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Report on the Vienna Basin pilot area model

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Description The report presents the results of the modelling in the Vienna Basin pilot area of the TRANSENERGY project. The modelling comprises 3D heat transport simulations.

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5.2.3 Detailed hydrogeological modelling

5.2.5 Detailed geothermal modelling

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1 Introduction

The report presents the results of the modelling in the Vienna Basin pilot area of the Transenergy project. The overall aims and scientific questions tackle the estimation of hydrogeothermal potentials and resources in the Vienna Basin. Until the publishing of this report no hydrogeothermal utilization for energetic purposes has been realized, although there is a considerable potential to be expected in this region. In this context a sustainable future geothermal development has to found on a harmonized bilateral evaluation of the existing resources and their quantification in terms of geometrical and numerical models. As the Vienna Basin was in the past and is still intensively used for hydrocarbon exploitation, possible conflicts to the hydrocarbon industry have to be considered.

The modelling comprises the following different approaches:

i. A regional scale 3D heat transport modelling covering the entire pilot area.
ii. A local to regional scale 2D raster calculation approach in order to estimate the available Heat in Place and expectable Heat Recovery Factors[1] at selected hydrogeothermal plays.
iii. An experimental estimation of the Heat Recovery Factor based on 3D parameter modelling.
iv. A local scale scenario modelling of the most promising hydrogeothermal play.

In this context approach (i) delivers crucial data input and boundary conditions for approach (ii) and (iv) in terms of temperature conditions. Approach (iii) in turn delivers empiric functions, which allow the derivation of Heat Recover Factors from hydraulic rock properties in a first approach.

As there are currently no geothermal installation for energy supply in the investigated hydrogeothermal plays and as the main relevant geothermal aquifers are supposed to represent connate, closed systems (no free or forced convection expected), pure conductive modelling will meet the requirements. Therefore a static hydraulic model has been neglected.

The presented report is clearly focussing on the achieved regional scale 3D heat transport model (i). Further above described modelling approaches will be presented in different reports published on the project related homepage.

1.1 Modelling software

The modelling of the regional scale geothermal model (approach i) is carried out using the software package COMSOL Multiphysics, a state-of-the-art finite element simulation software. For the scenario modelling (approach iv), which is the next step, as well as the parameter study (approach iii) the software package FEFLOW™ is used. The 2D raster

[1] The term Heat Recovery Factor (HF) quantifies the fraction of Heat in Place (HIP), which can technically be used. The HF is typically varying in the range of <0.1 (less than 10% of the available HIP can be used) and 0.3.

calculations (approach ii) have been performed using the software package Surfer™ (Golden Software).

1.2 Geographical setting

The Vienna Basin pilot area covers the central and north-eastern parts of the Vienna Basin. Crystalline outcrops, namely the Leithagebirge in Austria and the Little Carpathian Mountains in Slovakia define the eastern boarder of the model, the western boarder is defined by the boundary between the Flysch Zone and the Upper Austroalpine Bajuvaric nappe system. The southern boundary is defined by the Leopoldsdorf fault system. The maximum extension of the model area is about 150x75 km laterally and 15 km in depth. For more information on the geographic and geological background please refer to chapter 5.2 of the '*Summary report of geological models'* from March 2012 (Maros 2012).

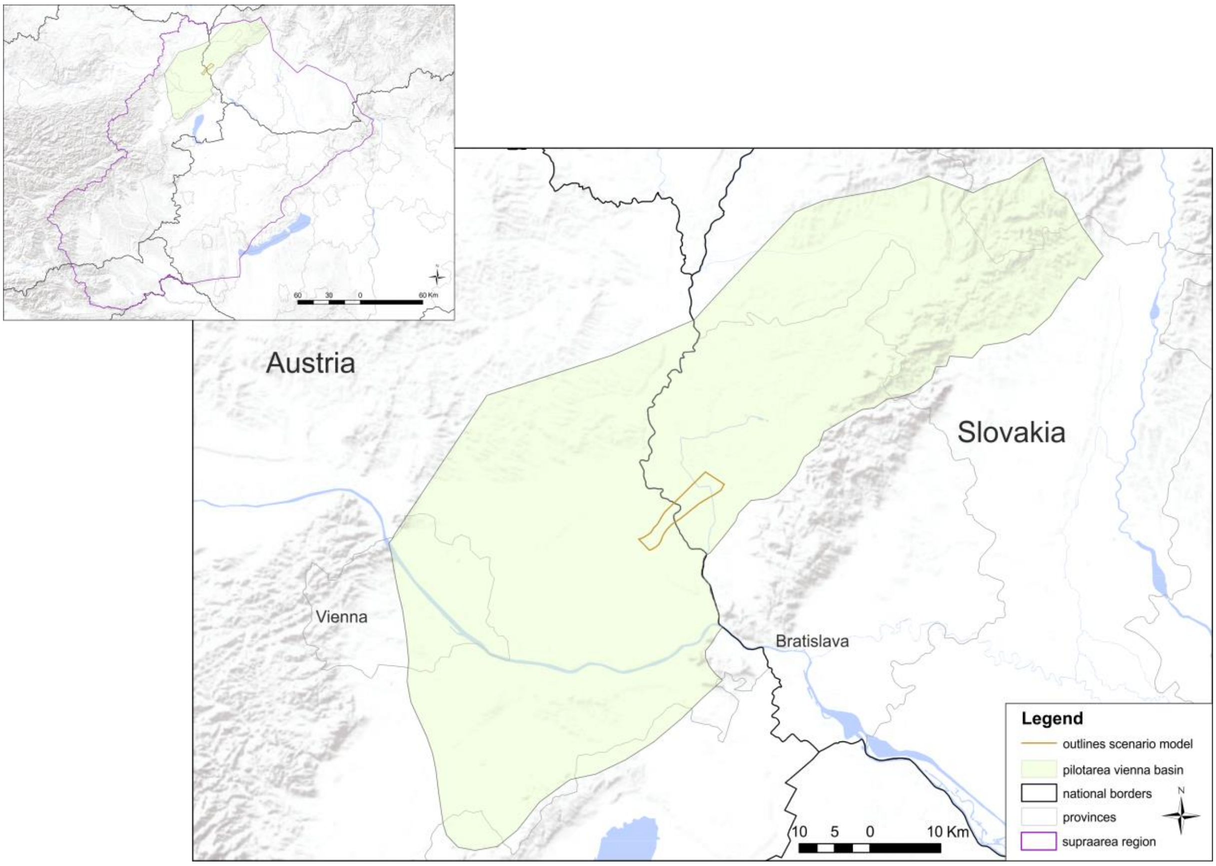


Figure 1. Delineation of pilot area and the scenario model "Schönfeld-Láb".

1.3 Geological and hydrogeological setting

From a hydrogeological point of view the Vienna Basin pilot area was confined by the following boundaries:

(a) The Leopoldsdorf fault systems (west).
(b) The geological boundary between the carbonatic nappes of the Upper Austroalpine and Carpathian units and the northwards bounding Flysch- and Klippen Zones including a small buffer (north-west).
(c) The recharge area of the carbonatic nappes at the Carpathians (east).
(d) The geological boundary between carbonatic and metamorphic as well as crystalline units of the Central Alpine and Tatric units (south-east).

In general boundaries (a) and (b) represent no-flow boundaries. Boundaries (c) and (d) represent the recharge boundaries of active circulations systems, which are confined to the margin areas of the Vienna Basin.

The pilot area covers the most relevant hydrogeothermal reservoirs of the Vienna Basin. However, an actively recharged hydrodynamic system at the western margin of the southern Vienna Basin has not been considered for the pilot area due to an assumed high vulnerability to overexploitation. It has been showed in previous studies, that the hydrodynamic[2] reservoir in the western part of the southern Vienna Basin does not show significant chances for a future energetic utilization of subsurface thermal waters. The main reasons for that are given by an already existing intense balneological use and only little remaining resources. Nevertheless, the output of previous studies considering the southern Vienna Basin will also be presented and discussed in the description of the pilot area Vienna Basin.

Inside the Vienna Basin the following 5 relevant hydrogeothermal plays[3] have been identified:

(1) Triassic carbonates of the Upper Austroalpine and Carpathian units: (a) Tirolic nappe system – Hauptdolomit & Wetterstein Dolomite (Age: Nor to Anis), (b) Juvavic nappe system: Wetterstein Dolomite (Anis) [AUT & SK].
(2) Clastic sediments (deltafront sands and sandstones) of Eggenburgian and Ottnangian age [SK & AUT].
(3) “Aderklaa Conglomerates” at lower Badenien age [AUT].
(4) Central Alpine and Tatric Units (Mesozoic carbonates) [AUT & SK].
(5) Triassic carbonates at the Austroalpine and Carpathian units between Lakš N.V. and Šaštin – Stráže.

It has been agreed between the involved partners, that hydrogeothermal reservoirs at younger stratigraphic age than Lower Badenian are not within the scope of Transenergy due to low reservoir temperatures and locally existing intense hydrocarbon exploitation.

[2] Hydrodynamic system: Geothermal reservoir with an active recharge and discharge of subsurface thermal water

[3] Following the Canadian Geothermal Code for Public Reporting (Deibert & Tohody, 2010) the term “Geothermal Play” describes a subsurface volume of accumulated heat, contained in the rock matrix as well as in pore fluids in a qualitative way. In this context a Geothermal Play confines a geological unit, which is expected to bear hydrogeothermal reservoirs with existing geothermal Resources and Reserves.

The subsequent **Table 1** summarizes the most important hydrogeological characteristics of the selected hydrogeothermal plays.

Table 1: Overview on relevant geothermal plays at the Vienna Basin pilot area

Pos. (Priority)	Name of Geothermal Play	Tectonic Unit	Stratigraphic Age	Lithology	Type of Porosity	Type of Recharge
1	(a) Hauptdolomit (Tirolic Nappes) (b) Wetterstein Dolomit (Juvavic Nappes)	Upper Austroalpine and Carpathian Units (Basement of the Vienna Basin)	a) Upper Triassic (Nor) b) Middle Triassic (Anis – Ladin)	Dolomites and Limestones	Fractured Reservoir	No recharge; connate and locally overpressured formation waters
2	Deltafront Sediments	Neogene of the Vienna Basin	Lower Miocene (Eggenburgian to Ottnangian)	Sands and Sandstones	Porous Reservoir	No recharge, connate formation waters at hydrostatic pressure.
3	Aderklaa Conglomerate	Neogene of the Vienna Basin	Middle Miocene (Badenian)	Conglomerates	Porous Reservoir	No recharge, connate formation waters, locally underpressured due to hydrocarbon exploitation
4	Central Alpine & Tatric Carbonates	Central Alpine & Tatric Units	Jurassic to Middle Triassic	Dolomites and Limestones	Fractured Reservoir	Active recharge and discharge, hydrostatic pressure?
5	Lakš N.V. / Šaštin – Stráže structure	Austroalpine and Carpathian allochthonous basement of the Vienna Basin	Upper Triassic (Norium) to Middle Triassic (Anisium – Ladinium)	Dolomites and limestone	Fractured Reservoir	Semi – open system, pressure conditions?

The following Figure 2 shows the combined outlines of all identified geothermal plays within the Pilot area. The subsequently following Figure 3 to Figure 5 show the outlines of the individual plays in detail.

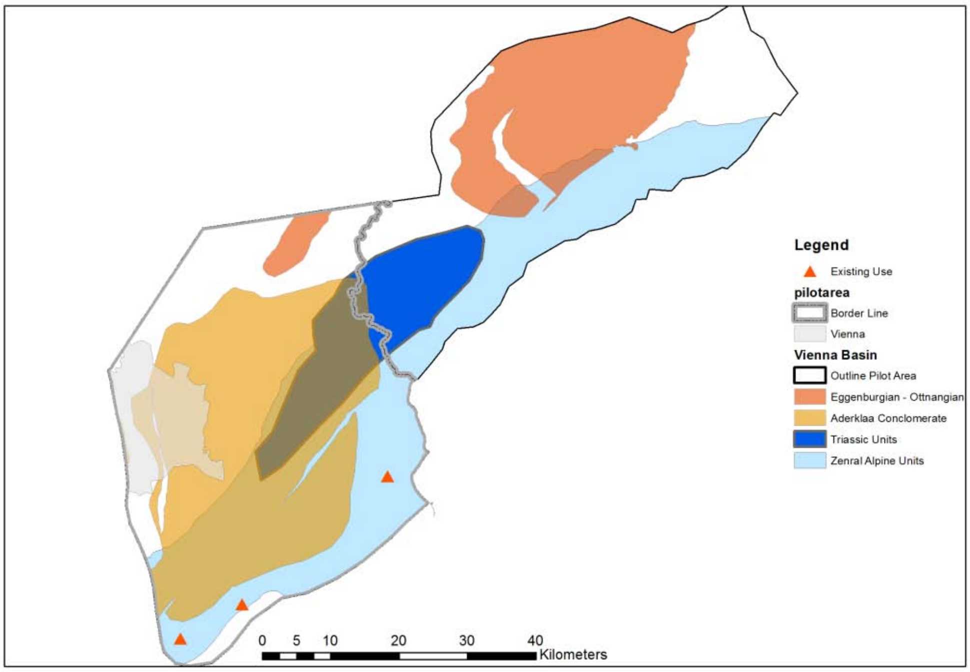


Figure 2: Combined outline of all identified geothermal plays at the Vienna Basin pilot area

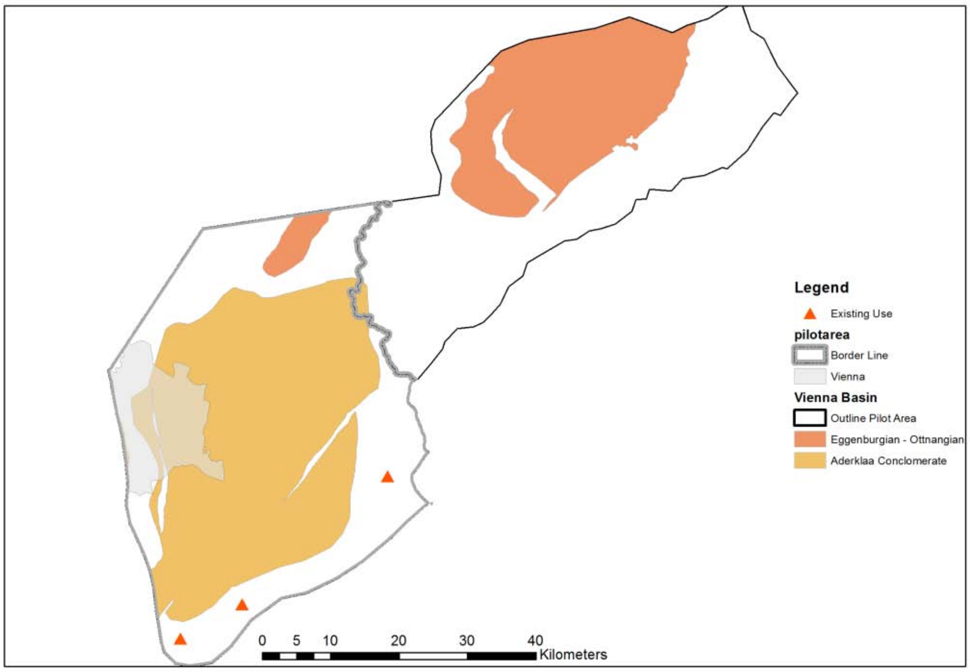


Figure 3: Outline of Eggenburg - Ottnangian Deltafront and Aderklaa Conglomerate geothermal plays

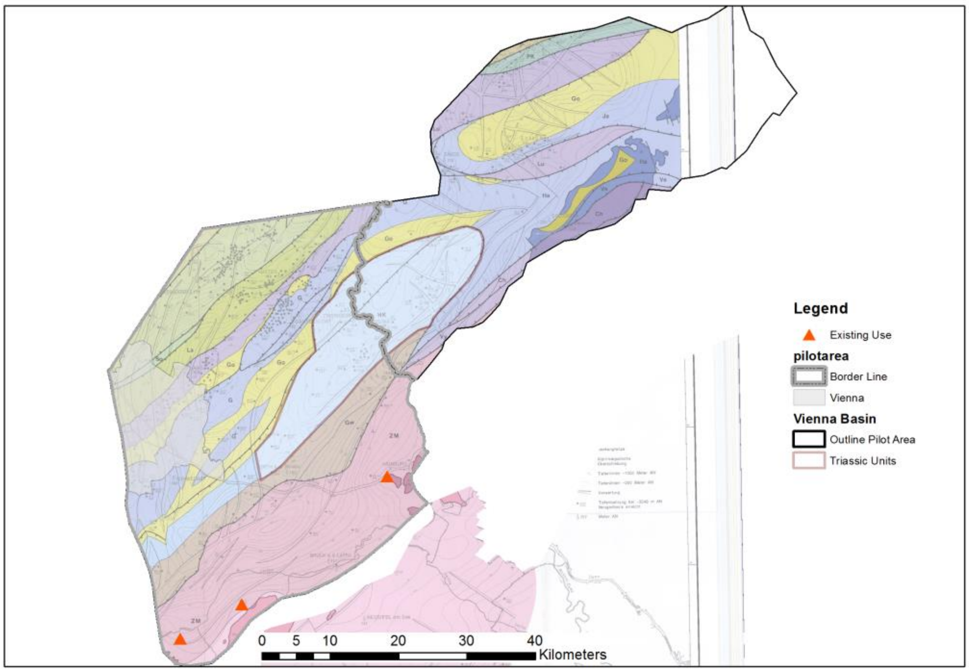


Figure 4: Outline of the Triassic carbonates of the Austroalpine and Carpathian Units

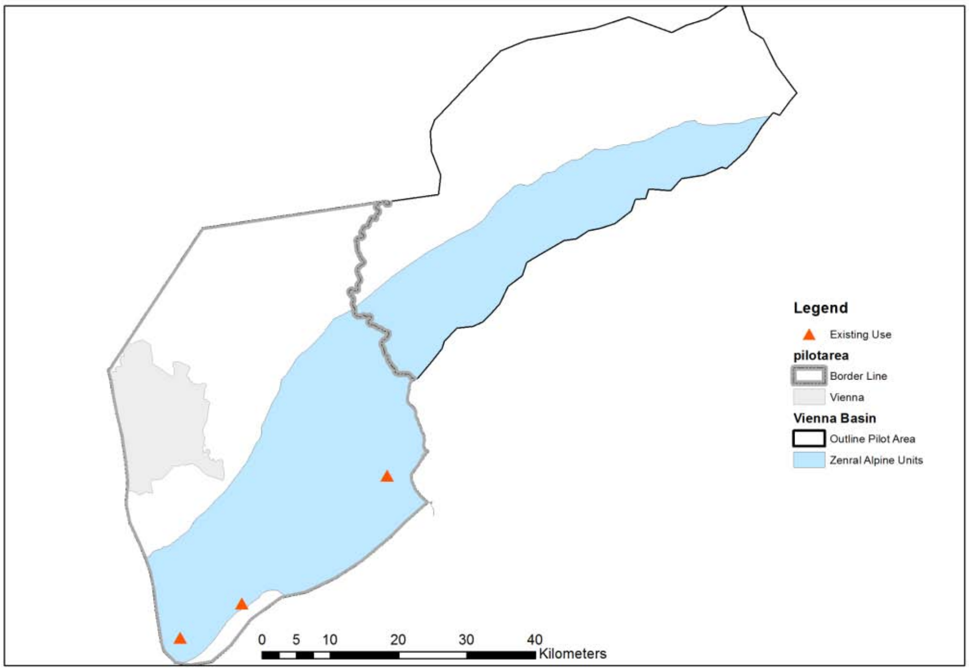


Figure 5: Outline of the Central Alpine & Tatric Unit Geothermal Play

The above shown outlines of the presented hydrogeothermal plays follow main geological boundaries, irrespective to facies changes as well as internal lithological build-ups. The geothermal play #5 (Lakš N.V. / Šaštin – Stráže structure) has not been displayed as it has not been considered in the modelling. The decision not to implement hydrogeothermal play #5 founds on the circumstance that it is only covered by Slovakian territory and was already described at Konečnŷ et al. (1995).

The subsequent Figure 6 shows the stratigraphic stage of the identified relevant geothermal plays at the Neogene basin fillings of the Vienna Basin. They predominately consist of deltaic to limnic to fluviatile sands, sandstones, conglomerates and breccia. The Aderklaa Conglomerate was intensively used for hydrocarbon exploitation in the past and therefore shows depressured conditions at some parts. In recent time it has been used for reinjection of used formation waters from hydrocarbon exploitation at other geological units in order to re-establish pressure and due to favourable conditions for reinjection. For that reason utilization conflicts with the hydrocarbon industry may be expected for this geothermal reservoir.

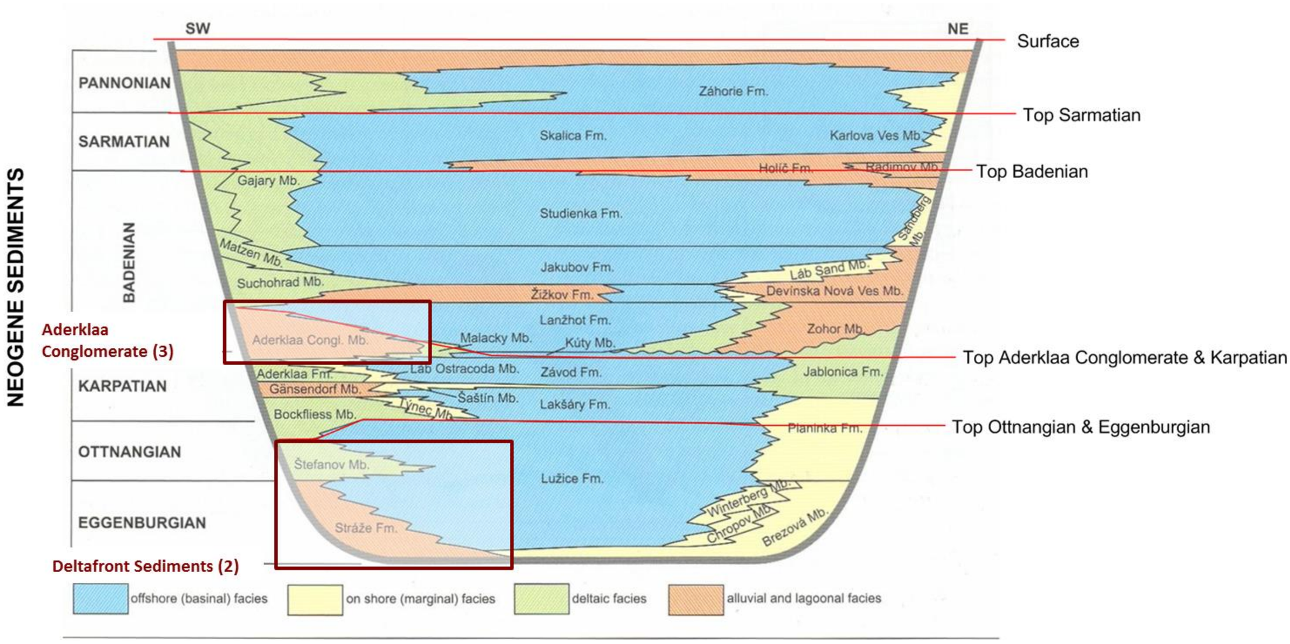


Figure 6: Overview of the identified hydrogeothermal plays at the Neogene basin fillings of the Vienna Basin, combined with the surface of the modeled main geological horizons.

Geothermal plays in the Triassic units of the Upper Austroalpine and Carpathian Units may be divided in two different reservoir systems: (a) Middle Triassic carbonates (Wetterstein Dolomite) associated to the so called Juvavic Nappe system and (b) Upper to Middle Triassic carbonates (Hauptdolomit, Wetterstein Dolomite) associated to the so called Tirolic Nappe system. The outlines of both plays are shown in the subsequent figure in terms of a cross section through the central part of the Vienna Basin near the Austrian – Slovakian border. Both plays are of great importance for future hydrogeothermal utilization, as both reservoir systems are currently not used for hydrocarbon exploitation and as they both are crossing the border between Austria and Slovakia. In turn both reservoirs bear connate and highly mineralized thermal water, which may offer challenge in the technical use.

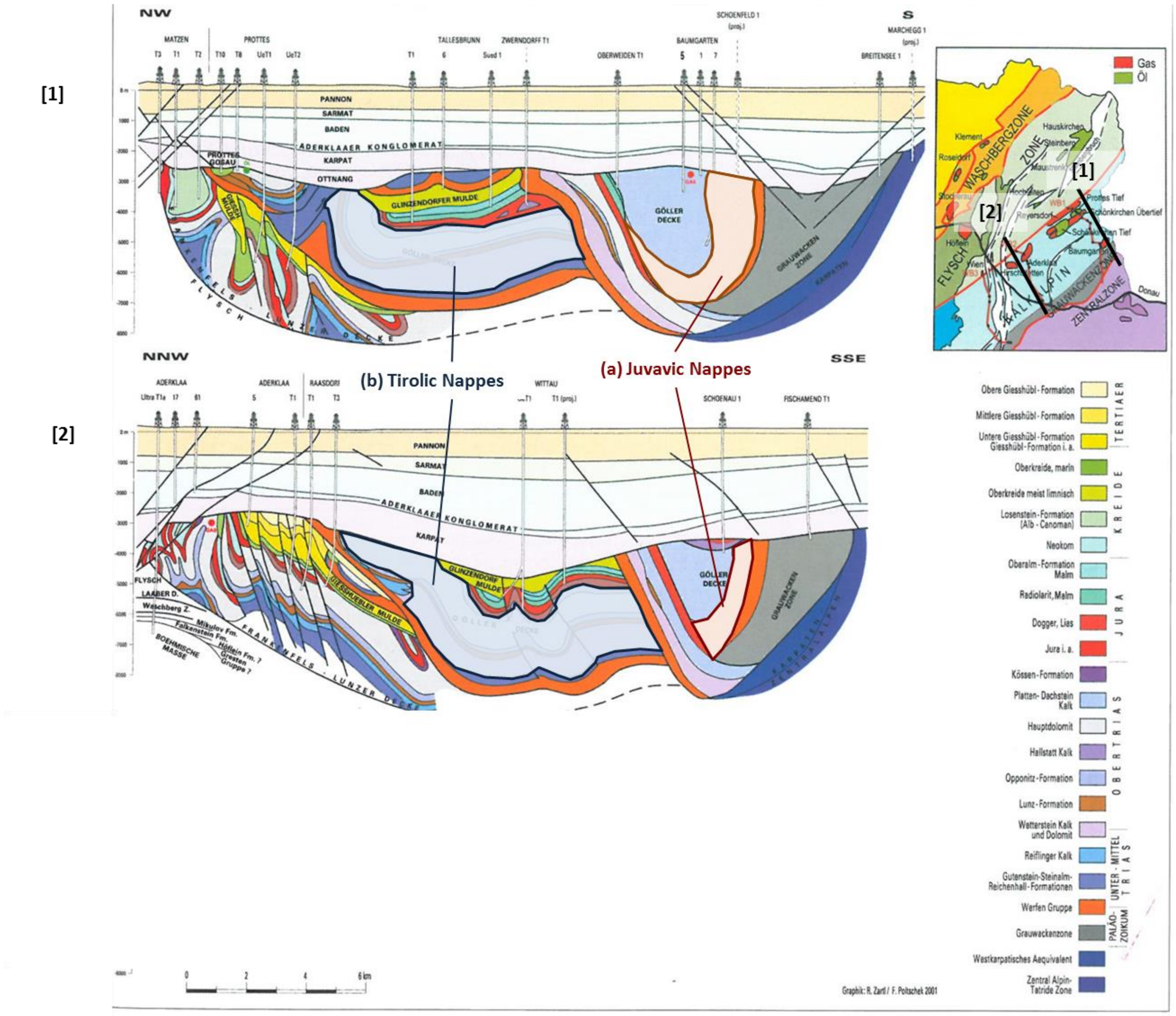


Figure 7: Outline of the geothermal reservoirs at Triassic carbonates of the Austroalpine and Carpathian Units shown on two cross sections through the central Vienna Basin (taken from Wessely 2006, edited by the author).

The geothermal play at the Tirolic Nappes (b) comprehends geological units from Upper Trias (Nor) to Middle Trias (Anis). The most relevant reservoirs are represented by Hauptdolomit (Nor) and Wetterstein Dolomite (Anis) – hydraulic barriers given by anhydrites and mudstones at the stage of Karn (Lunz Formation, Opponitz Formation) will not be regarded, as the thickness of these formations is rather low. Future utilization conflicts with hydrocarbon exploitation have to be expected, as reservoir (b) indicates the existence of hydrocarbons in some areas of the reservoir.

Reservoirs of the Juvavic Units (a) are represented by dolomite and limestone of the Wetterstein Dolomite formation. In opposite to reservoir (b) no indications of hydrocarbons have been revealed at exploration wells.

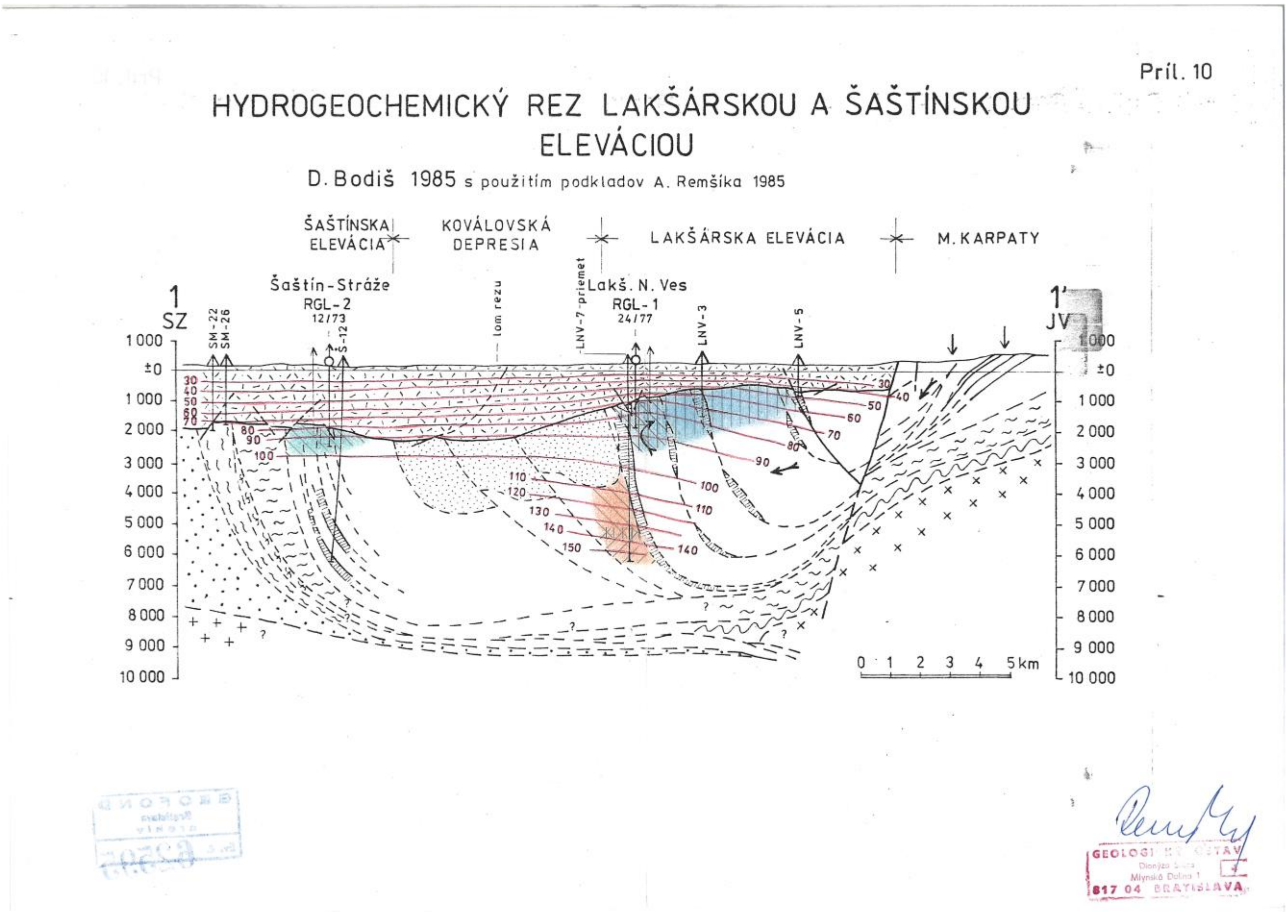


Figure 8: Schematic cross-section through the Lakš N.V. / Šaštin – Stráže structure (provided by SGUDS).

Other relevant reservoirs at the Triassic Units of the basement of the Vienna Basin exist at the region between Lakš N.V. and Šaštin – Stráže. In opposite to the above described reservoirs of the Triassic basement, these reservoirs are believed to be at least partly recharged by water inflow at the margin of the Vienna Basin and by cross-flow at Neogene deposits. As this reservoir is only affecting Slovakian territory and has already been comprehensively described at Konečnŷ et al. (1995) it will not be considered in the detailed analyses of the geothermal resources in the Vienna Basin pilot area.

The Central Alpine & Tatric Units geothermal play (play #4) is associated to fractured carbonates from Jurassic to Middle-Triassic Age, which represents the sedimentary cover of crystalline rocks, which belong to Central Alpine and Tatric Units from a tectonic point of view. This geothermal play is dominated by a hydrodynamic system showing recharge areas both on Austrian and Slovakian sides (see also Figure 9). Presently hydrogeothermal use is limited to balneological utilization at several Austrian sites (e.g. Bad Deutsch Altenburg and Mannersdorf). Although trans-boundary is evident, the maximum observed water temperatures of this hydrodynamic system are limited to approximately 50°C due to shallow circulation depths. For that reason this hydrogeothermal play has not been set into the focus of the Vienna Basin pilot area modelling. Furthermore the hydrodynamic concept is currently not entirely understood. For that reason it has been decided not to include this play in the regional scale thermal modelling (approach -i-).

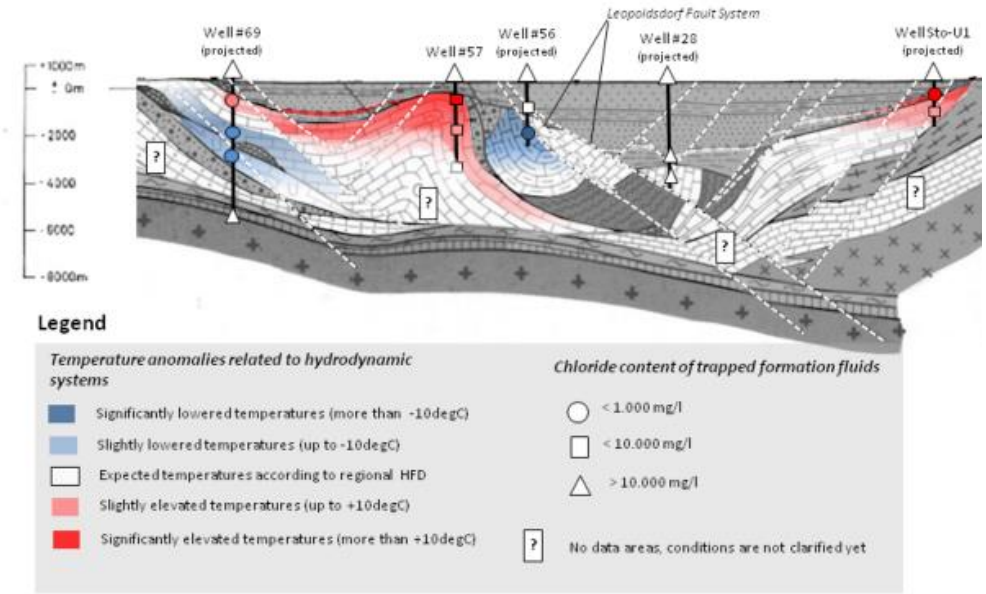


Figure 9: Hydrothermal cross-section through the southern Vienna Basin. The Central Alpine & Tatric Units Geothermal Play is situated on the right hand side of the cross-section and is represented by the well Sto-U1 (taken from Goetzl et al, 2010).

1.4 Technical Utilization schemes

As the overall aim of the detailed modelling at the Vienna Basin pilot area is represented by the evaluation of hydrogeothermal potentials and resources with respect to a sustainable reservoir management, different hydrogeothermal utilization schemes has been designed. According to the Modelling Manual of the project Transenergy (http://transenergy-eu.geologie.ac.at/) the following technical utilization schemes will be considered at the Vienna Basin pilot area:

Table 2: Key values of the technical utilization schemes considered at the pilot scale modelling

Pos.	Name	Well-type	Production Temperature / (Production yield)	Inlet Temperature	Annual Operational Hours
1	*General*	- Single Well - Dublet	> 30°C / (-)	25°C	8760 (100%)
2	*Combined Electric Power and Heat Supply*	- Dublet	> 105°C / (50 l/s)	55°C	7880 (~90%)

3	*Combined Local Heating and Balneological use*	- Dublet	> 60°C (25 l/s)	25°C	5690 (~65%)
4	*Balneological Use*	- Single Well	>35°C (-)	20°C	8320 (~95%)

For all technical utilization schemes a minimum operational lifetime of 30 years will be presumed.

It has to be pointed out, that technical schemes #3 and #4 are limited to the hydrogeothermal play #4 (Central Alpine & Tatric Units) due to expected high contents of minerals in the other geothermal plays. The general scheme #1 can be seen as a very hypothetic scenario, which was predominately applied to the calculation of the stored Heat in Place.

2 Regional scale numerical modelling

The aim of the modelling in the Vienna Basin was to calculate the overall geothermal conditions at the Vienna Basin in order to allocate thermal boundary conditions and input data for (i) the evaluation of hydrogeothermal potentials at the identified geothermal plays (see also chapter 1.3) and (ii) for the subsequent scenario modelling at the Schoenfeld – Láb area. Temperature data from more than 160 hydrocarbon wells was used for validation of the results. Furthermore, the output of this model will deliver crucial input like boundary and initial conditions for a smaller and more detailed scenario model. In the central and northern Vienna Basin no major thermal water systems are expected, therefore pure conductive modelling was applied.

2.1 Pilot model

2.1.1 Horizontal extent

The horizontal extend of the model is a 127x50 km-square circumscribing the model extends displayed in Figure 1. The south-western boundary at the Leopoldsdorf fault has been adjusted in order to take the fault geometry into account. This was necessary to consider the thermal anomaly, caused by a major thermal water system located right beyond the fault (see Chapter 2.1.5).

2.1.2 Vertical extent

The upper boundary is defined along the topography - surface, the lower boundary is set in a depth of 15 km below sea-level. This big vertical extend is needed to take all geological features of the Vienna Basin into account, as the lowest part of the pre-tertiary basement is situated in a depth of about 12 km below sea-level.

2.1.3 Geometry

The major surfaces were modelled using the software package Gocad™ and have been afterwards transferred to COMSOL Multiphysics™ via ASCII files.

The following main geological units have been considered:

i. Crystalline basement; including Bohemian Massive, Tatric and Lower Alpine Units (aquiclude)
ii. Flysch units (aquiclude)
iii. Mesozoic Carbonates : Mesozoic cover of the Central Alpine and Tatric units (aquifer)
iv. Calcareous Alpine (Upper Alpine) Units (aquifer)
v. Neogene basin sediments (both aquifers and aquicliudes).

The Upper Alpine Units were subdivided on the basis of 3D interpolation of the material properties into the following nappe systems: Bajuvaric-, Tirolic-, Juvavic- nappe systems as well as Gosau Units and the Greywacke Zone (see Chapter 2.1.6).

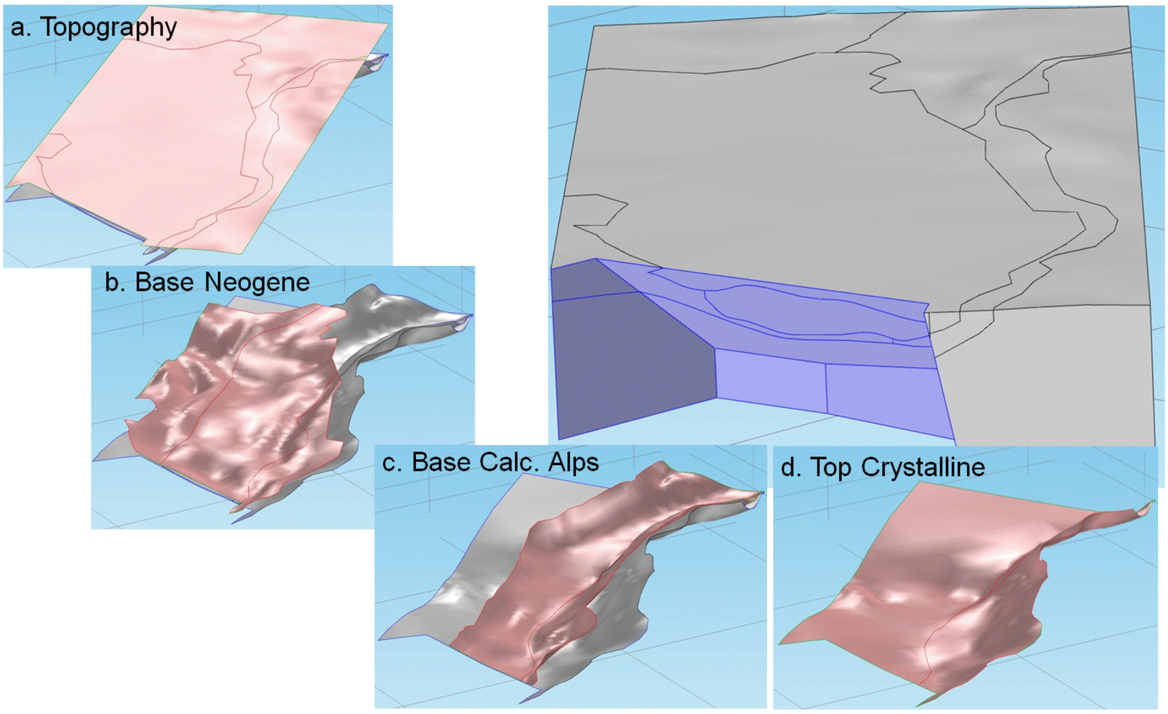


Figure 10: Comsol model. a-d: Major surfaces building up the model.

2.1.4 Mesh

The mesh (numerical representation of the geometry) consists of around 3.4 million tetrahedrons, ranging from around 0.5 to 10 kilometres (side length). The smallest elements are found in the Neogene Sediments, while the largest ones are located in the crystalline subdomain.

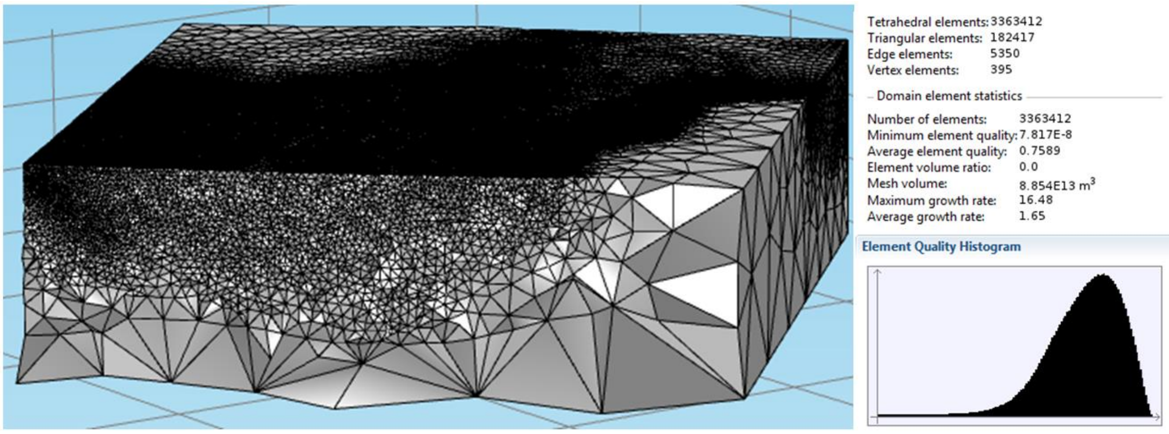


Figure 11: Left: Mesh representation, cut through the basin. Right: Mesh statistics. Both screenshots from COMSOL Multiphysics.

2.1.5 *Boundary conditions*

The surface temperature is set as boundary condition on the top of the model as altitude dependent function derived by Götzl et al (2010):

$$T_C(z) = 12°C - 0.0041\frac{°C}{m} \cdot z \tag{1}$$

At the bottom of the model a constant heat flux boundary condition was applied and iteratively adapted using measured temperature data from more than 160 wells. This iterative procedure resulted in an average bottom heat flux of 71 mW/m².

To map the thermal anomaly at the Leopoldsdorf fault, a fixed temperature boundary condition was set at the concerning boundaries (see the blue boundaries at Figure 10). The used temperature values were obtained from a model of the southern Vienna Basin from a previous study (Götzl et al, 2012).

2.1.6 *Material properties*

Using drilling core measurements and results from previous geothermal studies in the Vienna Basin, the required petrophysical parameters (porosity, thermal conductivity, heat capacity and density) could be determined. The selection of investigated rock samples and borehole measurements followed available wells from the hydrocarbon industry, but considering all relevant main geological units. The Crystalline, Flysch Units and the Upper Austroalpine Mesozoic Carbonates are considered to have invariant, isotropic material properties. The variation of parameters within the Calcareous Alps, consisting of Bajuvaric-, Tirolic-, Juvavic-, the Gosau Units, are taken into account through 3D interpolation functions. The Greywacke zone is also part of the same subdomain. Table 3 shows a compilation of the material properties used for steady-state modelling. Since the heat capacity is not used in the stationary heat equation, it is not listed in the table.

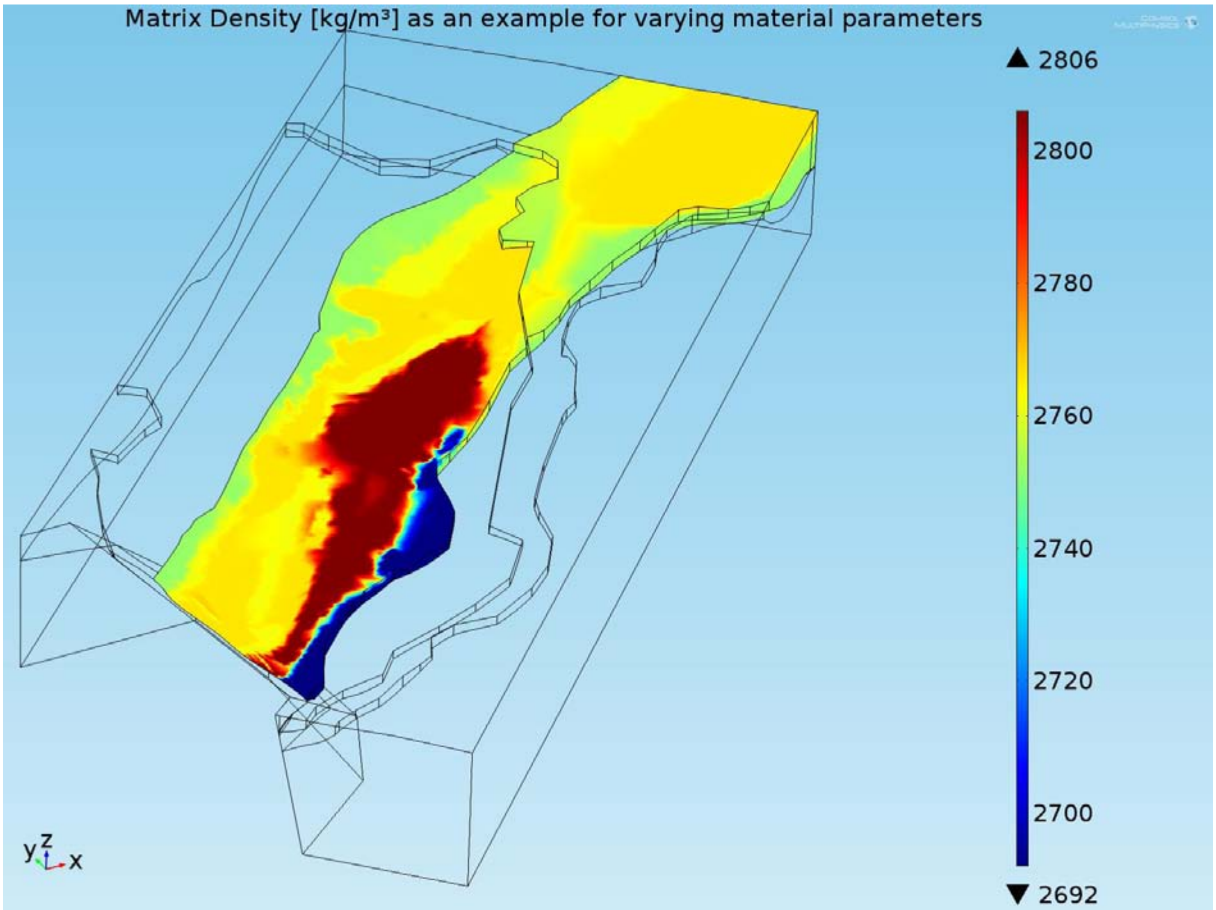


Figure 12: Matrix density of the Upper Alpine Units [kg/m³]; example for variation of material properties.

Table 3: Material properties used for modelling of the pilot area.

	Horizon	Thermal Conducivity (Matrix) - [J/(m*K)]	Porosity [%]	Matrix Density [kg/m³]
	Neogene Sediments	3.20	21.72	2060
Calc. Alpine	Gosau Sediments	3.17	0.04	2762
Calc. Alpine	Tirolic	3.24	0.04	2766
Calc. Alpine	Bajuvaric	2.74	0.05	2752
Calc. Alpine	Juvavikum	4.34	0.04	2806
Others	Greywacke	4.81	0.02	2692
Others	Mesozoic Carbonates	3.90	0.05	2595
Others	Flysch	3.80	0.07	2634
Others	Crystalline	3.67	0.02	2634

2.1.7 Calibration and validation of the model

The calibration of the model is based on empirical (Figure 14) and statistical evaluation of the residuals between measured (derived from Drill Stem Tests) and modelled temperature values. The aim of the calibration is to derive an optimal value for the basis heat flux, while the thermal properties of the different geological units are fixed. Otherwise one would run the risk of getting lost in too many degrees of freedom. Figure 13 shows the statistics of the residuals with a bottom heat flux of 71 mW/m² (optimal fitting). The modelled temperature values are compared to measurements from 'Drill Stem Tests' and show a mean deviation of 0.02(±6.8) K or +0.33(±8.1) % (Figure 13b). The absolute deviation (Figure 13a) is evaluated as geometrical distribution with p=0.163 and delivers an expected value for the deviation of 6.13 (±5.6) K. The statistical evaluation of the results is carried out using *Matlab, Excel* and *'Grapher 8'*.

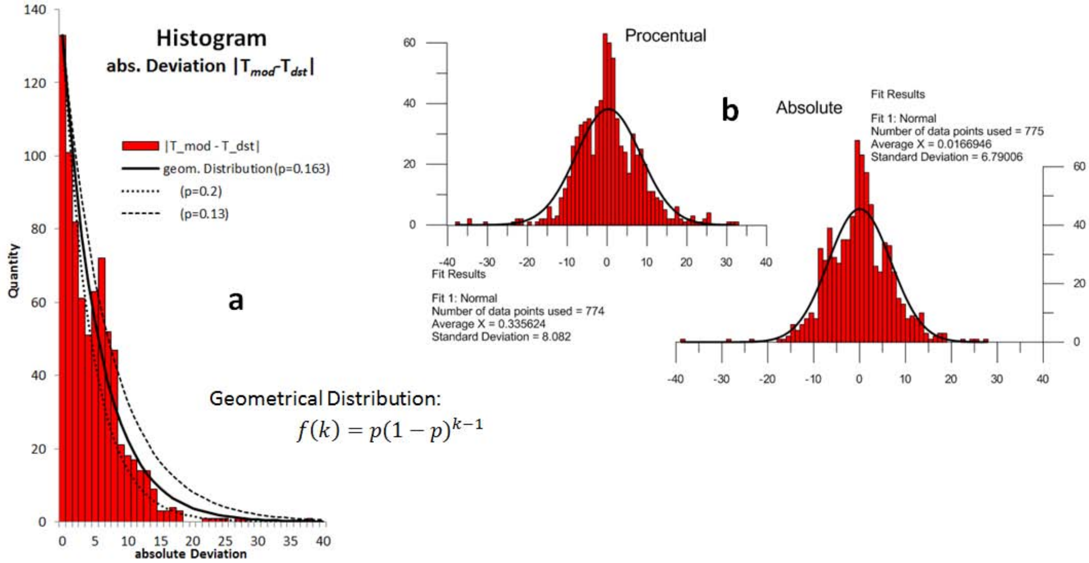


Figure 13: Statistics of the deviations between measured and modelled temperatures.

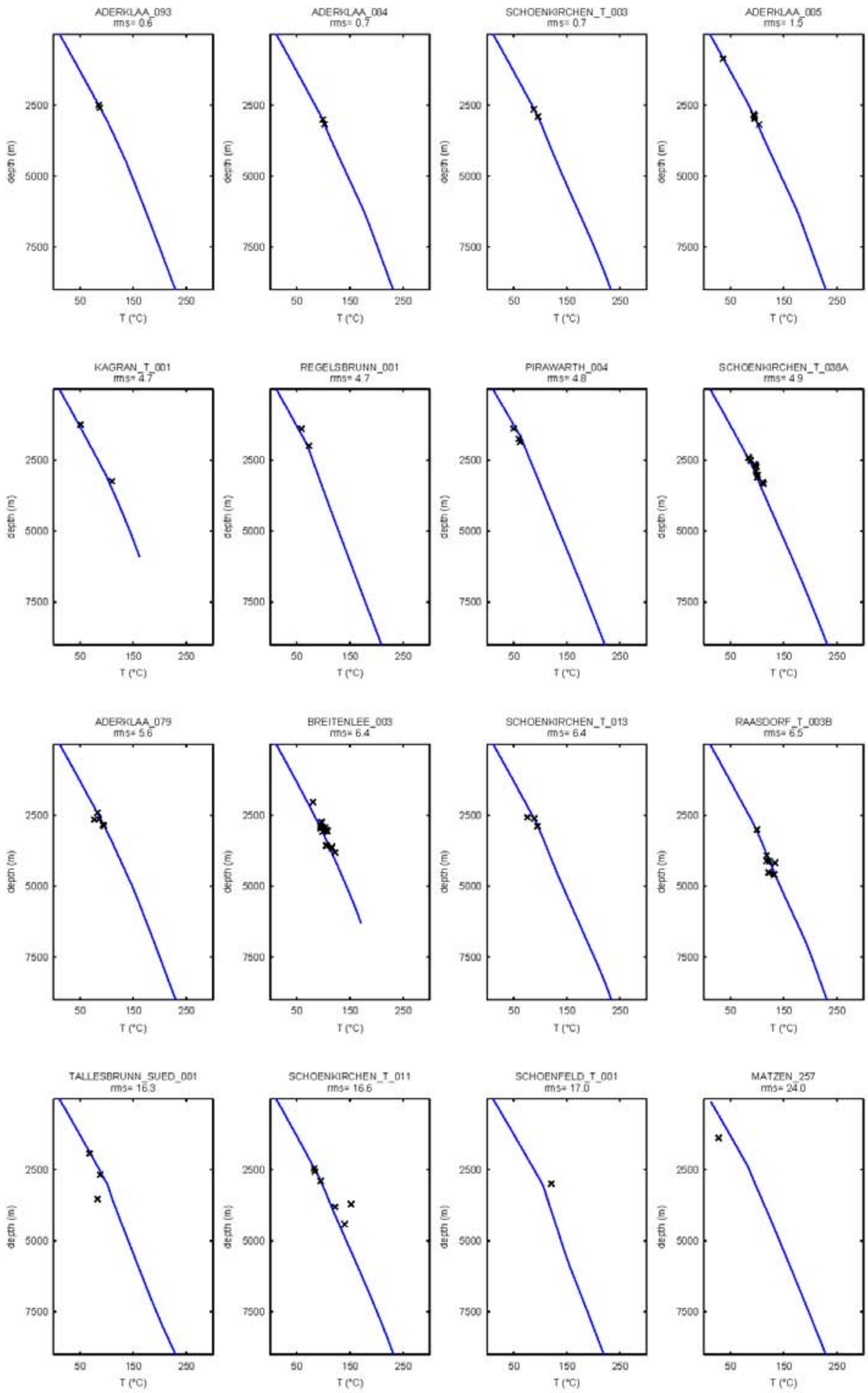


Figure 14: Compilation of comparisons between DST-temperatures (x's), and modelled temperature data (blue lines). The profiles are sorted via the rms-fit from good (upper left) to poor (lower right corner).

3 Parameter study in order to estimate empiric Heat-Recovery-Factors

3.1 Introduction

The term “Heat-Recovery-Factor” (HF) describes the amount of heat stored in a porous subsurface volume (Heat in Place), which can technically be utilized. Analytical approaches to calculate HF values are for example described by Gringarten (1978). While the influence of the initial and actual reservoir temperature on the HF can easily be considered, influences of the hydraulic properties and the geometrical settings of the reservoir are mostly limited to site-specific empirical surveys. In general the HF is for a geothermal aquifer is varying between 0 (0% of the stored heat can be technically utilized – this represents the situation at an aquiclude) and 0.3 (30% of the stored heat can be extracted).

In order to estimate the technically amount of energy, which can be used for energy supply (hydrogeothermal resources) an empirical investigated has been executed based on a numerical 3D parameter study in order to correlate the non-temperature depending components of the HF to hydraulic rock properties, which can be derived from borehole investigations. The parameter study founds on an idealized homogenous and isotropic Darcy-flow 3 layer block. As a consequence of this the elaborated results can be applied both on porous sedimentary geothermal plays as well as on fractured geothermal plays in a first approach. The achieved correlations between HF and hydraulic rock properties have been used in order to estimate the geothermal resources based on a simplified 2D raster approach (see also chapter 6.2).

3.2 General workflow and model set-up

The numerical parameter study was carried out using the software package FEFLOW™ by applying the following workflow:

1. Geometrical dimensioning of the model geometry with respect to interferences at the model boundaries.
2. Build-up of the model geometry
3. Setting of default material properties and boundary-conditions.
4. Set-up of the parameter study: variation of parameters and scenarios.
5. Simulation cycles, post-processing and intepretation.

3.3 Geometrical dimensioning

The inapproriate geometrical dimensioning of a numerical model may lead to errative results due to insufficient boundary conditions, which are mostly represented by constant or no-flow conditions. In case the extend of the model in three dimensions (x-,y,z direction) is chosen too small, feedback loops may leed to biased results, which are commonly overestimating physical transport effects.

The relevant transport effects are represented by (a) hydraulic flow around the geothermal doublet (no-flow conditions at the lateral model boundaries) and (b) conductive heat transport provoced by the geothermal use towards the base of the model (constant heat-flux conditions).

In order to consider hydraulic flow (a) the lateral extend of the cube has been set 5 times larger than the maximum supposed distance between the production and injection well (hydrogeothermal doublet). The hydrogeothermal doublet itself has been placed around the midpoint of the cube.

In a next step the vertical length of influence towards the base of the model due to the injection of cold water with respect to thermal conduction was executed using analytical approaches based on the Gaussian error-function. This was done in order to calculate the minimum distance bewteen the base of the model an the base of the investigated aquifer assuming (i) 50 years and (ii) 100 years of constant reinjection of cold water at a temperature difference of ΔT = 50°C reffered to the undisturbed temperature level of the aquifer.

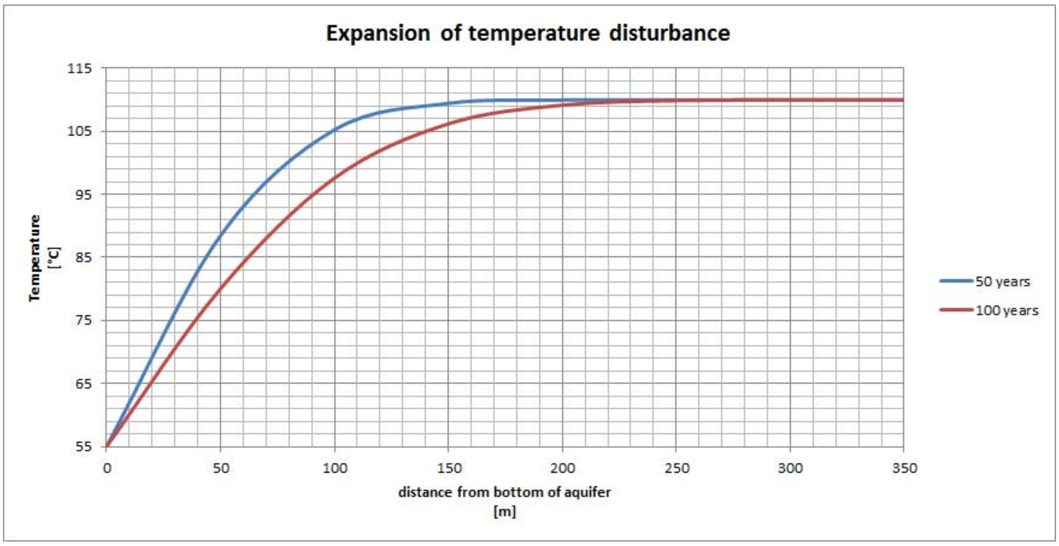


Figure 15: Expansion of a temperature disturbance of ΔT=50°C based on conductive heat transport.

As shown in Figure 15 the maximum expected propagation of a temperature disturbance driven by conduction at the assumed conditions is limited to around 200 meters. At means a minimum distance of 200 meters had to be considered between the base of the reservoir and the base of the model in order to avoid conflicting thermal boundary conditions.

3.4 Definition of model

Geometrical dimension	3D Lateral extend: 5000 x 5000 meters Vertical extend: 5000 meters Vertical Datum: depth below surface
Geometrical build-up	3 layers Layer 1: Aquiclude (marlstone), Interval [0 – 2500] Layer 2: Aquifer (dolomite), interval [2500 – x] Layer 3: Aquiclude (marlstone), interval [x – 5000] x... Base of Aquifer: variation between 2600 - 3500
Material properties	Hydraulic: conductivity (isotropic), porosity (isotropic) Thermal: thermal conductivity (isotropic), volumetric heat capacity (isotropic) See also Table 4
Boundary conditions	Thermal: - Top: constant temperature of10°C - Bottom: constant heat flux of 70 mW/m² - Lateral: isolated - Injection well: constant temperature of 55°C Hydraulic: - Hydraulic head: 0 m (hydrostatic pressure) - Lateral: isolated (no flow) - Injection & production well: constant yield of 50 l/s - Screen length (effective thickness of aquifer): 2/3 of the total thickness of the aquifer
Coupled transport processes	- Heat conduction (steady & transient) - Darcy flow (transient) - Advection & convection (transient)
Simulated operational period	50 years

Table 4: Default material parameters of the numerical model used for the parameter study

Unit	K [x,y,z]	ϕ_{eff}	ρc_p	λ
	[m/s]	[%]	[MJ/(m^3 K)]	[W/(m K)]
Layer 1 (Marlstone)	10^{-11}	2	2.4	3.50
Dolomite	10^{-7}	7	2.5	5.62
Layer 3 (Marlstone)	10^{-11}	2	2.4	3.50

3.5 Applied workflow of the numerical modelling

i. Simulation of the steady state temperature field

ii. Parameter study: coupled thermal- hydraulic field (transient)

- Variation of aquifer thickness and screen lenghts (2/3 of the aquifer thickness): 50 meters – 1000 meters
- Variation of the distance between the production- and injection well: 100 meters – 1000 meters.
- Variation of the hydraulic conductivtiy at the aquifer: 10^{-10} m/s - 10^{-5} m/s .
- Variation of yield (production = injection): 10 l/s – 150 l/s.

4 RESULTS

4.1 Regional scale thermal model

The result of the pilot area model is given by a 3D temperature distribution, which is the fundament of the hydrogeothermal resource evaluation at the Vienna Basin pilot area as well as the detailed scenario modelling. COMSOL provides all necessary post-processing tools for visualisation and export of the results. Figure 16 and Figure 17 show examples for temperature distributions at specific surfaces. In the same way it is also possible to display isothermals or depth-slices. All plot data can be exported in multiple graphics formats as well as in ASCII format for further processing.

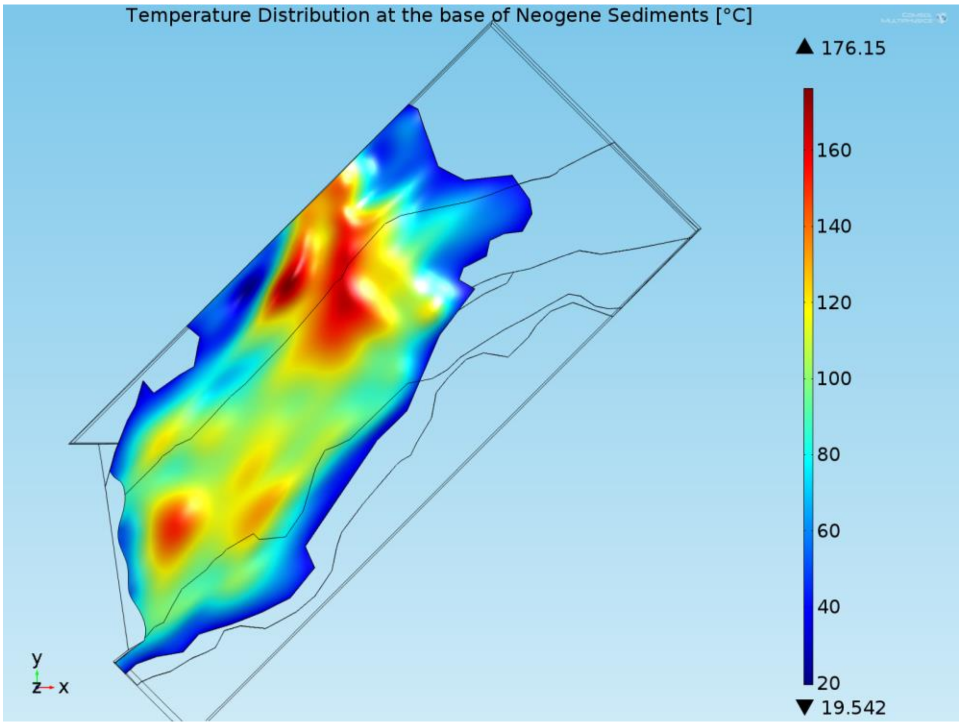


Figure 16: Temperature distribution at the Base of the Neogene sediments [°C].

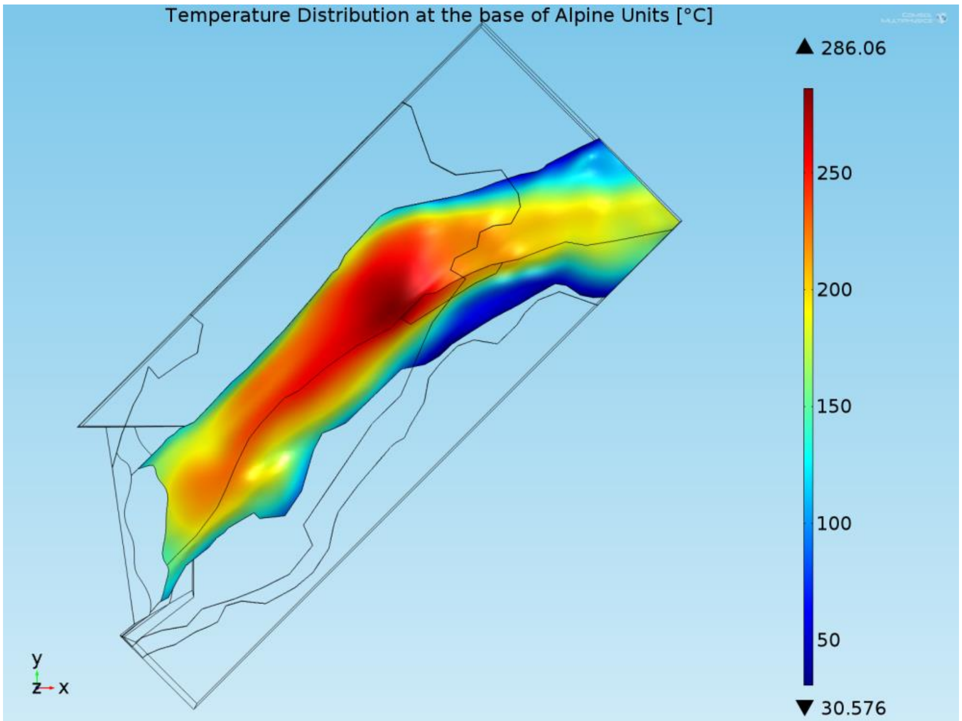


Figure 17: Temperature distribution at the base of the Alpine Units.

4.2 Parameter study

The parameter study was aiming to derive an estimative correlation between the so called Heat Recovery Factor and hydraulic reservoir properties (transmissivity). The following chapter is treading the main outcomes and findings of the executed numerical studies. The correlation itself will be presented at a separate report published on the Transenergy website.

The main results achieved are represented by:

- The effect of the aquifer thickness on the Heat Recovery Factor (HF)
- The effect of the hydraulic conductivity on the HF
- The role of the distance between the wells of a dublet
- The influence of the yield (production, injection) on the HF with respect to the hydraulic conductivity of the aquifer

The Heat Recovery Factor is crucially governed by the minimum distance between the two wells (production and injection) of a hydrogeothermal dublet. Therefore the chosen approach is to correlate the HF with the required minimum distance between the wells of dublet as a function of the above listed parameters of influence.

4.2.1 The effect of the aquifer thickness

The starting point of all numerical parameter studies was represented by a steady state thermal model (heat transport by conduction) with respect to the chosen different aquifer thicknesses.

The modelling was performed using FEFLOW™, which lead to the calculation of the stored Heat in Place (HIP) considering the bulk aquifer volume (heat stored in fluids as well as in the solid rock matrix). The calculated HIP represents the maximum possible amount of heat, which can be extracted from the subsurface volume. This is equal to a HF of 1 (100% heat recovery).

The subsequent Table 5 shows the calculated HIP for the different aquifer thicknesses:

Table 5: Calculated Heat in Place considering different aquifer thicknesses

Aquifer thickness [m]	Volume of aquifer [m^3]	HIP aquifer [J]	Mean capacity of aquifer [GW]
50	1.25×10^{9}	8.5×10^{16}	3
100	2.5×10^{9}	1.7×10^{17}	6
500	1.25×10^{10}	9.4×10^{17}	36
1000	2.5×10^{10}	2.1×10^{18}	80

The mean capacity is referring to the HIP assuming a total operation time of 50 years in full operation (8760 hours per year).

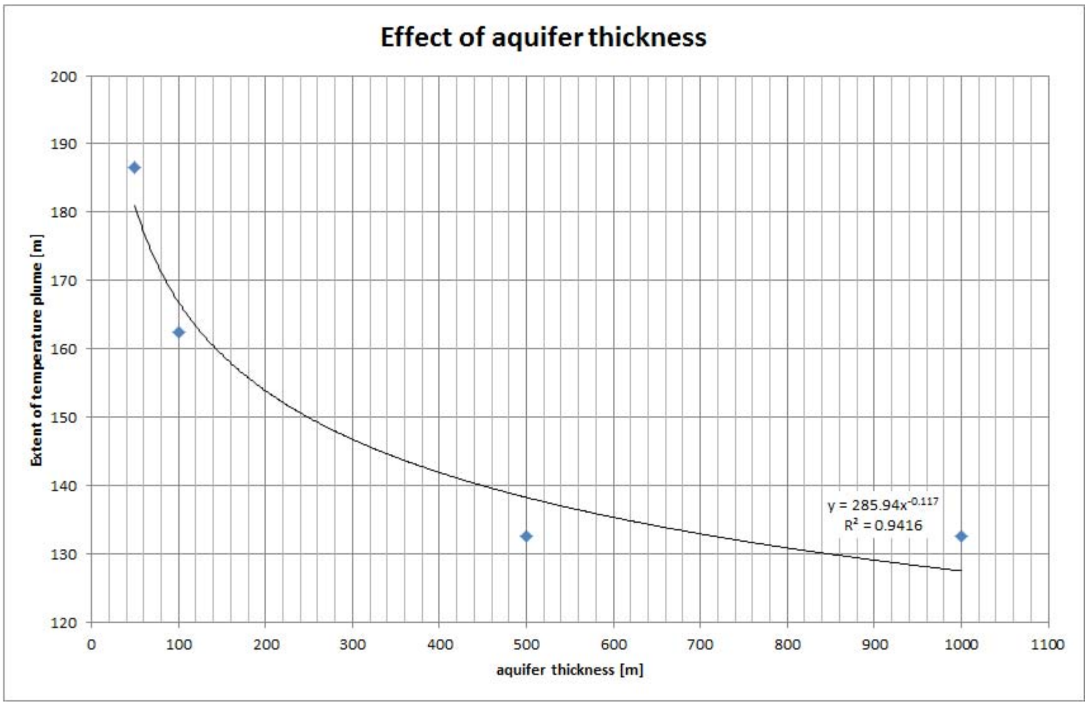


Figure 18: Maximum extend of a thermal plume as a function of different aquifer thicknesses

For investigating the influence of the aquifer thickness on the Heat Recovery Factor a varying screen length of 2/3 of the aquifer thickness was assumed (equals the effective thickness of the aquifer). The influence of the aquifer thickness on the HF was estimated by picking the maximum extend of the thermal plume around the injection assuming a constant injection at a temperature level of 55°C. As shown in Figure 18 the maximum extend of the resulting thermal plume shows saturation trends. The maximum extension of the plume does not rise significantly after reaching a critical thickness of around 500 meters. A significant sensitivity was observed in small thicknesses below 100 meters. However, the total observed range of variation was limited to the factor 1.4 assuming aquifer thicknesses between 50 meters and 1000 meters (factor: 20). Therefore the overall sensitivity of the aquifer thickness can be seen as low.

4.2.2 The effect of the hydraulic conductivity

The effect of the hydraulic conductivity on the Heat Recovery was investigated assuming an aquifer thickness of 100 meters (screen length of 60 meters) and an initial mean reservoir temperature of 81°C. It was defined a priori, that the extension of the plume is limited to an attenuation of the reservoir temperature of 1°C.

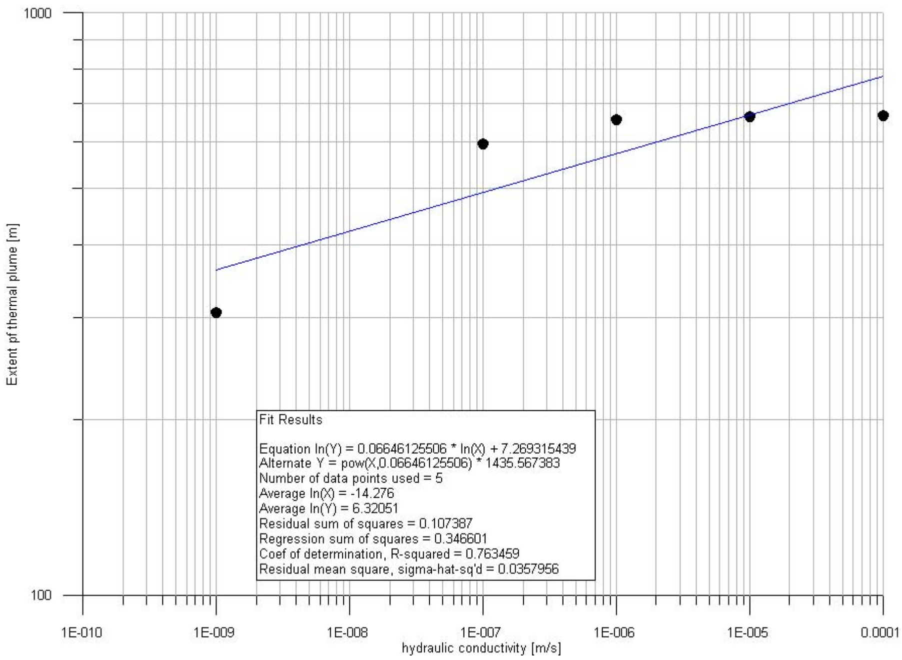


Figure 19: Extent of thermal plume as a function of hydraulic conductivity for a distance of 1000 meters between the wells of a hydrogeothermal dublet.

As shown in Figure 19 the maximum extension of the thermal plume as a function of varying hydraulic conductivities once again show a clear saturation at hydraulic conductivities above 10^{-7} m/s. In case of a well distance of 1000 meters the maximum extension of a hydrothermal plume is limited to around 700 meters.

4.2.3 The effect of the distance between the wells

It has to be pointed out, that the distance of the wells has a considerable influence on the hydraulic regime between the wells (hydraulic gradients) and therefore influences the thermal breakthrough time. Once again the behaviour of saturation may be expected for critical distances of around 1000 meters between the wells. At greater distances the effect of influencing the hydraulic regime can be neglected. In the framework of the parameter study several different distances between the wells in the range of 100 meters and 1000 meters have been assumed. Considering an operation lifetime of 50 years as well as an aquifer thickness of 100 meters it was aimed to (i) identify a minimum required distance between the wells of a dublet and (ii) to investigate the thermal breakthrough time as a function of the hydraulic conductivity and the well distance.

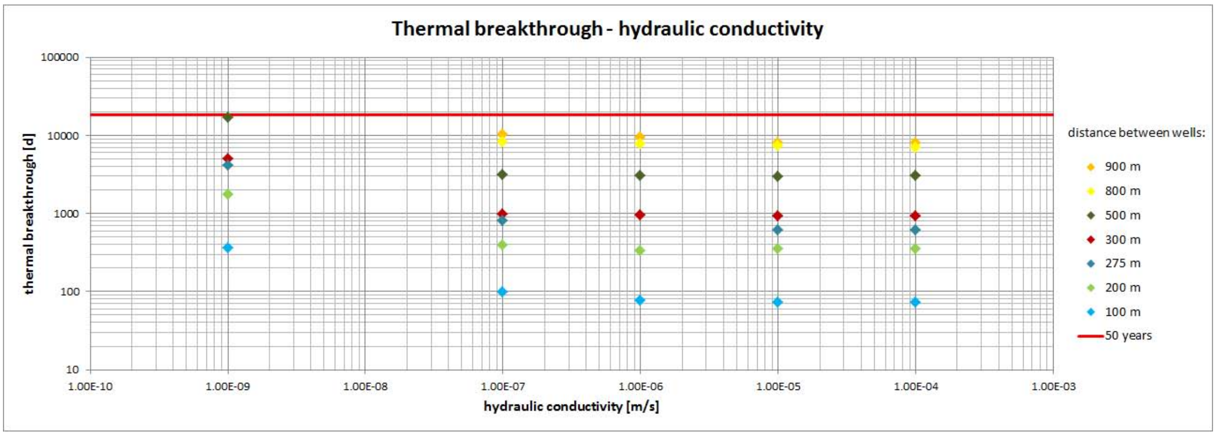


Figure 20: Thermal breakthrough time as a function of the hydraulic conductivity for different distances between the wells.

As shown in Figure 20, well distances below 500 meters led to a thermal breakthrough before the presumed 50 operational years irrespective to the assumed hydraulic conductivity. Even at well distances of 900 meters early thermal breakthroughs have been observed for hydraulic conductivities above 10^{-8} m/s. For that reason a minimum required distance between the wells of a dublet of 1000 meters is proposed for the chosen scenario (aquifer thickness of 100 meters).

In the subsequent Figure 21the distribution of the reservoir temperature is shown for several hydraulic conductivities and different distances along a cross section between the production well and the injection well of a hydrogeothermal dublet. As the reservoir is approached by an idealized homogeneous porous aquifer, all graphs except for small hydraulic conductivities show similar slopes of the attenuation of temperatures. At small hydraulic conductivities (10^{-10} m/s) the effect of heat transport by conduction starts to become more important. This is resulting in a steeper slope of the attenuation along the cross section.

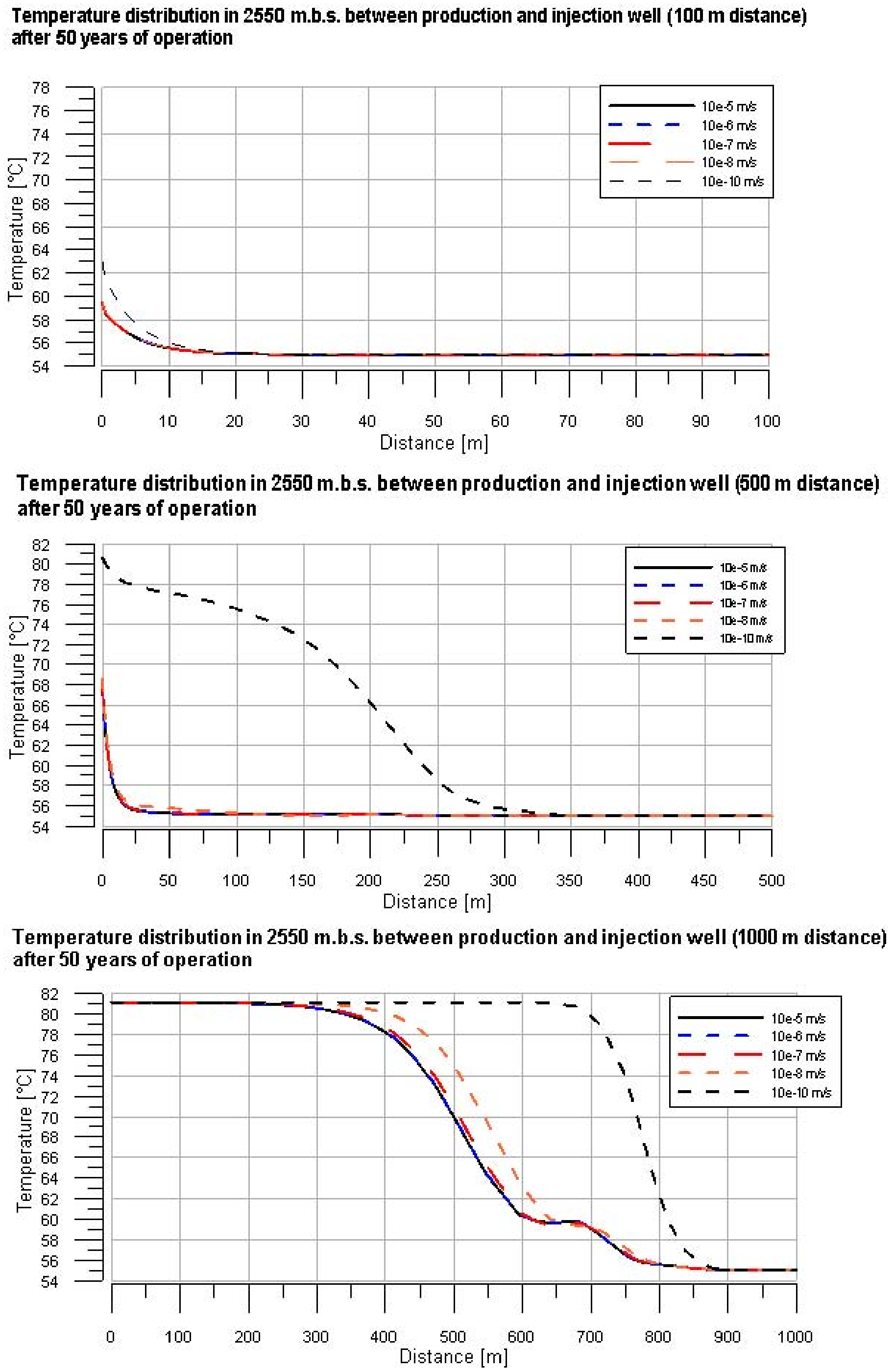


Figure 21: Temperature distribution in a depth of 2550 m between the production (0 m) and the injection well (well distance: 100 m, 500 m and 1000 m).

4.2.4 The effect of the yield with respect to the hydraulic conductivity

In order to investigate the effect of varying constant yields on the maximum extension of a thermal plume the above mentioned default aquifer parameters (thickness: 100 meters, hydraulic conductivity 10^{-7} m/s) were assumed. As shown in the subsequent Figure 22 a linear correlation between the yield and the maximum extension of the thermal plume at a significant sensitivity has been observed.

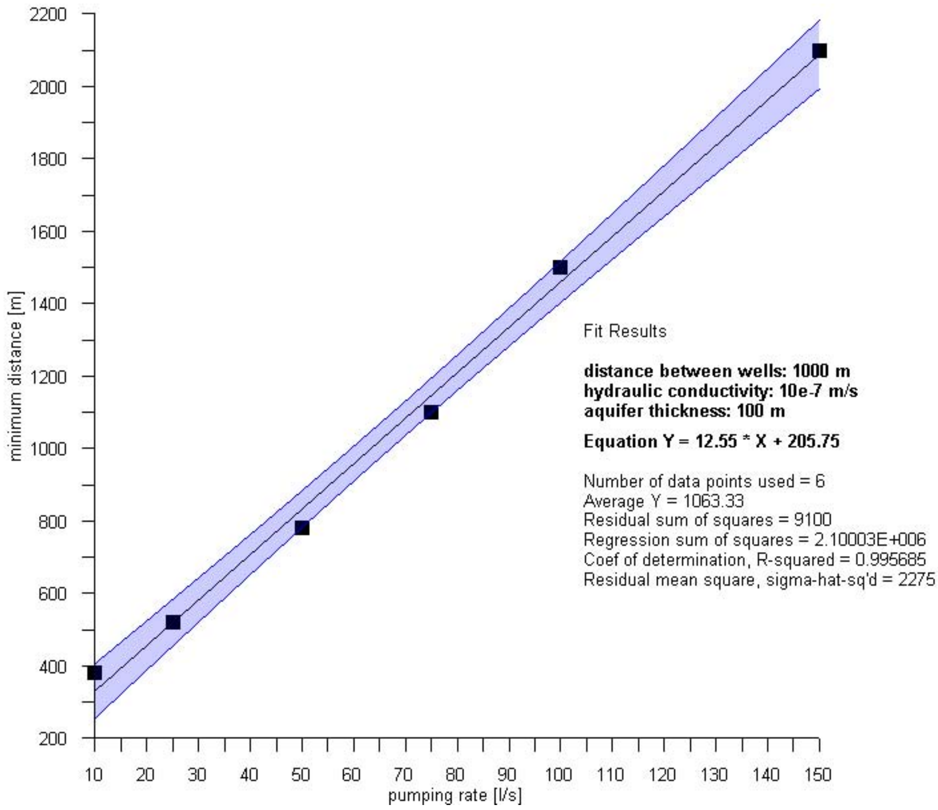


Figure 22: Extent of the thermal plume (=minimum distance) as a function of the pumping rate. The blue area covers the range of confidentiality associated to the linear fitting.

The yield crucially influences the hydraulic regime at the reservoir. In order to derive a more general correlation between the HF and the yield more parameters studies with respect to varying aquifer thicknesses and hydraulic conductivities will have to be executed.

5 Summary and Conclusions

The results of the regional scale thermal modelling deliver crucial data for further estimation of hydrogeothermal resources at the Vienna Basin pilot area and will be used for the subsequently following scenario modelling. The statistical evaluation of the results shows a good fit to the measured data. In total 775 DST temperature values from 235 wells were used for validation of the modelled subsurface temperatures. This evaluation shows that the applied simple 3D conductive thermal model was able to fit the observed subsurface temperatures in satisfying way although neglecting the effect of thermal convection. For the current study the measured temperatures are only used for validation of the model, detailed interpretation of these results is left open for further research.

The executed parameter study exhibits the dependence of the minimum required distances between the wells of a hydrogeothermal dublet as function of the aquifer thickness, the hydraulic conductivity and the yield. The distance between the wells of a dublet is in turn crucially influencing the so called Heat Recovery Factor (amount of technically extractable heat) of a geothermal reservoir. The influence of the aquifer thickness and the hydraulic conductivity shows a similar asymptotical behaviour passing critical values of (i) an aquifer thickness of more than 500 meters and (ii) a hydraulic conductivity of above 10^{-7} m/s. The yield of course shows of course a great influence on the minimum distance between the wells of a hydrogeothermal dublet. In order to consider the influence of the yield in a more general way further parameter studies will have to be executed assuming greater thicknesses of the aquifer as well as varying hydraulic conductivities.

6 Outlook

The following chapter is dealing with the remaining modelling steps in the framework of the Vienna Basin pilot area analyses. The modelling will focus on:

- The detailed scenario modelling at a selected hydrogeothermal play
- The 2D based raster analyses in order to estimate the hydrogeothermal potentials (Heat in place) and hydrogeothermal resources for the selected geothermal plays at the Vienna Basin pilot area.

6.1 Local scale scenario modelling

The scenario modelling is still in progress and will be reported separately. Nevertheless, the methodology and actual state of progress will be discussed in this chapter.

6.1.1 Introduction

The Wetterstein-Dolomite geothermal play has been figured out to be the most promising trans-boundary geothermal reservoir in the Vienna Basin pilot area (see also chapter 1.3). Because of the high salinity of the thermal waters of this aquifer they are not applicable for balneological purposes. Hence, the only possible utilisation can be a pure energy usage, realized by a dublet installation with complete reinjection of the thermally deployed brine.

The main objectives of the detailed scenario modelling are represented by:

- Analyses of the hydraulic influence of (i) fault systems and the geometrical shape of the reservoir on the coupled hydraulic and thermal conditions of different doublet-use scenarios, represented by different locations and operational settings.
- Calculation of Indicated geothermal Resources based on different assumptions of the hydraulic behaviour of the geothermal plays (see above).
- Calculation of Indicated geothermal Resources for different hydrogeothermal utilization scenarios (see also chapter 1.4).

The area of interest shows a lateral extension of about 15 x 3 km, striking approximately along a SE-NW direction. The river March and the Austro-Slovakian boarder crosses the body right in the middle in N-S direction. On the Austrian side, large parts of the watersides of the river March are protected by "Natura 2000 - European Nature Reserve". Hence no surface hydrogeothermal installations, such as wells or heating facilities are considered to be legally allowed in this area. In opposite "Záhorie Protected Landscape area" is situated on the Slovakian side along the river Morava / March. Despite of this fact, the location of the Slovakian hydrogeothermal dublets has been set within this protection area nearby the village of Visoká pri Morave. This was done in order to investigate possible trans-boundary hydraulic flow and thermal influences at the reservoir.

On the Austrian side of the reservoir three abandoned hydrocarbon wells (SCH-T1, SCH-1 and BG-4) could possibly be used (re-entry) for geothermal usage (OMV AG & ARGE Tiefe Geothermie, 2009) and supply the Gänserndorf / Strasshof area (approx. 20.000 inhabitants) with energy (heat and electric power). At least the above mentioned have proofed the evidence of thermal water at the investigated reservoir (see also Table 6). On the Slovakian side we considered the Zohor – Láb – Záhorská Ves triangle containing about 10.000 inhabitants as a plausible area for geothermal supply of heat.

Table 6: Depth interval and maximum observed temperatures at DST tests for the Wetterstein-Dolomite geothermal plays, observed at Austrian hydrocarbon exploration wells.

Well	Drilled Depth Interval (m b.s)	Maximum observed temperature (degC)
SCH-T1	2985 - 3508	121
SCH-1	3042 - 4005	128
BG-4	2784 - 2842	92

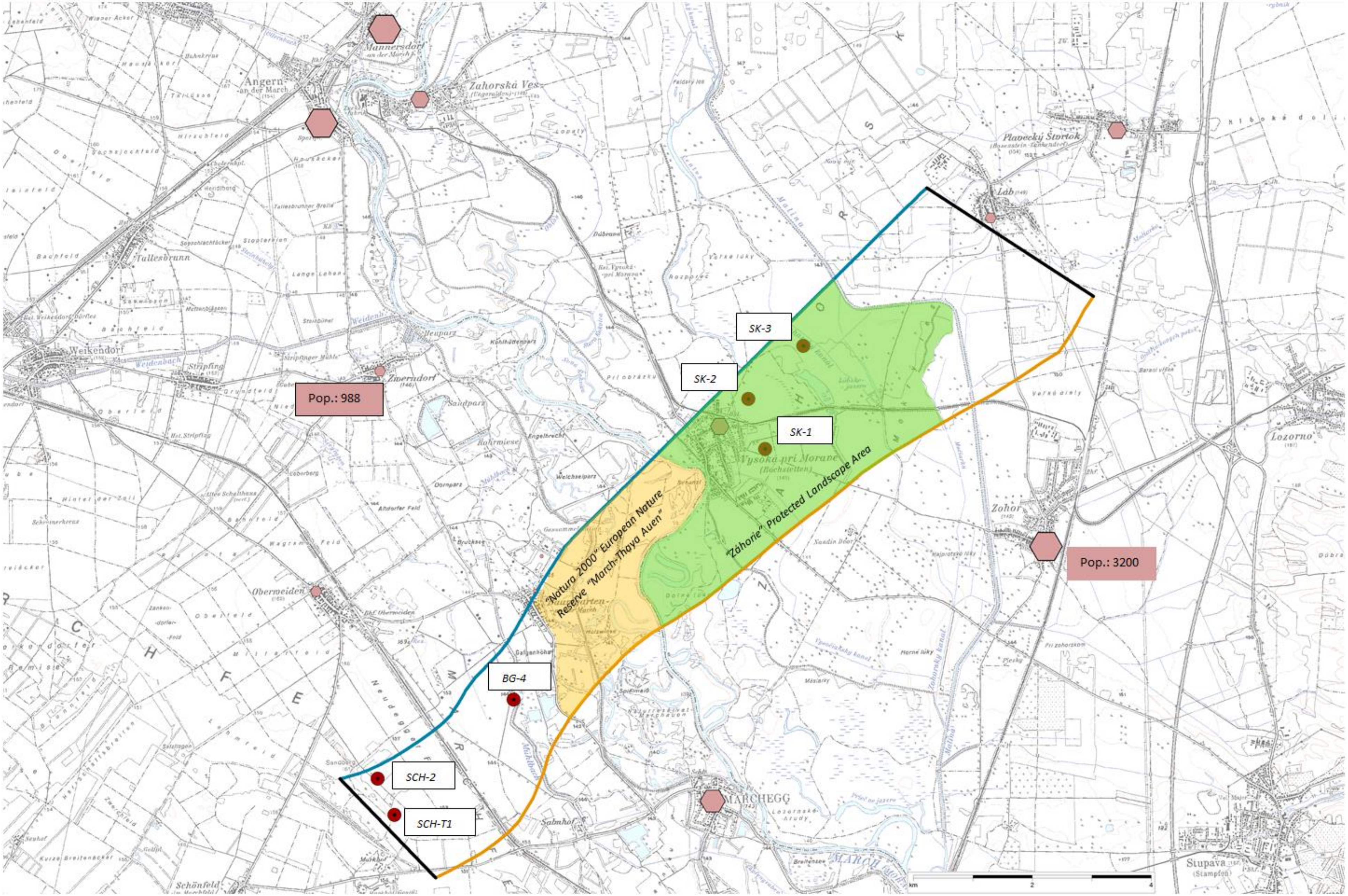


Figure 23: Outline of the scenario model „Schoenfeld-Láb". The red dots show possible well locations, the size of the hexagons display the population of the bigger settlements in the vicinity of the hydrogeothermal play 'Wetterstein-Dolomite'.

6.1.2 Model setup

The scenario modelling is carried out using the Finite Element subsurface Flow Simulation software FeFlow™. The model setup in FeFlow™ works as follows: The geometry is defined in two dimensions only - this called “Supermesh”. Afterwards it is translated into a triangular mesh. In the third step this triangular mesh is then extruded multiple times to produce a three-dimensional geometry consisting of various prisms. In general there are two different approaches to fulfil this task: The more common way is to start with a horizontal plain and extrude the geometry in the z-direction. In this case the geometry of the Wetterstein-Dolomite geothermal play implies a vertical approach, where the geometry is defined as cross-section and then extruded horizontally. The model consists of 90 sub-vertical slices with a maximum distance of around 150 metres. The minimum mesh size around the wells is about 10 metres. The “in-slice” resolution ranges from approx. 3 metres around the well-screens up to about 250 metres at the boundaries of the model. The fault zones are approximated by high-permeability zones of a lateral thickness of 50 metres.

<u>Well setup</u>

Two of the three selected wells on the Austrian side of the model-block drilled the Wetterstein-Dolomite complex at a tectonically undisturbed position, while one well hits a known fault zone. Since there is no information about fault systems on the Slovakian part of the Aquifer, one exemplary fault is assumed, where two of the three hypothetic wells are located. Hence all different ‘fault’- ‘no fault scenarios’ have been considered by combination of different wells in terms of geothermal doublets. The applied matrix of combination is shown in (Figure 24).

Extraction \ Reinjection	Sch T1	BG 4	SK 2	SK 3		Extraction		Reinjection
Sch T1		x			1	no fault	->	fault
Sch 2	x				2	no fault	->	no fault
SK 1			x		3	fault	->	fault
SK 2				x	4	fault	->	no fault

Figure 24: Compilation of the considered doublets.

<u>Simplifications and modifications</u>

Since the two SCH – wells are located very close to the model boundary they were displaced about 300 m towards northeast to reduce effects produced by the model-boundary (no flow and fixed temperature boundary conditions). Furthermore the wells SCH-T1 and BG-4 are set on the same slice, so only one refinement is necessary for both wells. The same approach was applied to the hypothetical wells Slovak 2 and 3. The wells Slovak 1 & 2 as well as SCH T1-2 are dislocated (shifted) in a way that only one lateral refined slice is necessary for two wells (see also Figure 25).

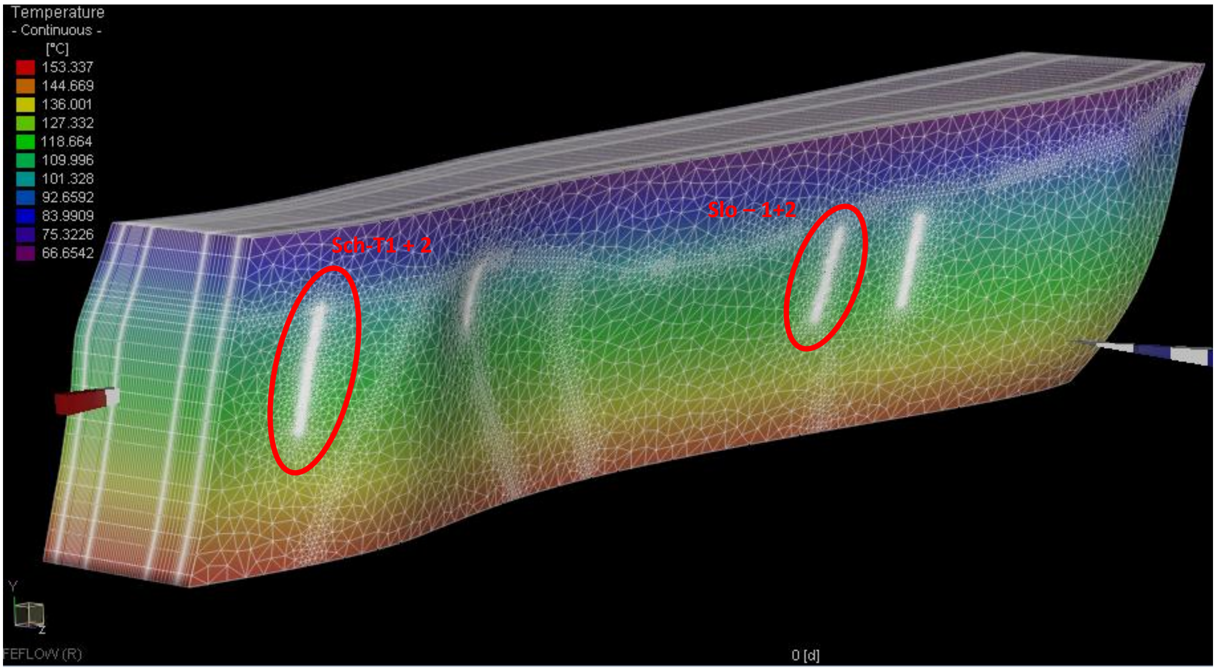


Figure 25: 3D Feflow-model of the Wetterstein-Dolomite hydrogeothermal play used for the scenario modelling.

6.1.3 *Material properties*

The thermal parameters can be adopted from the steady-state model of the pilot area (Table 3). In addition flow properties have to be added to the model. In this context the following assumptions have been applied: The Wetterstein Dolomite is a typical fractured reservoir. Hence, the flow behaviour is, strictly speaking non-Darcy. A common approximation for fractured reservoirs is the tensor form of the Darcy equation, where it is possible to incorporate the conductivity as anisotropic values. Log interpretations done in previous studies indicate a main fracture orientation of the Wetterstein Dolomite of 110/70 (strike/dip-Notation) towards North-Northeast.

Inside the fault zones crossing the Aquifer the conductivity is expected to be elevated. No exchange between the Neogene Sediments and the Dolomite is expected, so a very small conductivity is assigned for the sedimentary layers above. There is an evidence for an approximately 50 metres thick layer of Breccia at the base of the Neogene. The influence of such a high conductivity layer can be surveyed in the framework of the scenario modelling.

6.1.4 *Boundary conditions*

Since there is no natural flow occurring in the considered aquifer, all boundaries can be considered as "no flow boundaries". The hydraulic head has to be set at some nodes at the top as reference and of course at the well nodes a "Well BC" has to be set. To take the fact into account, that the fractures are not evenly distributed, not the whole well screen is activated as "Well BC". Instead the Well boundary condition has only been applied on five nodes per well (see also Figure 26). If a well screen is hitting a fault zone, the activated nodes are placed inside that fault zone, otherwise they are distributed randomly over the screen. The reinjection temperature is assumed with 50 °C and applied as constant Temperature BC at the points of reinjection.

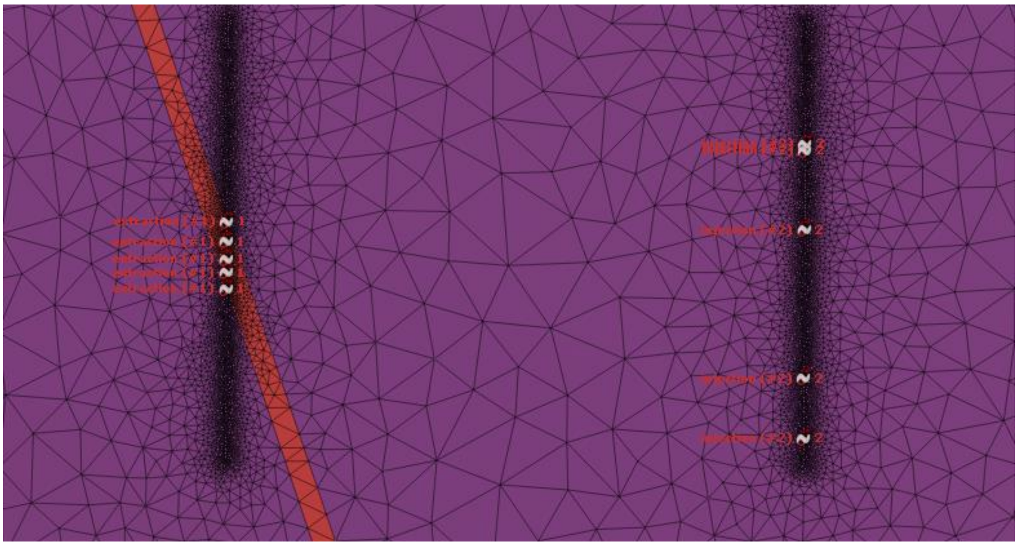


Figure 26: Distribution of the “Well BC” at the screens of the wells SK-2 and SK-3. Red: fault zone

6.1.5 Results

The results and more detailed information on the workflow of the scenario modelling will be reported at a separate report.

6.2 Estimation of hydrogeothermal potentials and resources in geothermal plays at the Vienna Basin pilot area

For all selected hydrogeothermal plays at the Vienna Basin pilot area hydrogeothermal potentials and resources will be investigated at several scales of resolution. Starting at the most general level the following scalar significant values describing the theoretical geothermal potential (maximum available amount of geothermal energy) for all selected hydrogeothermal plays (see also chapter 1.3) will be calculated:

- The Natural Heat Recovery
- The stored Heat in Place
- The Advective Heat Content (fraction of natural Heat Recovery)
- The actual Degree of Exploitation with respect to hydrogeothermal use.

All analyses will be performed using 2D raster- (resolution 100 meters up to 1000 meters) as well as scalar probabilistic approaches.

In a second processing step the hydrogeothermal resources will be calculated for selected geothermal plays at the following different levels of confidence:

- Inferred Geothermal Resources (low confidence): hardly any reservoir parameters known
- Indicated Geothermal Resources (medium confidence): direct measurements of rock properties (raster interpolation) and reservoir temperature as well as reservoir pressure and chemical composition are available.

The hydrogeothermal resources will be derived from the previously calculated Heat in Place by applying the Heat Recovery factors gained from the parameter study.

7 LITERATURE

Deibert L. & Toohey B. (eds)., 2010, The Canadian Geothermal Reporting Code for Public reporting, Canadian Geothermal Energy Association (CanGEA), Calgary.

Götzl G., Motschka K., Janda C., Bottig M., Hoyer S., Brüstle A.K., Zekiri F., Faber R., Gegenhuber N., Schubert G., Berka R. (2012), Thermalp, Drei-dimensionales geothermisches Modell in Teilen der Ostalpen unter Berücksichtigung der Temperaturleitfähigkeit, der Wärmeproduktion und regionalen Grundwasserströme. Endbericht im Auftrag der Österreichischen Akademie der Wissenschaften, Geologische Bundesanstalt Wien. ISBN-Online: 978-3-7001-7353-3; doi: 10.1553/THERMALP.

Goetzl G., Faber R., Janda C., Schubert G. & Zekiri F., (2010), Coupled geothermal – hydraulic 3D modeling of the Southern Vienna Basin. A state of the art decision planning tool for sustainable hydrothermal exploitation inside an environment of sensitive hydraulic circulation systems, Proceedings World Geothermal Congress 2010 Bali, Indonesia, 25-29 April 2010.

Götzl G., Ostermann V., Kalasek R., Heimrath R., Steckler P., Zottl A., Novak A., Haindlmaier G., Hackl R., Shadlau S., Reitner H. (2010), GEO-Pot: Seichtes Geothermie Potenzial Österreichs. Überregionale, interdisziplinäre Potenzialstudie zur Erhebung und Darstellung des oberflächennahen geothermischen Anwendungspotenzials auf Grundlage eines regelmäßigen Bearbeitungsrasters, Österreichische Wasser- und Abfallwirtschaft, Bd. 60, S. 120 -129, Springer Verlag.

Gringarten A. C., 1978, Reservoir Lifetime and Heat Recovery Factor in Geothermal Aquifers used for Urban Heating; Pageoph, Vol. 117 (1978, 1979); Birkhäuser Verlag, Basel.

Konečný M., Lexa V., Marcin J., Maťo D., Pereszlényi J., Pašeková M., Pôbiš P., Roháč J., Slávik J., Vass M., Zvara D.,1995, Atlas geotermálnej energie Slovenska. Franko, O., Remšík, A., Fendek, M. (eds.). - Geologický Ústav Dionýza Štúra, Bratislava, ISBN 80 – 85314 – 38 - X, s. 268.

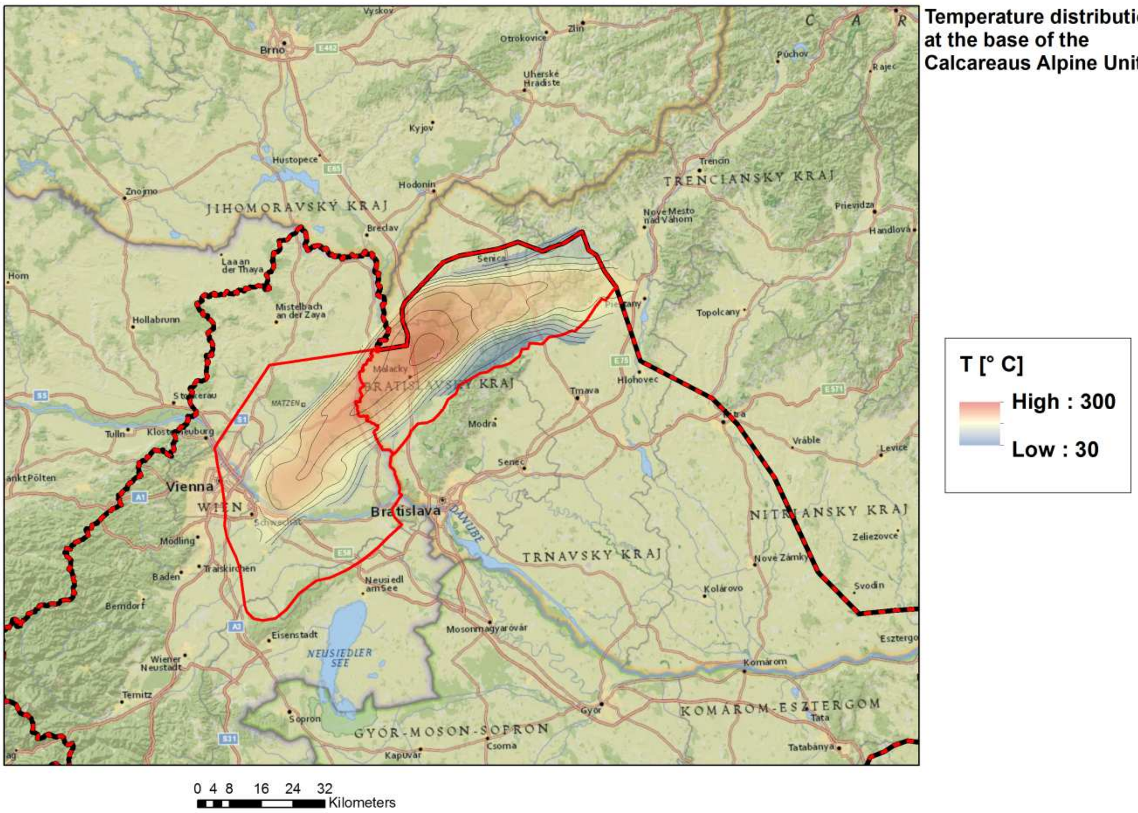
Maros G. (ed.) (2012), Summary report of geological models. 31.03.2012. http://transenergy-eu.geologie.ac.at.

OMV AG & ARGE Tiefe Geothermie (2009), Nutzungsmöglichkeiten Tiefer Geothermie im Wiener Becken (Tiefscholle), Projektphase 1 (Nachnutzung vorhandener KW-Infrastruktur). Unveröffentlichter Bericht im Auftrag der OMV AG, Wien.

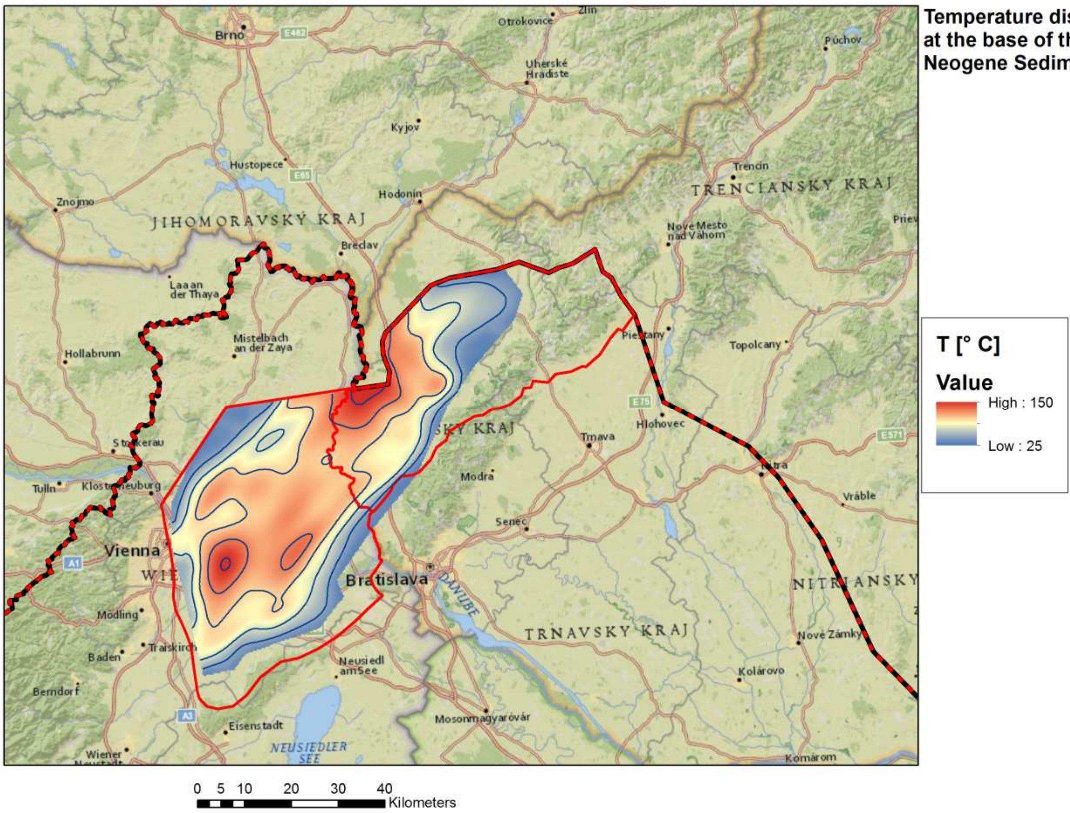
Wessely G. (ed.), 2006, Geologie der Österreichischen Bundesländer - Niederösterreich; Geologische Bundesanstalt, Wien.

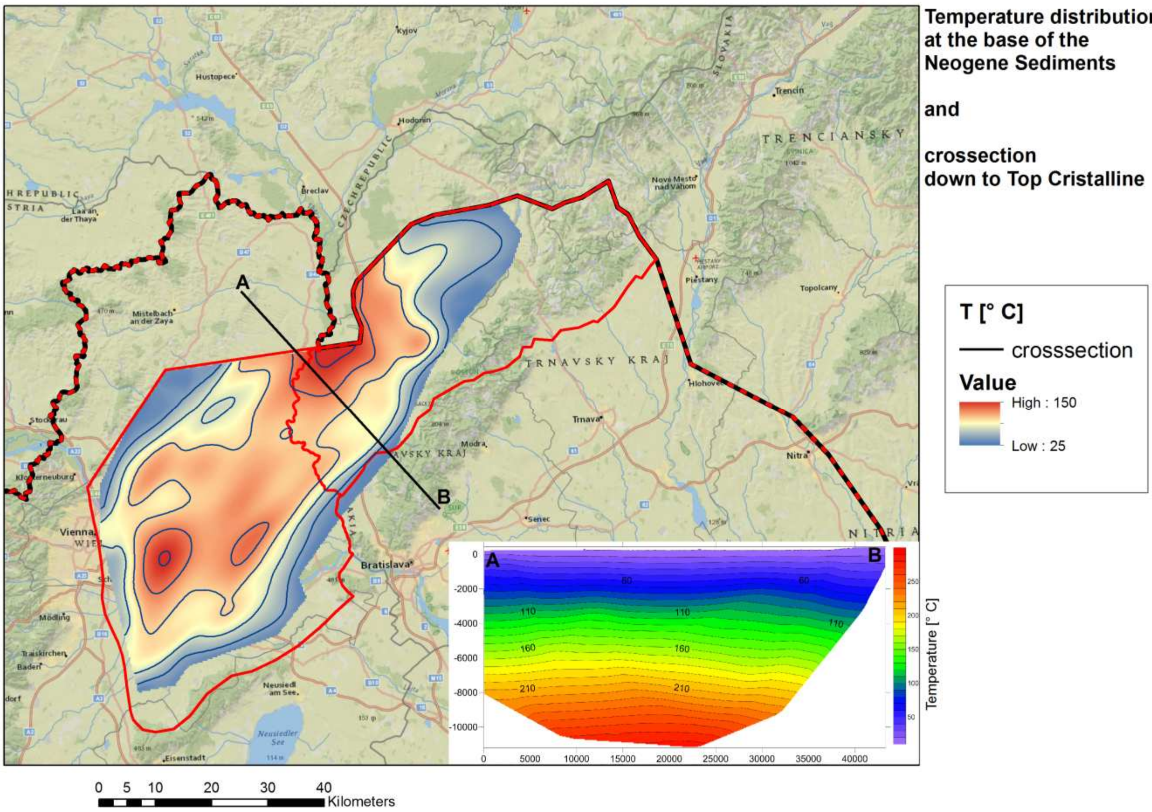
Annex I

Temperature distribution at the base of the Calcareaus Alpine Units



Temperature distribution at the base of the Neogene Sediments





Temperature distribution at the base of the Neogene Sediments

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