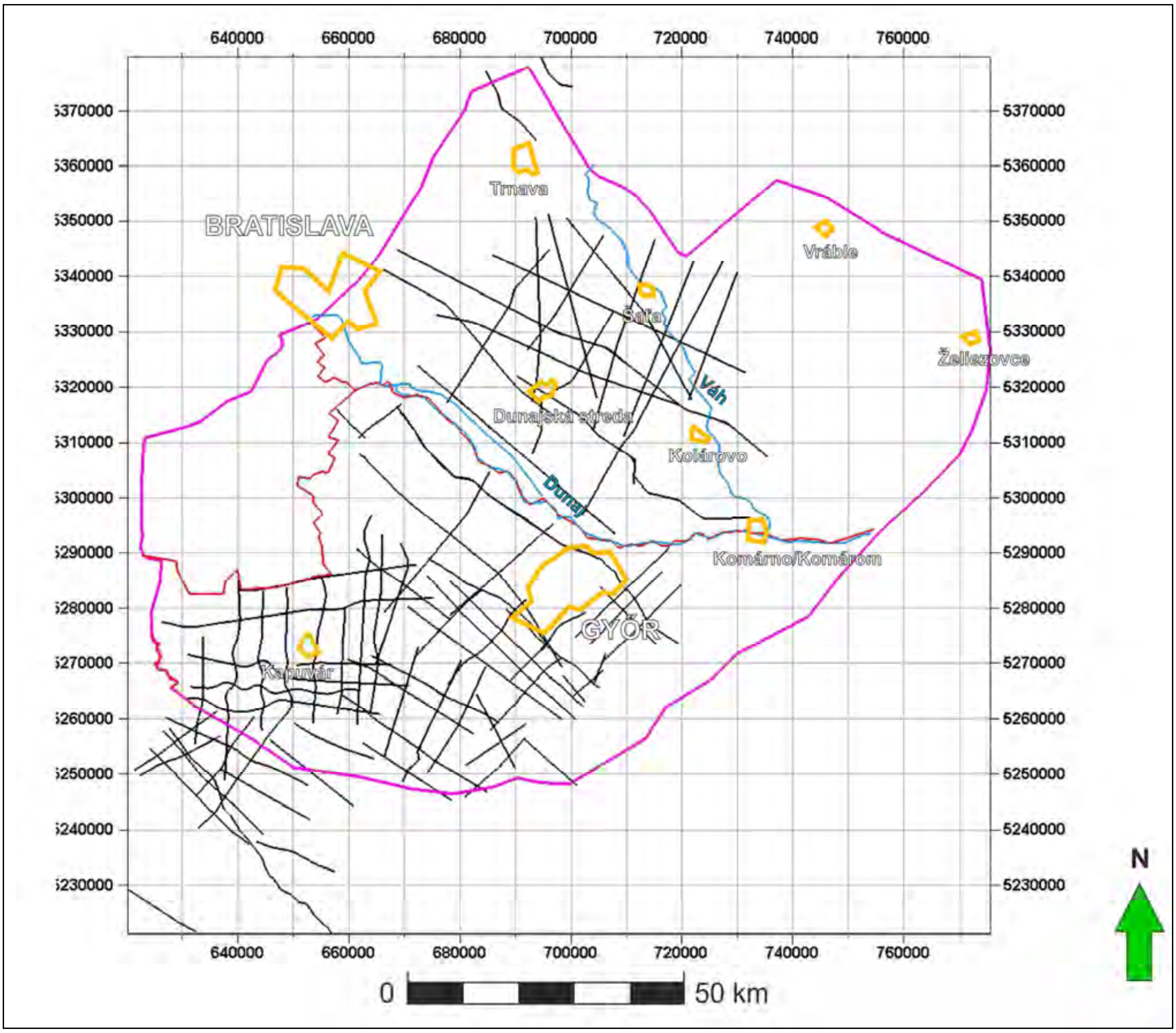

Fig. 2.2 Localization of seismic profiles

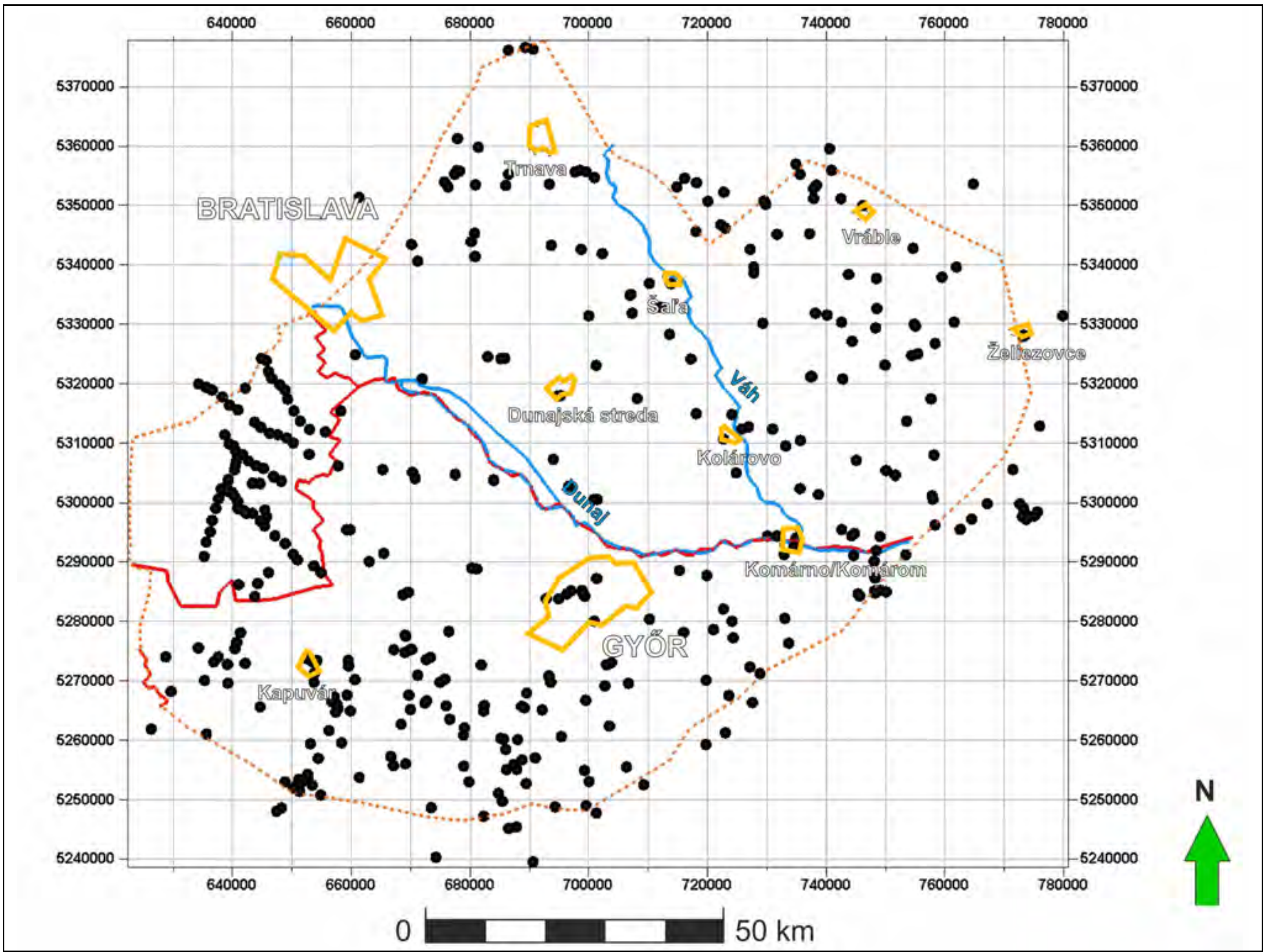

Fig. 2.3 Localization of wells

2.4. Results and discussion

2.4.1. Stratigraphy

Because of the geological structure of the pilot area the final model comprises zones (formations) in 8 horizons which we defined as base surfaces at chosen stratigraphic boundaries of the core column (e.g. Pre-Badenian surface). These zones (Table 2.2) are not the strict equivalents of the formations of the stratigraphic charts of the participating countries, but are purpose-created for the needs of the project by correlating and unifying the similar complexes of each country (for example the Late Pannonian zone "MPl" is equivalent of Zagyva and Nagyalföld Fms. in Hungary, the Volkovce and Beladice Fms. in Slovakia and the Rohrbach Fm. in Austria).

The topmost surface of our model - the Earth's surface in fact - was created using the SRTM (Shuttle Radar Topography Mission) project's global digital elevation model, spearheaded by the U.S. National Geospatial-Intelligence Agency (NGA) and the U.S. National Aeronautics and Space Administration (NASA). Altough the SRTM model in some cases showed a few metres differences especially near the major rivers against other local data, it is the most useful model with sufficient accuracy for our purposes which covers the whole area.

Horizon: Pre-Cainozoic basement

The Pre-Cainozoic basement of the basin at the western and northern boundary is built up of several units of the Central Eastern Alps and Central Western Carpathians, while in the south-eastern part of the basement units of the Transdanubian Central Range are also present, belonging to the ALCAPA unit. In the Slovakian part the basement is built up of Hercynian crystalline rock complexes and mainly Late Paleozoic and Mesozoic cover sequences of the Tatric and Veporic units as well as of superficial nappe systems of Fatricum and Hronicum composed mainly of Mesozoic (dominantly Triassic – Jurassic) sedimentary sequences. The Tatric and Veporic units continue into Hungarian and Austrian territories as their equivalents in the Lower Austroalpine nappe systems. The Transdanubian Central Range forming the basement in the southern part of the area is built up of a sequence of Paleozoic rocks (dominantly clastic rocks also with carbonates), massive Triassic and Jurassic strata dominantly formed in platform or open-sea environment. Cretaceous sediments of terrestrial or shallow-water environment are terminating the Mesozoic part of this succession.

Table 2.2 Summary of the stratigraphical and lithological content of horizons and zones of the model

Surface	Horizon	Zone (Formation)
▼*SRTM (surface)*	–	–
▼ *Base Q*	Quaternary	undivided
Top U. Pann.▲	Late Pannonian basin fill	MPl - fluvial-lacustrine-continental sediments *(Late Pannonian - Pliocene)*
▼*Base U. Pann.*		Md - lacustrine sediments *(Late Pannonian)*
Top E. Pann.▲	Early Pannonian basin fill	Mplf - shallow-water clay/silt *(Late Miocene - Pannonian)*
		Mpc - near-shore psephite/psamite *(Late Miocene - Pannonian)*
		Mptb - turbidite *(Late Miocene - Pannonian)*
▼*Base E. Pann.*		Mpcm - calcareous and clayey marl *(Late Miocene - Pannonian)*
Top Sarm.▲	Sarmatian basin fill	Msrt - rhyolitic/andesitic volcanoclastics *(Sarmatian)*
▼*Base Sarm.*		Msmf - shallow-marine and brackish clay/marl *(Sarmatian)*
Top Bad.▲	Badenian basin fill	Mbmf - shallow-marine and open basin claymarl *(Badenian)*
		Mbc - shoreline coarse/grained clastics/marl *(Badenian)*
▼ *Base Bad.*		Mbls - shallow-marine fossil-bearing limestone *(Badenian)*
Top Neovolc.▲	Neogene volcanites	Mbzt - subvolcanic dacite, dacitic volcanoclastics *(Badenian)*
		Mbptr - trachyte, trachytic agglomerate *(Badenian - Pannonian)*
▼ *Base Neovolc.*		Mba - subvolcanic and effusive andesite *(Badenian)*
Top Mi1/Pg.▲	Early Miocene and Paleogene	Mkb - open-marine silt/clay *(Karpatian-Badenian)*
		Olb - intertidal/lacustrine sandstone/silt/clay *(Oligocene)*
		Olf - fluvial/lacustrine clay/marl/sandstone *(Oligocene)*
		Olmf - open marine/restricted basin clay/marl *(Early Oligocene)*
		E2-3ml - open and shallow marine silty and clayey marl *(Middle - Late Eocene)*
		E2ls - shallow marine limestone, calcareous marl *(Middle Eocene)*
▼ *Base Mi1/Pg*		PcE2ml - shallow marine marl *(Paleocene/Early Eocene)*
Top Pre-Cen.▲	Pre-Cainozoic basement	K2ml - pelagic limestone/marl *(Senonian - Early Paleocene)*
		K2ls - platform limestone *(Senonian)*
		J - Jurassic in general *(mainly limestones)*
		T3ls - platform limestone *(Late Triassic - Early Jurassic)*
		T3p - platform carbonates *(Carnian - Rhaetian)*
		T3d - platform carbonates *(Norian - Rhaetian)*
		Tkbls - basinal marl/limestone *(Carnian)*
		Tpd - platform dolomite *(Ladinian - Carnian)*
		Tacb - shallow marine bituminous limestone *(Anisian)*
		T1cb - continental/near-shore siliciclastics *(Early Triassic)*
		Pt - continental siliciclastics *(Middle - Late Permian)*
		C_Tgr - granitoid rocks of the Tatric and Veporic megaunits *(Carboniferous)*
		OC_Tr - low-grade metamorphic rocks of the Transdanubic megaunit *(Ordovician - Carboniferous)*
		Pz_Vcr - medium-grade metamorphic rocks of the Veporic megaunit *(Early Paleozoic ?)*
		PzF/PzS - medium-grade metamorphic rocks of the Tatric and Austroalpine megaunit *(Early Paleozoic ?)*

The Pre-Cainozoic basement rocks are correlated only on the base of lithology and sedimentology. The Senonian part of the rock-pile represents a kind of post-orogenic basins formation, covering the principal nappe boundaries. The correlation of older rocks is much more complicated, because of differences in the Late Cretaceous regional tectonic behaviour, and also of the significant Tertiary faulting. In fact they are parts of a complicated Alpine thrust/fault system, comprising several nappe systems and para-autochthonous Mesozoic and Late Paleozoic rock units, as well as their magmatic and metamorphic "cores". Since only a small part of all wells reached the basement - especially in the deeper central parts and troughs - during the modelling of the Pre-Cainozoic surface (Fig. 2.4) we respected the works of Hrušecký (1999), Pěničková at el. (1984), Fusán et al. (1987) and Császár et al. (2000). In the horizon of Pre-Cainozoic basement rocks we distinguished the following facies types:

- **K2ml:** pelagic limestone/marl *(Senonian - Early Paleocene)* - Jákó and Polány Marl Fm.
- **K2ls:** platform limestone *(Senonian)* - Ugod Limestone Fm.
- **J:** Jurassic in general *(mainly limestones)*

- **T3ls:** platform limestone *(Late Triassic - Early Jurassic)* - Dachstein, Kardosrét and Norovice Fms.
- **T3p:** platform carbonates *(Carnian - Rhaetian)* - Dachstein Limestone and Dolomite, Hauptdolomit Fms.
- **T3d:** platform carbonates *(Norian - Rhaetian)* - Hauptdolomit Fm., Ederics Limestone and Sédvölgy Dolomite Fm.
- **Tkbls:** basinal marl/limestone *(Carnian)* – Sándor-hegy, Veszprém, Lunz, Oponice and Partnach Fms.
- **Tpd:** platform dolomite *(Ladinian - Carnian)* – Budaörs, Ramsau Dolomite Fms., Podhradie, Vysoká and Wetterstein Limestone Fms.
- **Tacb:** shallow marine bituminous limestone *(Anisian)* - Gutenstein, Steinalm, Tagyon, Megyehegy, Iszkahegy and Aszófő Fms.
- **T1cb:** continental/near-shore siliciclastics *(Early Triassic)* - Csopak, Köveskál, Hidegkút, Arács, Alcsút-doboz, Lužná, Benkovský potok and Šuňava Fms.

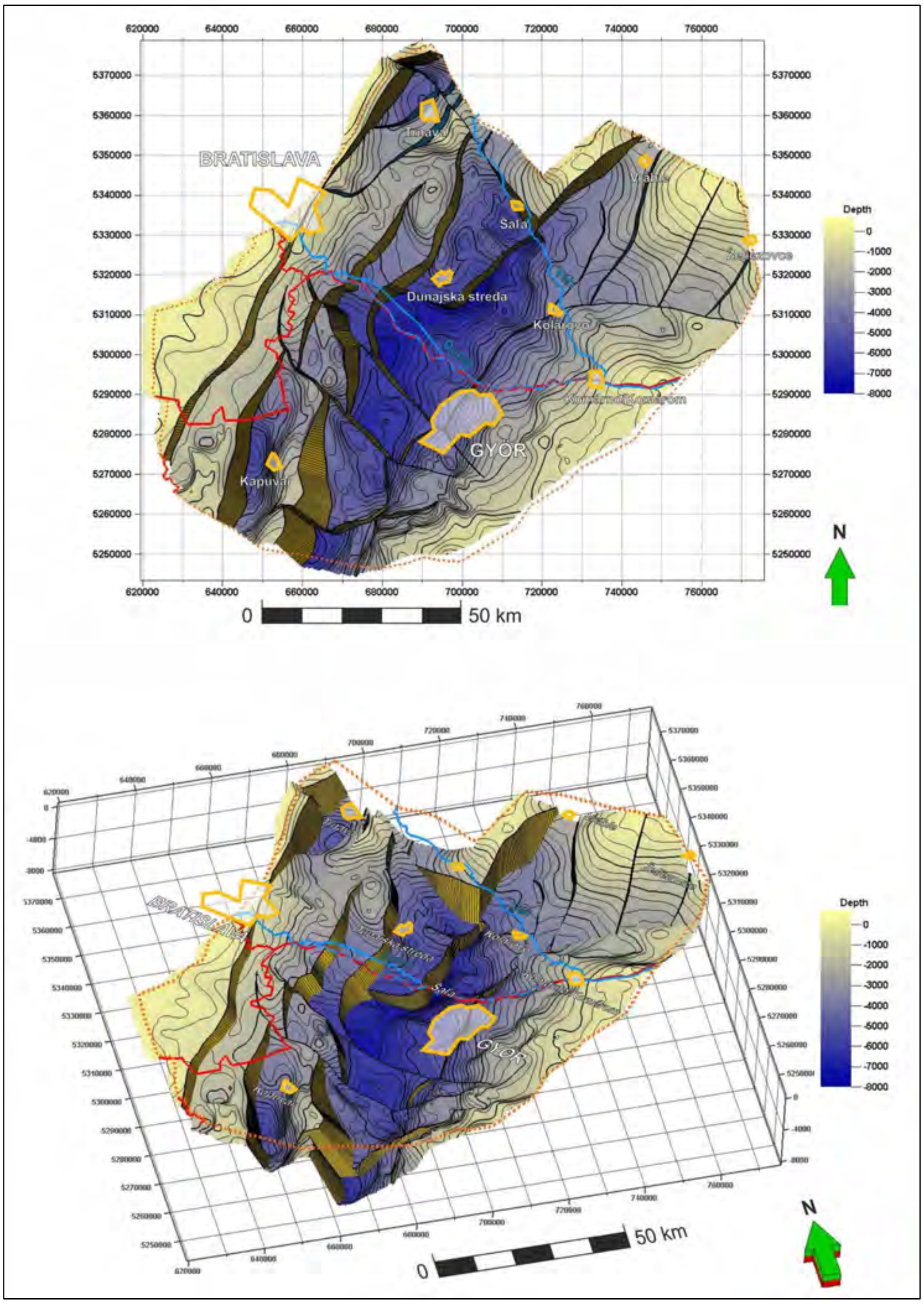

Fig. 2.4 The modelled top surface of Pre-Tertiary basement in 2D (above) and 3D (below, from SSW)

Legend to Figs 2.4.- 2.10.
1 - major cities; 2 - rivers; 3 - state borders; 4 - project boundaries

(Note for Figs. 2.4-2.10: since the slightly rotated 3D view shifts the relative position of objects on the surface - cities, rivers, borders - for the correct position please see the 2D view of each pair of Figures)

- **Pt:** continental siliciclastics *(Middle - Late Permian)* - Balatonfelvidék and Devín Fms.
- **C_Tgr:** granitoid rocks *(Carboniferous)* - Tatric and Veporic megaunits
- **OC_Tr:** low-grade metamorphic rocks *(Ordovician – Carboniferous)* - Transdanubic megaunit: Balatonfőkajár, Lovas, Alsóörs, Szabadbattyán, Polgárdi, Kékkút, Úrhida, Nemeskolta and Mihályi Fms.
- **Pz_Vcr:** medium-grade metamorphic rocks *(Early Paleozoic?)* - Veporic megaunit
- **PzF/PzS:** medium-grade metamorphic rocks *(Early Paleozoic?)* - Tatric and Austroalpine megaunit.

Horizon: Paleogene - Early Miocene

This horizon represents a very early stage of the Danube Basin evolution, and/or some relics of the pre-existing structurally different phases. Since the Paleogene and Early Miocene deposition represent the same sedimentary cycle in the studied area, we grouped these horizons together.

There are two genetically different occurrences of this horizon: the Paleogene of the Hungarian Paleogene Basin (here the Buda-type Paleogene) and separately the Central Carpathian Paleogene in the Blatné Depression (NW part of the area). The Tertiary rocks of the Buda-type Paleogene in the area are known only from the Transdanubian unit on the southern rim of the area. This type of succession is characterized by shallow-water to terrestrial sedimentation and is represented by shallow-water limestones, sandstones, marls and clays as well as coal occurrences. Paleogene rocks in the Blatné Depression occur only in smaller amounts without outcrop in the studied area and are represented mainly by flysch-type clastics (Hričovské Podhradie and Domaniža Fms.) or carbonates (Dedkov vrch and Jablonové Fms.), therefore they were joined together for their very limited occurrence.

Early Miocene deposits occur in the NE part of the area (Blatné Depression, Slovakia) as well as in the SW (Transdanubian area, mainly in Hungary). In the Blatné Depression the Eggenburgian marine depositional area was paleogeographically connected to those in the northern part of the Vienna Basin. It belongs to the Čausa Fm. In the Ottnangian the depositional environment started to be brackish, and only a small remnant of these deposits assigned to the Bánovce Fm. is preserved. The Karpatian marine deposits of the Lakšárska Nová Ves Fm. and alluvial-deltaic Jablonica Fm. are present in the northern part of the Blatné Depression and in the Dobrá Voda Depression. Early Miocene deposits in the Transdanubian part represent a stratigraphical continuation from the underlying Buda-type Paleogene and are built up of fluvial – lacustrine or brackish-water gravels, sands and clays sometimes with coal layers (Somlóvásárhely and Tekeres Fms.). The distribution of Paleogene and Lower Miocene formations is presented in Fig. 2.5.

The facies types can be recognized and correlated as follows:

- **Mkb:** open-marine silt/clay *(Karpatian-Badenian)* - Tekeres Schlier and Somlóvásárhely Fms., Čausa, Jablonica, Bánovce and Lakšárska Nová Ves Fms.
- **Olb:** intertidal/lacustrine sandstone/silt/clay *(Oligocene)* - Törökbálint, Mány and Lučenec Fms.
- **Olf:** fluvial/lacustrine clay/marl/sandstone *(Oligocene)* - Csatka Fm.
- **Olmf:** open marine/restricted basin clay/marl *(Early Oligocene)* - Kiscell, Tard and Hrabník Fms.
- **E2-3ml:** open and shallow marine silty and clayey marl *(Middle - Late Eocene)* - Padrag Marl Fm. together with Szentmihályi Andesite Fm.
- **E2ls:** shallow marine limestone, calcareous marl *(Middle Eocene)* - Szőc Limestone Fm.
- **PcE2ml:** shallow marine marl *(Paleocene/Early Eocene)* - Csolnok, Csernye and Priepasné Fms.

Horizon: Neogene volcanites

We included into this horizon all Neogene volcanic products regardless of to which stratigraphic, genetic or petrographic group they belong. Although the existence of several buried Neogene volcanic bodies in the area is well known, our model is the historically first attempt to create an approximate spatial image of these volcanic centres. In our model we distinguished five volcanic bodies: the Pásztori, Rusovce, Kráľová and Šurany bodies proven by boreholes and the anticipated Gabčíkovo volcano. Unfortunately almost all these volcanic bodies are deeply buried, so there is only a limited number of borehole data available. Since similar volcanic bodies known from the surface always comprises products several volcanic phases, dykes and vein systems they are also problematic for seismic interpretation, usually we were able to contour these bodies only very roughly (Fig. 2.6). The degree of knowledge about these bodies is variable.

From the petrographical point of view the volcanic bodies Rusovce, Kráľová and Šurany represent mainly products of Early Badenian (sometimes even Karpatian?) to Sarmatian intermediary andesitic-dacitic volcanism similar to the slightly younger Central Slovakian Neogene volcanites. All three volcanic bodies were penetrated by at least one well and show more or less clear magnetic anomaly (Seiberl et al., 1998), what was an important help for contouring the bodies.

Table 2.3 Summary of known well and seismic data of the neovolcanic bodies in the Danube Basin area

Volcanic centre	Country	Wells	Seismic sections
Pásztori	Hungary	Pá-1, 2, 4; Tét-5, 6	VPA-10, 21, 23, 92; VPE-27, 29
Rusovce	Slovakia	HGB-1	–
Kráľová	Slovakia	Kr-1	MXS-2, 3, 6 (?), 7A; 552/77
Šurany	Slovakia	Š-1	–
Gabčíkovo	Hungary / Slovakia	Msz-1 (?)	XK-1/85; VPE-39 (?) *(Hungary)* 551/81-82 *(Slovakia)*

The Pásztori volcanic body also shows very clear magnetic anomaly and it is specific from the petrographic point of view, since it - or at least its topmost parts - is built of alkalic rocks (trachytes) and is probably genetically related to nearby alkali basalts (Harangi, 2001). The shape of the Pásztori volcanic body due to the complicated seismic record is not known, we in general respected the idea of Mattick et al. (1996) of a buried, probably subaqual volcano situated on the hanging wall of a remarkable SE-dipping normal fault, where the products of the multi-phase volcanic activity are interlayering with the sedimentary fill on the continously subsiding basement.

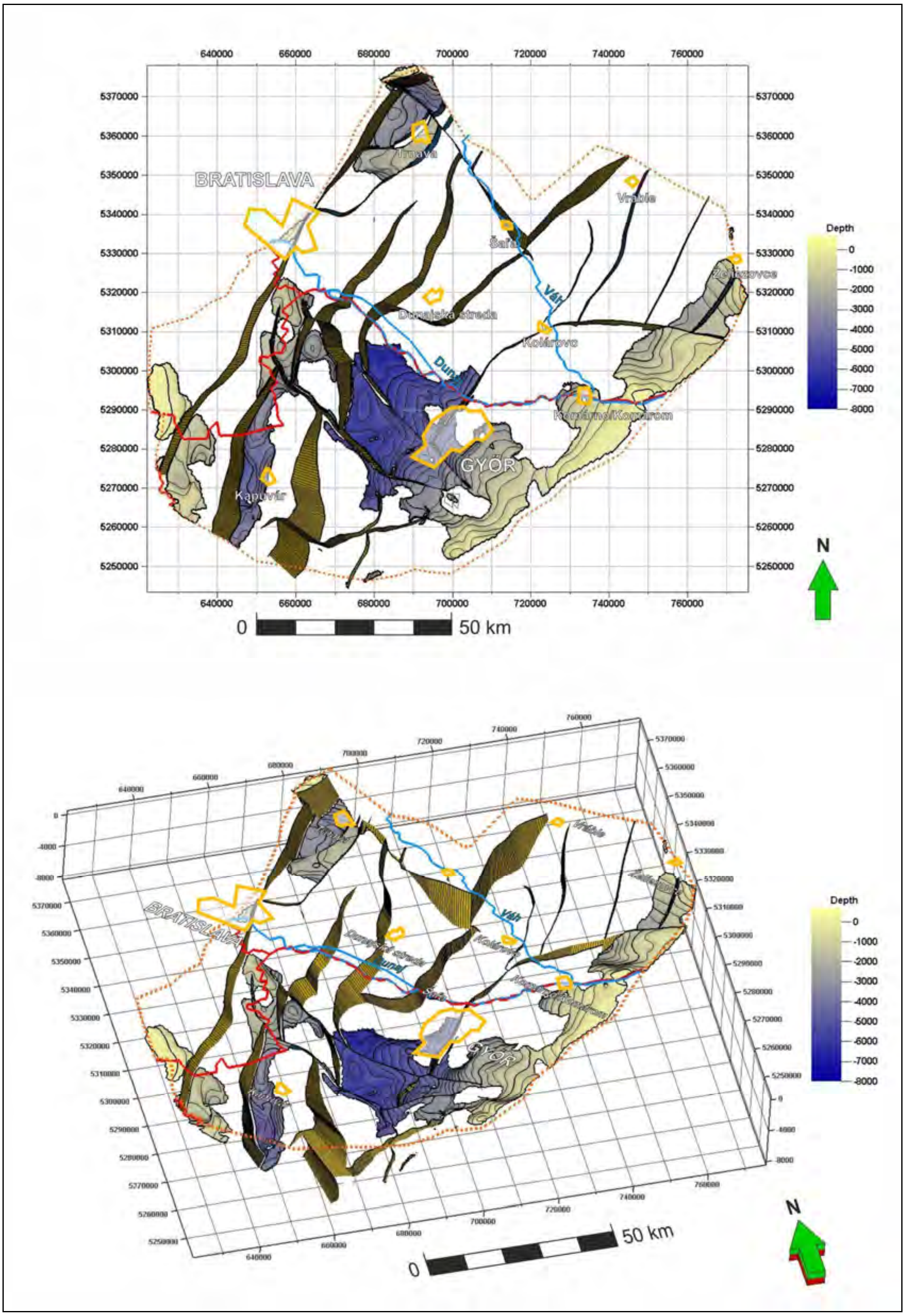

Fig. 2.5 The modelled top surface of the Paleogene - Early Miocene horizon 2D (above) and 3D (below, from SSW)

The most problematic among these volcanic complexes is the biggest one assumed in the wider vicinity of Gabčíkovo village. It is the deepest part of the Danube Basin with estimated depths up to 8 km (Kilényi et al., 1991) so the subsidence of the basin floor in these area was so extreme, that all wells terminated in the Pannonian - thus all complexes below are practically hypothetic, we have no (and obviously never will have) rock samples from these complexes. However, based on the nearest borehole data from the well Msz-1 (village Mosonszolnok, Hungary) situated already on SW-NE elongated morphologic elevation we suppose similar

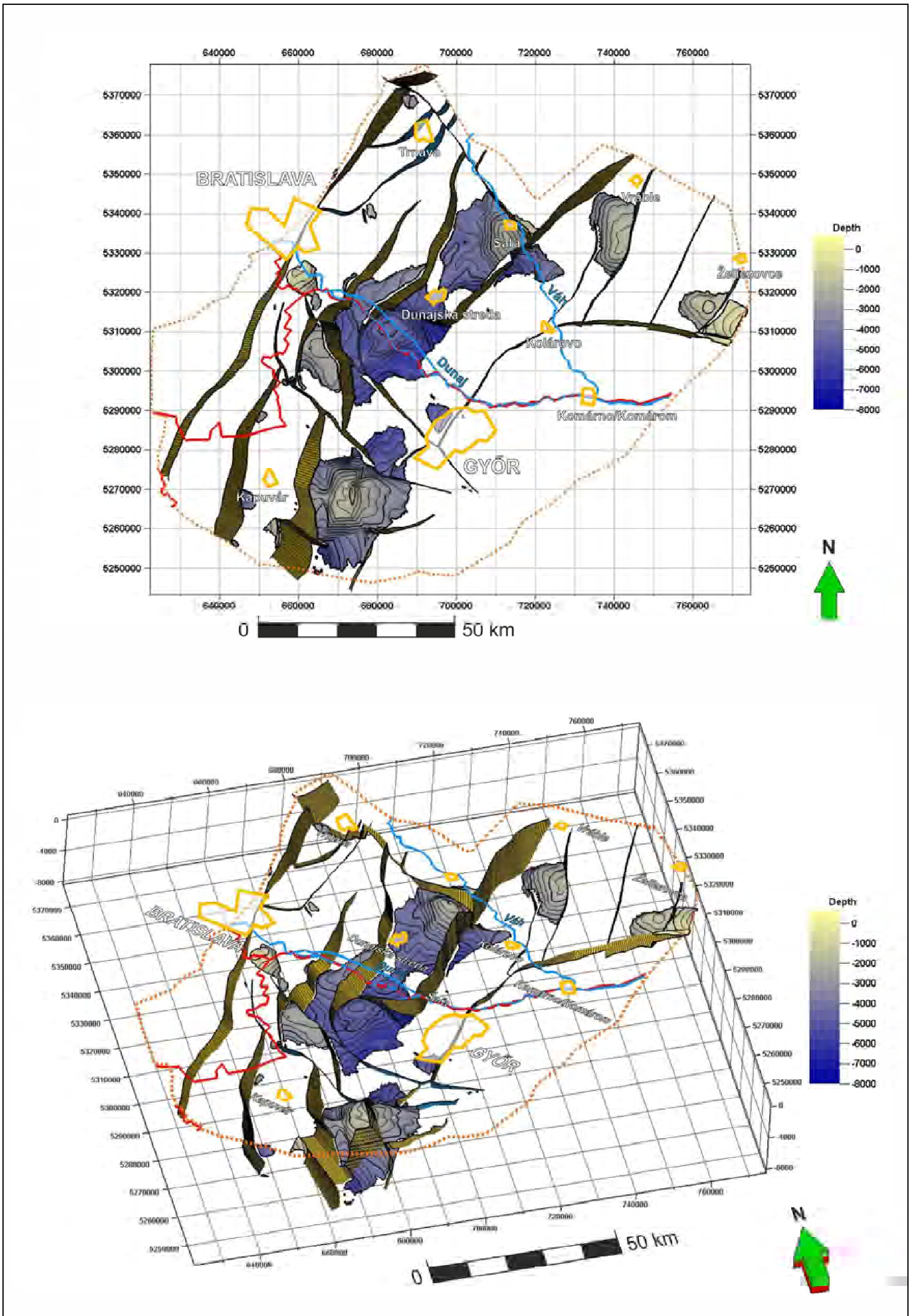

Fig. 2.6 The modelled top surface of mainly neovolcanic bodies in 2D (above) and 3D (below, from SSW)

andesitic composition as the most of similar bodies (Šurany, Kráľová etc. - except Pásztori). The existence of the deeply buried Gabčíkovo stratovolcano is not a new idea, it was mentioned first time by Vass et al. (1988) and discussed mainly by geophysicists. Volcanoclastics in general, despite of their composition do not show significant magnetic anomalies, thus the very strong and also spatially huge magnetic anomaly near Gabčíkovo (Seiberl et al., 1998) is according to Fiľo et al. (2000), Kubeš et al. (2001) and Bezák et al. (2004) probably caused by two different sources: 1. a deeper source most probably amphibolites of the Tatric (?) crystalline (ca. 5-6 km depth); 2. an overlying huge andesitic complex (top at ca. 3.2 km depth). Since we assume total depth estimates of Kilényi et al. (l.c.) of about 8 km to be more realistic, our model calculated the depth of the basement below supposed volcanic body between 7.8-6.5 km. We also suppose only a relatively thin layer of Early Badenian (or maybe older) basal clastics below this volcanic body, thus we can estimate the height of the body from ca. 7.5-6.5 km up to 4.3-4.4 km in the topmost part of the body - a generally ca. 2-2.5 km high volcanic body. The reasons, why we modelled this horizon below the Badenian sediments even if these volcanites can be sometimes of younger age, are: a) below the volcanites there is - if any - usually only a thin cover of Lower Badenian (or Lower Miocene ?) b) the base surfaces of the volcanites are too deeply buried and very problematic to detect in the seismic profiles through the whole column of structurally very complicated volcanic complex.

The horizon of Neogene volcanites contains lithological types:

- **Msrt:** rhyolitic/andesitic volcanoclastics (Sarmatian-Pannonian);
- **Mbzt**: dacite-volcanoclastics, subvolcanic dacite, andesite (Badenian);
- **Mba**: subvolcanic andesite, andesite volcanoclastics, andesite dyke (Badenian).

The Badenian formations (Mba, Mbzt) roughly correspond to Magasbörzsöny - Dobogókő and Šurany (or Burda) Fms. while the Sarmatian - Pannonian part (Msrt) is representing the Pásztori volcanic body.

Horizon: Badenian basin fill

The lower part of the Early Badenian is missing all over the area due to Early Badenian tectonic movements and erosion. Badenian successions start with the upper part of the Early Badenian with abrasional basal breccia and conglomerate. The Early Badenian transgression came from the S-SW. In this time two main sedimentary basins formed by Early Badenian tectonic movements existed in the SW part of the area: the Csapod Trough in its western part and the Győr Basin in the East divided by the Mihályi Ridge (Hungary), the transgressional event formed in both basal clastic formations (Pusztamiske Fm.). Independently in the NE part of the area (Želiezovce Depression, Slovakia), the Early Badenian basal clastics represented by polymict conglomerates of the Bajtava Fm. transgressively cover the older Štúrovo Paleogene units, and/or the Pre-Tertiary sedimentary and metamorphic rocks. They are associated with algal limestone and sandstone (Leitha Fm., "Leithakalk"), basinwards passing into fine calcareous sandstone and siltstone. Deep-basin (shallow bathyal) facies are represented by fine siliciclastic sediments: sandy silt, silty clay marl with sandstone intercalations (Tekeres Formation), and sandy-silty clayey marl classified into the Baden Fm.

During the Middle and Late Badenian times, the depositional area subsided and widened, covering almost the whole modelled area. The Middle Badenian deposits in their NE and NW parts of the basin (Špačince Fm.) in Slovakia contain organogeneous algal limestone and sandstone. In the Slovakian part of the basin, the depositional log continues with the Late Badenian Madunice and Pozba Fms., comparable with the Szilágyi Clay/Marl Fm. The spatial distribution of the Badenian sediments is illustrated in Fig. 2.7.

The horizon of Badenian sedimentary fill contains facies types:

- **Mbmf:** shallow-marine and open basin clay marl *(Badenian)* - Szilágy, Baden, Tekeres Schlier, Báhoň, Pozba and Bajtava Fms.
- **Mbc:** shoreline coarse/grained clastics/marl *(Badenian)* - Pusztamiske, Jakubov and Špačince Fms.
- **Mbls:** shallow-marine fossil-bearing limestone *(Badenian)* - Lajta and Studienka Fms.

Horizon: Sarmatian basin fill

With the onset of the Sarmatian a significant change occurred, which was triggered by the restriction of the open sea connections of the Central Paratethys. Biogenic calcareous sediments of shoreline facies (Tinnye Formation) and fine-siliciclastic sediments (grey, greenish-grey clay marl, sand, silty clay marl) of shallow-marine facies (Kozárd Fm.) were deposited. The Late Sarmatian carbonate successions indicate a considerably productive carbonate factory of subtropical climate.

In the northern part, the Sarmatian transgression manifested in the deposition of a brackish shallow-water succession (Vráble Fm.), which unconformably overlies various Badenian formations and Pre-Neogene formaions in the marginal part of the basin. The Sarmatian basin fill is built of mostly brackish marine clay and marl with abundant sandy intercalations, containing mostly shallow marine molluscan and foraminiferal fauna. Spatial distribution of Sarmatian sediments is shown on Fig. 2.8.

After correlation we joined all Sarmatian sediments into one facies type:

- **Msmf:** shallow-marine and brackish clay/marl *(Sarmatian)* - Kozárd, Tinnye and Vráble Fms.

The contemporaneous volcanic complexes represented by acid tuffite, andesitic sand and also lava flows were included in the not age-specific horizon of Neogene volcanites (Msrt).

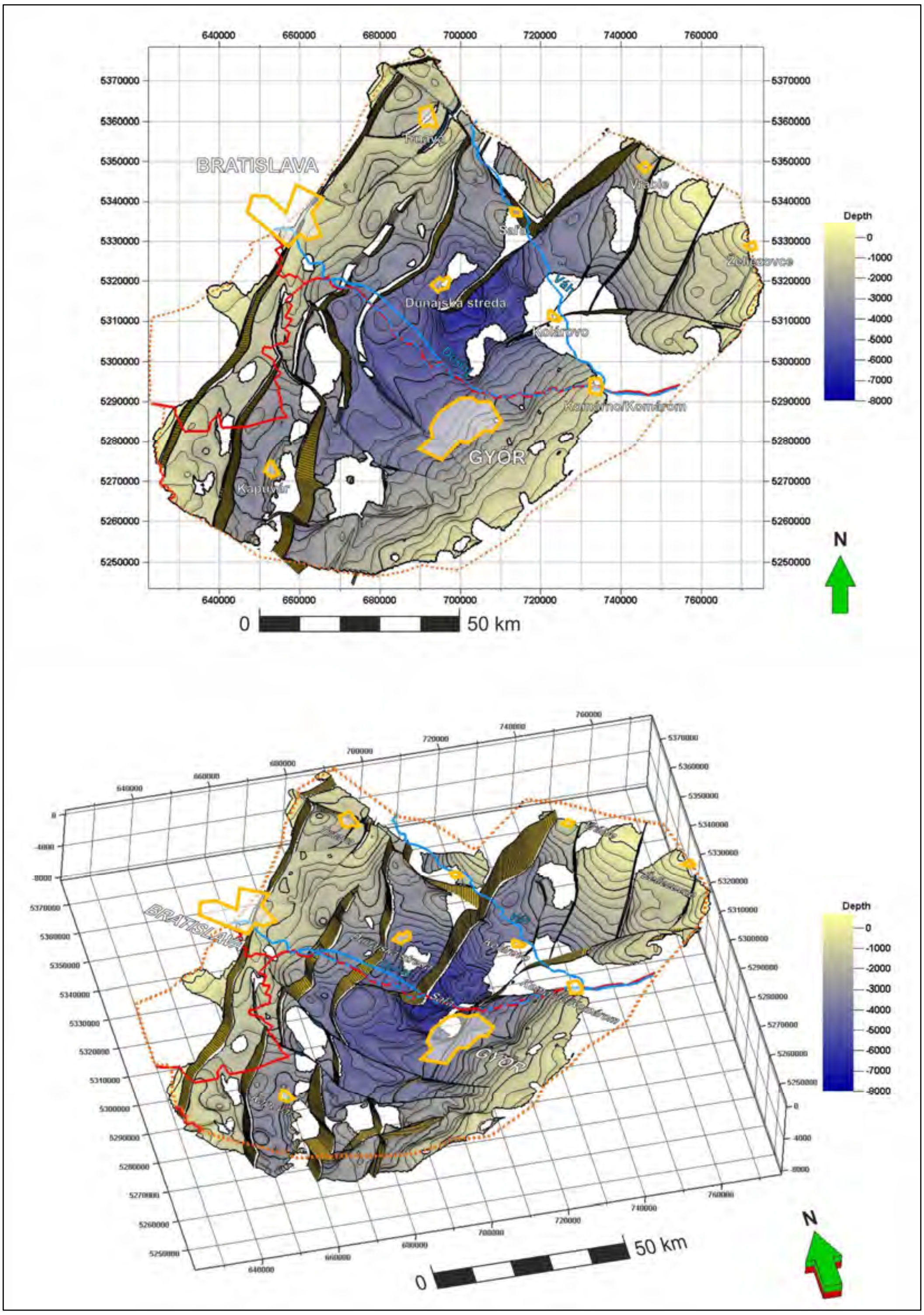

Fig. 2.7 The modelled top surface of Badenian sediments in 2D (above) and 3D (below, from SSW)

Horizon: Early Pannonian basin fill

The Pannonian (Late Miocene and Pliocene) geohistory of the project area is characterized by the presence of the Lake Pannon, isolated from a large open sea Paratethys about 12 Ma ago. The lake reached its largest extent between 10-9.5 Ma, than it was gradually infilled by sediments carried from the surrounding Alps and Carpathians from the NW. The Vienna Basin was the first major sub-basin to be infilled, where the open lacustrine sedimentation was replaced by the deposition of deltaic, and later alluvial units 9.5-10 Ma ago. Then the shelf-slope system started to prograde across the large, deep Danube Basin. The lower part of the Pannonian basin fill - in fact only this part belongs to the previous "Pannonian s. s." in the Slovakian/Austrian realm – contains clayey-silty deposits of subaqueous slopes, shallow water clay and marl, fine-grained sand, silt; variegated clay and limestone.

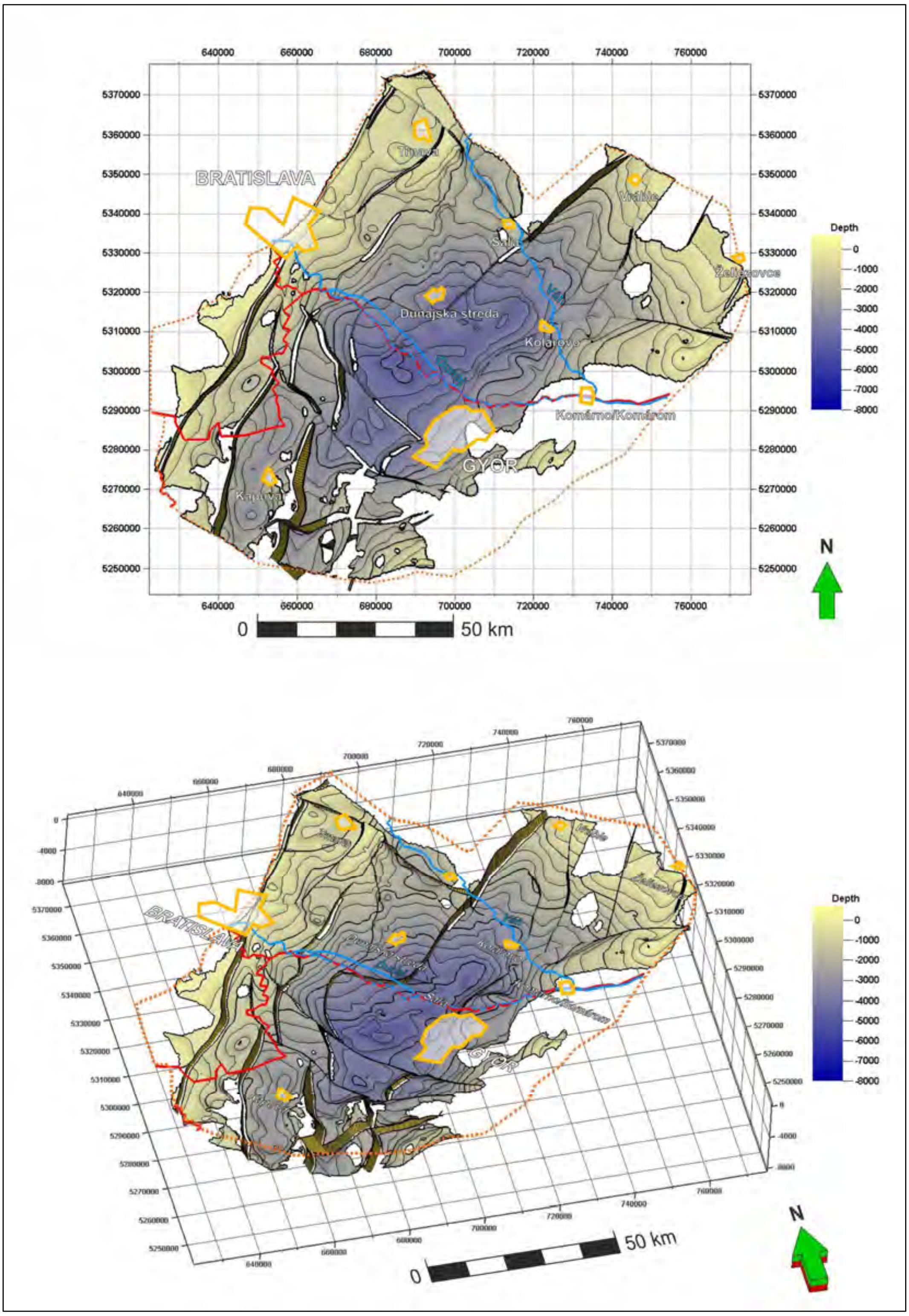

Fig. 2.8 The modelled top surface of Sarmatian in 2D (above) and 3D (below, from SSW)

In our model we defined the Lower Pannonian horizon as the Iványka Fm. in Slovakia which is correlated with numerous dominantly marly beds in Hungary (Peremarton, Endrőd, Zsámbék, Szolnok, Algyő, Békés, Csákvár Marl Fm., partly also the lower part of Tihany, Újfalu formations). All these formations formed from shallow water to lacustrine environment, the Iványka Fm. also contains prograding deltaic lobes.

- **Mplf:** shallow-water clay/silt *(Late Miocene - Pannonian)* - Algyő–Szák–Csákvár Clay Marl, Csór Silt, Zsámbék Marl and Ivanka Fms.
- **Mpc:** near-shore psephite/psamite *(Late Miocene - Pannonian)* - Kisbér–Zámor–Kálla–Diás Gravel, Békés Conglomerate, Piešťany Mb. of the Iványka Fm.
- **Mptb:** turbidite *(Late Miocene - Pannonian)* – Szolnok sandstone Fm.

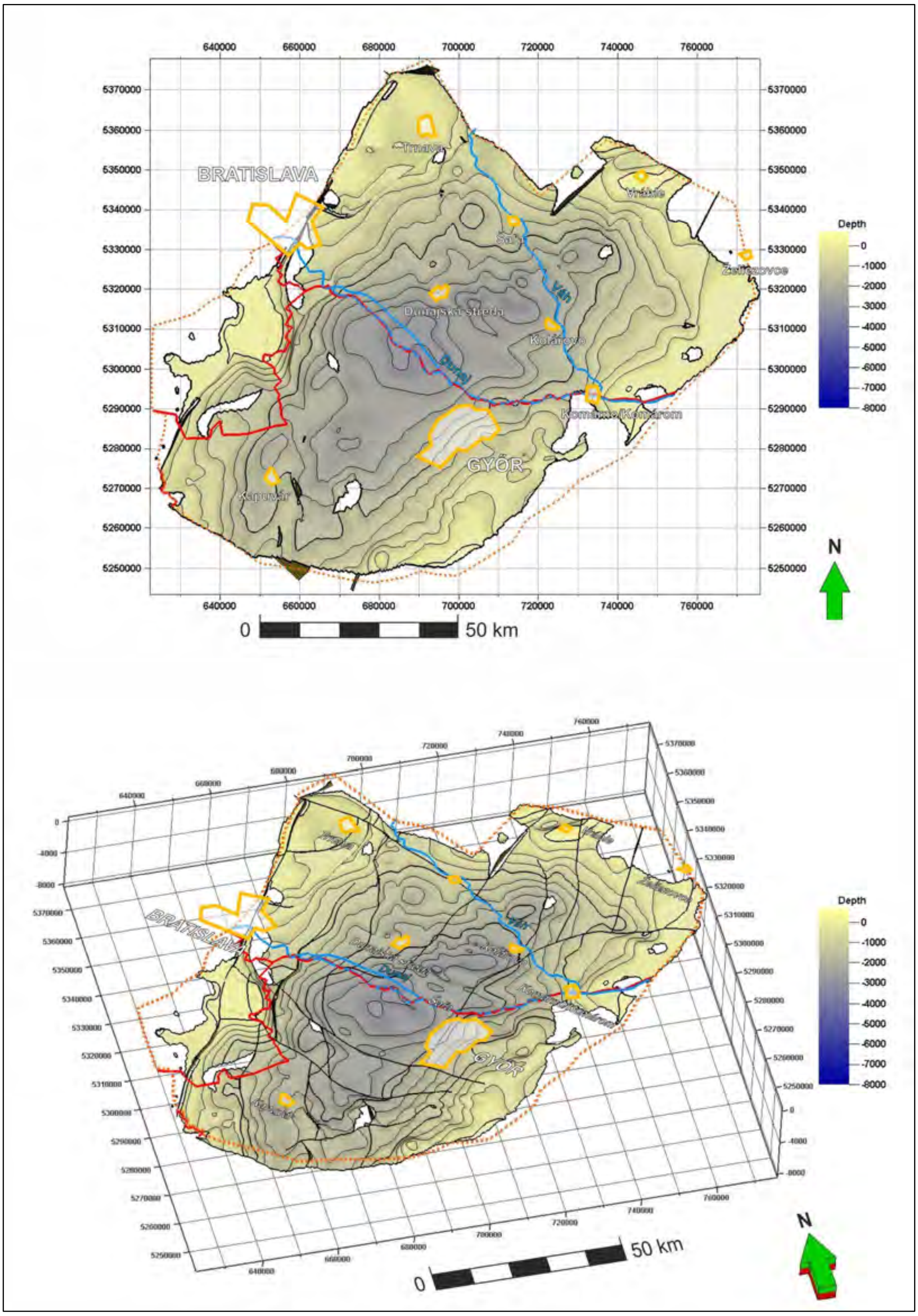

Fig. 2.9 The modelled top surface of Early Pannonian in 2D (above) and 3D (below, from SSW)

- **Mpcm:** calcareous and clayey marl *(Late Miocene - Pannonian)* - Endrőd and Bzenec Fms.

Horizon: Late Pannonian basin fill

We joined the Late Pannonian (Pontian) and Pliocene (Dacian and Romanian) sediments due to their lithological similarities and unclear definition of the boundary between them into one horizon. In the central parts of the Danube Basin their thickness exceeds sometimes 2,500 m. They developed in continuing and further shallowing lacustrine environment changing upward into deltaic and fluvial facies.

The Late Pannonian horizon is present almost in the whole territory, except around the Leitha Mts. on the west, the NW foothills of the Transdanubian Range and partly also in the E part of the area on the foothills of the Central Slovakian Neogene Volcanic Field. The criteria for defining the boundary between the Late Pannonian and Quaternary are not solved yet, in the presented scale.

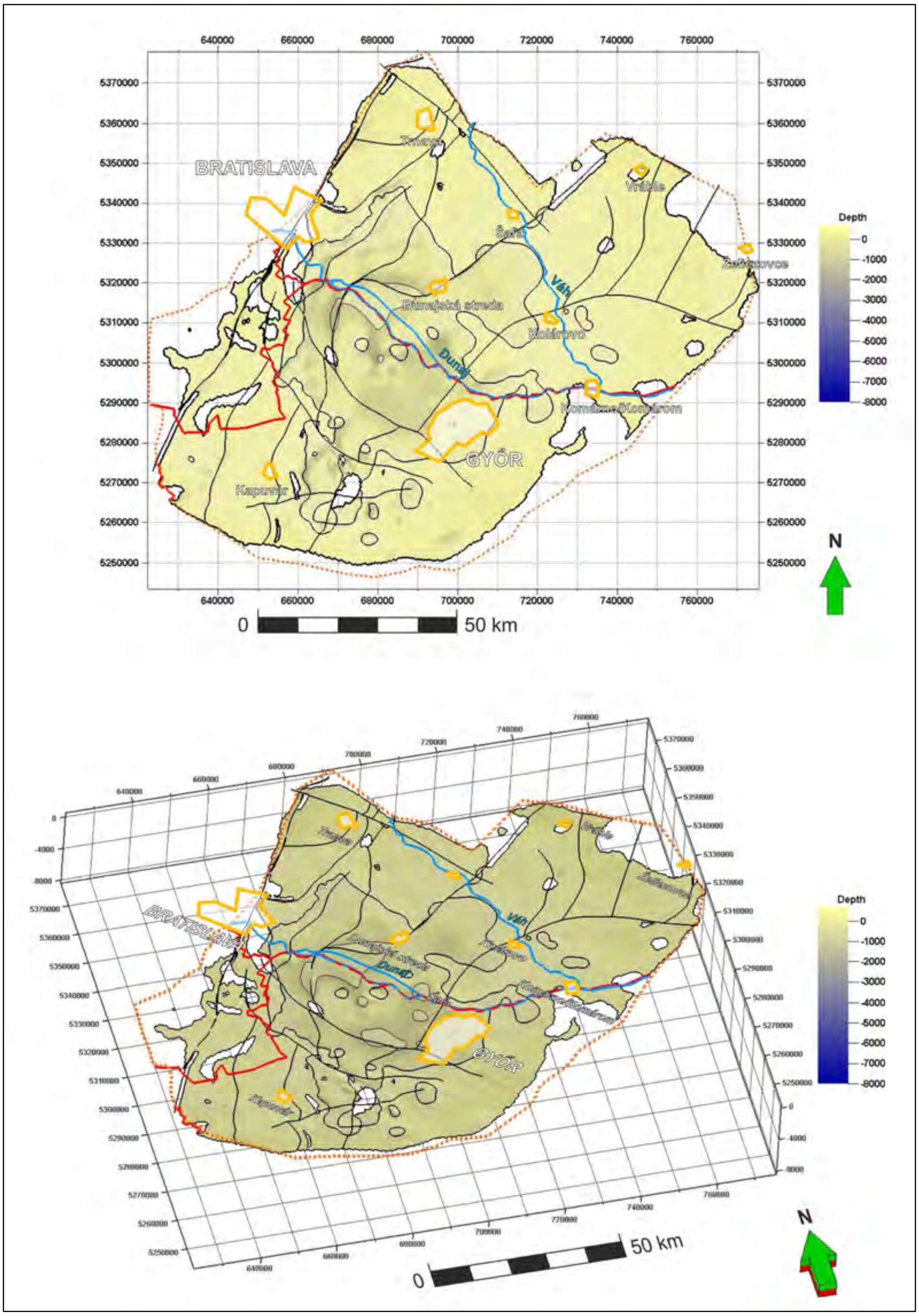

Fig. 2.10 The modelled top surface of Late Pannonian in 2D (above) and 3D (below, from SSW)

In general, the horizon is built mainly of alluvial and lacustrine deposits, which we grouped into two zones:

- **MPl:** a more variegated complex of fluvial – lacustrine and continental clastics, usually in higher stratigraphic position, roughly corresponding with the *Pliocene (Dacian-Romanian)* - Kolárovo, Nagyalföld, Hanság, and Variegated Marl formations.
- **Md**: a more homogenous lacustrine complex (Md), stratigraphically lower *Late Pannonian/Dacian/Pontian* - Volkovce, Torony, Újfalu, Zagyva and Rohrbach Clay formations.

Horizon: Quaternary

The Quaternary horizon was modelled mostly on the basis of the compiled results of the DANREG project (Császár ed., 1998, Scharek et al., 2000).

However, we have got borehole as well as seismic data on the base surface of the Quaternary, showing significant differences in the interpretation of the depth of this surface. The method of joining Slovakian, Hungarian and Austrian datasets of different quality, age of compilation and thus stratigraphic interpretation did not work, so we used the mentioned DANREG outputs, where the same task was once already solved by an international team of experts. Because of the differences in the interpretations and terminology, and also of often small thickness of the deposits, we were not able to divide this horizon into zones.

2.4.2. Structural pattern

The recent structure of the Danube Basin is a product of the Middle Miocene to Pannonian tectonic history, mainly. Due to the huge thickness of basin fill (exceeding 8 km in the central parts) there are many different views of the probable structural patterns. The main fault direction in the area is SW-NE (see Figs. 2.11. and 2.12.) combined with numerous and usually not well detectable faults of roughly perpendicular direction (S-N or SE-NW).

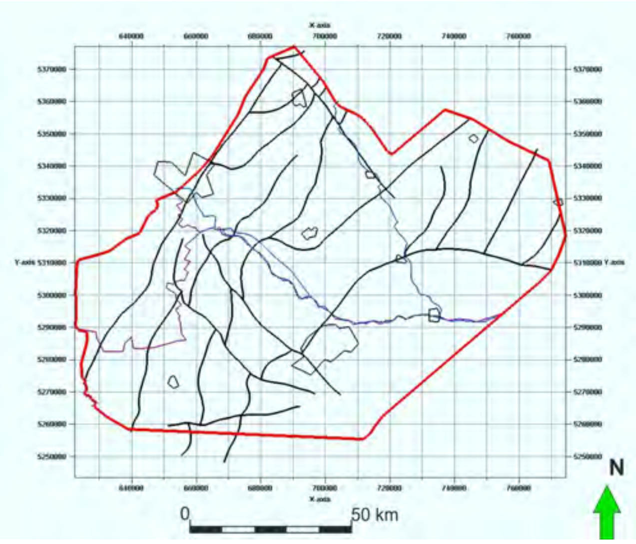

Fig. 2.11 2D fault map

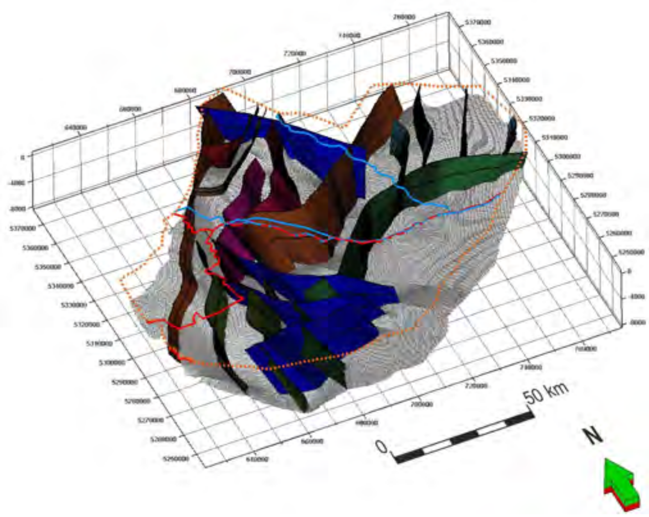

Fig. 2.12 Faults of the area in the 3D model on the basal Pre-Tertiary surface

The basement is dissected by them to a set of elevations and depressions (Fig. 2.13): in Slovakia there are four main depressions defined by NE-SW faults (from N to S): Blatné, Rišňovce, Komjatice and Želiezovce depressions. Except the northernmost and the oldest Blatné Depression, the other depressions are directing into the Central, so-called Gabčíkovo Depression near the Slovakian-Hungarian border, whose depth exceeds 8,500 m. This depression is continuing further to the SW into the Kenyeri - Győr Trough. On the NW side of the Mihályi Ridge an other fault-defined depression, the Csapod Trough of smaller depth is located.

Among these depressions expressively elevated areas - ridges - are located. Since some of them reach the surface - mostly outside the studied area in the mountains Malé Karpaty, Považský Inovec, Tríbeč, Mid-Hungarian Range and Leitha Mts. - another ones stay buried as the Mihályi (-Úľany?) ridge and the Levice and Komárno elevations.

The fault pattern used in the model is strongly simplified for the purposes of further use in the hydrogeological model. The fault model is based on the seismic record, in the areas with poor coverage by seismic profiles we considered also different available sources (Hrušecký, 1999; Pěničková at el., 1984; Fusán et al., 1987; Tari 1994, Dudko et al., 2000, Császár et al., 2000, Maros et al., 2012) as well as personal consultations with experts (our thanks belong especially to M. Kováč and M. Pereszlényi).

Since the model was created on seismic and well data of different quality and density, while some modelled faults well correspond to known fault lines, many of them are hypothetical, created for reasons of steep basement morphology, or on the other hand, some smaller faults are neglected or joined together into one fault zone for the optimization of the model. At the beginning of the project the team of geologists working on modelling agreed to deal with only those faults which have a vertical dislocation at least 500 meters. However, in many cases we could not follow this, because of the fading out or forking of the fault planes, or simply because geologically important lines (for example the Rába line) had less vertical dislocation.

The faults finally included in the model can be divided into two main groups according to their directions: NE-SW faults and faults roughly perpendicular to them of NW-SE or W-E directions. Since the majority of seismic profiles is oriented roughly in the NW-SE direction, faults perpendicular to that direction are much better traceable than faults parallel to them. Thus, we should expect much more faults in NE-SW directions but we were not able to incorporate them into our model.

Faults of NE-SW direction incorporated into the model, as they are shown in Fig. 2.13:

A. Normal fault on the SE slopes of the Malé Karpaty Mts. continuing into Austrian territory in the area of lake Neusiedl and Leitha Mts., created by joining of main and some smaller faults together, active to recent;

B. Two curved normal faults on the S and SE side of the Blatné Depression; simplified from more faults (e.g. the Považie fault system), terminated at the end of Sarmatian;

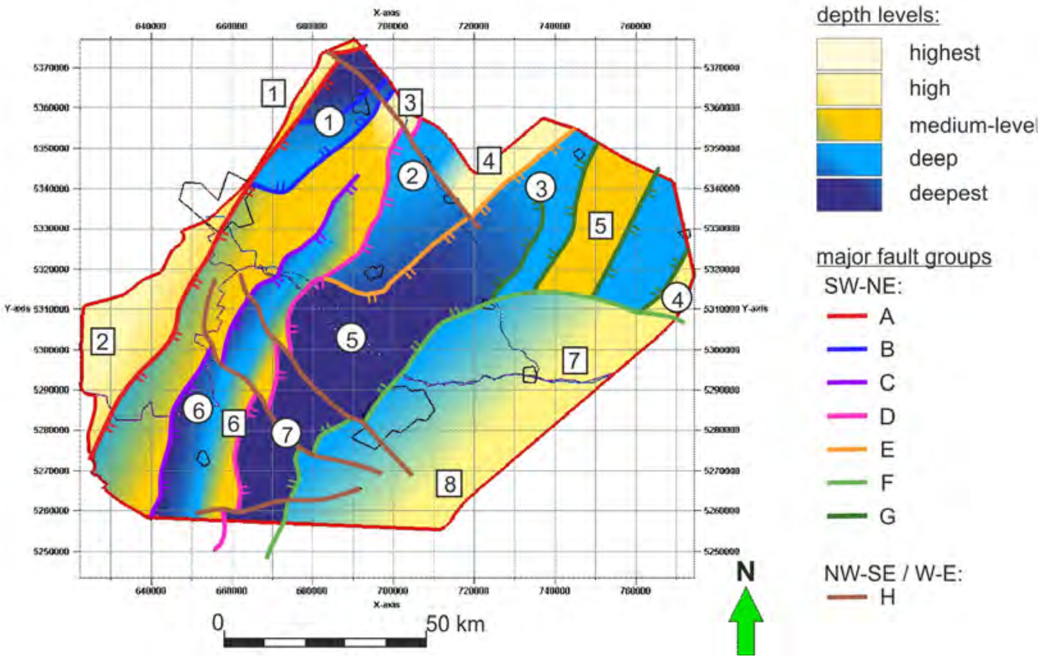

Fig. 2.13 Structural scheme of the modelled area: main elevated areas *(numbers in rectangles): 1 - Malé Karpaty Mts.; 2 - Leitha Mts.; 3 - Považský Inovec Mts.; 4 - Tribeč Mts.; 5 - Levice High Block; 6 - Mihályi (-Úľany?) Ridge; 7 - Komárno High Block; 8 - Transdanubian High Block;* main depressions *(numbers in circles): 1 - Blatné Depression; 2 - Rišňovce Depression; 3 - Komjatice Depression; 4 - Želiezovce Depression; 5 - Gabčíkovo Depression; 6 - Csapod Trough; 7 - Kenyeri-Győr Basin; for faults: see text*

C. Normal fault NW of the Csapod Trough – hypothetical, dipping to the SE, terminated mainly at the end of Sarmatian, some parts in the Pannonian;

D. Ripňany - Galanta fault - very steep normal fault on SE side of the Považský Inovec Mts. dipping to the SE, active to recent;

E. Mojmírovce fault - very steep normal fault dipping to the SE delimiting the elevation of the Tríbeč Mts., active to recent;

F. Rába - Hurbanovo - this south-dipping tectonic surface is one of the geologically most important ones in the area, which was originally a Mesozoic overthrust plane of the Transdanubicum onto the Austroalpine and Tatric-Veporic units, but during the early Middle Miocene was rejuvenated and functioned as an extensional listric plane in opposite direction; in the model we modelled this fault as a complicated curved normal- to reverse fault cut by NW-SE strike-slip faults, terminated at the Pannonian;

G. normal faults in the E part of the area to the NW (Šurany fault) and SE of the Levice High Block;

We were able to define only four major faults in NW-SE direction (H. in Fig. 2.13):

- the problematic Ludina line in the northernmost part of the area cutting the NE-SW directed Malé Karpaty, Blatné Depression, Inovec and probably even Mojmírovce faults. The character of the fault is unclear, we modelled it as a steep normal fault dipping to the SW, in the N part with a dextral strike-slip component;
- two parallel NW-SE and one rather W-E directed normal faults with dextral strike-slip component dipping to the NE or N, respectively; all three appear in the Transdanubic block, the two NW-SE faults cut the Kenyeri-Győr Trough, Mihályi Ridge and Csapod Trough, the third and southernmost W-E fault after cutting the Mihályi Ridge continues off the studied area.

These faults are dividing the area into higher or deeper level blocks, whose relative positions are summarized in Fig. 2.13.

One of the most important outputs of the modelling were cross sections demonstrating the resume of the geological structure of the area (Fig. 2.14).

2.5. Conclusions

The whole TRANSENERGY project area - called the supra area - was subdivided into five partial basins called pilot areas, where the State Geological Institute of Dionýz Štúr was entrusted with the work on the Danube Basin pilot area. For the purposes of the project we created a 3D geological model of the area as an input for hydrogeological model, but its partial results have their specific importance and can be evaluated independently.

The 3D model was built from all available data (409 wells and 82 seismic sections) known from the area regarding many published works about the structure of the basin. For the purposes of the model a unified and simplified stratigraphical scheme was compiled derived from the Slovak, Hungarian as well as Austrian local stratigraphic charts, which can be considered an important result. However similar attempt already was made in the framework of the project DANREG, our harmonized stratigraphic scheme is based more on lithology and genetic features and can be considered more universal.

The 3D geological model itself is the historically first attempt of its kind to visualize the whole Danube Basin in 3D and in the future can serve as a base for further, more

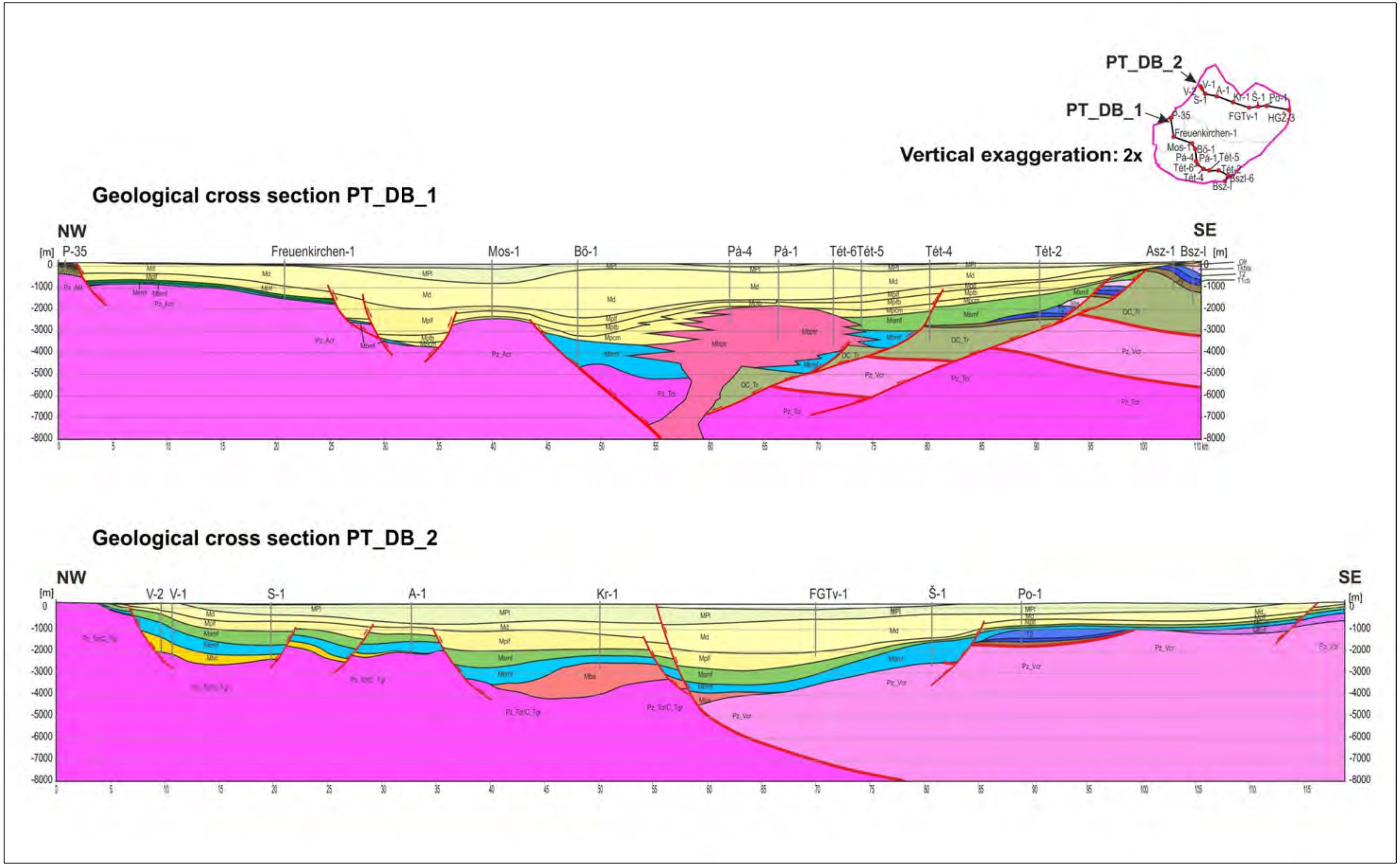

Fig. 2.14 Cross sections created based on the 3D geological model

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Q	*Pleistocene - Holocene*: sediments in general
MPl	*Late Miocene - Pliocene*: fluvial-lacustrine-continental sand, silt, clay marl; mottled clay; lignite; gravel
Md	*Late Miocene (Late Pannonian):* lacustrine, sediments of delta plain: clay marl, silt, fine-grained sand; calcareous clay, variegated clay, lignite,dolomite; freshwater limestones, boglime and travertine
Mplf	*Late Miocene - Pannonian:*clay silt deposite on underwater slope, shallow-water clay marl, fine-grained sand, silt; variegated clay, limestone
Mptb	*Late Miocene - Pannonian:* turbidite
Mpcm	*Late Miocene - Pannonian:* lacustrine calcareous marl – clay marl; sandstone
Msmf	*Sarmatian*: shalow-marine – brackish-water, mollusc-bearing clay - clay marl; sand-sandstone, calcareous
Mbmf	*Badenian*: shallow-marine and open basin foraminiferal mollusc-bearing clay marl, clay
Mbptr	*Miocene, Badenian - Pannonian:* trachyte agglomerate, tuff
Mba	*Badenian*: subvolcanic andesite, andesite pyroclastics, andesite dyke
Olf	*Oligocene*: fluvial-lacustrine-paludal clay, clay marl, sand-sandstone, gravel, conglomerate
Tkbls	*Late Triassic - Carnian*: basinal marl and limestone, bituminous limestone, dolomite
T2	*Middle Triassic* sediments in general
T1cb	*Early Triassic*: siliciclastic and carbonate formations
P1	*Middle-Late Permian*: continental siliciclastic formation
PzF-PzS	*Paleozoic*: medium-grade polymetamorphic formations with Alpine overprint (gneiss, mica schist, phyllite, pegmatite, leucophyllite, quartzite, quartz schist)
OC_Tr	*Early Paleozoic?:* Veporic unit - gneiss, schist, phyllite, marble
Pz_Vcr	*Ordovician - Carboniferous:* Low-grade metamorphic formations (slate, calc-phyllite, quartz phyllite, quartz metasandstone, metaconglomerate, basic metatuffite, limestone)
Pz_Tcr	*Early Paleozoic?*: Tatric unit - gneiss, schist, phyllite, marble, amphibolite
Pz_Tcr/C_Tgr	*Early Paleozoic?, Carboniferous:* Tatric unit - gneiss, shist, phyllite, marble, amphibolite, biotitic and two-mica granite, granodiorite and tonalite, leucocratic granite, diorite
Pz_Acr	*Early Paleozoic?:*Austroalpine units - gneiss, schist, phyllite, marble, amphibolite
	geological boundary
	nappe overthrust plane
	normal fault
Po-1	borehole

Legend to Fig. 2.14

precise models. Based on the formerly compiled unified stratigraphic chart we agreed on the horizons to be modelled, however during the work two additional horizons were created (Paleogene - Early Miocene and Neogene volcanites). The final model contains horizons defined by their age - except the Neogene volcanites (bottom to top):

- Pre-Cainozoic basement surface (divided into 15 zones);
- Paleogene - Early Miocene (divided into 7 zones);
- Neogene volcanites - not age-specific horizon (divided into 3 zones);
- Badenian sedimentary fill - without volcanites (divided into 3 zones);
- Sarmatian - without volcanites (containing only one zone);
- Early Pannonian - comprising "Pannonian s.s." (divided into 4 zones);
- Late Pannonian - comprising Pontian and Pliocene (divided into 2 zones);
- Quaternary (undivided).

The structural pattern of the area was simplified after several consultations into a scheme of 7 approximately SW-NE and 4 roughly NW-SE to W-E faults.

The model is also the first attempt to visualize the Neogene volcanic bodies buried below younger sediments. In addition to well and seismic data the geophysical - mostly geomagnetic - anomalies were considered for their contouring. We defined five buried volcanic bodies in the area: Šurany, Kráľová, Rusovce, Pásztori and Gabčíkovo. The most problematic among them is the Gabčíkovo volcano, whose existence was contemplated formerly by different authors. The main argument for defining this volcanic body was the huge magnetic anomaly measured in the area and showing very similar image as other bodies proven by wells.

The final 3D geological model and the "by-products" of the modelling (e.g. stratigraphic scheme) were used - according to their primary aim - as an input to thermal and hydrogeological modelling of the same area in the next working phase of the project. Some of the products of the model can be, however, useful also separately (cross-sections, base-maps etc.) and the model itself, we hope, will serve as a base for more accurate models in the future.

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3. Assessing Thermal Groundwater Flow in the Danube Basin by Numerical Simulations

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Abstract. The article presents the results of the steadystate as well as transient modelling performed within the Danube Basin pilot area of the TRANSENERGY project with the focus on Late Pannonian aquifer and to less extent on adjacent thermal karst aquifers.

The research of geothermal potential of the Danube Basin was accomplished by utilizing fully three-dimensional coupled models of groundwater flow and heat transport at different temporal and geographical scales. Several scenarios of possible energy extraction from the most favourable geothermal aquifers of the area are compared in this study.

The area of Danube Basin offers significant potential for geothermal utilization, what is under interest of investors on energy market. To foresee effects of new geothermal installations, two principal scenarios of geothermal utilization were investigated: single wells and geothermal doublets. Furthermore, a detailed examination on possibilities of interstate geothermal energy exploitation was performed as well. The study investigates the scenario of common geothermal energy use directly at the state border, by means of two geothermal doublets, organized in a tight 2 by 2 diagonal cluster. The aim of this study, performed by transient coupled flow and heat simulations, was to test the proposed wells configuration and estimate operating life of the system by prediction of thermal breakthrough.

Keywords: geothermal modelling, heat flow, transboundary

3.1. Introduction

The utilization of the geothermal water is spread throughout the whole pilot area on Slovak and Hungarian side and partly on Austrian side. The utilization of geothermal water is performed by pumping and natural overflow from wells. The average yield of utilized geothermal water on Hungarian side of the Danube Basin pilot area is 51,349 m^3 per year and on Slovak side 87,631 m^3 per year.

The goal of modelling that comprises 3D groundwater flow and heat transport simulations was to provide information for better understanding of the hydrogeological and geothermal conditions in the pilot area. It is a first step in modelling process and basis for scenario analysis for sustainable utilization of the geothermal resources. The regional modelling simulations were calculated for steadystate conditions – steady flow and steady heat transport. Two scenarios of possible energy extraction from the distinguished geothermal aquifer of Danube Basin – Late Pannonian sedimentary unit are compared in the model – pre-utilization reflecting "natural conditions" with no pumping assumption and assumption considering influence of the production wells based on accessible data about the geothermal water extractions.

Because sustainable use of thermal groundwater is promoted in all three countries within the pilot area, a scenario of additional heat utilization by means of geothermal doublets was tested. But due to technical limits of water reinjection in Late Pannonian sands, which is the main geothermal aquifer in Danube Basin, also traditional direct use of geothermal energy by means of single exploitation wells was examined.

As an extension to the regional steadystate model, a separate modelling of a geothermal multiplet was performed, with intention to investigate thermal and hydraulic response of potential thermal water utilization at the Slovakia – Hungary state border.

This approach is the first attempt of conceptual and numerical presentation of studied geothermal system of the Danube Basin on Slovak, Austrian and Hungarian parts of the structure. It is based on current state of knowledge and data, which all have certain limitations, originating from uncertainty related to estimation of parameters of hydrogeological model. The information used for model set-up, verification and optimization is based on database of geological and hydraulic parameters, database about the utilization characteristics, both compiled within the framework of the TRANSENERGY project. Helpful sources of the data and interpretations were Atlas of Geothermal energy of Slovakia (Franko et al., 1995) Geothermal Atlas of Europe (Hurter and Haenel, 2002) and previous studies performed in Slovakia, Austria and Hungary.

3.2. Natural conditions of the region

The Danube Basin pilot area covers around 12,170 km^2 (Fig. 3.1.) and is geographically represented by the Danube Lowland in Slovakia and by the Little Hungarian Plain in Hungary. On the West it is bordered by the Eastern Alps, Leitha Mts. and Malé Karpaty Mts. On the North the basin has finger-like extensions which penetrate among the core mountains of Malé Karpaty, Považský Inovec and Tribeč Mts. On the northeast it is bounded by the Central Slovakian Neovolcanics and the Burda volcanics. Units of the Transdanubian Central Range are emerging on the southeast.

3.2.1. Climate and hydrology

The region on W and N shows influence from the Atlantic climate with higher precipitation partly affected by continental climate with lower precipitation and typical cold winters. In the area on S it is influenced by the Mediterranean climate. The heterogeneity of the relief (in wider vicinity of the pilot area), the differences in the rate of exposure to the predominantly westerly winds and the differences in altitude diversify this general climate pattern. This leads to distinct landscape regions showing differences in climatic conditions. The mean annual air temperature is in interval 10-12 °C. The precipitation ranges from 500 mm to more than 700 mm (in nearby mountains) based on differences in the regions. The mean annual potential evapotranspiration is in range 750-800 mm. The mean annual actual evapotranspiration is up to 450 mm (Atlas of Landscape of the Slovak Republic, 2002).

The Danube River in the studied area has discharge (input Slovakia – output Hungary) approximately in interval 2,500-3,000 $m^3.s^{-1}$ (based on data from 1994-1997). Main rivers that are tributaries to the Danube River on studied area are: Morava/March - 119 $m^3.s^{-1}$ (average discharge 1961-1999), Raab/Rába - 88 $m^3.s^{-1}$ (average discharge 1901-2000), Váh 161 $m^3.s^{-1}$ (average discharge 1931-1980), Hron 55 $m^3.s^{-1}$ (average discharge 1931-1980), Ipeľ/Ipoly 22 $m^3.s^{-1}$ (average discharge 1931-1980, ICPDR, 2005).

3.2.1.1. Important lakes in the Danube Basin area

Neusiedler See / Fertő tó – W edge of the Danube Basin pilot area. Neusiedler See / Fertő tó is located in the E of Austria and shared with Hungary - total surface area is 315 km^2 (at a defined water level). It has an average natural depth of only 1.1 m, its maximal water depth is 1.8 m. In the course of its history it has dried out completely several times. Since 1965 the water level has been stabilised by the outlet sluice based on an agreement of the Hungarian-Austrian Water Commission in 1965 (water level in April-August: 115.80 m a.s.l., October-February: 115.70 m a.s.l., transition periods March and September: 115.75 m a.s.l.). The main surface water input is through precipitation on the lake surface, secondly by smaller tributaries. Inflow due to groundwater is close to negligible. The lake water is characterised by a high salt concentration 2 $g.l^{-1}$, mainly in form of sodium carbonate (Na_2CO_3).

3.2.1.2. Important wetlands

The wetlands in the Alps and Carpathians also represent valuable drinking water reserves for millions of people. The current extent of wetlands in the Danube River basin is only a remnant of the former wetland systems.

The Donauauen National Park (Austria) with approximately 11,000 ha of floodplain forests, riparian habitats and oxbows between Vienna and Hainburg represents the last intact floodplain of the upper Danube (out of the studied area). Together with the *Floodplains of the Lower Morava and Dyje* (Austria, Czech Republic and Slovak Republic) it forms a transboundary "wetland of international importance" and was declared as a trilateral Ramsar Site.

The Neusiedler See and Fertő-Hanság (Austria and Hungary), a transboundary National Park since 1993, and World Heritage Site since 2003, is a 30,000 ha shallow steppe lake area with a huge reed belt, adjacent small soda lakes.

Szigetköz and Žitný Ostrov Floodplain Complex (Hungary and Slovak Republic), an extended meander zone around the low water bed of the Danube River are protected landscape areas, including small-scale nature reserves.

3.2.2. Geology

The geology of the Danube Basin is described in very detail in the separate article on the geological model by authors Kronome et al. of this issue. In general it forms a bowl-like shaped Pre-Tertiary sedimentary basin. Its basement is composed of crystalline and metamorphic rocks and cover sequences of the Central Alpine crystalline basement, Carpathian Tatric crystalline rocks and partly Triassic to Cretaceous limestones, Palaeozoic and Mesozoic rocks of the Transdanubian Central Range, Lower and Upper Austroalpine nappe complexes, Tatric unit (a continuation of the Central Alpine units). Its geological evolution is strongly dependent on the basement movement behaviour in the Neogene. During the whole basin formation, starting in Early Miocene, different sedimentary processes took place in every part of the area. This resulted in a very complicated geological composition, with frequently alternating lithologies in both lateral as well as vertical directions. Thus, the basinal filling consists of almost all kinds of marine, lacustrine and fluvial sediments, intercepted by stratovolcanic bodies. During the Late Miocene (Pannonian) a more or less uniform Pannonian Basin developed, the formation of which may have started in the Late Badenian. Predominantly fine siliciclastic sequences of different facies accumulated in the area, which have a maximum thickness of about 6,000 metres. The overwhelming part of the successions of the deeper basin facies is made up homogeneous pelitic deposits; distal turbidites are represented by separate sand bodies. Underwater slope sediments are represented predominantly by dark grey clay marl. Deposits of the alluvial plain are represented by frequent alternation of fluvial and lacustrine fine-grained sand, silt, clay and clay marl beds locally with lignite horizons (Maros in Rotár-Szalkai et al., 2012). Because of favourable lithological and hydrogeological conditions, together with deep seating of the

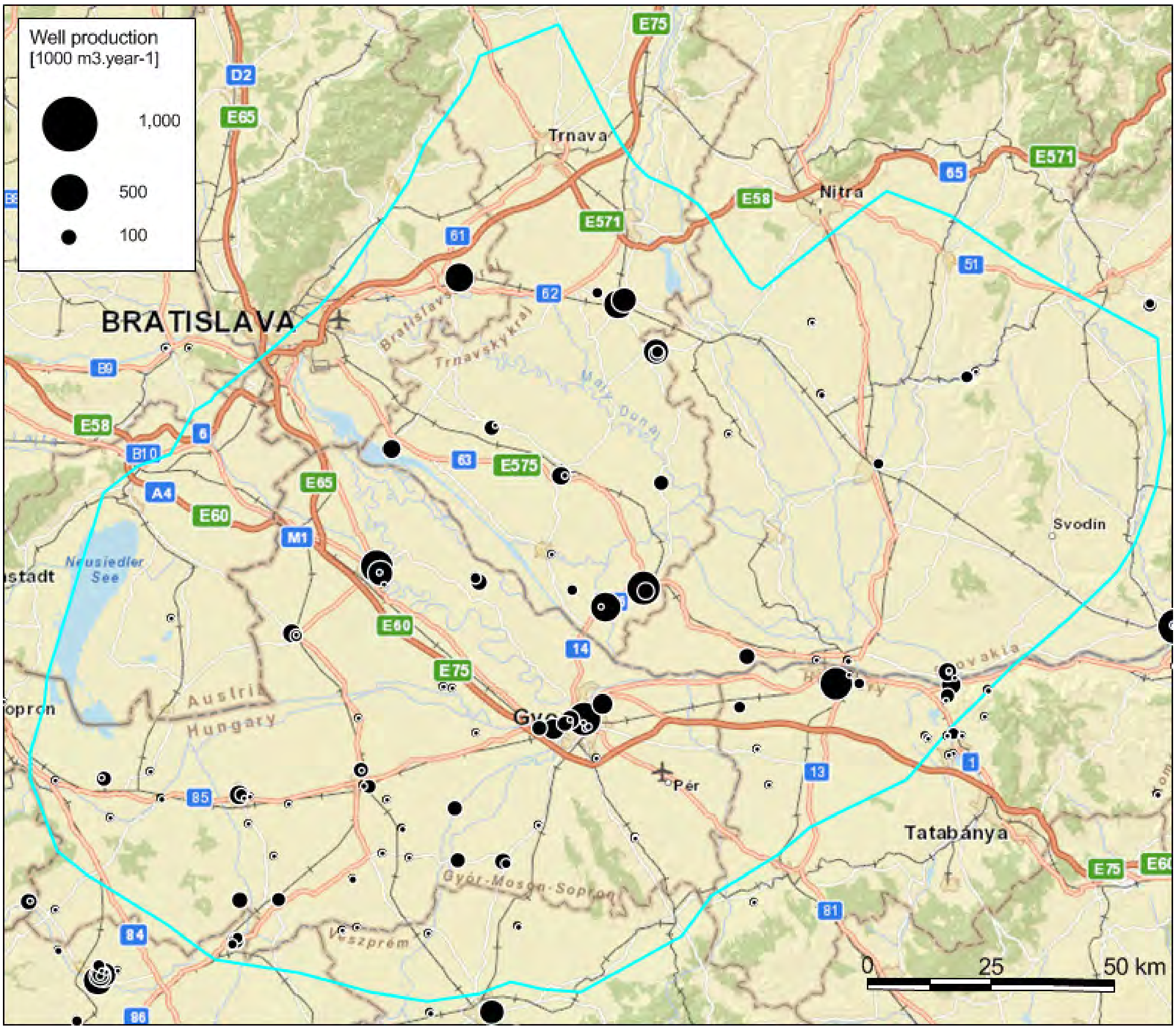

Fig. 3.1 Delineation of pilot model area with existing production wells with national and county boundaries (Topography: ArcGIS World Map © ESRI)

especially Late Pannonian sequences, these are of main interest from the geothermal point of view.

The Quaternary deposits deposited upon erosive base and accumulated in depressions. However in the Gabčíkovo Depression the deposition was continuous from the older sediments (Maros, et al., 2012).

3.2.3. Hydrogeology

The crystalline basement has no significant influence on the groundwater flow system. The crystalline rocks have fissure-type permeability. Usually they can be characterized by intensive heterogeneity, decreasing fissure aperture closing downwards causing the decreasing of permeability, and enhanced hydraulic conductivity due to tectonic effects.

From the hydrogeological build-up of the Danube Basin it can be assumed that the Carpathian crystalline basement of the Danube Basin does not contain relevant geothermal aquifers. However, suitable aquifers are bound to Mesozoic aquifer systems of separate structures and sands or sandstones of Pannonian, Pontian and Dacian age within the Tertiary basin fillings.

The Levice Block is located in the north-eastern part of the Danube Basin. It is composed of Mesozoic rocks of the higher nappes and locally underlain by the remnants of the Mesozoic envelope of the crystalline complex (Fusán et al., 1979). This Mesozoic plateau dips first smoothly and then more steeply westwards. It has only westward continuation. The aquifer layer is formed by mainly Triassic dolomites together with the basal Badenian clastics. The temperature of the water is 69-80 °C, and the mineralization reaches around 19 $g.l^{-1}$.

The Dubnica Depression is a special type of basement aquifer. It is filled mainly with Miocene sediments underlain by crystalline schists and granitoids of the Veporicum. The aquifer is formed by basal Badenian clastics (conglomerates, sandstone) at a depth between 1,000-2,000 meters. It represents a closed reservoir, with temperature of 52-75 °C, and mineralization ranging around 10-30 $g.l^{-1}$.

The *Komárno Block* extends between Komárno and Štúrovo. It is fringed by the River Danube in the S and by E-W Hurbanovo fault in the North, with the latter separating it from the Veporic crystalline unit. The southern limit along the Danube is of tectonic nature as well, and therefore the Komárno Block is a sunken tract of the northern slope of the Gerecse and Pilis Mts. The surface of the Pre-Tertiary substratum plunges towards the North from a depth of approximately 100 m near the Danube to as much as 3,000 m near Hurbanovo fault. The Pre-Tertiary substratum of the Komárno Block consists largely of Triassic dolomites and limestones up to 1,000 m in thickness. These are underlain by a very thick Early Triassic shale formation. Palaeozoic units were revealed by drilling in the north-western section of the Komárno Block. These include Permian conglomerates, sandstones, greywackes and shales and Devonian limestones and lydites. From a hydrogeothermal point of view, the area is divided into High and Marginal blocks (Remšík, et al., 1992). The geothermal activity of the High Block has partly been known for long because of thermal springs at Štúrovo and Patince, 39 and 26 °C warm. The structure has a fast water circulation and is considerably cooled (water temperature is 20-22 °C at a depth of 600-800 m, 24.5-26.5 °C at 1,100-1,300 m, and around 40 °C at 3,000 m). The Komárno High Block is encircled by the Marginal Block in the West, North and East. The latter contains groundwaters whose temperature exceeds 40 °C (highest so far noted temperature is 68 °C). Transmissivity in the High Block varies from $1.54.10^{-4}$ to $1.28.10^{-3}$ $m^2 \cdot s^{-1}$. Transmissivity in the Marginal Block ranges from $5.07.10^{-5}$ to $2.21.10^{-4}$ $m^2 \cdot s^{-1}$.

The representative *block of Graz Palaeozoicum* (part of the Late Austroalpine nappes) *in Bük-Sárvár region* shows other type of the carboniferous basement aquifers. Although the known spatial extent of the aquifer formed by Devonian dolomite is not too big, the hydrogeological character is not uniform. Conductive areas can be found only related to wider open fractures. They are most often along the elevated blocks of the dolomite basement. Two separated fractured flow systems were explored by boreholes. The reservoir of Rábasömjén together with the directly covering Miocene aquifers (limestone and sandstone layers) forms a significant closed system. The reservoir of Bük is separated from the reservoir of Rábasömjén at northwest along tectonical zones. It is supposed that the Bük reservoir has got its recharge area in the foreground of Wechselgebirge Mts.

The Danube Basin and the Neogene sub-basins of Kisalföld are filled with several thousand meters thick porous sediments.

The northern part of the territory is situated in the dish-like shaped Danube Basin. The more than 6,000 meter deep basin has brachysynclinal structure. The older layers which crop out at the edge of the basin can be found at gradually deeper position toward the centre of the basin. The Miocene and Pannonian complexes are composed mostly of unconsolidated strata of gravels, sands and clays. These are locally cemented by calcium carbonate to form conglomerates, calcareous sandstones, or organogenic limestones.

The covering Quaternary layers are represented by gravel and sands. The maximum thickness (520-600 meters) occurs in the region of Gabčíkovo and Baka.

The Miocene aquifers are connected in each case to the basement aquifers, especially to highs of the basement and form a single flow system. They are represented by Badenian or Sarmatian sands and limestones. They contain fossil waters with high salinity.

The Late Miocene low permeable and thick marl and clay sequences together with the Early Pannonian layers act as regional aquicludes. They separate the flow system of the basement from the deep (usually thermal water) flow system of the porous formations characterized as the Pannonian reservoir.

The structure of the lower part of the Late Pannonian formation is likely to have interlayer leakage, intergranular permeability and confined groundwater level. It contains thermal waters with temperature 42-92 °C which are bound mainly to sands and sandstones aquifers. The aquifer layers of the central part in the thermal water system crop out at the edges of the depression. Towards the interior part of the basin the number of sandstone aquifer layers increases but simultaneously thickness, porosity and permeability decrease as a result of sediment compaction within the young sedimentary basin. Commonly, the sand bodies are lens-shaped and cannot be followed laterally to long distances. The sandy aquifer layers vary with aquitard clay, sandy clay layers. The vertical and lateral extent of the aquifer layers are varying abruptly. Commonly, the up to 10 meters thick sand bodies are lens-shaped which cannot be followed to long distances laterally.

The Quaternary sediments form a common unconfined reservoir. The flow system of the cold groundwater represented in this sequence is in hydraulic connection with the Pannonian flow systems. The groundwater regime depends on the discharge from the Danube. At the Gabčíkovo region the surface regime, with all signs of common groundwaters from Quaternary alluvia, takes effect to a depth of 30 meters. Below this limit the influence of deep regime becomes evident with all its dynamic features.

The alluvial aquiferous Quaternary formation is of specific hydrogeological importance. The thick gravel and sand layers represent a great amount of good quality water. The discharge in some places exceeds 8 $m^3.s^{-1}$ of water. It has great potential for the future drinking water resources.

With respect to lithology, the aquifer and overlying beds have been divided into six hydrogeological units. Each represents a complex with different ratio of aquifers and aquicludes. The waters in the Central Depression are either marinogenic or petrogenic and are divided into five chemical types (Franko et al., 1995).

3.3. Geothermal conditions

The highest heat flow densities have been recorded in the centre of the depression ($q > 85$-90 $mW.m^{-2}$) and do not correspond neither to lower temperatures ($T < 45$ °C) nor thermal gradients. Whereas heat flow generally decreases towards the margins of the Danube Basin, temperature in depth increases. This irregularity is caused by a cold water body, which is bound to the uppermost hydrogeological unit showing a maximum thickness of 460 m. The colder zone gradually perishes downward and the temperature field corresponds to the heat flow. Badenian volcanoclastics at depths of 5,000–6,000 m may contain geothermal waters with aquifer temperature exceeding 200 °C. They can be utilized by applying reinjection for reasons of sustainability. Because of its post-Sarmatian evolution, the Danube Basin has a bowl-like brachysynclinal shape.

The upper boundary of the geothermal water body was in Slovak studies and research works located at depths of 1000 m below the surface and at the bottom it is confined by a fairly impervious substratum - an aquitard (clays) which plunges from the surrounding area towards the centre of the basin to a depth of up to 3,400 m below surface (Franko et al., 1995).

3.4. Regional modelling

The aim of the regional numerical modelling was to simulate the hydrogeological and geothermal conditions in the geothermal water body of Pre-Neogene and Neogene fill of the Danube Basin. The goal of modelling that comprises 3D groundwater flow and heat transport simulations was to provide information for better understanding of the hydrogeological and geothermal conditions in the pilot area. The modelling simulations were calculated for steady state conditions – steady flow and steady heat transport. Two scenarios are compared in the model – pre-utilization reflecting "natural conditions" with no pumping assumption and assumption considering influence of the production wells based on accessible data about the geothermal water extractions.

3.4.1. Methodology

The character of the problem requires a tight approximation of complex faulted geology with discrete line and point features, such as rivers and point water abstractions, where steep pressure and temperature gradients are unavoidable. Therefore a finite element model was chosen as the most appropriate. Programme FEFLOW (Diersch, 2006) is capable of solving coupled groundwater flow, mass transfer and heat transfer problems in three dimensional porous domains. Its powerful mesh generators enable to construct good quality triangular meshes with inclusion of discrete finite elements representing wells, faults, etc. The programme uses finite element analysis to solve the groundwater flow equation of both saturated and unsaturated conditions as well as mass and heat transport, including fluid density effects and chemical kinetics for multi-component reaction systems.

3.4.1.1. Horizontal extent

The model area is outlined in accordance with the TRANSENERGY project pilot area (Fig. 3.1). It encompasses all important sedimentary structures of Neogene age predominantly, in which majority of utilizable thermal groundwaters are present. The model boundary was demarcated in accordance with all hydrogeological knowledge, along well defined hydrogeological limits.

3.4.1.2. Vertical extent

From the top the model is limited by the topographical surface, adopted from the digital elevation model SRTM. To the depth the model extends down to -10,000 m a.s.l.

3.4.1.3. Horizontal resolution

Due to expected elevated hydraulic and thermal gradients around fault zones, rivers and wells, the computing mesh needed to be locally refined around these features. Thus the generated mesh, consisting of triangular prisms, counting up to 31,114 nodes per slice (in total 373,368), forming 61,602 elements per layer (total 677,622).

3.4.1.4. Vertical resolution

The model adopted a geological model consisting of 8 hydrostratigraphic units:

- Quaternary - phreatic
- Late Pannonian
- Early Pannonian
- Sarmatian
- Badenian
- Badenian volcanites
- Cainozoic
- Mesozoic, Palaeozoic and crystalline basement

Late Pannonian was further subdivided into two formations: delta plain and delta front. For this purpose a sequential indicator Kriging was performed upon borehole data using GSLIB (Deutsch & Journel, 1998, Fig. 3.2).

Due to large thickness of the basement layer, it was divided into 2 numerical sub-layers. To mimic the effect of pre-sedimentation exposition of the uncovered bedrock to weathering, a separate, 10 m thick layer with elevated conductivity at the top was created. It is in accordance with findings in several deeper boreholes reaching bedrock, where often intensively altered or karstified rocks of several meters thickness were observed.

Due to unknown hydraulic function of regional faults, it was impossible to explicitly define faults in the model. They manifest themselves only in morphology of individual model layers.

3.4.1.5. Flow boundary conditions

The outer limit of the model was chosen to follow natural hydrogeological boundaries, defined either by extent of thermal water bearing horizons or by groundwater divides. Thus, its setting as a no-flow boundary was justifiable.

All across the top surface a Dirichlet boundary condition (constant groundwater head) was set (Fig. 3.4). The purpose of it was to prescribe realistic groundwater

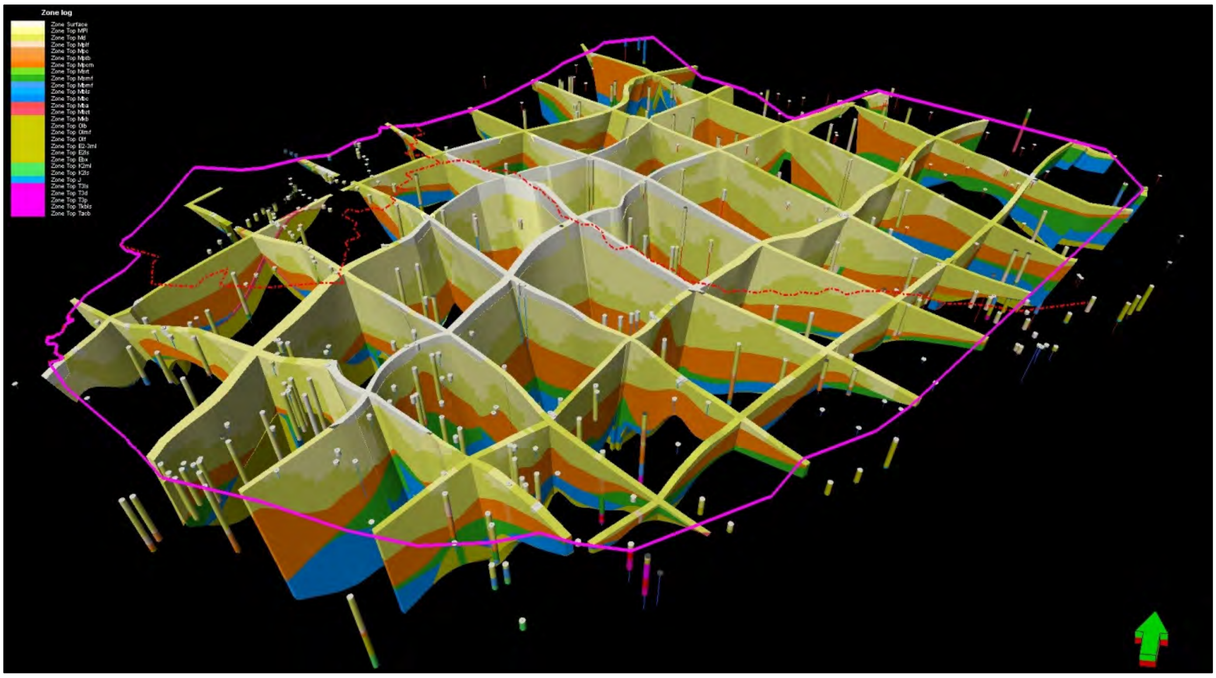

Fig. 3.2 Fence diagram of geological model. Colours depict main hydrostratigraphic units: light grey – Quaternary; pale green – delta plain facies of Late Pannonian; light green – delta front facies of Late Pannonian; ochre – Early Pannonian; dark green – Sarmatian; light blue – Badenian sediments; dark blue – Badenian volcanites; olive green – Cainozoic; magenta – Mesozoic. Green arrow points to the North

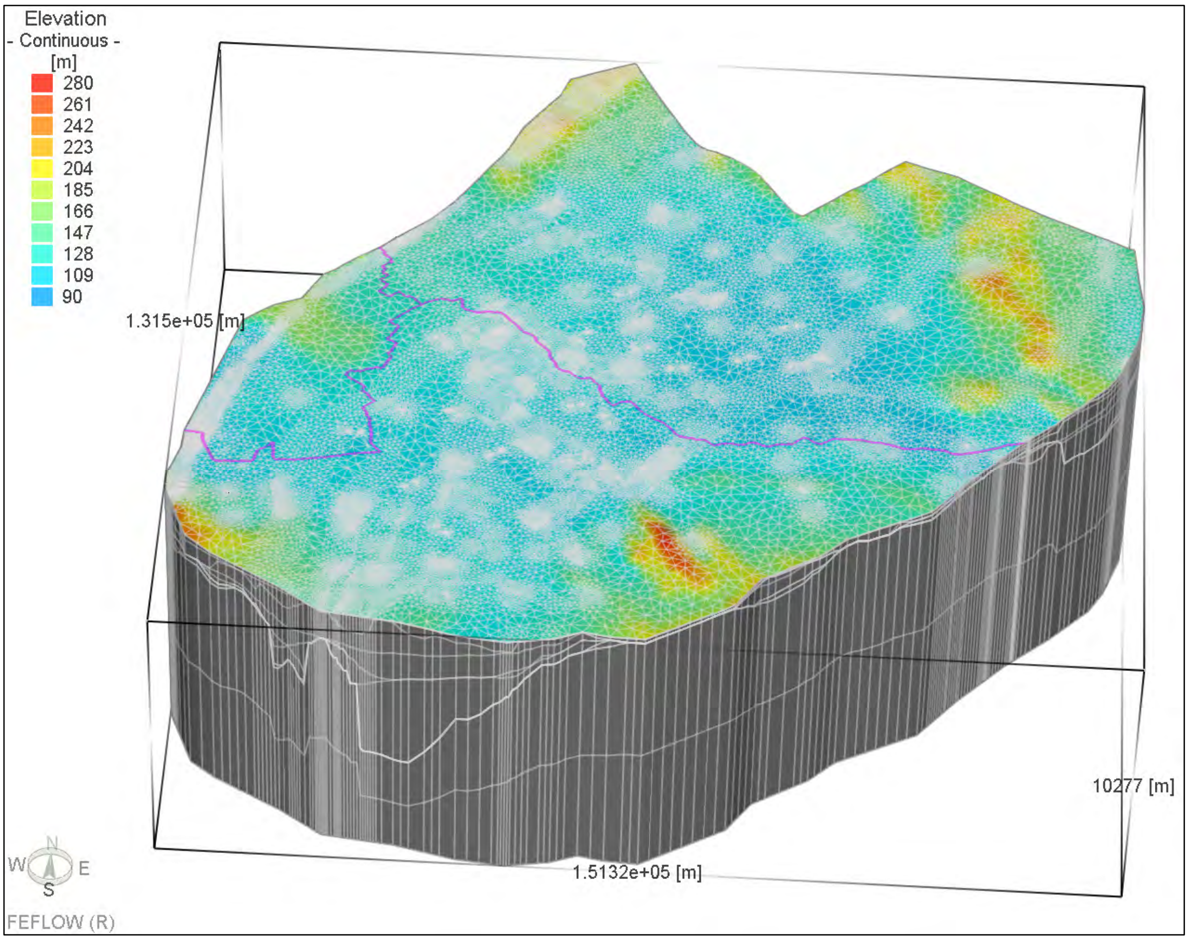

Fig. 3.3 Geometry of the pilot area model. Vertical exaggeration 5x

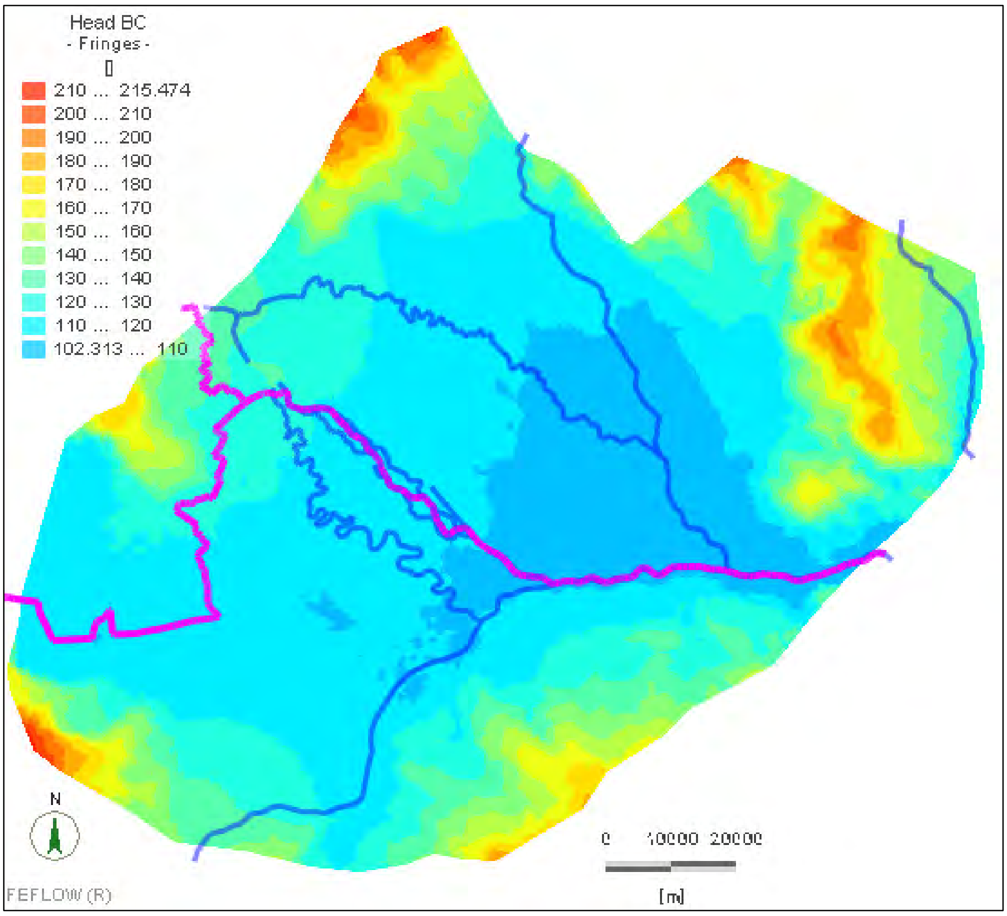

Fig. 3.4 Constant hydraulic head boundary condition (m a.s.l.) in the Quaternary aquifer

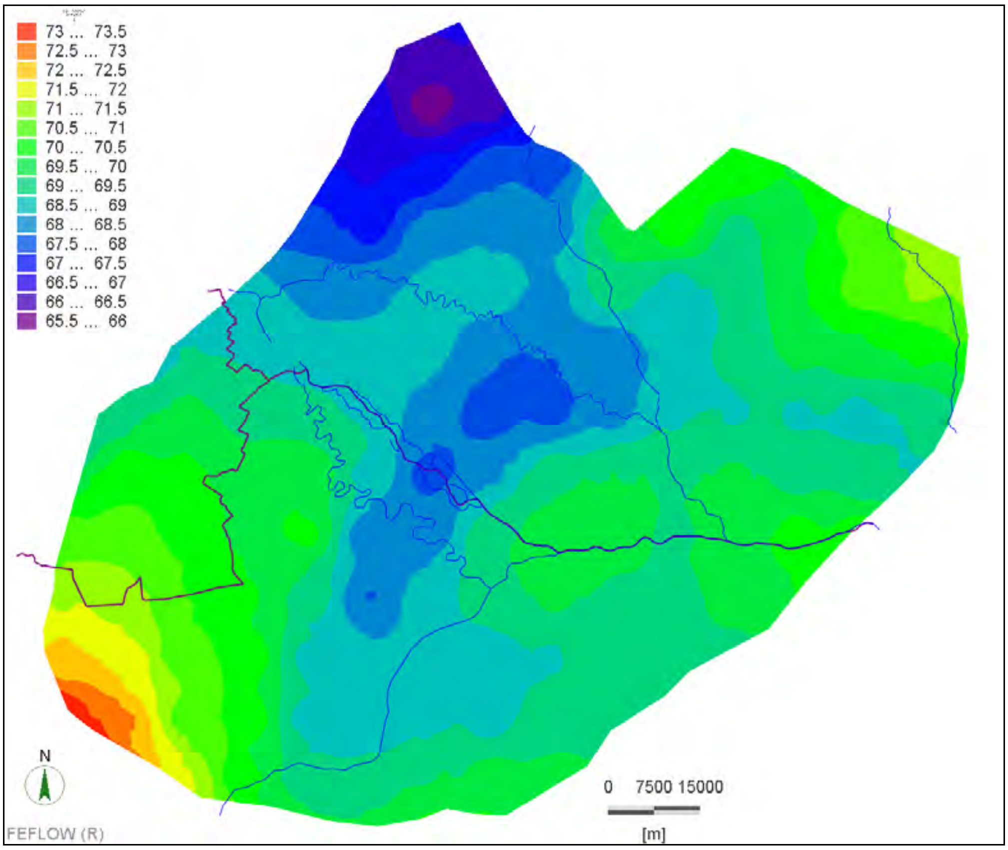

Fig 3.5 Constant basal heat flux (mW.m^{-2}) boundary condition at depth -10,000 m a.s.l. (from Lenkey et al., 2012)

potential of cold water Quaternary aquifers lying on top of thermal aquifers. The groundwater heads were adopted from the calibrated supra-regional groundwater model (Tóth et al., 2012).

For the utilization variant of the model a second order (Neumann) boundary condition was also applied at screen intervals of all active pumping wells. Average reported well yields from years 2007-2010 were assigned as pumping rates. FEFLOW internally sets a special 1D linear finite element along well screens, to better approximate flow within a borehole.

3.4.1.6. Thermal boundary conditions

At the base of the model a Neumann (constant heat flux) boundary condition was set out. The values of basal heat flux were taken from the supra-regional conductive thermal model of Lenkey et al. (2012) (Fig. 3.5). At the ground surface a Dirichlet boundary condition with uniform temperature 10 °C was set out, which corresponds to annual mean air temperature in the model area.

Radiogenic heat production in rocks is subtle, but not negligible source of total heat in present in geothermal systems. In FEFLOW it can be added as a material property (internal source), although in fact it acts as a boundary condition of the second order. Because exact concentrations of uranium, thorium and potassium are not available to allow calculation of produced radiogenic heat, estimates based on published data were used instead.

3.4.1.7. Recharge and discharge

Because of prescribed head boundary condition at the top of the model, all groundwater recharge is handled at this boundary. Generally, water is infiltrated into the model at areas with higher head elevations and discharged at lower. The quantity of recharged and discharged groundwater is not constrained by any means, making it possible that at some locations within the Quaternary aquifer groundwater fluxes and flow velocities can be unrealistically high. But as the Quaternary aquifer with relatively cold water is not in the centre of our research, and acts solely as a pressure load on lower thermal aquifers, this poses no restrictions to deep geothermal waters evaluation.

3.4.1.8. Material properties

Hydraulic conductivity is a very sensitive parameter, determining groundwater flow and heat transport in a model. At the same time, it is also very difficult to be assessed, especially in deeper parts of the model out of testing boreholes reach. Furthermore, data acquired from boreholes represent only the screened horizons, usually selected as the best permeable zones and thus overestimating the hydraulic conductivity. Another problem is high spatial heterogeneity of permeability, owing to frequent interchanging of very contrasting rocks within short horizontal and especially vertical distance. All this lead us to adopt an approach, in which hydraulic conductivi-

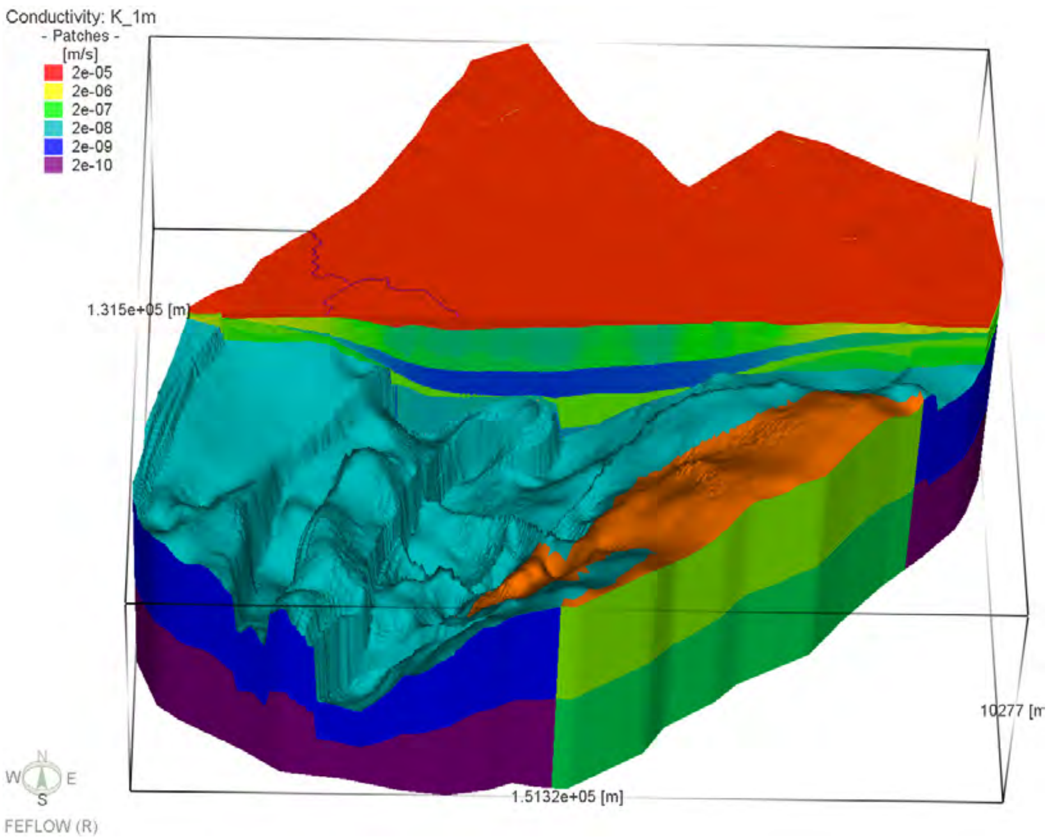

Fig. 3.6 Horizontal hydraulic conductivity distribution in the sedimentary basin (partial cut-out) and basement rocks. Higher values in the bedrock refer to Mesozoic carbonates

ties of individual model layers, corresponding to hydrostratigraphic units, were estimated based on borehole tests or data found in literature, regionalized and further adjusted in calibration process.

Quaternary sediments had been best investigated by well tests, therefore in the topmost model layer hydraulic conductivities correspond to measured values very closely.

In deeper Neogene sediments hydraulic conductivities are estimated. In this environment, typical of strong interchanging of impervious clayey aquitards with permeable sandy local aquifers, the enhanced flow along strata is mimicked by a high degree of anisotropy in direction perpendicular to bedding direction, up to three orders of magnitude. Decrease of permeability and porosity with depth was also accounted for.

Igneous, metamorphic and carbonate bedrocks have a very low isotropic permeability and effective porosity, also decreasing with depth. Exception is the few meters thick upper part, which, prior to covering by younger sediments, underwent weathering and sometimes karstification, leaving behind higher porosity and permeability.

Although in real geological settings faults and fissures often play a significant role in water movement as either highly conducting zones or hydraulic barriers. However, without a comprehensive and targeted research, their function, if any, remains obscure. Therefore it seems justifiable, especially in sedimentary basins filled with clastics, whose plasticity is able to seal any faults immediately, to exclude fault's hydraulic features and take account for only its juxtaposition.

Main heat transport parameters comprise volumetric heat capacity and thermal conductivity of rock and water, longitudinal and transversal thermal dispersivity, porosity. Fortunately, good database of these values exists for Neogene sediments and Mesozoic carbonates, too; for numerical values see Tab. 3.1. Values for the rest of the rock types present in the model were adopted from other published data.

3.4.1.9. Calibration and validation of the model

Initial values of hydraulic parameters were stepwise adjusted during multiple simulation runs to achieve best match between measured and computed hydraulic pressures at 149 measured points in the whole area. Resulting simulated pressures are compared with the measured ones in Figs. 3.7 and 3.8.

Since environmental groundwater heads measured at boreholes use a column of water with a density influenced by temperature and dissolved salts content that is identical to that of the water that surrounds the well, sensu Lusczynski (1961), they had to be converted into freshwater equivalent heads for use in numerical simulations. For this purpose groundwater heads in all boreholes with known temperature distribution and TDS were reevaluated. This involved calculation of average thermal gradient, from which average temperature in whole water column was calculated. Together with weighted average of TDS, an average water density in a borehole was obtained. Freshwater equivalent heads at reference temperature 10 °C, TDS=0 mg.l^{-1} and density of pure water 999.7281 kg.m^{-3} were then calculated using equation of McCutcheon et al. (1993).

Calibration of geothermal parameters was based on 67 downhole temperature measurements. Great effort was made to select data from measurements on closed, non-operated boreholes only. However, due to missing information and disturbances of pressure and temperature field caused by drilling, this could not be guaranteed in many cases, which adds some extra error into the calibration results (Fig. 3.9).

Tab. 3.1 contains values of parameters, used in the pilot area model. The values for different model layers are coming from different sources: where possible, especially in shallow parts of the model, direct assignment of statistical means of individual parameters was applied. In the rest of the model the parameter values were obtained from inverse modelling or by guessing, based on published data.

3.4.2. Results of regional modelling

Constructed regional model is simplified numerical representation of hydrological and geothermal characteristics of the pilot area and enables simulation of basic features of the geothermal system.

3.4.2.1. Hydraulic head distribution

Distribution of hydraulic heads in the model depends primarily on boundary conditions and spatial distribution of hydraulic conductivities (Fig. 3.12). In the upper parts hydraulic potentials are reflecting hydraulic heads set as constants in Quaternary, in deeper horizons hydraulic pressures are equilibrated, resulting in lower head differences.

3.4.2.2. Evaluating effects of thermal wells utilization

Simulation of theoretical infinite pumping of 112 existing operating geothermal wells, with total yield summing up to 219 l.s^{-1}, was performed to predict future evolution of pressure and thermal field in the area and to help identifying potential adverse impacts of extensive and unsustainable thermal water over-abstraction. It also serves as a base for calculation of transboundary induced flows and energy transfer. The simulations were performed as steady flow and steady heat transport, practically meaning that results show a hypothetical situation in infinite future, if current amounts of water would be extracted. This, off course, is unrealistic, but results can highlight potentially problematic places. For instance, areas with very high pressure drop can indicate closed geothermal structures. Similarly, boreholes where a high temperature decrease is predicted should turn attention towards possible future risk of cold front arrival and thus shortening the production life of a site.

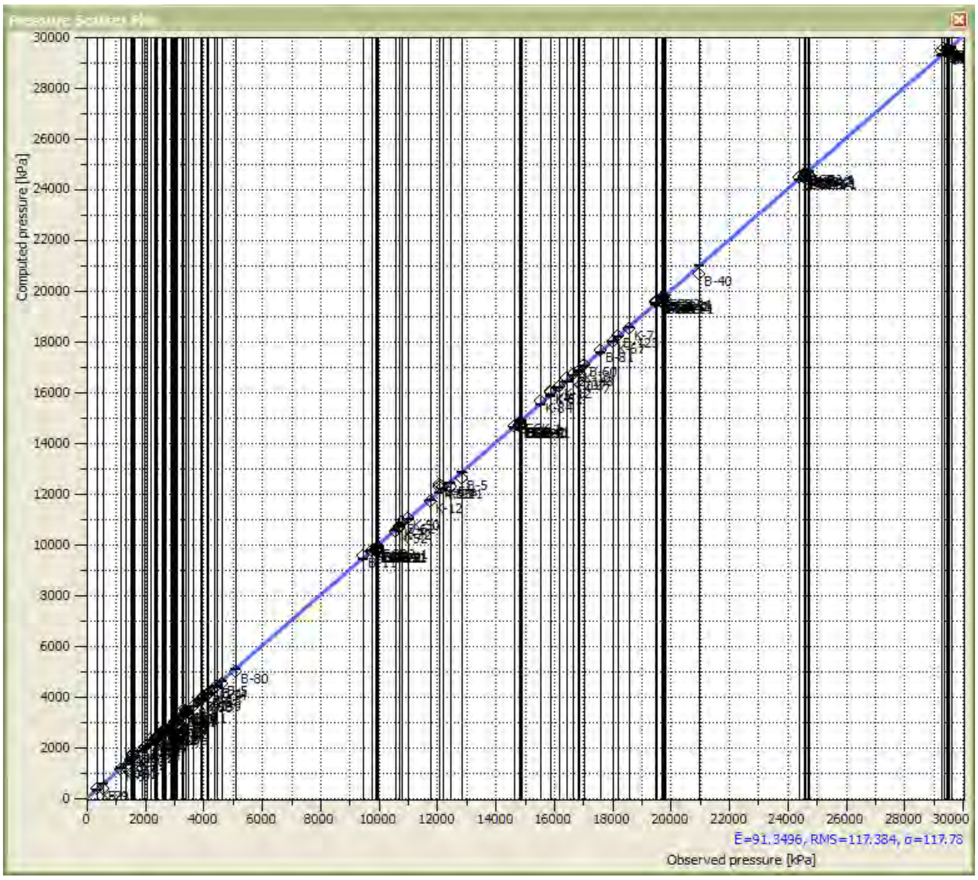

Fig. 3.7 Goodness of fit between computed and measured pressures in boreholes, natural pre-utilization state

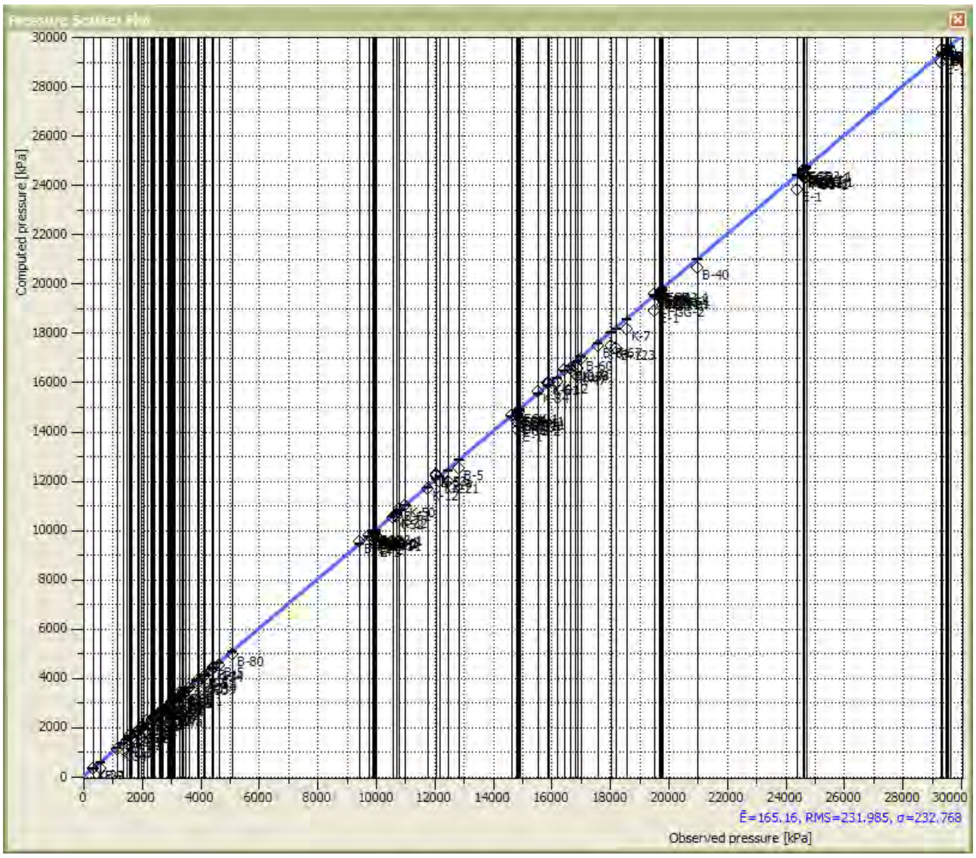

Fig. 3.8 Goodness of fit between computed and measured pressures in boreholes, steady pumping scenario

Tab. 3.1 Parameters used in the pilot area model

Model Layer	Horizontal hydraulic conductivity [$m.s^{-1}$]	Vertical hydraulic anisotropy [-]	Porosity	Specific storage [m^{-1}]*	Radiogenic heat production [$\mu W.m^{-3}$]	Heat conductivity of solid [$W.m^{-1}.K^{-1}$]	Heat conductivity of fluid [$W.m^{-1}.K^{-1}$]	Expansion coefficient [K^{-1}]*	Volumetric heat capacity of solid [$J.K.m^{-3}$]	Volumetric heat capacity of fluid [$J.K.m^{-3}$]	Longitudinal dispersivity [m]	Transverse dispersivity [m]*	Anisotropy of solid heat conductivity [$W.m^{-1}.K^{-1}$]*
Quaternary	1.268×10^{-5}	0.1	0.276	1×10^{-4}	0.8	1.974	0.6	0	3.420×10^{6}	4.186×10^{6}	50	5	1
Late Pannonian - delta front	3.228×10^{-8} - 3.526×10^{-6}	0.01 - 0.082	0.111	1×10^{-4}	1.3	2.219	0.6	0	2.737×10^{6}	4.186×10^{6}	50	5	1
Late Pannonian - delta plain	6.080×10^{-8} - 1.0883×10^{-5}	0.01	0.181	1×10^{-4}	1.3	1.769	0.6	0	2.750×10^{6}	4.186×10^{6}	50	5	1
Early Pannonian	3.327×10^{-9} - 9.159×10^{-7}	0.01	0.083	1×10^{-4}	1.3	2.406	0.6	0	2.999×10^{6}	4.186×10^{6}	50	5	1
Sarmatian	4.922×10^{-7}	0.002 - 0.007	0.111	1×10^{-4}	1	2.42	0.6	0	2.737×10^{6}	4.186×10^{6}	50	5	1
Badenian	1.277×10^{-8} - 4.642×10^{-6}	0.002 - 0.009	0.113	1×10^{-4}	1.2	2.754	0.6	0	2.496×10^{6}	4.186×10^{6}	50	5	1
Badenian volcanites	5.688×10^{-6}	0.001 - 0.005	0.1	1×10^{-4}	0.2	2.24	0.6	0	2.700×10^{6}	4.186×10^{6}	50	5	1
Cainozoic	1.047×10^{-8} - 4.445×10^{-6}	0.001 - 0.005	0.08	1×10^{-4}	0.7	2.554	0.6	0	2.598×10^{6}	4.186×10^{6}	50	5	1
Weathered basement: Mesozoic	6.960×10^{-6}	0.001	0.1	1×10^{-4}	1.1	2.7	0.6	0	2.584×10^{6}	4.186×10^{6}	50	5	1
Weathered basement: Palaeozoic and crystal-line	2.000×10^{-8}	0.01	0.1	1×10^{-4}	1.1	3.11	0.6	0	2.584×10^{6}	4.186×10^{6}	50	5	1
Upper non-weathered basement: Mesozoic	6.960×10^{-7}	0.01	0.03	1×10^{-4}	1.1	2.7	0.6	0	2.600×10^{6}	4.186×10^{6}	50	5	1
Upper non-weathered basement: Palaeozoic and crystalline	2.000×10^{-9}	0.1	0.03	1×10^{-4}	1.1	3.11	0.6	0	2.600×10^{6}	4.186×10^{6}	50	5	1
Lower non-weathered basement: Mesozoic	6.960×10^{-8}	0.1	0.01	1×10^{-4}	1.1	2.7	0.6	0	2.600×10^{6}	4.186×10^{6}	50	5	1
Lower non-weathered basement: Palaeozoic and crystalline	2.000×10^{-10}	1	0.01	1×10^{-4}	1.1	3.11	0.6	0	2.600×10^{6}	4.186×10^{6}	50	5	1

* Default values in FEFLOW

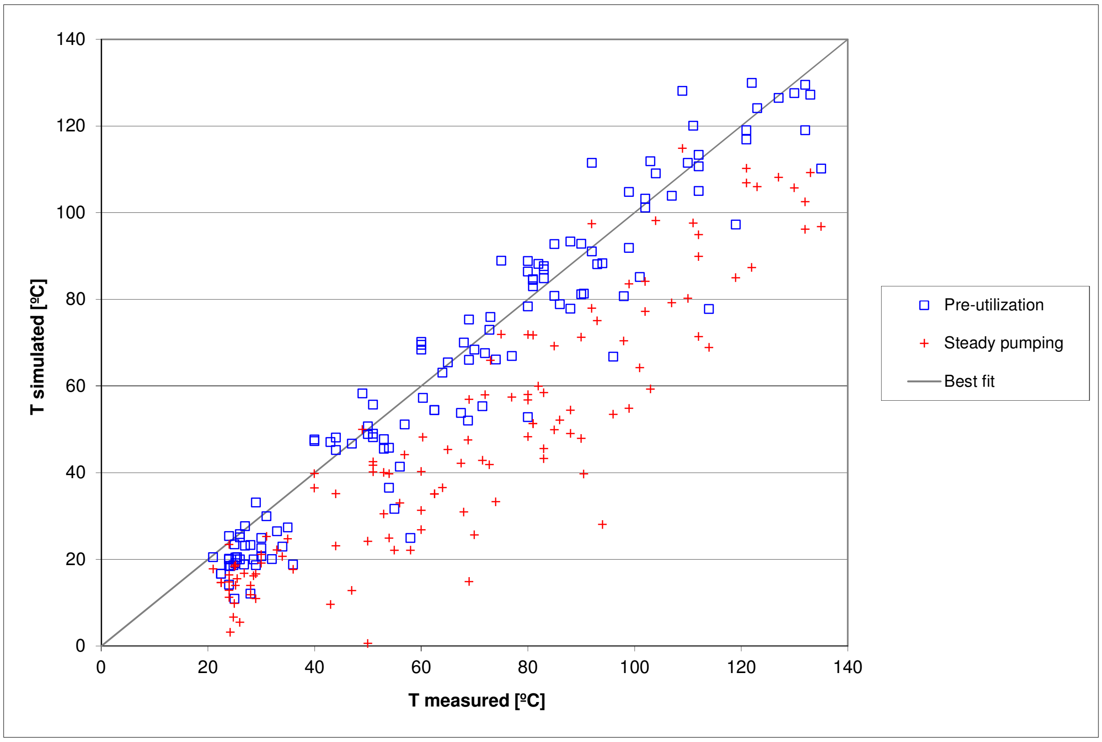

Fig. 3.9 Comparison of temperature evolution in boreholes for two model scenarios: pre-utilization and steady pumping. Obvious is systematic temperature decrease when pumping is functional, resulting from enhanced circulation of cold Quaternary waters into deeper thermal aquifers causing shortening of travel times. Root mean square error (RMSE) for first scenario is 9.32 and 13.31 for the latter

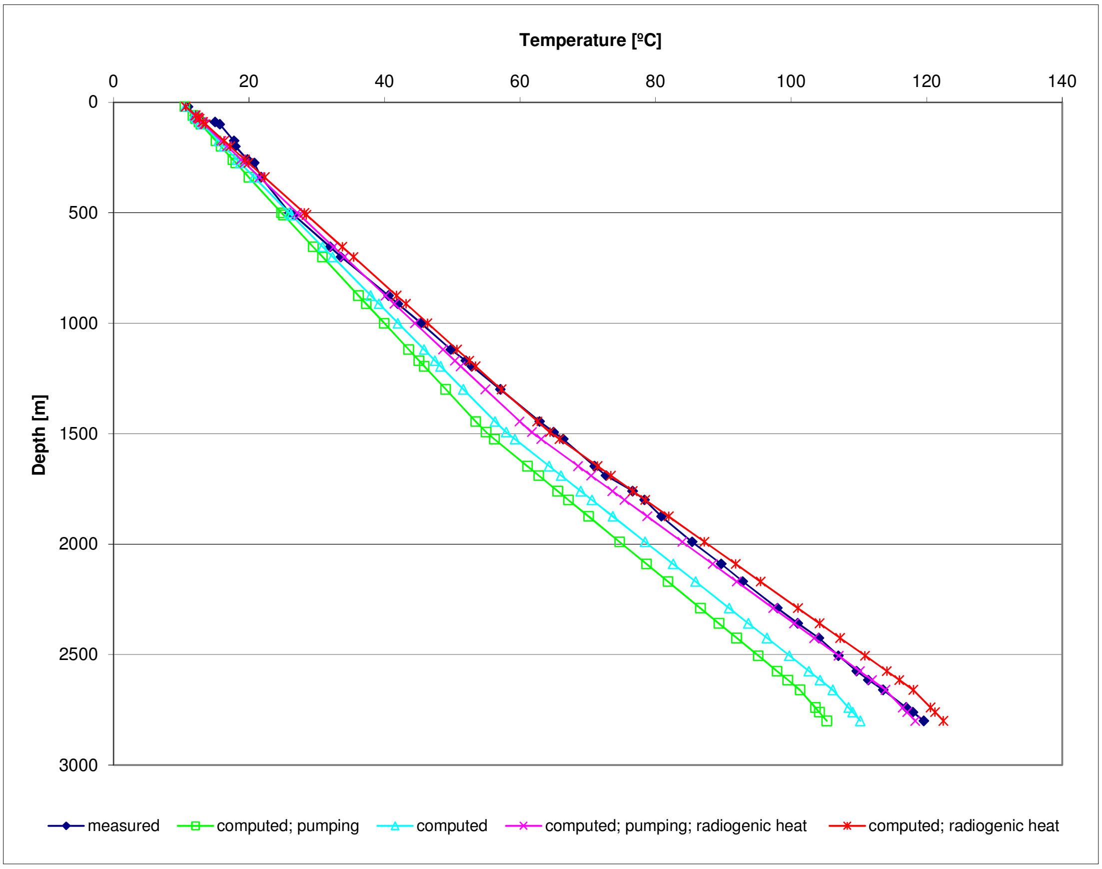

Fig. 3.10 Comparison of different model set-ups on goodness of fit between computed and measured temperatures, example from the monitoring well GPB-1 Boheľov. Best match was achieved for both scenarios, natural pre-utilization state and steady pumping, with inclusion of radiogenic heat production

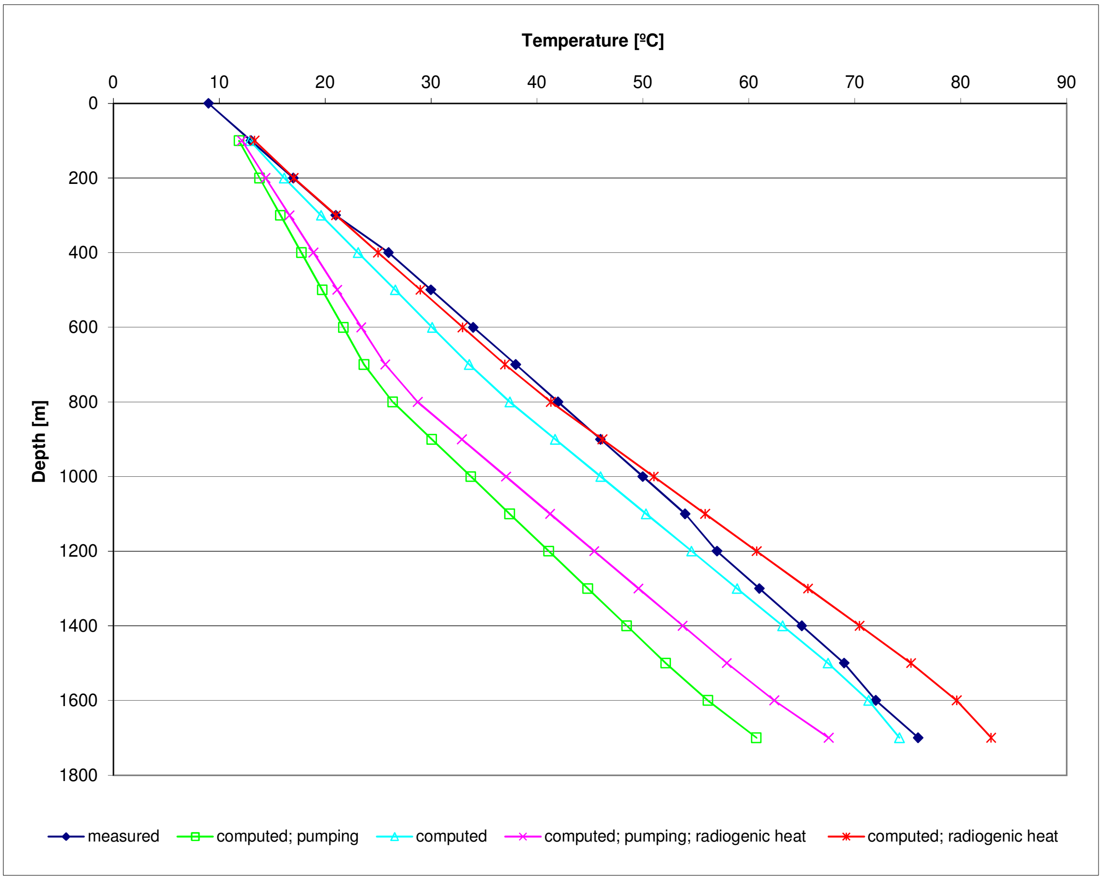

Fig. 3.11 Comparison of different model set-ups on goodness of fit between computed and measured temperatures, example from the monitoring well Di-1 Diakovce. Steady pumping scenario exhibits significant deviation from measured temperatures in upper 800 meters. It can be attributed to cooling by increased infiltration of cold Quaternary water induced by pumping

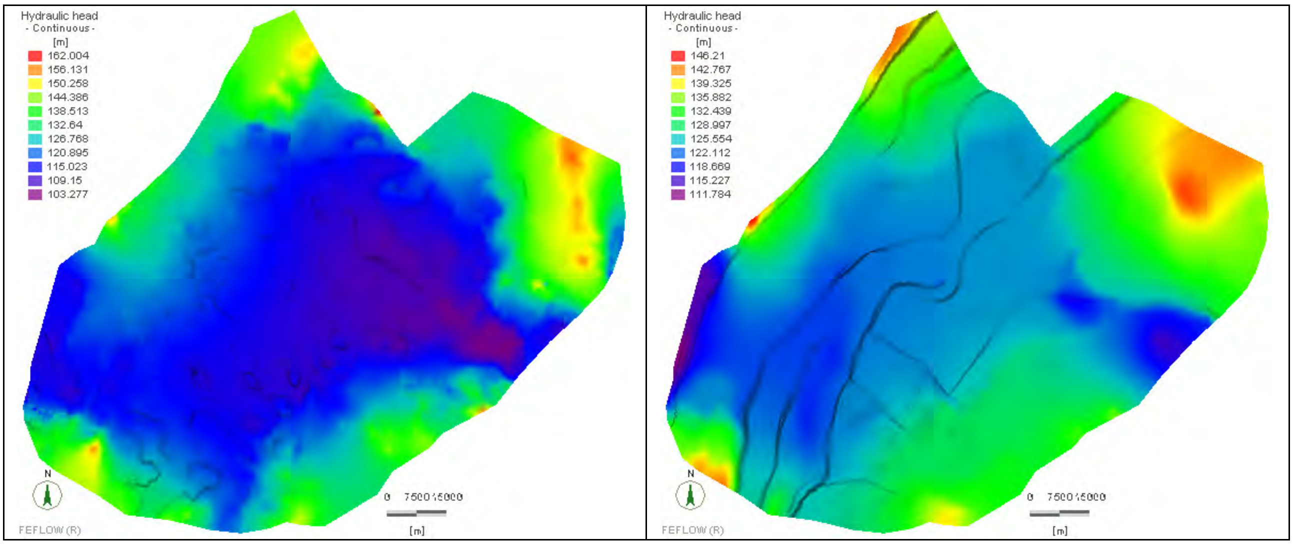

Fig. 3.12 Distribution of computed hydraulic heads at the base of Late Pannonian (left) and base of Cainozoic (right), pre-utilization state. Remember that pictures show values on whole model layer, while respective hydrostratigraphic units cover only central part of the area. The same principle applies for all similar maps in this paper

Pumping thermal water from utilized wells in the area is causing a decrease in hydraulic pressure in penetrated geothermal aquifers, as well as adjacent aquitards and basement rocks. The impact is emphasized in mountainous areas in the southeast and northwest parts of the basin. Moreover, due to induced general decrease of temperatures caused by enhanced circulation (see next chapter), colder water with higher density is promoting pressure increase in deeper parts of the Central Depression, because groundwater head at the top is maintained at constant level by recharge. These changes are visualized on Figs. 3.13 a-d.

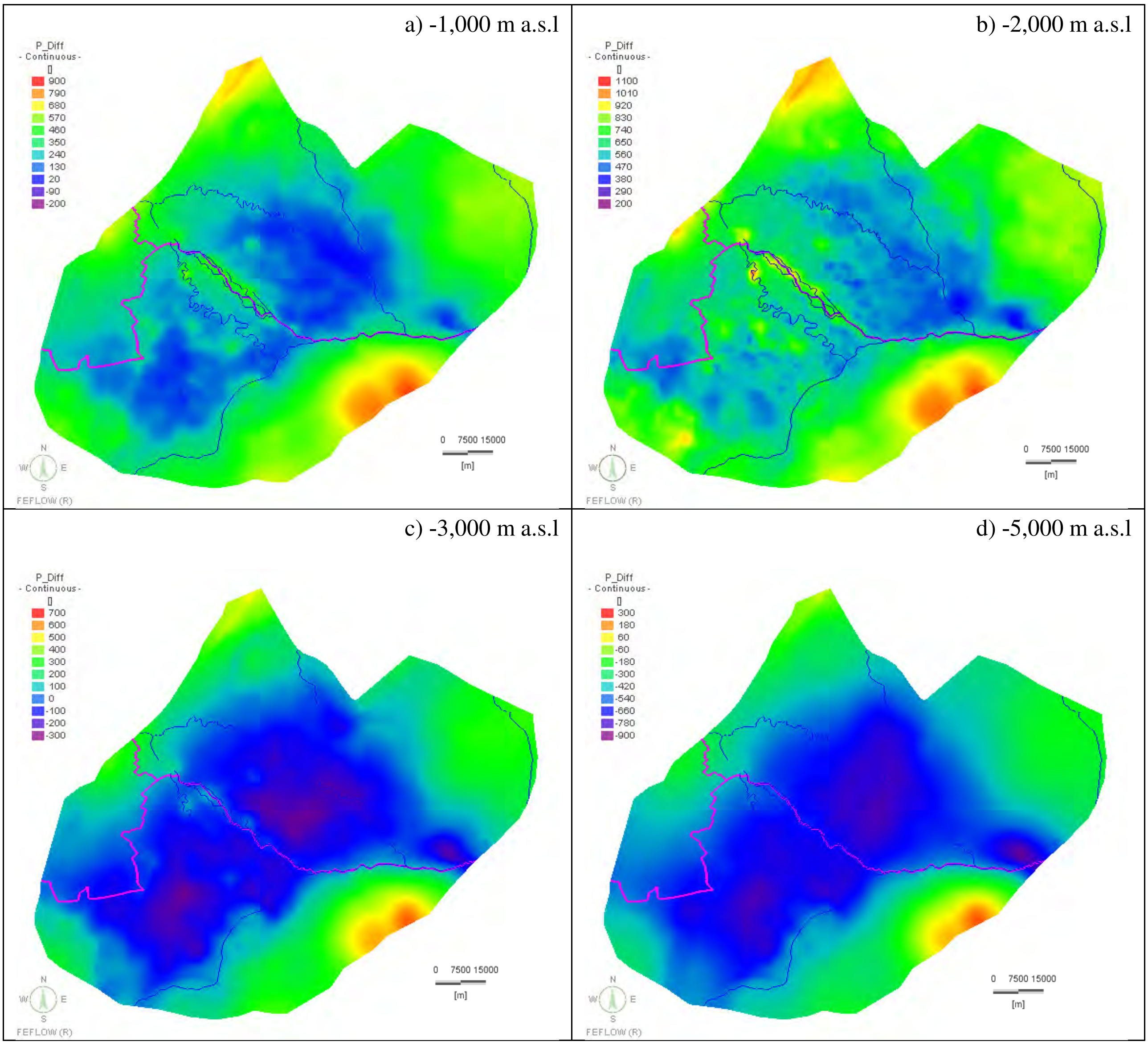

Fig. 3.13 Pressure differences (Pa) caused by steady pumping at different depth levels

3.4.2.3. Temperature distribution

In Pre-Quaternary rock formations conduction is the main mechanism for heat transport. Due to relatively intensive water interchange between recharge and discharge zones in the Quaternary sediments, convection is of high importance. The convection driven heat transport is also dominating in the karstified Mesozoic carbonate formations in Gerecse and Pilis Mts. and Komárno High Block. Intensive recharge of precipitation is causing a considerable cooling of the whole carbonate massif (Fig. 3.14a-d).

Notable is also cooling effect of thick Quaternary gravels and sands along the central part of the Danube River. Owing to large depth (up to 713 m) and high permeability of these sediments, rapid circulation of 10 °C cold groundwaters across the whole thickness, coming from almost infinite source – the Danube River, excavates heat from underlying Neogene sediments. This cooling propagates to large depths over 3 km (Figs. 3.14a, b and c).

3.4.2.4. Transboundary aspects evaluation

One of the major goals of the TRANSENERGY project is to have a closer look at transboundary aquifers. In the Danube Basin pilot model three countries meet: Hungary, Slovakia and Austria, sharing important geothermal aquifers.

Naturally, national borders do not prohibit movement of groundwater mass and heat. It is also the case of the pilot model area. The Quaternary, Neogene and also Mesozoic aquifers are developed on all sides of state borders. The hydraulic and geothermal models created show significant amounts of water and energy moving from state to state either naturally or, in a close vicinity of operating wells, by forced convection. This promotes international cooperation in managing geothermal resources.

Figure 3.16 shows computed flow trajectories with travel times, induced by steady pumping in utilized thermal wells at long-term average rates. The most intensive

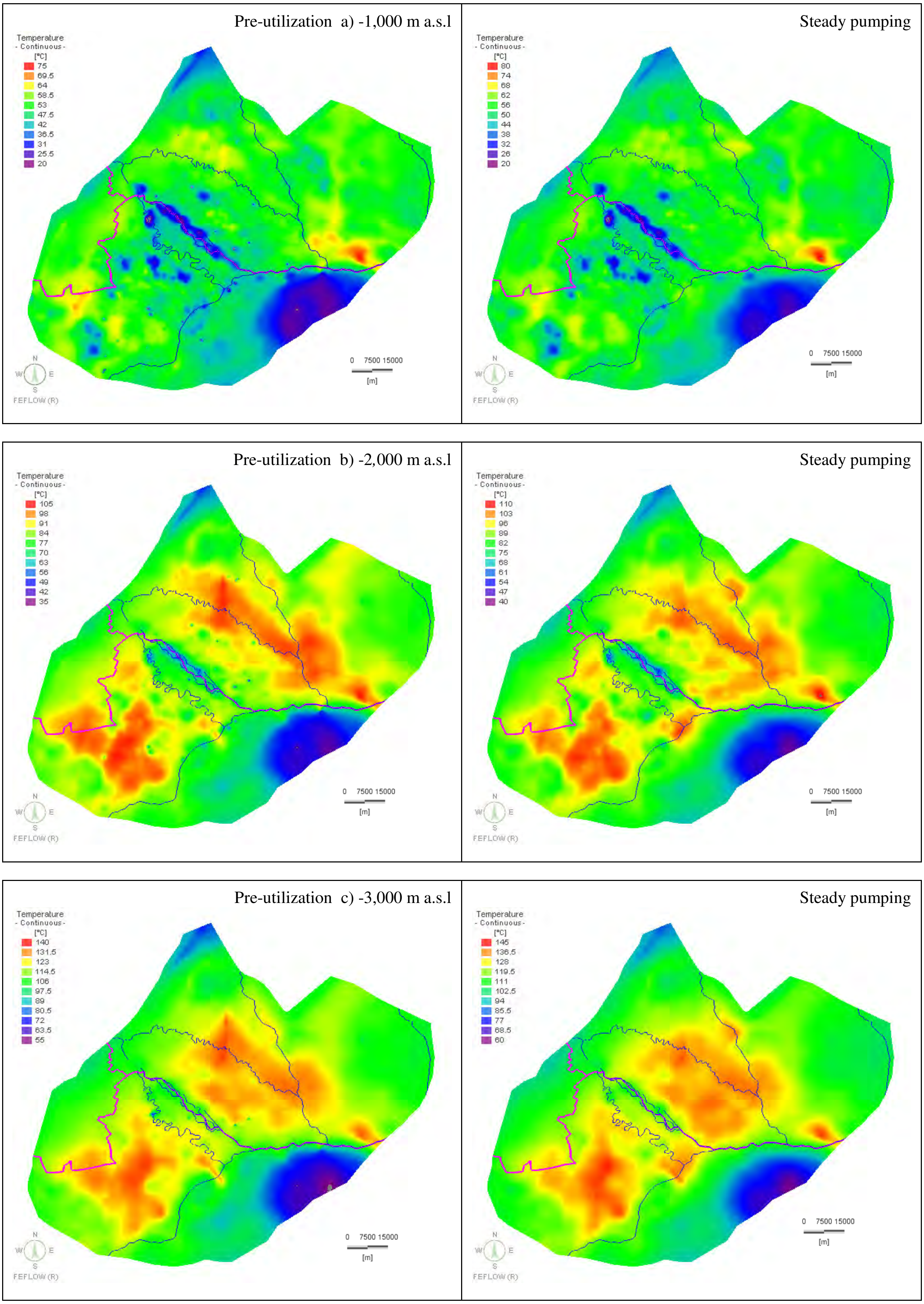
Pre-utilization a) -1,000 m a.s.l
Steady pumping
Temperature - Continuous - [°C]
75 69.5 64 58.5 53 47.5 42 36.5 31 25.5 20
80 74 68 62 56 50 44 38 32 26 20
Pre-utilization b) -2,000 m a.s.l
Steady pumping
105 98 91 84 77 70 63 56 49 42 35
110 103 96 89 82 75 68 61 54 47 40
Pre-utilization c) -3,000 m a.s.l
Steady pumping
140 131.5 123 114.5 106 97.5 89 80.5 72 63.5 55
145 136.5 128 119.5 111 102.5 94 85.5 77 68.5 60
0 7500 15000
[m]
N
W
E
S
FEFLOW (R)

Fig. 3.14

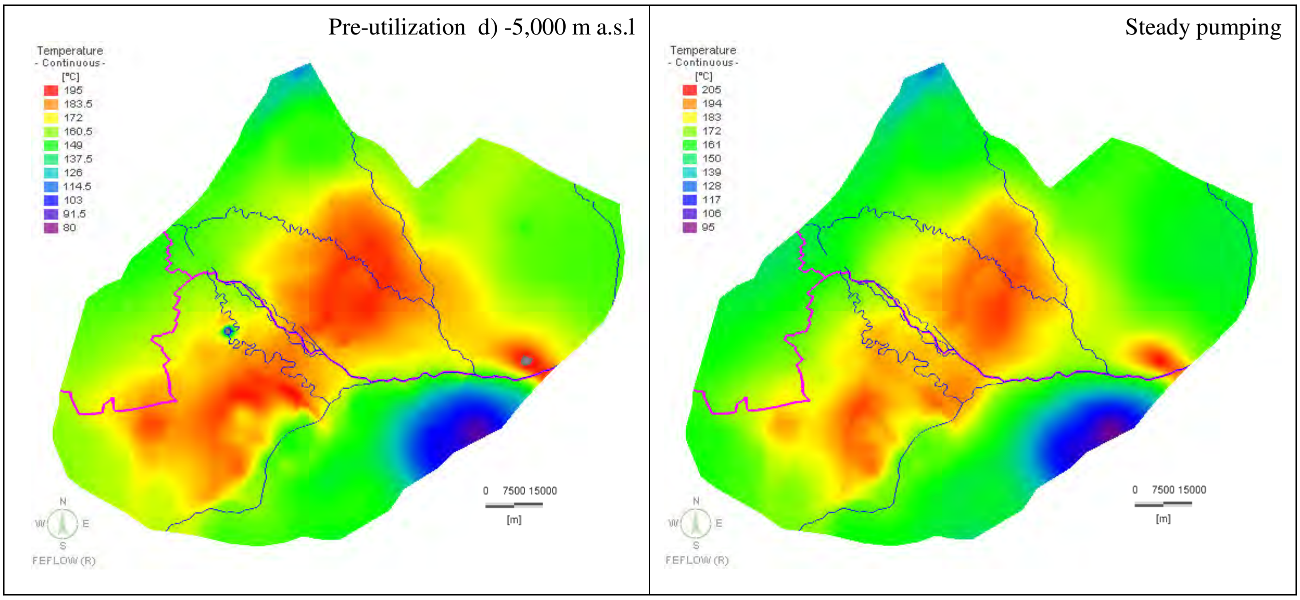

Fig. 3.14 Temperature distribution at different depth levels. Compared are both state scenarios: pre-utilization and steady pumping. Mind the different colour scales

transboundary flow is in Komárno-Štúrovo area in central east.

Here water that precipitated onto outcropping carbonates in Gerecse-Pilis Mts. percolates through partly karstified limestones and dolomites towards the Danube River, where it seeps into the river or is partly captured by several wells. The lateral extent of well capture zones may be underestimated to some unpredictable level, because model assumes homogeneous aquifers, while in reality these are built up of interchanging permeable and impermeable layers of different thicknesses. Pumped amounts are withdrawn predominantly from more permeable layers that represent only a portion of total thickness. This forces water to flow at higher velocities in horizontal direction then would be predicted in homogeneous, albeit anisotropic media.

Amounts of groundwater flowing across national boundaries were quantified by calculating flow budget for different model domains. Results are summarized in Figs. 3.17 and 3.18.

3.4.2.3. Energy balance

Geothermal modelling is a useful tool for calculating thermal energy associated with different parts of studied area. Separate calculations were made to evaluate thermal power (MWt) for all 3 involved countries (Fig. 3.19). In this chart the total energy balance of the whole model, partitioned between individual countries, is provided by visually comparing the thermal power of existing utilized wells, radiogenic heat inflow and deep heat inflow. Here the power of geothermal wells is calculated as energy released from pumped amount of water by cooling from reservoir temperature to the reference temperature 25 °C. Within the portion of the model at the Slovakian territory there are 33 wells, in Hungary 78 and in Austria only 1 well. The radiogenic heat inflow contributes to the total heat contained in the rock and pore water depending on the volume of rock, porosity and radiogenic heat production, see Tab. 3.1. The so-called “deep heat inflow” is the heat flux across the bottom boundary of the model, situated at the depth 10,000 m b.s.l., summed for the respective portion of the area of each country.

3.4.3. Geothermal utilization scenarios

The Danube Basin, occupied by Slovakia, Hungary and partly Austria is a true transboundary geothermal structure. Although no utilization conflicts exist yet on this large area, the current utilization magnitudes and forecasted growing demand for future geothermal installations and balneological sites may cause problems. Modelled groundwater temperatures and pressures may significantly drop due to excessive production, especially after long-term exploitation.

The steady state models allowed identifying sensitive areas within the large territory of this pilot area, where future monitoring of the main geothermal aquifer (Late Pannonian porous reservoir) should be established. Scenarios of additional direct use of thermal groundwater proved the necessity of reinjection.

The aim of the numerical modelling was to investigate impacts of additional geothermal installations on thermal and pressure conditions in the Late Pannonian porous aquifer, along with evaluation of geothermal resources that can be potentially harvested. The modelling comprises steady state 3D groundwater flow and heat transport simulations. Two scenarios are compared – extraction of geothermal energy by geothermal doublets and direct use of thermal groundwater by pumping.

A detailed study on bilateral cooperation (SK-HU) on geothermal energy exploitation was performed as well.

The scenario analysed common use of geothermal energy right at the state border by two geothermal doublets, organized in a tight 2 by 2 diagonal cluster. The main goal of this study, performed by transient coupled flow and heat simulations, was to test the proposed wells configuration and estimate operating life-time of the system by prediction of thermal breakthrough.

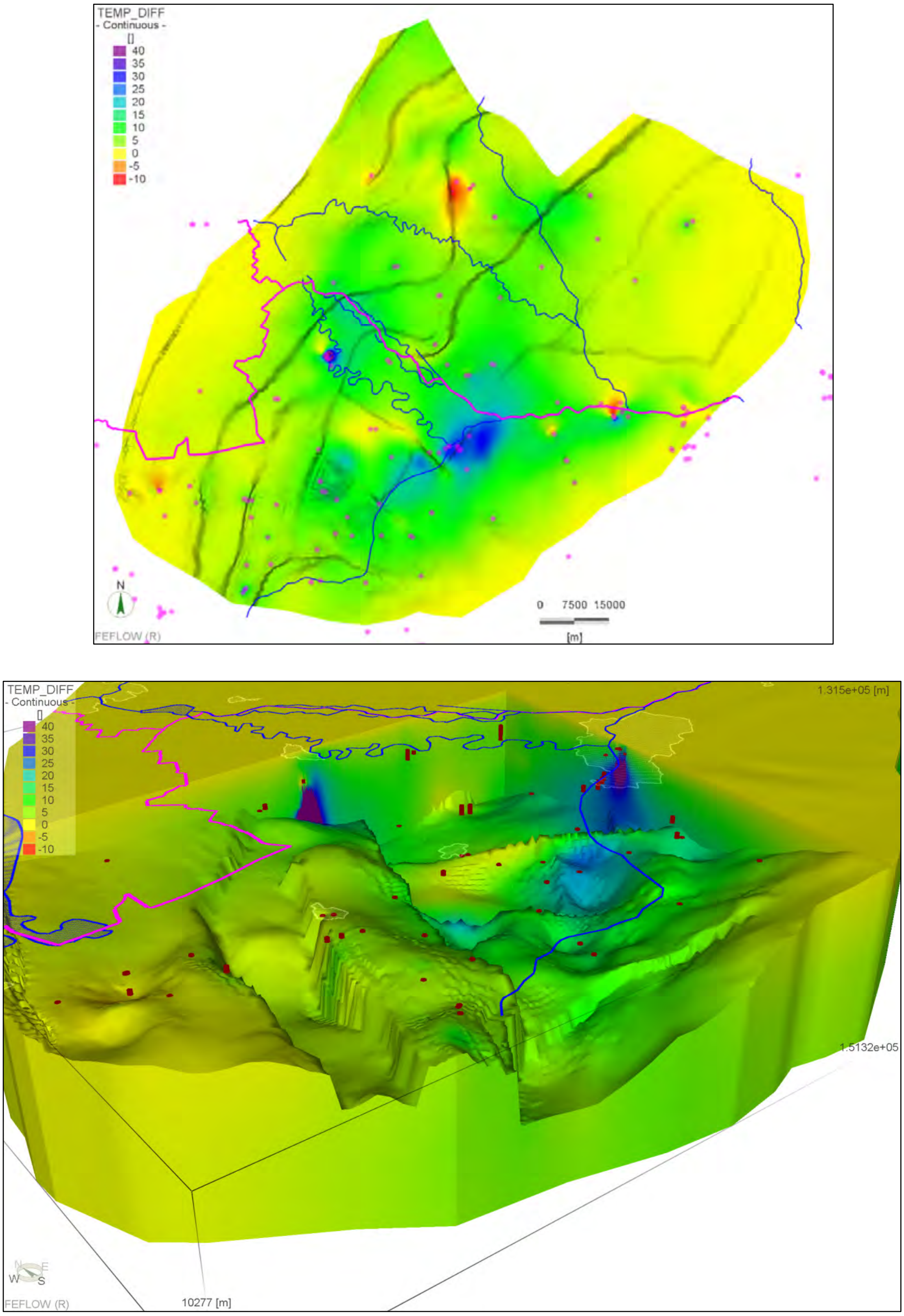

Fig. 3.15. Difference in temperature between the pre-utilization state and the steady pumping scenario. a) Basement of Late Pannonian; b) Example of temperature decrease around production wells in Hungary, partial cut out of sedimentary fillings. Wells locations are indicated by red cylinders

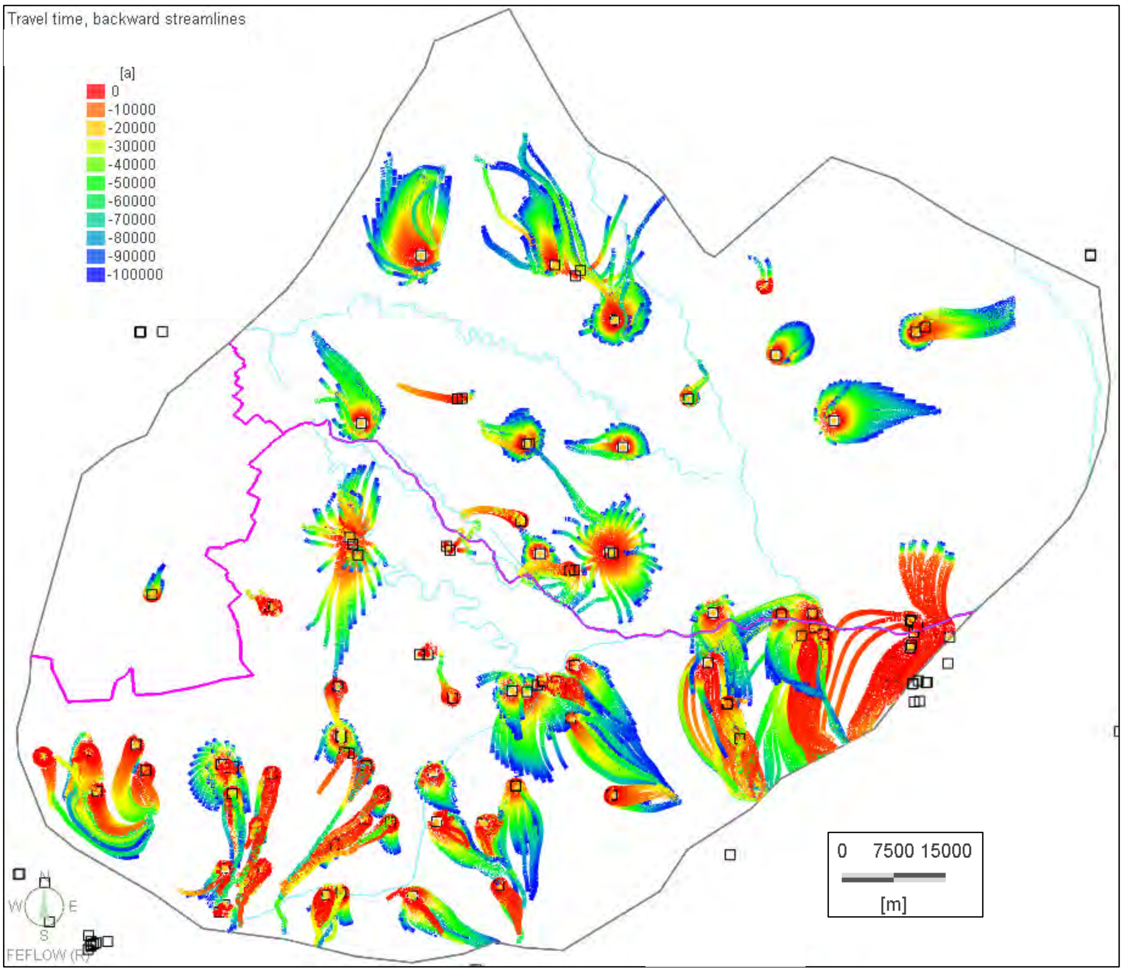

Fig. 3.16 Vertical projection of 3D flow paths towards thermal wells with travel time [years]

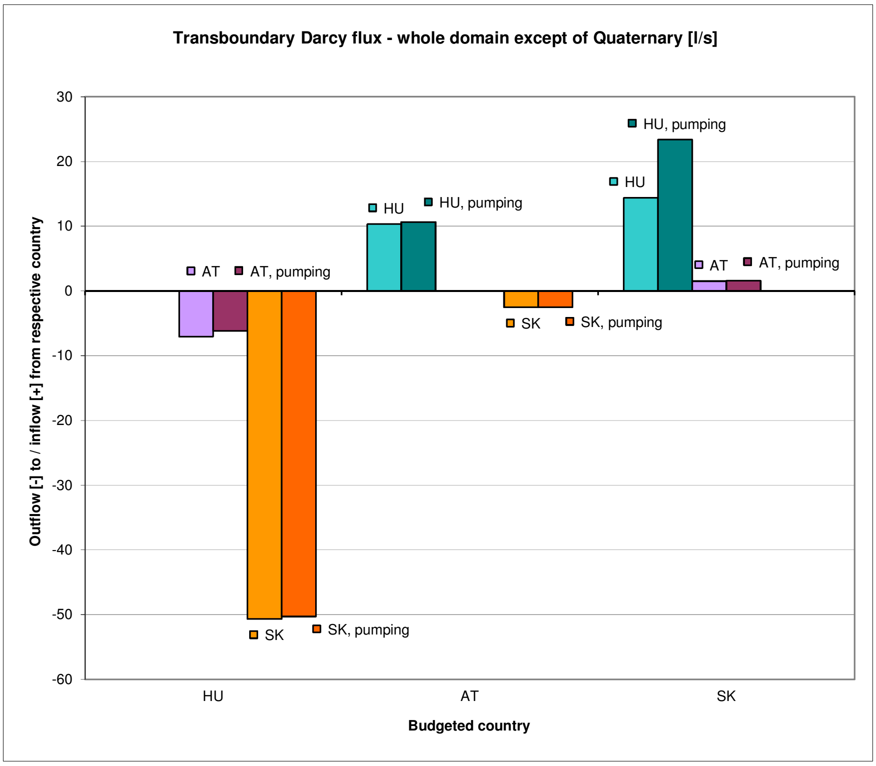

Fig. 3.17 Transboundary flow within Pre-Quaternary rock formations among Hungary, Slovakia and Austria quantified for two model scenarios

New hypothetical well installations were emplaced in the area of the Late Pannonian geothermal play, containing thermal water over 30 °C. In total 21 suggested geothermal doublets were inserted uniformly within this area away from existing geothermal installations. Pumping and re-injection wells were separated by a distance of 2 km. Due to limited permeability of the Late Pannonian sediments, pumping and re-injection rates were set to 20 $l.s^{-1}$ only, with temperature of re-injected water at 25 °C. For simplicity, the entire thickness of the Late Pannonian hydrostratigraphic unit (0–2,580 m) was supposed to be screened.

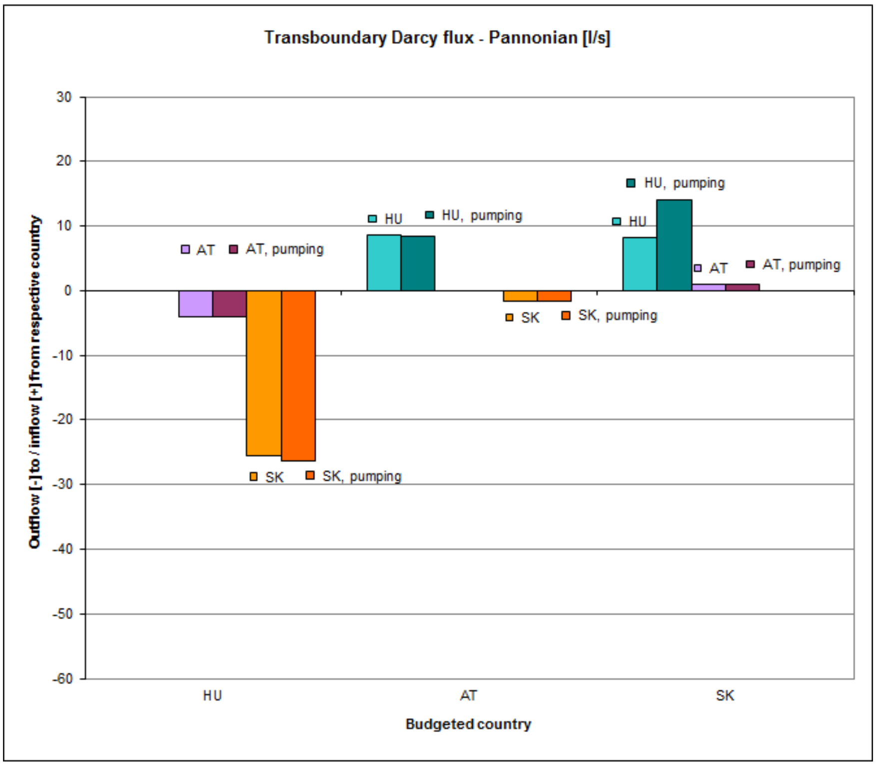

Fig. 3.18 Transboundary flow exclusively within Late Pannonian sediments among Hungary, Slovakia and Austria quantified for two model scenarios

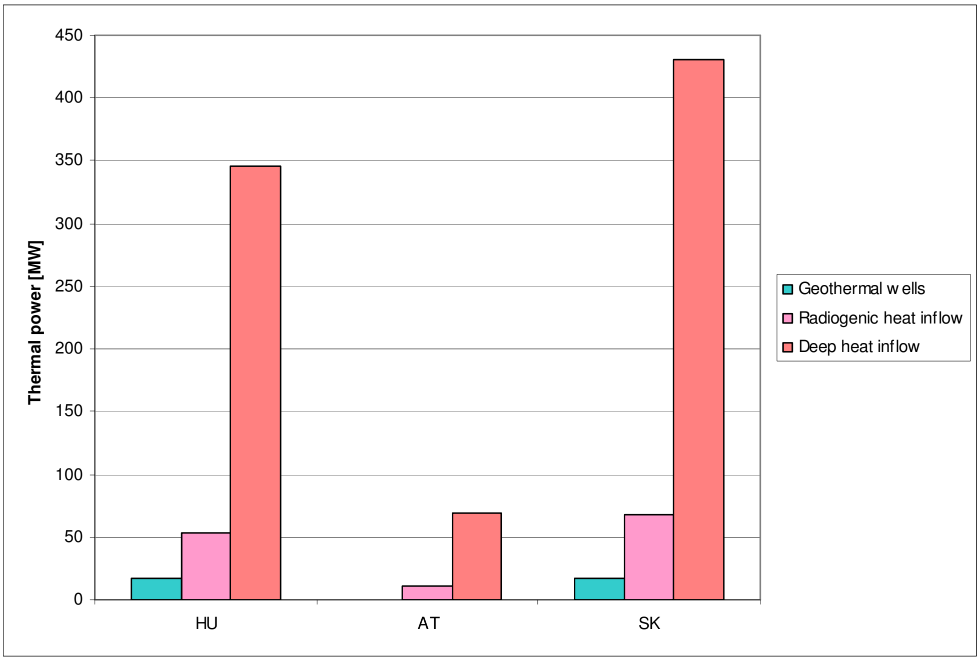

Fig. 3.19 Thermal power of wells, radiogenic heat generation and basal heat inflow in the whole model, divided among Hungary, Slovakia and Austria

3.4.2.4. Potential installations scenarios

The aim of the numerical modelling was to investigate impacts of additional geothermal installations on thermal and pressure conditions in the Late Pannonian geothermal aquifer of the Danube Basin, together with evaluation of geothermal resources that can be potentially harvested by the respective means. The modelling comprises steady state 3D groundwater flow and heat transport simulations, i.e. running for infinity and assuming recharge-open structures. Two scenarios are compared – extraction of geothermal energy by means of geothermal doublets and direct use of thermal groundwater by pumping. The results of the two scenarios are compared.

The area where new hypothetical well installations were emplaced is the area of the Late Pannonian geothermal aquifer, which extent was defined by recoverable heat in place (identified resources), with temperature of water over 30 °C (Fig. 3.20).

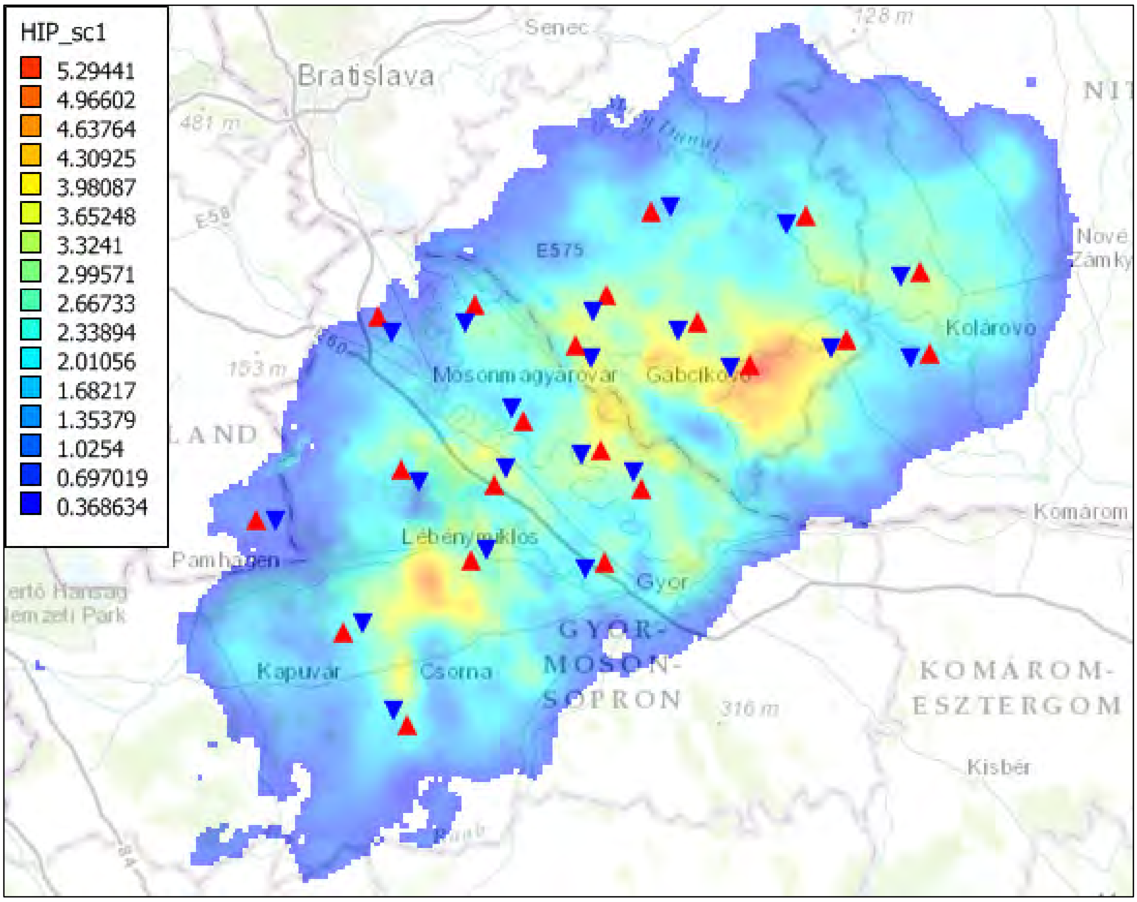

Fig. 3.20 Extent of the Late Pannonian geothermal play with hypothetical doublets (red triangles – suggested pumping wells; blue triangles – suggested reinjection boreholes). Colour indicates identified geothermal resources (MW)

Steady state simulation with additional 21 geothermal doublets revealed a significant effectiveness of the thermal energy harvesting (Fig. 3.21). It also showed that in some areas a potential for additional installations still remains.

Utilization of pumping wells without re-injection shows significant cooling of the area in broader vicinity of the wells (Fig. 3.22). Comparing to the doublet scenario, the temperature decrease is much more striking.

While temperature effects show generally similar pattern in both models, the two scenarios differ more significantly when it comes to hydraulics, especially groundwater pressure. As in the doublets scenario the extracted water is returned into the same aquifer and the negative pressure changes are compensated by the increasing groundwater head near the reinjection wells, these changes are limited only to the relatively close vicinity of the wells (Fig. 3.23).

This picture is radically different from the scenario without re-injection (Fig. 3.24), where pressure drop affects the entire aquifer, with magnitude increasing towards the basin centre. In large areas the groundwater head drops over more than 100 meters, which would significantly affect technical limits of pumping, not only at new wells, but also at existing ones.

By analysing the energetic balance of the models, the energetic impact of the two scenarios was also studied. In the scenario with re-injection, 55.46 MW of potential sustainable geothermal energy to be used was identified. For the scenario without reinjection, the calculated thermal power is higher, 82.32 MW, due to lower reference temperature, comparing to the return temperature of doublets: 30 °C. However the real energetic use would be much lower, since this number assumes extraction of all energy stored in the water by cooling it to the ambient temperature of 10 °C, which is only theoretical. At the same time a decrease of thermal power of existing geothermal wells of 3.64 MW was observed, which is due to the cooling of significant portions of the targeted aquifer.

Utilization of pumping wells without re-injection shows significant cooling of the area in broader vicinity of the wells (Fig. 3.22). Comparing to the doublet scenario, the temperature decrease is much more striking.

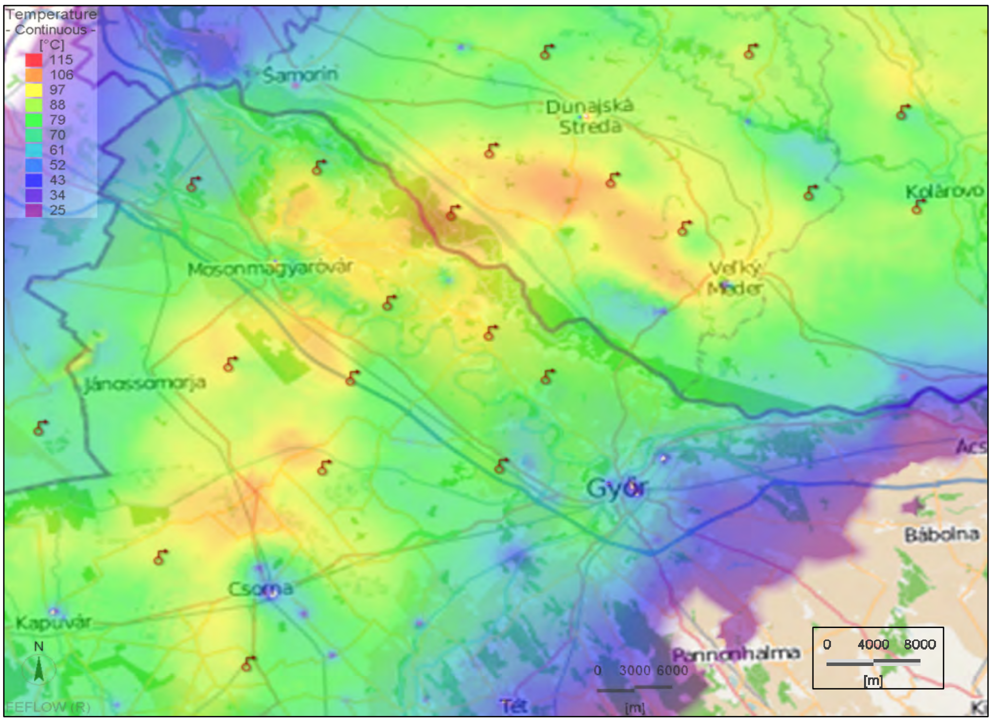

Fig. 3.21 Alteration of the thermal field (temperature changes: scale at top left) at the top of the Late Pannonian geothermal play caused by 21 hypothetical geothermal doublets (triangles: red - pumping, blue - reinjection wells). Purple squares are existing utilized geothermal wells

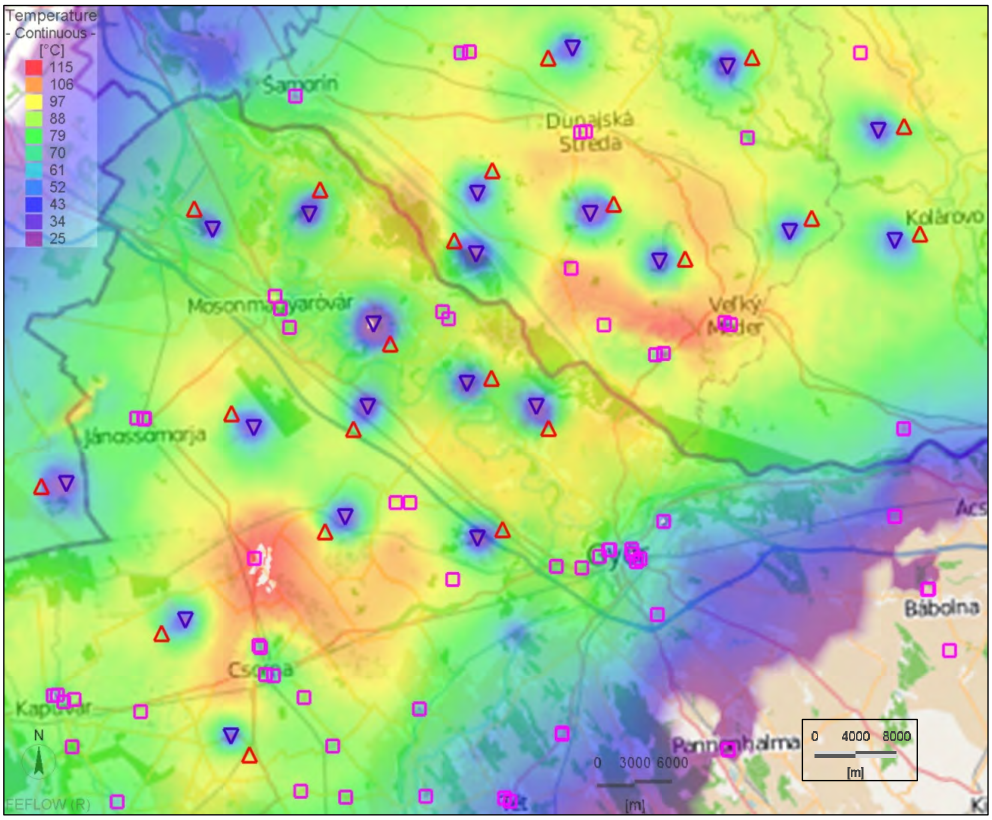

Fig. 3.22 Modification of the thermal field at the top of the Late Pannonian geothermal play caused by pumping wells (symbols)

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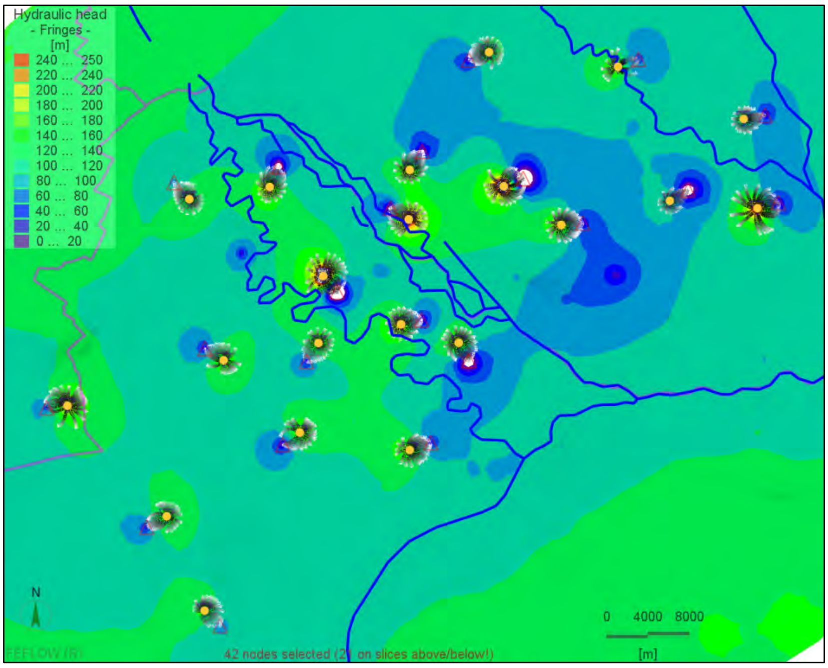


Fig. 3.23 Hydraulic heads field in the Late Pannonian geothermal aquifer, doublets scenario

3.4.4. Boundary doublet cluster scenarios

To investigate thermal and hydraulic response under 2 doublets utilization configuration in the Slovak – Hungary transboundary area a detailed model was set up. As a demonstration site for fissure – karst type aquifer in the Danube Basin pilot area the Mesozoic carbonates of the Komárno Marginal Block (sensu Slovak interpretation of the geothermal water bodies and geothermal structures) was chosen. The fissure – karst type permeability is suitable for reinjection of the energetically used water as proven by practical experience. The configuration of two doublets can be seen on Fig. 3.25.

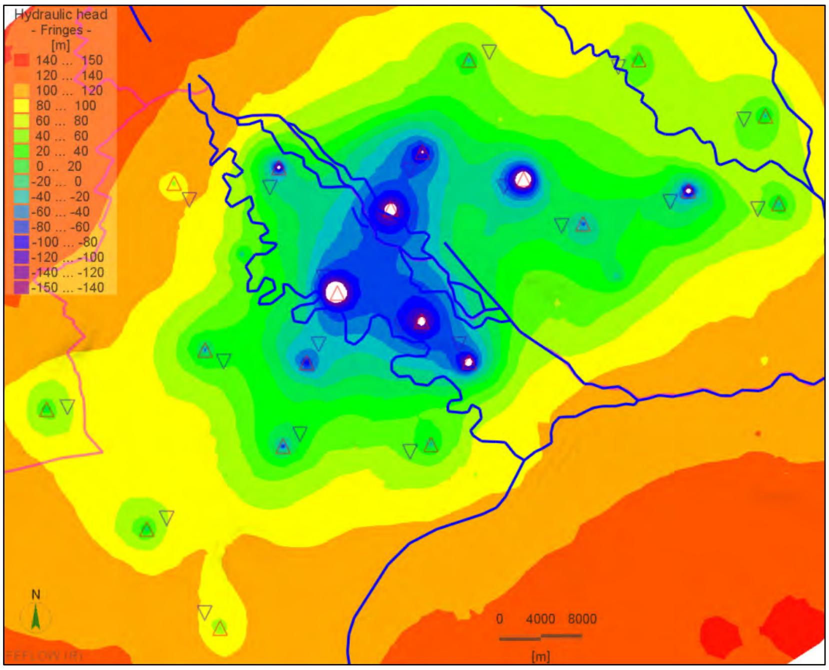


Fig. 3.24 Hydraulic heads field in the Late Pannonian geothermal aquifer, production/ pumping wells scenario

The evaluated hydrogeological structure (Komárno Marginal Block basement reservoir) is closed, and there is no water transfer from the surrounding structures. For modelling purposes a relatively small area of approximately 5x5 km has been chosen (Fig. 3.25.). The extent was determined by the impact of the doublets. For production two wells were designed to pump the geothermal water and two for its subsequent re-injection at a temperature of 15 °C. These two doublets are designed in the transboundary area of Slovakia and Hungary in a way that in each country there is one separate system. In the geothermal model, water is pumped from defined two wells and upon its use and cooling to 15 °C is injected back into the geothermal structure. The following text describes the model definition, its setting and evaluates the impact of the geothermal water use at different scenarios. For the modelling of flow and heat transport simulation program FEFLOW version 6.0 was used.

3.4.4.1. Model geometry

In horizontal direction the model domain was discretized into two-dimensional mesh of triangular elements (Fig. 3.26). This mesh was adjusted by linear gradation of nodes in places of suggested wells. The fining of mesh towards wells assures better conversion of simulations.

The basic layout of the model in vertical direction is shown in Fig. 3.27. In vertical direction the model is composed of four layers representing four main geological formations. The first stratum from the surface is formed by the Quaternary sediments, where fresh water table exists. The second layer consists of a sequence of the Tertiary sediments, overall acting as a hydrogeological isolator. Underneath are the Mesozoic rocks (limestones and dolomites), which form the principal geothermal aquifer, lying atop the crystalline basement, representing a hydrogeological isolator. The geometry of individual layers was adopted from the faulted geological model of the Danube Basin (Baráth, Fordinál, Kronome, Maglay & Nagy in Maros et al., 2012) and is visualized in Fig. 3.27.

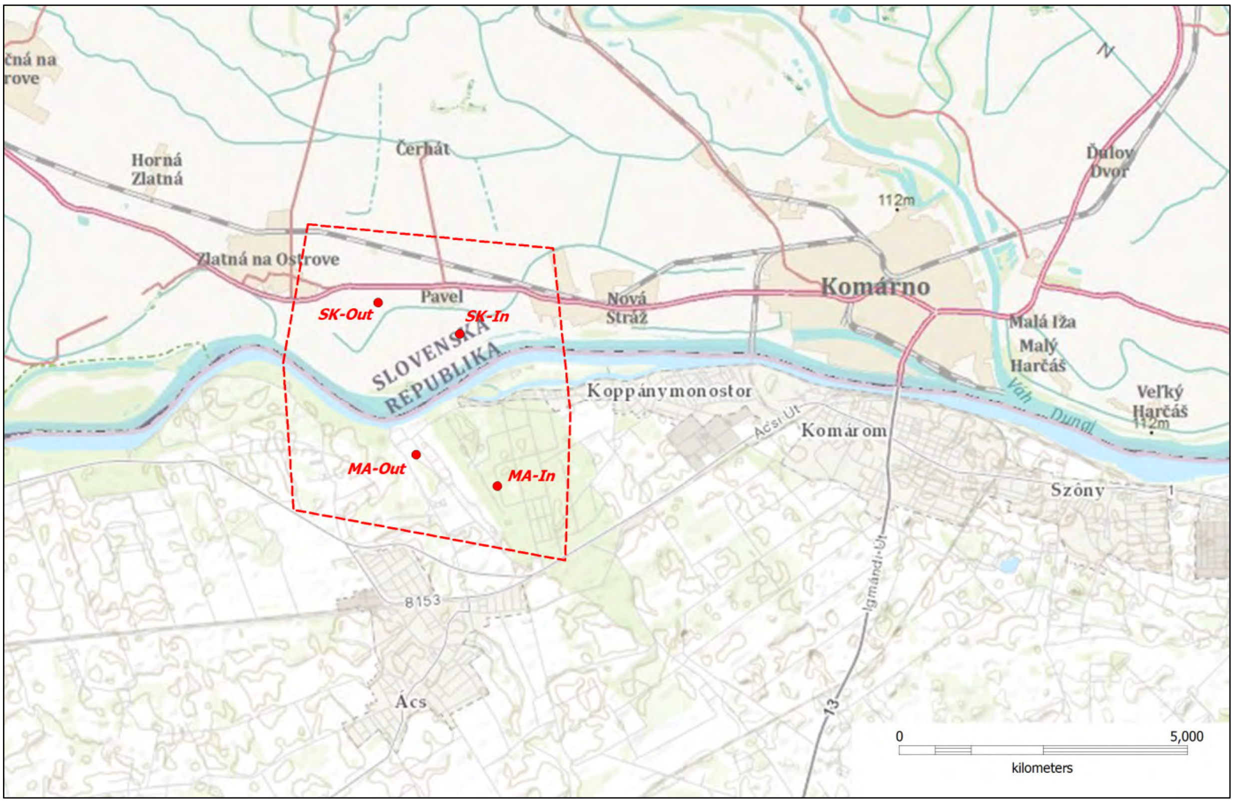


Fig. 3.25 Model area and design of the doublet cluster

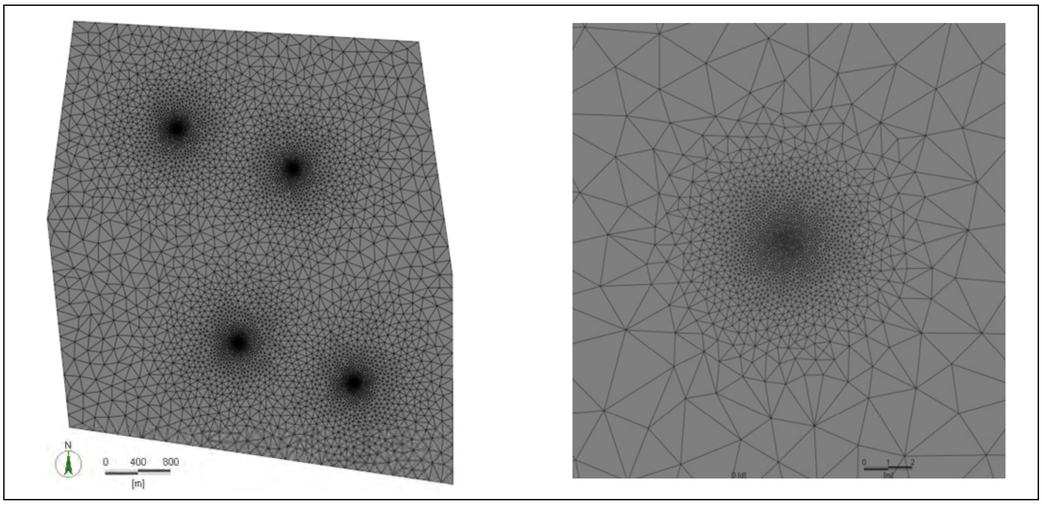


Fig. 3.26 Horizontal definition of the computing mesh (A – general overview of the model; B – detail of nodes refinement around wells)

Overall, it is obvious that layers are inclined in the SE-NW direction. Because no deep drilling exploration was performed in the close vicinity of the evaluated area, the thickness of the Mesozoic carbonates formation may not be exactly designated. It was estimated to be 300 m by expert judgement. This uniform thickness was assigned across the whole model. The lowermost layer was extended to a depth of 10 km b.s.l.

This division formed the basis of vertical network definition of the model. For the sake of better conversion and accuracy of results, these layers were further divided into several sub-layers with the same parameters. This led to final number of 11 layers delineated.

3.4.4.2. Material properties

Properties of rocks are the determining parameter of groundwater flow and heat transport. These properties are schematically shown in Figs. 3.28 and 3.29.

For groundwater flow the conductivity is a decisive parameter, which tensor is assigned to all materials individually along X, Y and Z directions. An example of this setup is in Fig. 3.28 and values for individual layers displays Tab. 3.2.

Setting of individual values was based on multiple sources and studies. In the first three formations (Quaternary and Tertiary sediments, Mesozoic rocks) they are based on previous surveys and research in the studied locality or in the surrounding area. In the case of Pre-Mesozoic rocks, the value was set so that the environment met the condition of hydrogeological isolator.

Tab. 3.2 Hydraulic parameters of rocks

Layer	Conductivity ($m.s^{-1}$)		
	X	Y	Z
Quaternary sediments	$1.05*10^{-4}$	$1.05*10^{-4}$	$1.05*10^{-5}$
Tertiary sediments	$4.00*10^{-6}$	$4.00*10^{-6}$	$4.00*10^{-9}$
Mesozoic rocks	$4.00*10^{-7}$	$4.00*10^{-7}$	$4.00*10^{-6}$
Crystalline rocks	$1.055*10^{-9}$	$1.055*10^{-9}$	$1.055*10^{-10}$

Similarly there were defined the parameters relevant for the transport of heat. These values are shown in Fig. 3.29 and in Tab. 3.3. In this case, values were also based on previous studies and on the results of the steady flow/steady heat transport model calibration.

The values of porosity in the direction from the surface gradually decrease from values 0.275 to 0.003. Like the porosity, values of the volumetric heat capacity of solid also decrease. Overall, the values range from $3.42*10^6$ to $2.4*10^6$ $Jm^{-3}K^{-1}$. The opposite character of values has the parameter of thermal conductivity of solid, which ranges from 1.0 in the Quaternary sediments to 3.0 $Jm^{-1}s^{-1}K^{-1}$ in the crystalline rocks.

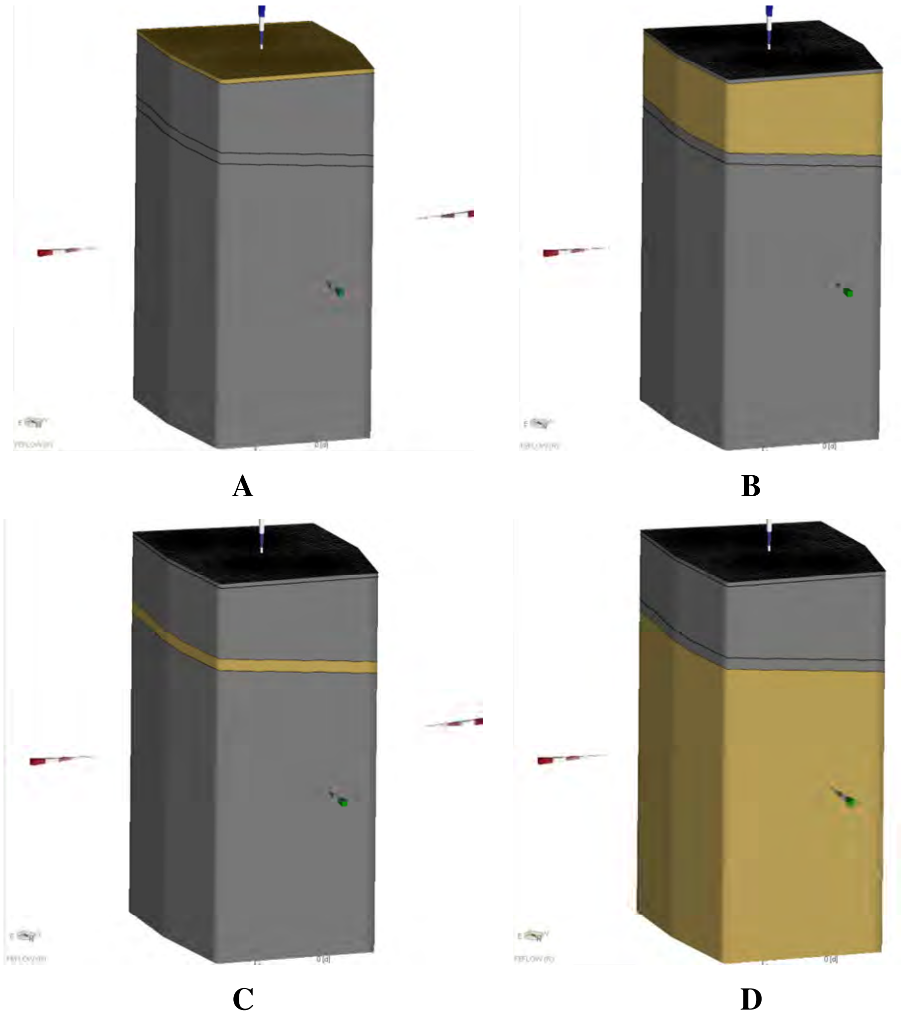


Fig. 3.27 Vertical stratification of the model (A – Quaternary sediments; B – Tertiary sediments; C – limestones and dolomites – geothermal aquifer; D – Crystalline – impermeable bedrock)

3.4.4.3. Boundary conditions

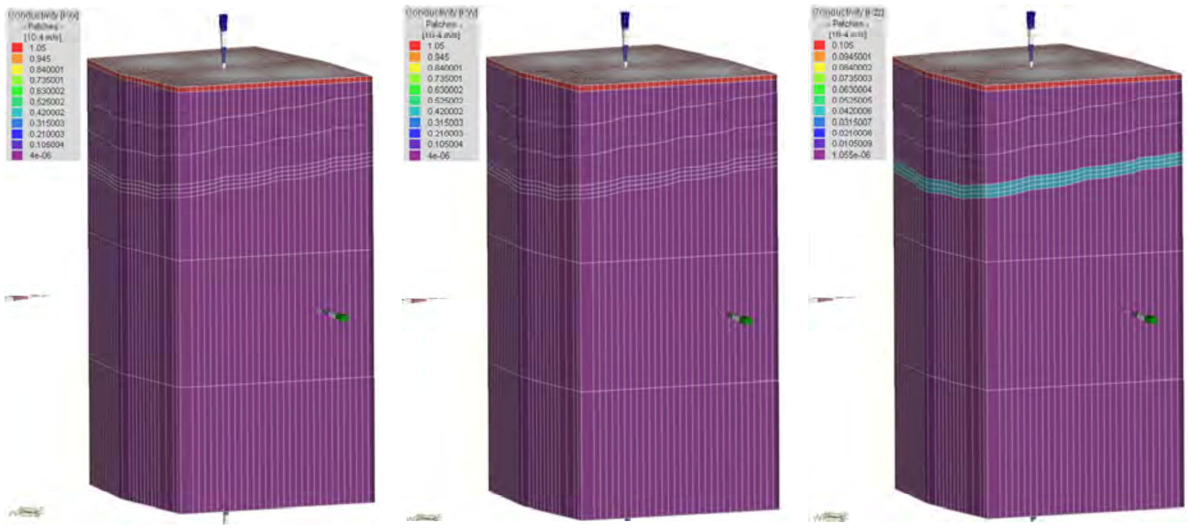
Boundary conditions determine the processes occurring at the edges of a model, and as such are crucial for any flow and heat transport simulations. For the steady-state modelling of the groundwater flow a static groundwater level was set in the top layer - the fresh water (Quaternary) aquifer. Absolute values of hydraulic potential in the first aquifer were imported from the results of accomplished regional modelling.

Boundary conditions for heat transport were set in a similar manner. Their distribution is shown in Fig. 3.29.

On the surface of the model a constant temperature boundary condition was set out, which is based on the long-term mean annual air temperature, which for the modelled area reaches 10 °C. At the bottom of the model at a depth of -10 km below the surface a constant heat-flux type boundary condition was set out. Heat flux values have been imported from the supraregional conductive thermal model of Lenkey et al. (2012). On average, this parameter reaches values around 0,06 Wm^{-2}.

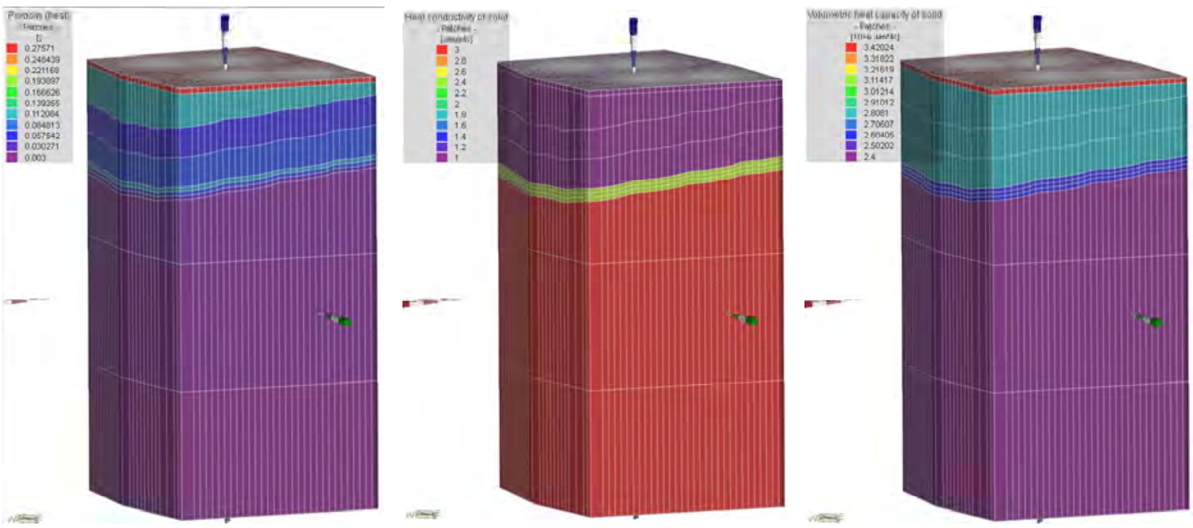
3.4.4.4. Steady flow and heat transport simulation

For the purpose of transient flow and heat transport modelling it is necessary to have defined initial pressure and water temperature conditions. To determine these spatial properties, a steady flow/steady heat transport model was created first. The purpose of this simulation was to determine the long-term steady temperature–pressure conditions in the geothermal structure, which shall initially define the conditions prior to the modelling the use of geothermal water. In this step the individual material properties were calibrated according to measured values of water temperature in existing geothermal wells.



A B C

Fig. 3.28 Values of conductivity in X (A), Y (B) and Z (C) direction



A B C

Fig. 3.29 Parameters for heat transport (A – Porosity; B – Volumetric heat capacity of solid; C – Heat conductivity of solid)

3.4.4.5. Transient heat modelling

The calibrated steady state model serves as a starting point of transient simulations. For this purpose, the model boundary conditions were modified by adding two pumping and two re-injection wells with constant flow rates assigned. These quantities are being varied during different model runs and the impact of using geothermal water was analysed. The whole thickness of the carbonate aquifer (300 m) was screened, i.e. from top depths between 1,890-2,170 m to bottom depths between 2,180-2,480 m b.s.l. The temperature of the re-injected water was set constant in all cases. We assumed that the technology allows pumped water to cool down to 15 °C. The transport

Tab. 3.3 Material parameters of rocks for heat transport modelling

Layer	Porosity	Volumetric heat capacity of solid ($J.m^{-3}.K^{-1}$)	Heat conductivity of solid ($J.m^{-1}.s^{-1}.K^{-1}$)
Quaternary sediments	0.275	$3.42*10^6$	1.0
Tertiary sediments	0.05 – 0.11	$2.80*10^6$	1.0
Mesozoic rocks	0.1 – 0.03	$2.60*10^6$	2.5
Crystalline rocks	0.01 – 0.003	$2.4*10^6$	3.0

of cooled water in geothermal collector in the direction from the injection wells to pumping wells was observed.

The results of this simulation are shown in Fig. 3.30. The visualization shows streamlines in the Slovak part of the geothermal water use system, while pathlines from wells on Hungarian side are not displayed. It displays the range of flow pathlines in direction from injection well to pumping well after 35 years, what is the expected lifetime of system for geothermal water use. It is obvious that during the system lifetime the cooled water does not reach the pumping system.

Cross-sectional view of the cooled water injection impact is shown in Fig. 3.31. Individual images show the effect of cooled water injection into the geothermal structure at time steps 0, 20,000, 60,000, 100,000 and 200,000 days of continuous pumping and injection of 50 $l.s^{-1}$ water from individual wells. In this picture the progress of cooled water transport between wells can be seen.

Similarly, this progress shows Fig. 3.32, which displays the water temperature changes at the base of carbonate collector. From this visualization is evident that the same character of heat transport is also within the Hungarian part of the geothermal system.

Figure 3.34 shows results of heat transport modelling at different rates of pumped and injected water after 35 years.

The results of these simulations prove that while using the projected system the cooled and re-injected water does not arrive into pumping wells. This result is identical for all simulated rates of pumped and re-injected water. From Fig. 3.35, it is clear that the re-injected water only begins to influence the temperature in pumping wells after not less than 100 years of continuous use. This result demonstrates that the evaluated structure is theoretically suitable for utilization of heat by means of thermal water re-injection.

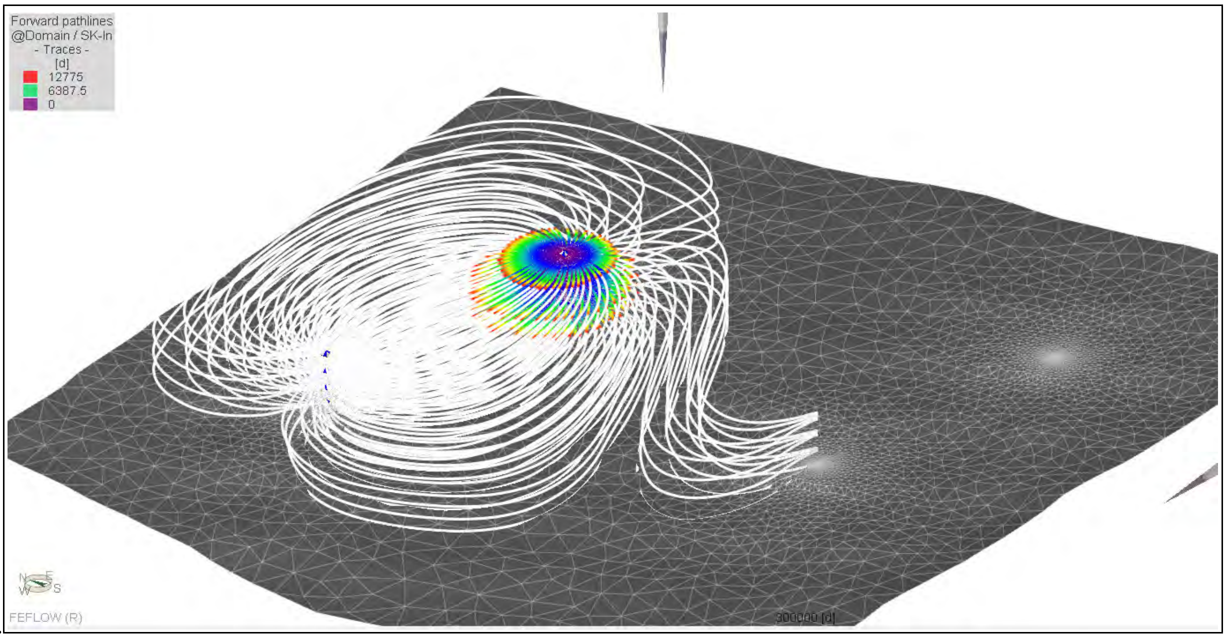


Fig. 3.30 Visualization of flow pathlines; white lines – long-term pathlines of water from Slovak-side injection well to pumping well; colour – travel time along pathline [days] 35 years after the operation start

3.4.4.6. Long-term impacts evaluation

Lastly, a thermal recovery of the structure was investigated, meaning that the time needed to return groundwater and rock matrix temperatures back to its pre-utilization state was questioned. To find the answer, a model was set up, in which starting water temperature and pressure conditions were the result of previous 35-years long utilization of a doublet system with the pumping/re-injecting rate of 35 $l.s^{-1}$. After 35 years the wells are

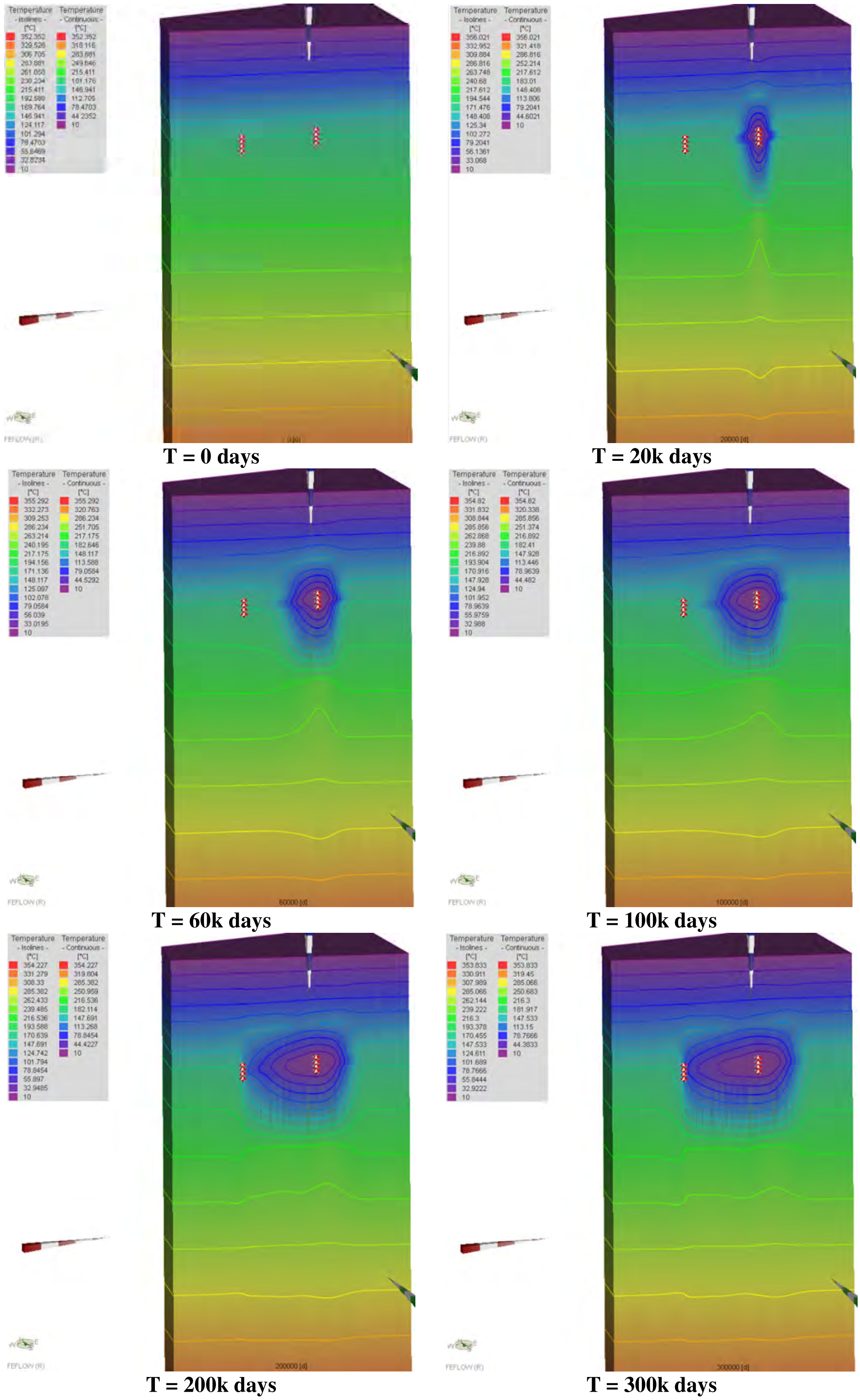


Fig. 3.31 Visualization of the water heat transport within the Slovak part of the system at pumping and injecting 50 l.s^{-1} of water in a doublet (production well left, injection well right)

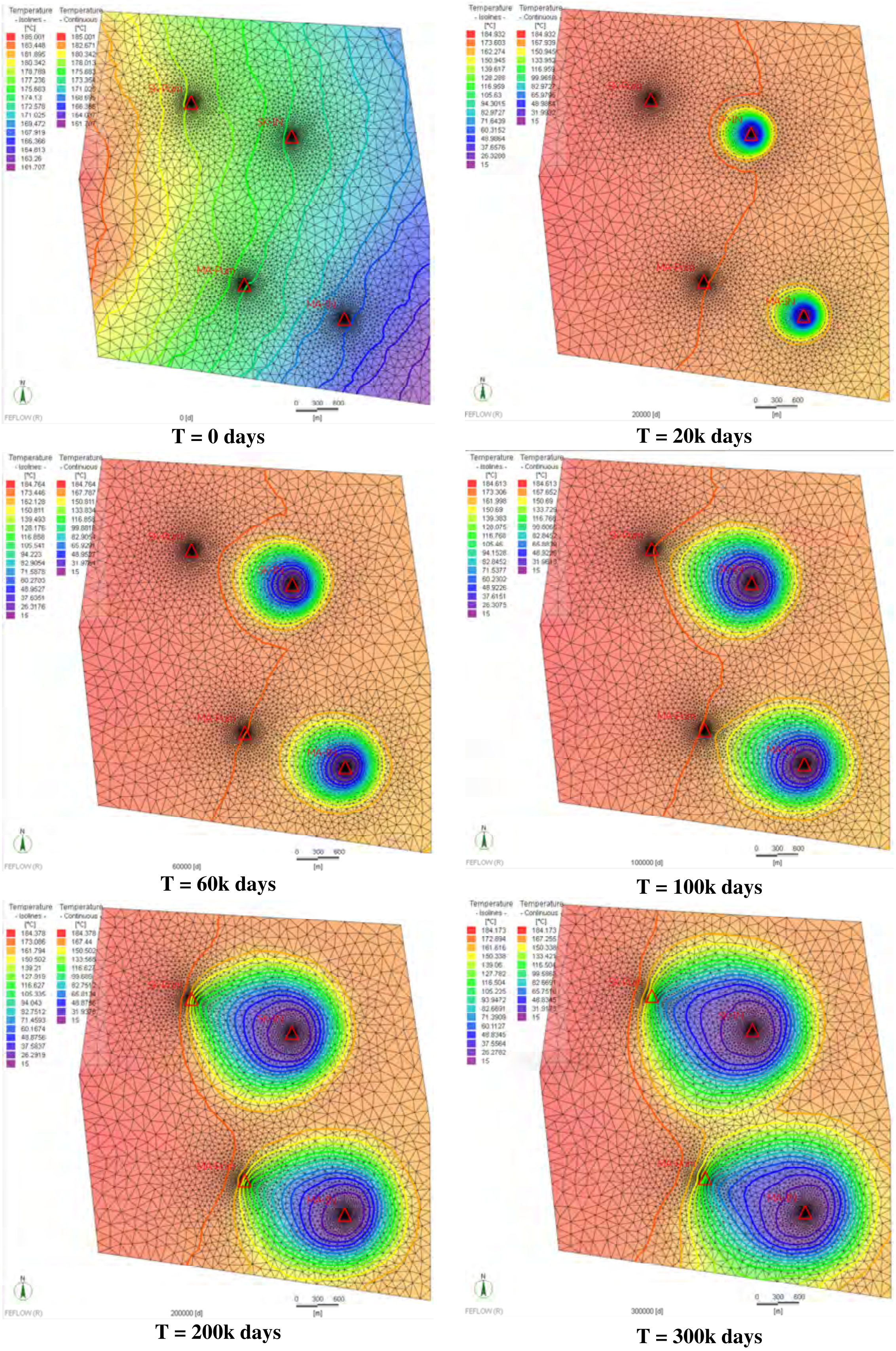
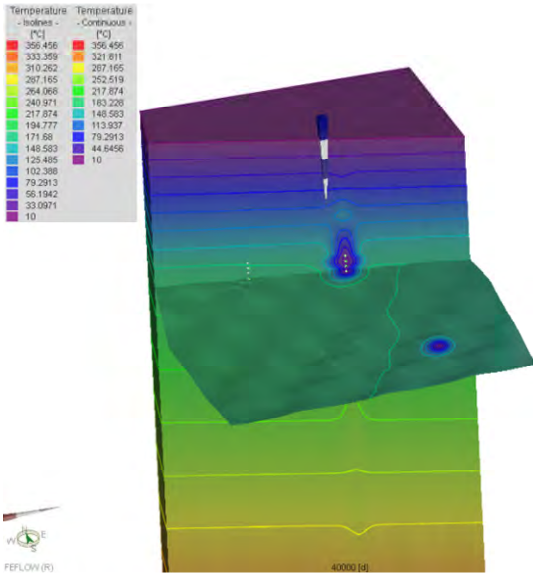
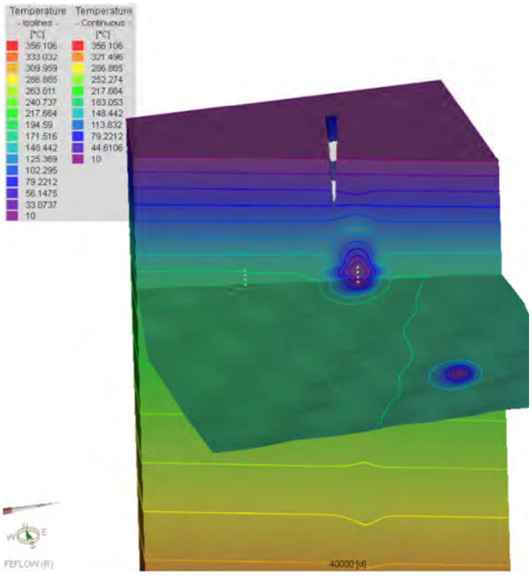


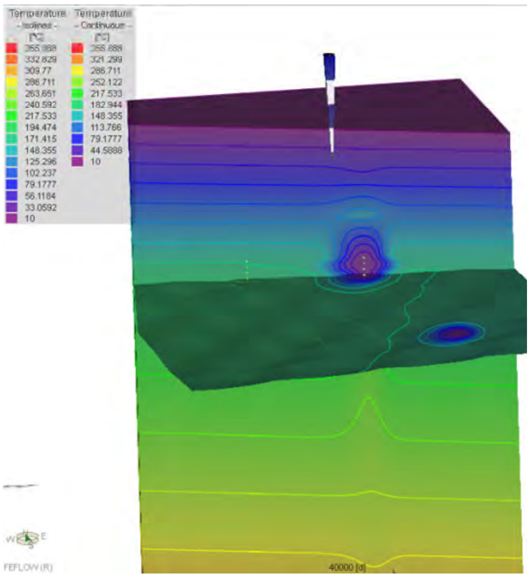
Fig. 3.32 Visualization of the thermal field development on the base of carbonate aquifer during pumping and injecting 50 $l.s^{-1}$ of water



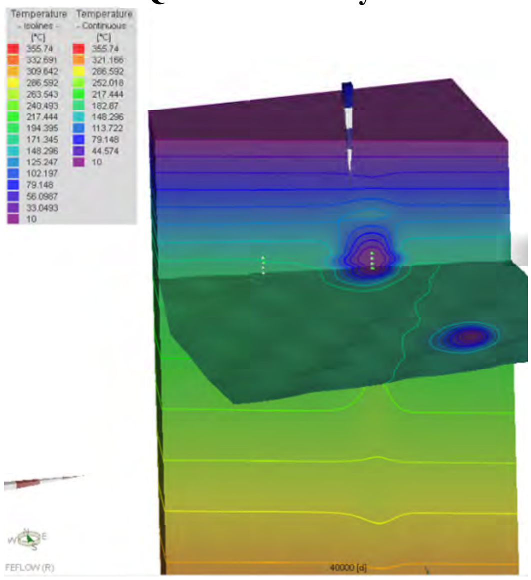
Q = 10 l/s / 40k days



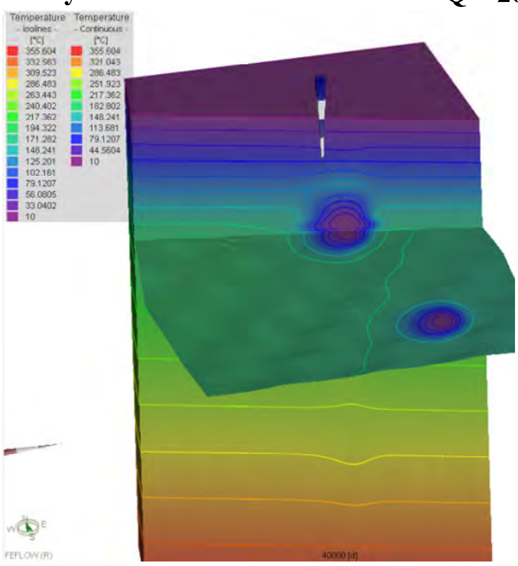
Q = 20 l/s / 40k days



Q = 30 l/s / 40k days



Q = 20 l/s / 40k days



Q = 50 l/s / 40k days

Fig. 3.33 Water cooling impact in geothermal aquifer at different levels of geothermal system utilization

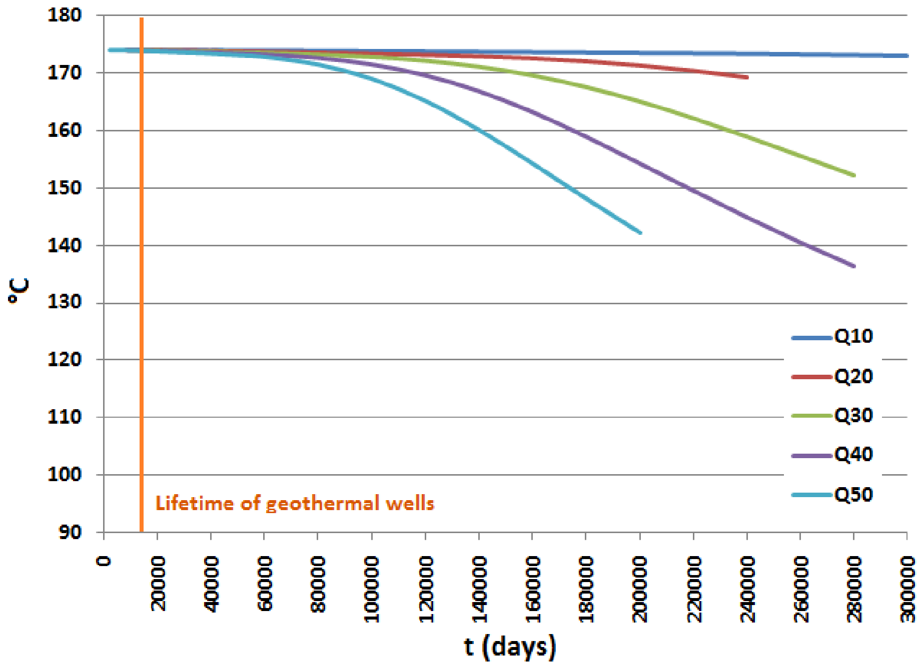


Fig. 3.34 The course of changes in water temperature in the pumping (production) well from the long-term point of view at different rates of pumped/injected water (Q, from 10 to 50 $l.s^{-1}$)

switched off and the thermal field of the structure begins to rebound. Because the carbonate structure is hydrodynamically closed (sealed), there is no direct water influx across the border and the only process that affects the water temperature is diffusion and heat conduction. The results of the simulation, depicted in the schematic Fig. 3.35, show that restoring of the disturbed thermal field can take as long as 2,500 years.

3.5. Conclusions

The aim of the numerical modelling was to simulate the hydrogeological and geothermal conditions in the geothermal aquifer of the Danube Basin. For the purpose of modelling a finite element model FEFLOW (Diersch, 2006) was chosen as the most appropriate. The vertical extent of the model is down to -10,000 m a.s.l. Due to expected elevated hydraulic and thermal gradients around fault zones, rivers and wells, the computing mesh needed to be locally refined around these features. The vertical resolution was based on geological model of the Danube Basin consisting of 8 hydrostratigraphic units that were divided into 11 modelling layers. The coupled hydraulic and geothermal modelling of the Danube Basin pilot area was focused on Late Pannonian geothermal aquifers. The constructed models show simulations of natural hydrogeological and geothermal conditions, expected to have existed before utilization of thermal waters by artificial pumping started. This scenario is compared to hypothetical conditions of continuous pumping of geothermal water, based on reported data form years 2007-2010, helping to identify possible tensions in sustainable thermal water use in the area.

Constructed regional model is simplified numerical representation of hydrological and geothermal characteristics of the pilot area and enables simulation of basic features of the geothermal system. The simulations were performed as steady flow and steady heat transport, practically meaning that results show a hypothetical situation in infinite future, if current amounts of water would be extracted. Simulation of theoretical infinite pumping of all existing operating geothermal wells was performed to predict future evolution of pressure and thermal field in the area and to help identifying potential adverse impacts of extensive and unsustainable thermal water over-exploitation.

In Pre-Quaternary rock formations conduction is the main mechanism for heat transport. Due to relatively intensive water interchange among recharge and discharge zones in the Quaternary sediments, forced convection is of high importance.

The hydraulic and geothermal models presented show significant amounts of water and energy moving either naturally or by forced convection from country to country across the border. This promotes international cooperation in managing geothermal resources.

Geothermal modelling is a useful tool for calculating thermal energy associated with different parts of studied area. Separate calculations were made to evaluate thermal power for all 3 involved countries.

Two regional steady-state model scenarios revealed new geothermal energy sources in the Danube Basin regions, reaching up to about 55 MW of thermal power. However, the impacts of additional pumping on existing installations as well as on global pressure field puts questions on future direct use of thermal water in the region, favouring re-injection.

The results of a detailed transient geothermal modelling of a doublet cluster can be summarized into next points:

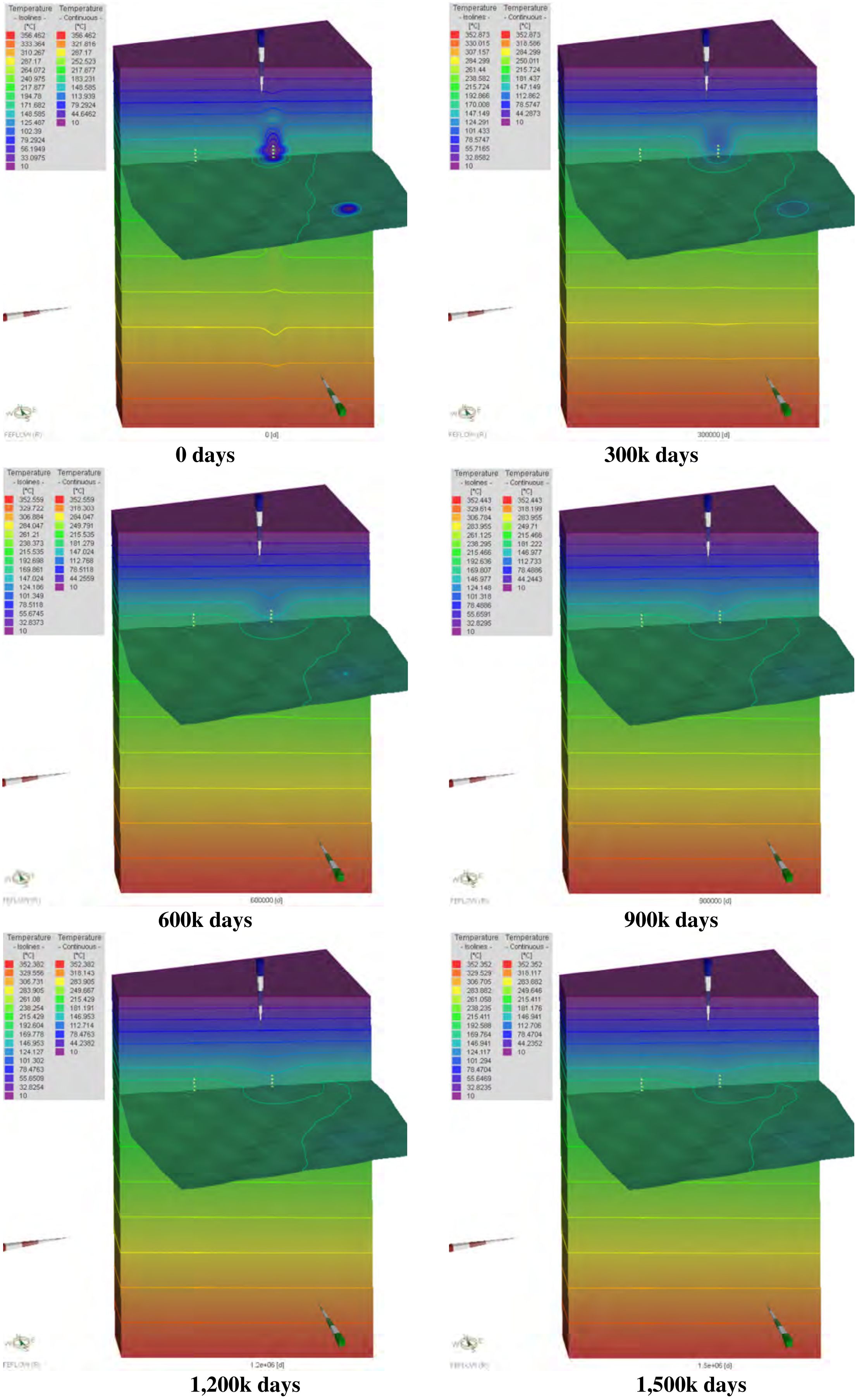


Fig. 3.35 Simulation of thermal recovery of an isolated geothermal aquifer after 35-years of a doublet utilization

• Modelled closed hydrogeological structure made of the Mesozoic carbonates is suitable for use by re-injection.

• It was found that re-injected cooled water within a period of system lifetime (35 years) does not affect pumping wells, what has a positive effect on the system performance and payback.

• Provided the input values of hydraulic and thermal properties of modelled environment are sufficiently accurate, it is possible to re-inject quantity of water in the range of 10 to 50 $l.s^{-1}$ without affecting the lifetime of the system.

• Parallel coexistence of two re-injection systems does not interact with each other.

• After system closure, restitution of thermal field back to the original state can take a very long time, but this effect has relatively small spatial extent.

Acknowledgements

The authors are thankful and acknowledge Prof. Em. Dr. Dr.h.c. Ladislaus Rybach who provided an invaluable feedback by thoroughly reviewing an earlier manuscript of this article. His competent suggestions and comments substantially improved the article, and any short-comings are solely the responsibility of the authors and should not tarnish the reputation of this esteemed person.

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4. Geothermal Water Utilization in Slovakia

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Abstract. In Slovakia, the use of geothermal water is bound to the aquifers of Mesozoic, Paleogene and Neogene age. These aquifers are located in the depths of 200 – 5,000 m. The geothermal water temperature reaches the values in the range of 15-240 °C. In the period 2000-2010 the geothermal water was utilized from 46 geothermal wells at 36 sites and from 13 geothermal waters bodies. Reinjection is implemented at one location (Podhájska). The average yield of the 46 exploited wells represents 6,323,167 $m^3.year^{-1}$ (236.65 $l.s^{-1}$). For all of these wells the relevant state water authorities have issued permits for the abstraction of geothermal water, in total amount 17,476,731 $m^3.year^{-1}$ (721 $l.s^{-1}$). Thermal energy potential of geothermal waters within individual units ranges from 1.1 MW_t to 1,316 MW_t. Summary calculated amount of geothermal energy from the geothermal water bodies defined in Slovakia equals to 6,234 MW_t. These values were calculated by geothermal balance method, volumetric method and mathematical modelling. Identified amount of geothermal energy (348 MW_t) in percentage terms compared to summary calculated amount of geothermal energy in Slovakia represents only 5.58 %. The exploited amount of geothermal water has been largely used for recreational purposes and heating of buildings, to a lesser extent for heating of greenhouses and mining air and fish farming.

Key words: geothermal energy, geothermal water abstraction, production potential, porous aquifers, karst-fissure aquifers

4.1. Introduction

The use of geothermal waters in Slovakia is historically associated primarily with the implementation of the spa facilities. Written records of the realization of these objects are known from the late 14th and early 15th century from the area of Turčianske Teplice, Dudince, Piešťany and Rajecké Teplice (Mulík, 1981). The utilization of geothermal water as a source of energy was launched in Slovakia in the second half of the 50s of the previous century. At that time in the spa premises the use of geothermal water was tested for heating buildings in the Spas Piešťany, Kováčová, Sklené Teplice. Trial tests of heat pumps operation in Piešťany, Turčianske Teplice were performed along with the use of heat exchangers and heating of buildings in Piešťany, Turčianske Teplice and Kováčová (Uhliarik, 1977).

Based on the results of research and geological exploration works carried out in the 70s and 80s of the last century, Geological Institute of Dionýz Štúr has earmarked 26 prospective geothermal areas (Franko et al., 1995). In 2007 the 27th geothermal area was allocated - Lučenec Basin (Dzúrik et al., 2007; Vass & Dzúrik, 2007).

After completion of geological works the existing wells gradually began to be used for recreational purposes, heating of greenhouses, unless the physico-chemical characteristics of geothermal water were suitable for the above purposes.

Development of the comprehensive database of geothermal wells, including their utilization was carried out in years 2007 to 2010 under the project „Evaluation of the Geothermal Water Bodies" performed by SGIDŠ. Data used in this evaluation were obtained from users of geothermal water or from Slovak Hydrometeorological Institute (SHMI). Other source of the data about the geothermal water utilization was coming from international project TRANSENERGY (Transboundary Geothermal Energy Resources of Slovenia, Austria, Hungary and Slovakia) described in the article Černák et al. of this issue. The data from TRANSENERGY project were obtained from field inspections and were compared with reported data to SHMI. In terms of Slovak division of geothermal areas this re-evaluation was done in Central Depression of Danube Basin, Levice Block and Komarno high Block.

From 2007 till 2010, the evaluation of geothermal water bodies Slovakia aimed on gradual building up a comprehensive database of geothermal water wells, including their use. In the framework of a geological project assessment of geothermal water bodies was implemented being consistent with the "Concept of geological research and exploration of the Slovak Republic for the years 2002 - 2006 with a prospect to 2010", which in 2002 was approved by the Government Resolution no. 334. This task also resulted from the current Act no. 364/2004, § 3, 4, 6 - processing of registration and evaluation of geothermal waters, as component of the groundwater in Slovakia and Government Resolution no. 46/2004 on the strategy for the implementation of the Water Framework Directive in Slovakia, where the government instructed the Ministers of the Environment, Agriculture, Health, Transport, Posts and Telecommunications to create conditions in their sectors and to ensure fulfilment of tasks in line with the strategy for the implementation of the Water Framework Directive (WFD) in SR according to the approved schedule of works by December 31, 2015.

4.2. Characteristics of geothermal water bodies

Sources of geothermal energy in Slovakia are represented mainly by geothermal waters, which are bound mainly to the Triassic dolomites and limestones of Inner Carpathians nappes; less to the Neogene sands, sandstones and conglomerates, or the Neogene andesites and pyroclastics. These rocks as collectors of geothermal waters off discharge areas are located at the depths of 200 - 5,000 m. In general, the temperature of these geothermal waters ranges from 15 to 240 °C. The collectors of geothermal waters with temperature more than 150 °C are located in Danube Basin Central Depression, Vienna Basin, Central Slovakian Neogene volcanics NW part (Žiar Basin), Humenné ridge, Beša - Čičarovce structure (Table. 4.1).

The binding of geothermal waters to those aquifers is evident from their natural discharges. They are conditioned by the folded-nappe tectonics of Mesozoic strata, which created far-reaching folds plunging from the mountain slopes to greater depths. On top of this, the young fault tectonics disturbed the Mesozoic strata by longitudinal and transverse faults. Far-reaching folds enable the connection of infiltration areas with the transition-accumulation ones. The crossing of longitudinal and transverse faults allows the groundwater to ascend to the surface through the Tertiary and Quaternary cover. This applies particularly for the intra-mountain depression. An example is, for instance, a hydrogeothermal structure in the western part of the Liptovská kotlina Basin with natural outflows in Bešeňová (Fig. 4.1). The geothermal waters are bound to the reservoirs without natural springs, or without infiltration areas (Central Depression of the Danube Basin, Levice Block).

In terms of geothermics the Western Carpathians can be divided into two parts, which vary widely in their geothermal activity and spatial distribution of the Earth's heat. Relatively low temperatures and densities of surface heat flux are characteristic for the central and northern part of the Inner Western Carpathians and for the western part of the Outer Flysch zone (30-40 °C at a depth of 1,000 m; 50-60 mW.m^{-2}). High subsurface temperatures and high heat flux densities are typical for the Neogene sedimentary basins and volcanic mountains of the Inner Western Carpathians (40-70 °C at a depth of 1,000 m; 70-120 mW.m^{-2}). Boundary between these geothermically different areas forms a zone of intensive horizontal temperature gradients, especially at the contact with volcanoclastic complex Pre-Neogene units of the Western Carpathians. The mean temperature at a depth of 1,000 m within the Western Carpathians is 45 °C, the mean heat flux density (arithmetic average of 136 wells) represents 82.1 ± 20.5 mW.m^{-2}.

Fig. 4.1 View of the mineral water outflows and travertine mound in Bešeňová (Photo: J. Madarás, 2012 in Liščák et al., 2012)

The highest heat fluxes in the Western Carpathian are in the Eastern Slovakia Neogene Basin (Fig. 4.2). The highest temperatures and heat flux density are in the central and SE parts (60-70 °C at a depth of 1,000 m; 100-120 mW.m^{-2}). The high values, namely 74.0 to 109.0 mW.m^{-2} with a mean value of 94.3 mW.m^{-2}, were also found in the Central Slovakia Neovolcanites, values higher than 90 mW.m^{-2} are typical for central and eastern part of the Danube Basin. Surprisingly low values, from 40.6 to 69.0 mW.m^{-2} with a mean value of 55.0 mW.m^{-2} were detected in the Vienna Basin. Significantly variable values (52.0 to 79.4 mW.m^{-2}) characterize the inner depressions of the Western Carpathians (Franko et al., 1995).

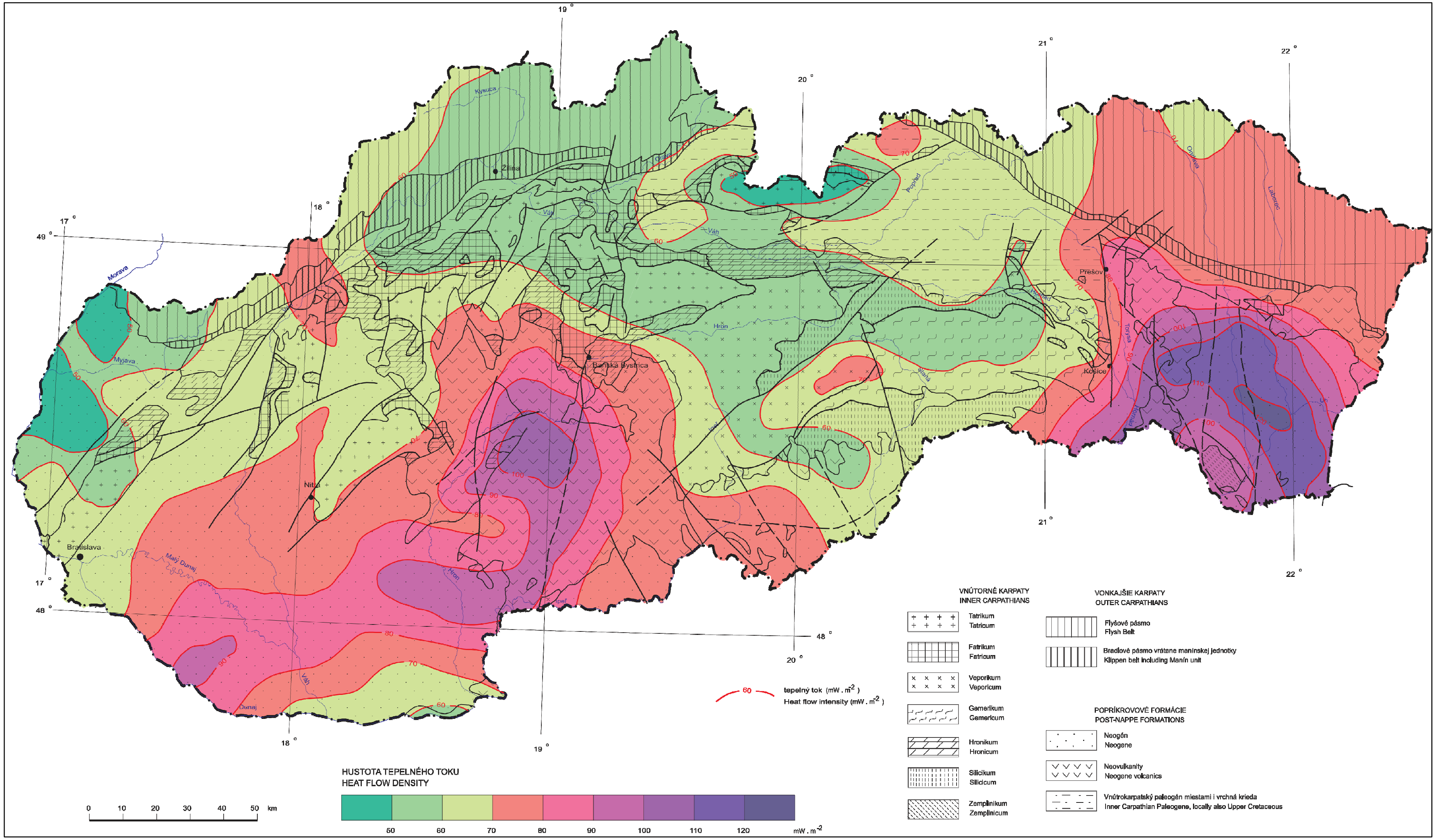

Fig. 4.2 Map of surface heat flow density of Slovakia, with underlay of geologic units (Franko et al., 1995)

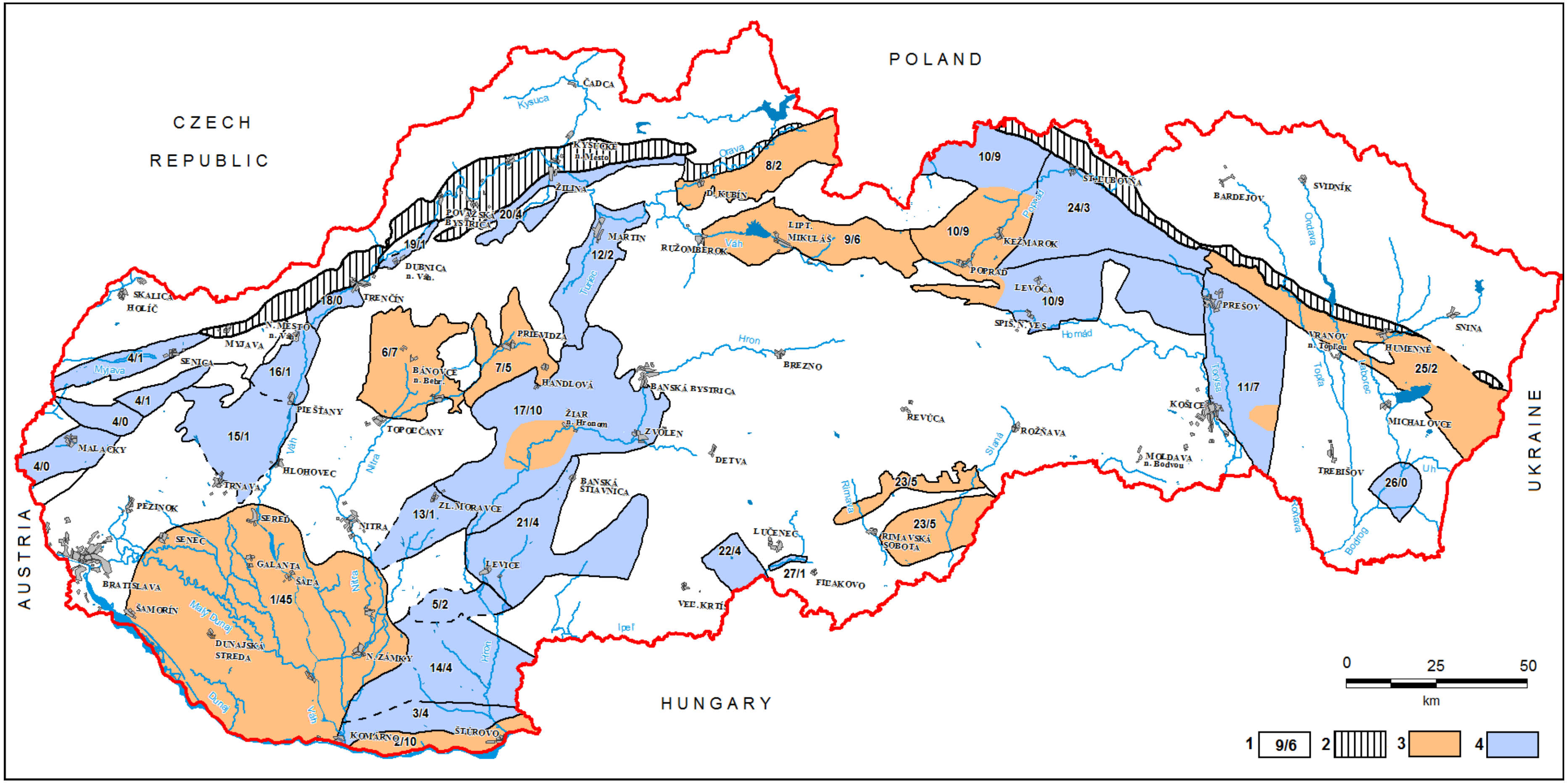

Fig. 4.3 Geothermal areas in Slovakia and status of their evaluation (Remšík in Remšík et al., 2011 – on the basis of Fendek et al., 2004)
1 - Danube Basin Central Depression, 2 - Komárno High Block, 3 - Komárno Marginal Block, 4 - Vienna Basin, 5 - Levice Block, 6 - Bánovce Basin, 7 - Upper Nitra Basin, 8 - Skorušina Basin, 9 - Liptov Basin, 10 - Levoča Basin W and S parts,p 11 - Košice Basin, 12 - Turiec Basin, 13 - Komjatice Depression, 14 - Dubník Depression, 15 - Trnava embayment, 16 - Piešťany embayment, 17 - Central Slovakian Neogene volcanics NW part, 18 - Trenčín Basin, 19 - Ilava Basin, 20 - Žilina Basin, 21 - Central Slovakian Neogene volcanics SE part, 22 - Horné Strháre - Trenč graben, 23 - Rimava Basin, 24 - Levoča Basin NE part, 25 - Humenné ridge, 26 - Beša - Čičarovce structure, 27 - Lučenec Basin

Legend: 1. - serial number of geothermal area/ number of geothermal wells; 2. - Klippen Belt; 3. - geothermal area, in which regional hydrogeothermal evaluation was implemented; 4.- geothermal area, in which regional hydrogeothermal evaluation was not implemented

Based on the distribution of the geothermal water collectors and geothermal field activity 27 prospective areas or structures were identified in the Slovak Republic suitable for obtaining geothermal energy. These defined geothermal areas, or structures, are termed as geothermal water bodies (as stated in the article Tab. 1.1 in the article by authors Černák et al. of this issue, Fig. 4.3).

Within the above defined geothermal areas or structures are present low-temperature geothermal sources of energy (temperature <100 °C), medium temperature sources (temperature 100-150 °C) and high temperature sources of geothermal energy (temperature> 150 °C). The low temperature geothermal sources are located in all 27-delineated geothermal areas, or structures; in 16 of them the medium temperature was detected and only in 5 the high-temperature geothermal energy sources is present. The incidence of the low-temperature, medium temperature and high-temperature geothermal energy sources in relation to individual defined geothermal areas or structures in Slovakia shows Tab. 4.1.

Tab. 4.1 Characteristics of geothermal water body – temperature water at surface

Type sources and their GTW temperature	Geothermal water body	No. of GTW bodies
Low temperature T < 100 °C	Danube Basin Central Depression, Komárno High Block, Komárno Marginal Block, Vienna Basin, Levice Block, Topoľčany embayment and Bánovce Basin, Upper Nitra Basin, Skorušina Basin, Liptov Basin, Levoča Basin W and S parts, Košice Basin, Turiec Basin, Komjatice Depression, Dubník Depression, Trnava embayment, Piešťany embayment, Central Slovakian Neogene volcanics SE part, Žilina Basin, Horné Strháre - Trenč graben, Rimava Basin, Trenčín Basin, Ilava Basin, Levoča Basin NE part, Humenné ridge, Beša - Čičarovce structure, Lučenec Basin	27
Medium temperature T = 100-150 °C	Danube Basin Central Depression, Komárno Marginal Block, Vienna Basin, Topoľčany embayment and Bánovce Basin, Liptov Basin, Košice Basin, Turiec Basin, Trnava embayment, Piešťany embayment, Central Slovakian Neogene volcanics NW part, Trenčín Basin, Ilava Basin, Žilina Basin, Levoča Basin NE part, Humenné ridge, Beša - Čičarovce structure	16
High temperature T > 150 °C	Danube Basin Central Depression, Vienna Basin, Central Slovakian Neogene volcanics NW part (Žiar Basin), Humenné ridge, Beša - Čičarovce structure	5

Legend: GTW – geothermal water

4.3. Geothermal waters abstraction and status of their use

In the period 2000-2010, 141 geothermal wells were registered in Slovakia, which made possible to verify the conditions for the geothermal water formation. Geothermal water was utilized from 46 wells situated in 36 sites within 13 Geothermal Water Bodies. This list does not include geothermal wells, which are used as curative sources under the supervision of the Ministry of Health, with exemption of the source FGC-1 in Čilistov.

In the period 2000-2010 from 46 operating geothermal wells 6,323,167 $m^3.year^{-1}$ (236.65 $l.s^{-1}$) were summarily taken. For all of these wells permits have been issued by relevant state water authorities for the abstraction of geothermal water, totalling 17,476,731 $m^3.year^{-1}$ (721 $l.s^{-1}$). The use of the wells represents 33% of allowances under the reported data on SHMI customers. However, many data are notified at an estimate, since some sampling devices lack of functional measuring equipment.

The largest average amount of geothermal water was collected from the following units of the geothermal waters in the years 2000-2010 (Tab. 4.2): Danube Basin Central Depression, Levoča Basin, W and S parts, Liptov Basin and Komárno High Block. During this period, from the perspective of individual geothermal wells the geothermal water was collected, with the highest exploited volumes values in the range of 100,000 to 1,000,000 $m^3.year^{-1}$ per well (Tab. 4.3).

By the Slovak Constitution, groundwater is the property of the state and the state is controling the utilization of the groundwater (geothermal water) through different Acts and regulations. To differentiate the usable amounts of groundwater (and geothermal water), Slovak legislation has defined principles for usable amounts classification into 3 categories: A, B and C, Appendix 3 in Decree of Government No.51/2008, implementing the Geological Act 569/2007). These categories are calculated based on level of information detail available for its calculation.

In other words we can say that 3 categories are degree of accuracy of calculation. Class A was defined as the amount of geothermal water, which is documented in the operating device for at least three years in terms of its quality, the water level (or pressure) regime and yield. Category B was defined as the amount of water that is determined based on a pilot hydrodynamic test covering at minimum 21 days and documenting the relationship of geothermal and surface water for at least 2 year period. Category C was defined as the amount of water that is calculated by geothermal balance, volumetric method, mathematical modeling and also documented groundwater regime of at least one year following a long series of observations of groundwater.

By the year 2010 available quantity of geothermal water was approved for 15 exploitation wells in category B and for 5 wells in category C.

Tab. 4.2 Annual geothermal water abstraction from geothermal water bodies during period 2000-2010

Name of geothermal water body	GTWU/ AGTW	Annual geothermal water abstraction											WP ($m^3.y^{-1}$)
		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	
Danube Basin Central Depression	20/45	1,564,468	1,655,123	1,516,581	1,671,838	1,855,086	1,904,187	1,827,212	2,414,828	2,293,046	2,256,956	2,247,476	4,756,237
Komárno High Block	4/10	433,441	496,570	495,920	497,770	500,350	486,929	468,070	494,490	571,791	642,629	586,495	1,974,888
Komárno Marginal Block	0/4												
Vienna Basin	0/2												
Levice Block	1/2	119,000	120,000		120,000			9,880	58,600	47,400	45,200	54,000	946,080
Topoľčany embayment and Bánovce Basin	3/7	12,300	230,000	186,500	113,400	130,994	168,842	185,703	185,465	192,889	203,962	207,059	629,020
Upper Nitra Basin	3/5					34,030	180,447	176,362	149,274	181,966	142,987	209,679	1,151,064
Skorušina Basin	1/2			63,600	38,000	37,800		29,500	20,949	38,000	38,000	37,998	1,860,624
Liptov Basin	3/6			332,791	37,600	83,670	621,223	622,008	776,906	1,496,704	1,487,896	1,123,514	1,616,609
Levoča Basin W and S parts	4/9	1,410,480	1,410,480	1,410,480	1,410,480	1,410,480	1,580,480	1,624,789	1,596,255	1,537,587	1,826,938	2,225,475	3,642,408
Košice Basin	0/7												
Turiec Basin	0/2												
Komjatice Depression	0/0												
Dubník Depression	0/4												
Trnava embayment	0/1												
Piešťany embayment	0/1												
Central Slovakian Neogene volcanics NW part	1/10						7,897	5,411	4,117	3,126	2,948	7,730	21,488
Trenčín Basin	0/0												
Ilava Basin	0/1												
Žilina Basin	1/4	48,450	49,100	49,600	65,430	65,850	59,950		60,646	5,5461	45,591	4,6128	70,000
Central Slovakian Neogene volcanics SE part	3/4	145,814	151,862	166,004	167,684	150,199	55,309	57,597	87,724	107,877	141,541	148,927	669,362
Horné Strháre - Trenč graben	1/4	59,096	59,096		51,709	51,709	51,709	16,236	16,284		14,990		180,248
Rimava Basin	0/5												9,000
Levoča Basin NE part	0/3												
Humenné ridge	0/2												
Beša - Čičarovce structure	0/0												
Lučenec Basin	1/1											5,591	346,896

Legend: AGTW – amount of geothermal wells, GTWU – amount of utilized geothermal wells, WP - water abstraction permit ($m^3.y^{-1}$)

Tab. 4.3 Overview of exploited geothermal wells with the highest values – mean yearly exploitaion of geothermal water for the period 2000-2010

Name of geothermal water body	Locality	Well	AAGTW ($m^3.y^{-1}$)	% from WPW
Liptov Basin	Bešeňová	ZGL-1	835,687	74
Levoča Basin W and S parts	Vrbov	Vr-2	716,091	83
	Vrbov	Vr-1	694,794	110
Komárno High Block	Štúrovo	FGŠ-1	408,683	81
Levoča Basin W and S parts	Poprad	PP-1	304,558	29
Danube Basin Central Depression	Senec	BS-1	295,132	78
	Galanta	FGG-2	230,661	70
	Galanta	FGG-3	294,255	89
	Veľký Meder	Č-2	232,512	92
	Horné Saliby	Di-2	198,459	43
	Topoľníky	FGT-1	179,314	59
Bánovce Basin	Bánovce nad Bebravou	BnB-1	156,396	45
Upper Nitra Basin	Nováky-Laskár	Š1 NBII	149,992	26
Danube Basin Central Depression	Veľký Meder	Č-1	148,333	47
	Horná Potôň	FGHP-1	120,015	67
	Dunajská Streda	DS-2	99,704	109

Legend: AAGTW - annual average amount of geothermal water abstraction, WPW - water abstraction permit for well

Fig. 4.4 Well head Č-1 Veľký Meder (Photo: D. Marcin, 2010)

Fig. 4.5 Well head Š1-NBII Nováky – Laskár (Photo: D. Marcin, 2011)

The geothermal water from 23 exploited wells (50%) is taken from the Neogene rock environment (sands, or sandstones) and 23 wells (50%) from the Mesozoic rock environment (Triassic carbonates). According to the value of the average annual collection of geothermal water (2000-2010) from the Mesozoic rock environment were withdrawn 142 $l.s^{-1}$ (60%) and from the Neogene geological environment 95 $l.s^{-1}$ (40%).

The active part of the wells in the Neogene aquifers is approximately at the depth level of about 1,200-1,550 m and in the Triassic aquifers at intervals of about 635-1130 m. The water temperature at the wellheads in the Neogene sediments is 19-91 °C (an average of about 60 °C), the temperature of the water at the wellheads in the Triassic carbonates is 20-80 °C (average of 42.5 °C). The mineralization of geothermal water from sandy collectors can range from 0.4 to 6.9 $g.l^{-1}$ (an average of 2.5 $g.l^{-1}$), the water mineralization in carbonates varies in the interval 0.5 to 19.6 $g.l^{-1}$ (in average of 3.25 $g.l^{-1}$).

From the regional point of view, the maximum use of geothermal energy in Slovakia is in the regions of Trnava, Nitra and Žilina. The greatest use of geothermal

Fig. 4.6 Well head FGT-1 Topoľníky (Photo: D. Marcin, 2010)

Fig. 4.7 Well Po-1 Podhájska (Photo: D. Marcin, 2012)

Fig. 4.8 Reinjection well in Podhájska GRP-1 (Photo: D. Marcin, 2012)

energy in Slovakia is currently for recreational purposes (87% of the number of sources used). Geothermal energy from 22 wells (48% of the sources used) is utilized for the purposes of building heating. The most important is the hospital complexes heating in Galanta as well as mining air heating in the lignite mine in Nováky (Fig. 4.5). In the year-round opened aquaparks and thermal pools based on geothermal water also hotel rooms are heated. This involves the sites of Dunajská Streda, Veľký Meder, Galanta, Horné Saliby, Senec, Čilistov, Poľný Kesov, Štúrovo, Podhájska, Bánovce nad Bebravou, Malé Bielice, Chalmová, Oravice, Bešeňová, Liptovský Mikuláš, Vrbov, Poprad and Veľká Lomnica.

In agriculture, the geothermal water is exploited from 11 wells (24% of the number of sources used) at 10 sites in winter for greenhouses heating, or plastic greenhouses at forcing the production of vegetables as well as the cultivation of flowers. In the Central Depression of the Danube Basin these wells are in Tvrdošovce, Gabčíkovo Topoľníky (Fig. 4.6), Topoľovec, Čiližská Radvaň, Horná Potôň and Dunajská Streda; in Levice Block in Podhájska and in Liptov Basin in Bešeňová. In Levoča Depression at the site Vrbov the geothermal water is used also for fish farming.

On a single site in Slovakia – in Podhájska – the geothermal water is exploited using re-injection system. Water from the exploitation borehole Po-1 (Fig. 4.7) passes through heat exchangers, in which it transfers the heat to technological water. Thermally utilized geothermal water for greenhouses heating by Slovkvet Company is reinjected into the well GRP-1 (Fig. 4.8) by pipe of a length of 2,300 m. Operating parameters of reinjection are for exploitation well Po-1 (T= 83.4 °C, Q = 5.6 $l.s^{-1}$, $P_{wellhead}$ = 0.385 MPa) and reinjection well GRP-1 (T= 40 °C, Q = 5.0 $l.s^{-1}$) during winter period. Wastewater from Termalpark is discharged into the stream Liska.

4.4. Thermal-energy potential of geothermal waters

Thermal energy potential of Slovakia (TEP) was comprehensively assessed in Geothermal Map of Czechoslovakia 1:500,000 with its total amount 5,804 MWt (Franko et al., 1989). Franko et al. (1990) determined the value of the thermal energy potential (Table 4.4) for the verified amount of 138 MWt and 5,666 MWt estimated amount specified in 25 geothermal areas. Evaluation of TEP in subsequent periods reflects the gradual increase of geological works, which provide information on the geothermal areas character. This information can be classified according to their quality data as predicted and proven. By its nature Geothermal Water Bodies have been divided in areas with amount of renewable geothermal energy (open and semi-open hydrogeological structure), and amount of non-renewable geothermal energy (closed hydrogeological structure). For utilization of geothermal water from closed structures the reinjection is needed.

For evaluation of the thermal energy potential of Slovakia in 1994, data from 61 geothermal wells for the period 1971-1991 were processed (Franko et. al., 1995). Wells verified amount of geothermal water of 900 $l.s^{-1}$ with a temperature of 20 °C to 92 °C and thermal energy 176 MWt. That represented around 3.2% from the total predicted amount of thermal energy. These quantities were bound to hydrogeological structures with renewable amounts of geothermal energy. Taking into account only the amount renewed, then it represented almost 32% of the total renewable and usable quantity of geothermal energy in Slovakia.

In the following period (1999, 2002 and 2009) thermal energy potential in Slovakia was estimated and assessed at amount 5,538 MWt and 6,653 MWt respectively. The use of this potential has been documented at the level of 130.97 MWt in 1999, 2002 (Fendek & Franko, 2000; Fendek, 2002) and in 2009 it was 163.86 MWt (Fendek & Fendeková, 2010).

Table 4.4 Overview of evaluation of thermal energy potential of geothermal waters in Slovakia

TEP till 31.12.1989 (Franko et al., 1990)			
Category	**Predicted amount**	**Proven amount**	**∑TEP**
	GE (MW_t)	GE (MW_t)	GE (MW_t)
ARE	484	138	622
ANE	5,182		5,182
∑	5,666	138	**5,804**
TEP till 31.12.1994 (Franko et al., 1995)			
Category	**Predicted amount**	**Proven amount**	**∑TEP**
	GE (MW_t)	GE (MW_t)	GE (MW_t)
ARE	406	147	553
ANE	4,956	29	4,985
∑	5,362	176	**5,538**
TEP till 30.6.1999 (Fendek & Franko, 2000)			
Category	**Predicted amount**	**Proven amount**	**∑TEP**
	GE (MW_t)	GE (MW_t)	GE (MW_t)
ARE	406	147	553
ANE	4,956	29	4,985
∑	5,362	176	**5,538**
TEP till 30.6.2002 (Fendek, 2002)			
Category	**Predicted amount**	**Proven amount**	**∑TEP**
	GE (MW_t)	GE (MW_t)	GE (MW_t)
ARE	390,5	162,5	553
ANE	4,868,8	116,2	4,985
∑	5,259,3	278,7	**5,538**
TEP till 30.6.2009 (Fendek &Fendeková, 2010)			
Category	**Predicted amount**	**Proven amount**	**∑TEP**
	GE (MW_t)	GE (MW_t)	GE (MW_t)
ARE	490	218	708
ANE	5,798	147	5,945
∑	6,288	365	**6,653**
TEP till 31.10.2011 (Remšík et al., 2011)			
Category	**Predicted amount**	**Proven amount**	**∑TEP**
	GE (MW_t)	GE (MW_t)	GE (MW_t)
ARE	1,307	227	1,534
ANE	4,927	121	5,048
∑	6,234	348	**6,582**

Legend: TEP - thermal energy potential, ARE - amount of renewable energy, ANE - amount of non-renewable energy (need to use reinjection)

Thermal energy potential was assessed in 2011 and in individual geothermal areas of Slovakia, its value was in range from 1.1 MWt to 1316,0 MWt. The total calculated amount of geothermal energy in defined geothermal areas in Slovakia is currently at level 6234,039 MWt (Tab. 4.5).

These values were calculated by geothermal balance, volumetric method and mathematical modelling. Identified amount of geothermal energy (345,04 MWt) in percentage terms compared to total calculated amount of geothermal energy in Slovakia represents only 5.58%.

Table 4.5 Thermal energy potential of geothermal waters in Slovakia (Remšík et al., 2011)

Geothermal water body	Category	Predicted amount		Proven amount		∑TEP	
		GW ($l.s^{-1}$)	GE (MW_t)	GW ($l.s^{-1}$)	GE (MW_t)	GW ($l.s^{-1}$)	GE (MW_t)
Danube Basin Central Depression	ARE	731.0	150.0	488.7	101.11	1,219.7	251.11
Komárno High Block	ARE	133.0	9.7	265.0	17.42	398	27.12
Komárno Marginal Block	ANE		227.5	15.9	2.62	15.9	230.12
Vienna Basin	ANE		511.0	37.0	9.5	37	520.5
Levice Block	ANE		126.0	81.0	20.74	81	146.74
Bánovce Basin	ARE	141.7	12.469	68.8	5.26	210.5	17.729
Upper Nitra Basin	ARE	140.0	29.12	57.9	7.05	197.9	36.17
Skorušina Basin	ARE	166.0	24.0	135.0	18.29	301	42.29
Liptov Basin	ARE	248.0	34.589	121.4	20.36	369.4	54.949
Levoča Basin W and S parts	ARE	424.6	75.4	226.3	34.24	650.9	109.64
Košice Basin	ANE		1,276.4	207.4	78.88	207.4	1,355.28
Turiec Basin	ARE		22.5	19.9	2.65	19.9	25.15
Komjatice Depression	ANE		392.64				392.64
Dubník Depression	ANE		808.3	36.0	3.70	36	812
Trnava embayment	ARE		33.5	14.5	0.55	14.5	34.05
Piešťany embayment	ARE		10.5	10.0	0.18	10	10.68
Central Slovakian Neogene volcanics NW part	ARE		82.6	80.6	9.47	80.6	92.07
Trenčin Basin	ARE		4.6				4.6
Ilava Basin	ARE		1.1				1.1
Žilina Basin	ARE		13.2	57.4	2.95	57.4	16.15
Central Slovakian Neogene volcanics SE part	ARE		26.4	64.1	3.84	64.1	30.24
Horné Strháre - Trenč graben	ARE		6.2	16.0	1.04	16	7.24
Rimava Basin	ARE	284.74	21.121	61.3	1.76	346.04	22.881
Levoča Basin NE part	ANE		1,316.0	19.0	4.55	19	1,320.55
Humenné ridge	ARE	341.0	750.5	6.0	0.41	347	750.91
Beša - Čičarovce structure	ANE		268.7				268.7
Lučenec Basin	ANE			11.20	1.04	11.2	1.04
∑ ARE	ARE	2,610.04	1,307.499	1,692.9	226.58	4,302.94	1,534.079
∑ ANE	ANE		4,926.540	407.5	121.03	407.50	5,047.570
∑ ARE + ∑ ANE	ARE+ANE	2,610.04	6,234.039	2,100.4	347.61	4,710.44	6,581.649

Legend: GW - geothermal water, GE - geothermal energy, ARE - amount of renewable energy, ANE - amount of non-renewable energy (need to use reinjection)

4.5. Conclusion

The assessment of the use of geothermal waters in Slovakia during the period 2000 - 2010 was based on the documentation available from the 141 registered wells and collection of data on geothermal waters as reported by users to the Slovak Hydrometeorological Institute in Bratislava. Based on data processing it can be concluded that geothermal water was utilized from 46 geothermal wells at 36 locations in 13 geothermal water bodies (geothermal areas) during last decade. This list does not include geothermal wells, which are used as healing sources and are at the competence of the Ministry of Health (source FGČ-1 in Čilistov is included in evaluation). Total average yearly amount of utilized geothermal water from 46 geothermal wells is 6,323,167 $m^3.year^{-1}$ (236,65 $l.s^{-1}$). For all of these wells relevant state water authorities issued permits for the abstraction of geothermal water, totalling 17,476,731 $m^3.year^{-1}$ (721 $l.s^{-1}$).

The utilization of geothermal water from wells represents 33% of allowed yield for utilization according to the reported data by customers to SHMI. Most of the reported data is based on estimate, since measuring devices or flowmeters are absent.

The highest average amount of geothermal water utilization in that period was reported in four geothermal waters bodies: Central Depression of Danube Basin, Levoča Basin W and S parts, Liptovská kotlina Basin and Komarno High Block. Geothermal water from 23 utilized wells (50%) comes from the Neogene sediments (sands and sandstones) and 23 utilized wells (50%) comes from Mesozoic sediments (Triassic carbonates) and Paleogene (breccias, conglomerates, sandstones). According to the value of the average annual utilization of geothermal water from period 2000-2010, 142 $l.s^{-1}$ (60%) of geothermal water is withdrawn from Mesozoic and Paleogene sediments and 95 $l.s^{-1}$ (40%) from Neogene sediments.

Thermal energy potential in individual geothermal areas in Slovakia varies from 1.1 MWt to 1,316 MWt. Total calculated amount of geothermal energy in Slovakia represents 6,234 MWt. These values were calculated by geothermal balance, volumetric method and mathematical modeling. To date knowledge identified amount of geothermal energy (348 MWt) in Slovakia represents only 5.58% of total calculated amount of geothermal energy.

The important task for future is continuous updating of knowledge about geothermal structures, the information database of geothermal water utilization and current state of issued water permits. The update should incorporate the information form database of geothermal sources that is treated as healing water under the competence of Ministry of Health with separate status and monitoring policy.

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The references in the text should be used preferably in parentheses. Names of cited authors in the text are written without first names or initials (e.g. Matula, 1969); the names of the co-authors are divided (e.g. Mišík & Sýkora, 1981). The name(s) is followed by a comma. If there are more authors, the first one, or the first two only are cited, adding et al. and publication year.

Mathematical and physical symbols of units, such as m, °C should be preceded by a space, e.g. 20 m, 50 °C, etc. In the case of % and ‰, the exemption shall be made: 10%, 2‰. SI units are preferred. Abbreviations of the units such as second, liter, etc. should be written without a period. Compass readings may be substitute by the abbreviations E, W, NW, SSE, etc. Brackets (parentheses) are to be indicated as should be printed, i.e. square brackets, parentheses or compound. Dashes should be typed as double hyphens.

Text of the article must be sent to Editorial office printed in two copies with line spacing 2, as well as on CD. Please for using preferable MS Word editor for PC. Figs. and Tabs. must be delivered in digital form in separate files. Paragraphs are marked with 1 tab space from the left margin, or by a typographic symbol. Greek character in the text must be visualized in the text by its name [e.g. Ʊ (omega)]. Indices and exponents should be properly marked.

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The high quality of illustrations is required. Their aim is the most effective documenting and explaining the text. When drawing them by hand or computer their maximum width 81 mm (width of column) or 170 mm (width of page) must be taken into account. Properly adapted figure (dimensions of letters, thickness of lines) can be reproduced also in the scale 1:1, but there is recommended to prepare figures in larger scale. The pen-drawn figures must be prepared by black ink using the template for figures. The minimum acceptable size of capitals and numbers in camera-ready figure is 2 mm. Maximum dimension of illustration in journal is 170x240 mm. Overlapping of illustrations should be avoided.

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The Publisher reserves the right to return the graphic supplements back to author after language correction, resp. demand him to replace them by the higher quality ones.

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References

The list of references should only include the works cited in the text. The references are stated in alphanumeric order, with hanging indent in the second and following lines. The denotation "in press" can be used only in the cases of acceptance of reviewed version of article by editorial board. The denotation "personal information" can be cited only in the text (e.g. Kováčik, pers. information, 2008). When referring the data by other author not being the co-author of referred publication, in the text he is cited in the following form: (Gerda in Kubka, 1975), though in the list of literature is stated only Kubka J., 1975.

Examples of referring:

Book

Gazda L. & Čech M., 1988: Paleozoic of the Medzev nappe. Bratislava, Alfa, 155.

Journal

Vrba P., 1989: Shear zones in the metapelite complexes. Mineralia Slov., 21, 135-142.

Anniversary volume

Návesný D., 1987: High-potassium rhyolites. In: Romanov, V. (ed.): Stratiform deposits of Gemericum. Spec. publ. Slov. Geol. Soc. Košice, 203-215.

Manuscript

Radvanský F., Slivka B., Viktor J. & Srnka T., 1985: Vein deposits of the Jedľovec nappe of Gemericum. Final report from the project SGR-geophysics. Manuscript-archive ŠGÚDŠ Spišská Nová Ves, 28.

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