Report on Bad Radkersburg – Hodoš pilot area model

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Date **31**-Januar-2013

Status final

Type Text

Description The report presents the results of the modelling in the Bad Radkersburg – Hodoš pilot area of the Transenergy project. The modelling comprises 3D groundwater flow and heat transport simulations.

Format PDF

Language En

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

Work package WP5 Cross-border geoscientific models

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 steady state modelling in the Bad Radkersburg – Hodoš pilot area of the Transenergy project. It was focused in aquifer in the Pre-neogene basement that is positioned in the narrow and deep Radgona –Vas tectonic halftrench south of the Burgerland swell. The Radgona – Vas tectonic halftrench is developed along the Rába fault system in SWS – ENE direction.

The main utilization in the area takes place in Benedikt and in the transboundary zone between Austria and Slovenia. In Bad Radkersburg (A) there is a thermal spa in the vicinity of state border with Slovenia. In 2008 a research borehole in Korovci (SI) in the vicinity of state border intended to capture the same aquifer less than 5 km from Bad Radkersburg spa was drilled which caused transboundary tensions between the two countries.

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 utilisation of the geothermal resources.

Presented approach is first attempt of conceptual and numerical presentation of studied geothermal system. It is based on current state of knowledge and data, which all have certain limitations. To account part of uncertainty, related to estimation of parameters of hydrogeological model, sensitivity analysis was performed.

1.1 Geographical setting

The Bad Radkersburg – Hodoš pilot area is situated at the national borders of Austria, Slovenia and Hungary. The south-western border is defined by the water divided between Drava and Pesnica Rivers. Towards the northeast the pilot are passes across Mura River, Goričko hills to the Hungarian national territory. The NW and SE borders are set along geological structures, South Burgenland Swell and Murska Sobota extension block respectively. It covers an area around 2078 km^2 (Figure **1.**Figure 1).

The mean annual air temperature in the modelled part of the area is 10 °C. Annual precipitation is estimated to 800 mm (Fridl et al., 1998).

Figure 1. Delineation of pilot model area with the production wells.

1.2 Geological and hydrogeological setting

Two geological units were delineated in the Bad Radkersburg – Hodoš pilot area: Neogene sediments and Pre-Neogene basement, the latter consisting of carbonate and metamorphic rocks. Geological description of the region can be found in the report on supra-regional geological model (Maros et al., 2012). Its resolution is 1:500 000, while 1:200 000 was applied to the pilot area. Quite some improvements of the supra-regional geological model were needed to accurately represent the local geological structure in the pilot area.

The modelling was focused on the Pre-Neogene basement aquifer in the Mesozoic carbonate and Paleozoic fissured metamorphic rocks along the Raba fault zone. This aquifer is situated in the narrow and deep Radgona – Vas tectonic half-graben developed along the Rába fault system in SWS – ENE direction, and south of the South Burgenland Swell.

The shape of the pilot area follows this major fault system on both (northern and southern) sides. According to our working hypothesis the South Burgenland swell represents a hydraulic barrier for the Radkersburg area (Jennersdorf TH1 and Güssing 1 wells). The metamorphic rocks on the Murska Sobota High act similarly. The western border of the area follows the surface water divide between the Drava and Pesnica Rivers.

In the south-eastern part of the area, in Slovenia, the metamorphic rocks prevail in the basement. Carbonate rocks can be found only in tectonic patches. Beyond the Bajan fault in Hungary, towards the east, the Mesozoic carbonate rocks occur in a wider range as a part of the Transdanubian Range.

The main utilization can be found in the transboundary zone between Austria and Slovenia, and there are favourable but unexploited possibilities in Hungary. In Bad Radkersburg (A) there is a thermal spa in the vicinity of state border with Slovenia. In 2008, a research borehole was drilled in Korovci (SI) in the vicinity of state border intended to capture the same aquifer as less than 5 km distant Bad Radkersburg spa causing transboundary tensions between the two countries.

In Benedikt, 11 km SWS from Bad Radkersburg, a borehole was drilled into the Raba fault zone fissured metamorphic rocks in 2004. We assume that the recharge mechanism is comparable with Bad Radkersburg and Korovci area.

In the Neogene sediments and sedimentary rocks above the basement no important thermal aquifers were identified, but according to logging results some thermal water bearing layers exist.

1.3 Temperature anomaly in Benedikt

By analysing older cores from borehole BS-2/76 and temperature measurements Ravnik et al. (1987) have determined a higher value of heat surface heat flow density in the Neogene rocks in Benedikt area compared to those around.

In 2004 a borehole Be-2 was drilled in Benedikt. Measurements carried out by Nafta Geoterm (Kraljič et al., 2005) have shown a very low temperature gradient in metamorphic rocks of the Pre-Neogene basement. In the interval from 800 to 1857 m a temperature difference of around 3 °C was determined.

Due to this discrepancy, a pure conductive model does not fit well the measured temperatures in Benedikt. A new local convection model has been developed to account for this phenomenon.

2 Numerical modelling

The aim of the numerical modelling was to simulate the hydrogeological and geothermal conditions in the permeable package of Pre-Neogene basement rocks (targeted aquifers). They are represented by Mesozoic carbonate and Paleozoic metamorphic rocks in the Raba fault zone.

Another challenge was to test potential for convection and existence of hydrothermal system with dominated vertical circulation in Benedikt with a local geothermal model with finer resolution.

2.1 Modelling software

For the purpose of this model we used FEFLOW 6.0 software package, developed by DHI-WASY GmbH. FEFLOW is a professional software package for modelling fluid flow and transport of dissolved constituents and/or heat transport processes in the subsurface. It offers all the functions needed for the modelling process from pre-processing of data, the simulation itself, and post-processing functions (DHI-WASY, 2012).

The modelling software is based on finite elements. Its user interface makes use of OpenGL (Open Graphics Library) for visualization.

2.2 Pilot model

2.2.1 Horizontal extent

The model area is outlined in accordance with the TE project pilot area (Figure 1).

2.2.2 Vertical extent

The upper boundary is defined along the topography - surface, whereas the lower boundary is set at the depth of 5 km in the Pre-Neogene basement rocks.

2.2.3 Horizontal resolution

The number of generated elements in the mesh is in total 1000 per each slice. The side length of triangular elements is around 1500 m. In vicinity of the boreholes the mesh is refined (side length of elements around 50 meters).

2.2.4 Vertical resolution

In the model two geological layers were defined (Neogene sediments and Pre-Neogene basement). Those geological layers were further subdivided into several numerical layers. Altogether, 16 numerical layers and 17 slices have been created (Figure 2). The uppermost slice is defined by the surface (DMR), followed by 7 layers in the Neogene. After the geological boundary between the Neogene sequence and the basement, 9 layers in the basement follow. The lowermost boundary in the model was set arbitrarily at 5 km depth.

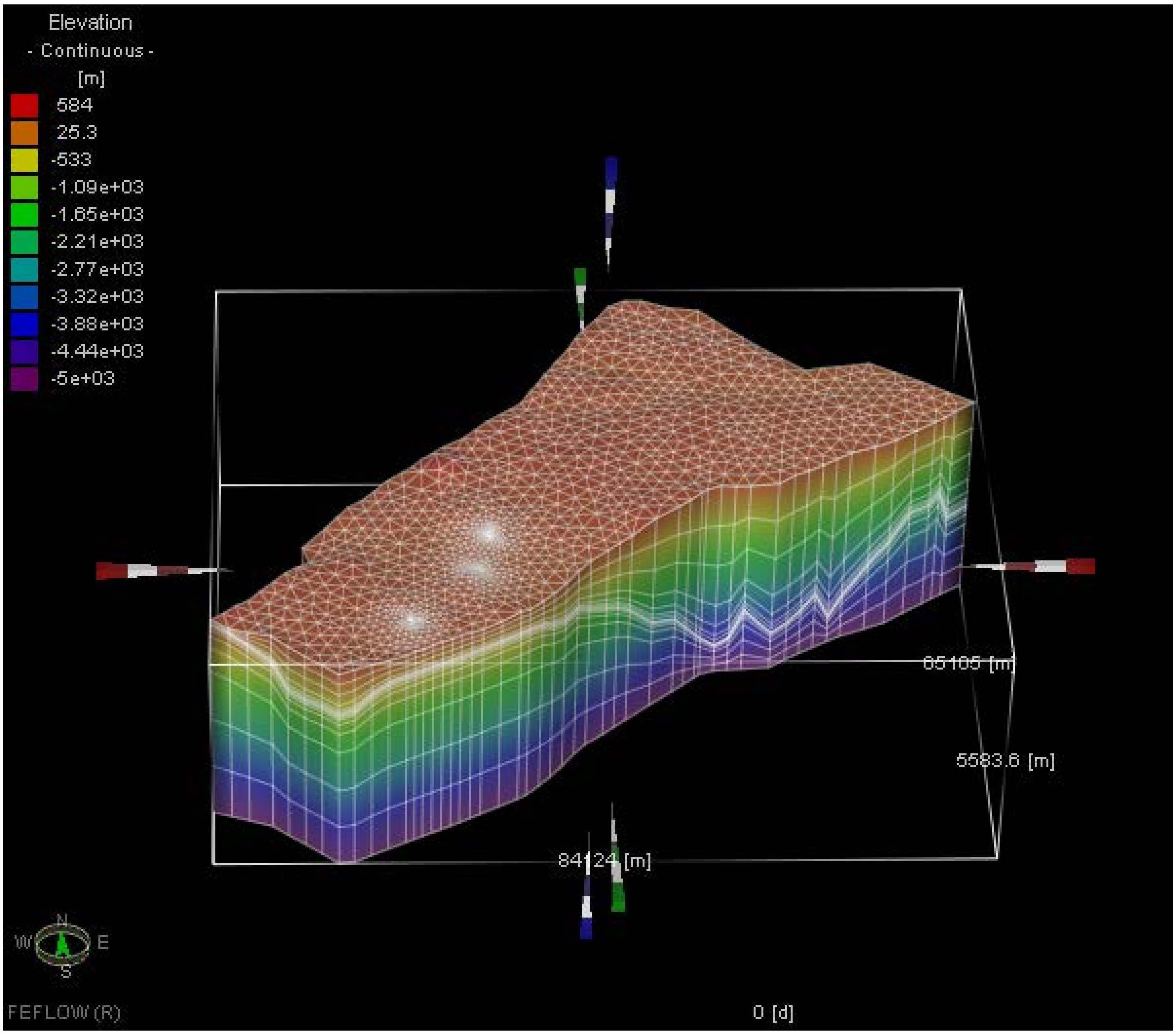

Figure 2. Geometry of the pilot area model.

Figure 3 shows the elevation of the base of Neogene. The Pre-Neogene basement dips in SW-NE direction in general. The depth of the basement in the proximity of Benedikt is around 700 m. Towards NE in deepest parts depth exceeds 3500 m. In the NW part of the area the basement is closer to the surface.

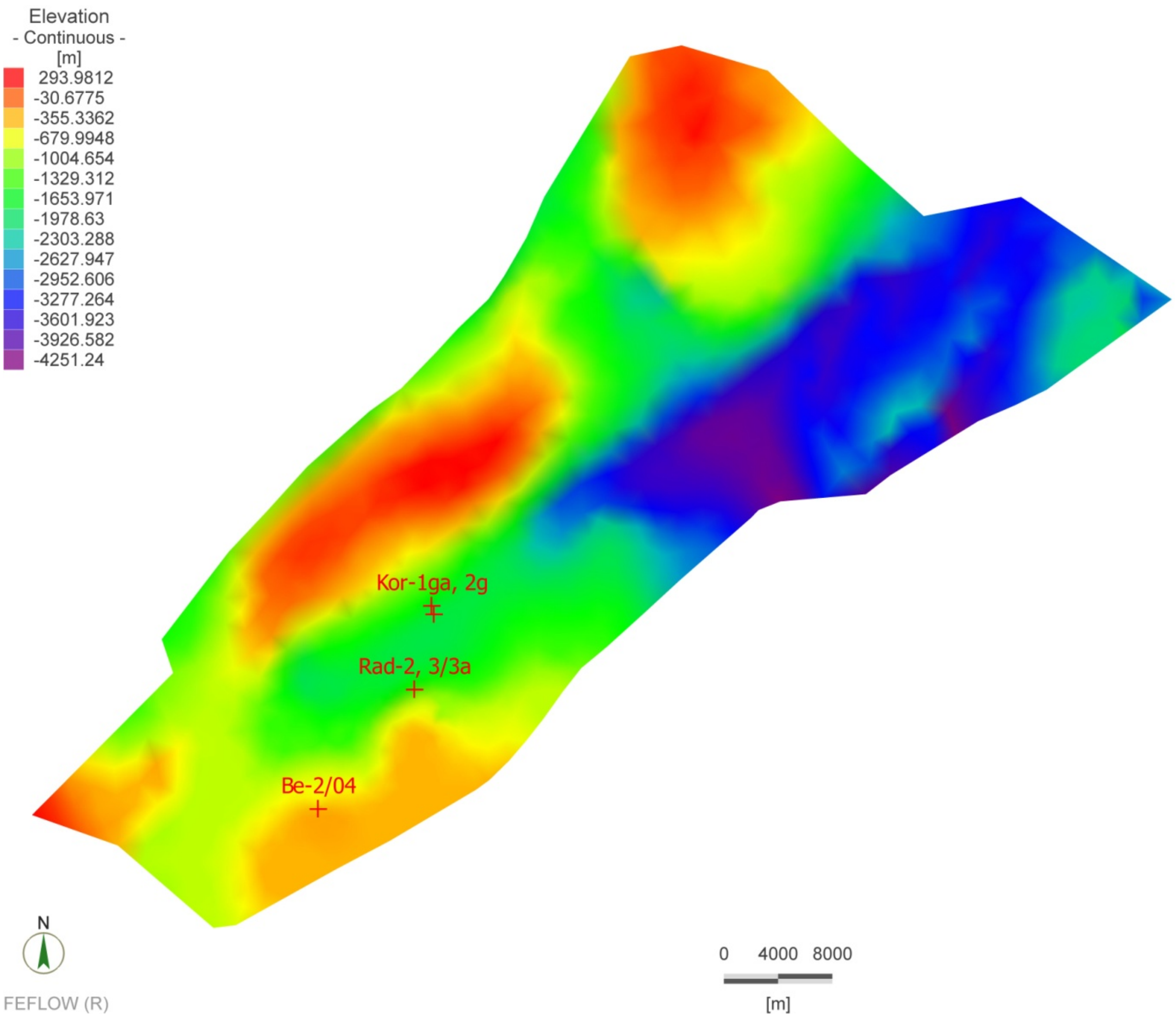

Figure 3. Elevation of slice 8 (base of Neogene).

2.2.5 *Boundary conditions*

Flow boundary conditions

The shape of the model area follows the major fault systems on both (northern and southern) sides. No hard data about hydrological role of the faults exist. It was assumed that South Burgenland swell on the north and the metamorphic rocks of the Murska Sobota extensional block represent a hydraulic barrier. Both boundaries were defined in the model as no flow boundaries. The western border of the area follows the surface water divide between the Drava and Pesnica Rivers. For the modelling purpose, it was set as fixed hydraulic head boundary at 200 m. At the eastern border of the model fixed hydraulic head boundary was set to 100 m. Those values were derived and interpolated from available hydraulic head data from Slovenian monitoring data (Be-2/04, Kor-1gα) (GeoZS database) and Hungarian piezometric data (NK-1 Nádasd, Va-1 Vasvár, K-30 Hévíz) (MFGI database).

Heat boundary conditions

In the NE part of Slovenia an elevated heat flow is characteristic due to thinner lithosphere. According to Rajver et al. (2002) the values of heat flux density are 80-120 mW/m^2 on average.

For the modelling purpose, the lowerrmost boundary was set as a uniform value at 0.1 W/m^2. The uppermost boundary is set as a uniform temperature 10 °C which corresponds to annual mean air temperature in the model area.

2.2.6 Recharge

Due to lack of information, recharge in the model is dependent on the boundary conditions. The model is recharged at the SW boundary, due to hydraulic gradient, caused by hydraulic head differences at SW and NE boundaries. Another source of recharge is infiltration which was defined in calibration at 1.5 mm/year.

2.2.7 Discharge

There is no known natural discharge from the basement rocks in the pilot area. Subsurface discharges in the model are simulated by the outflow at the NE boundary.

2.2.8 Material properties

Hydraulic conductivity is one of the most important hydrogeological parameters in the model. Hydraulic conductivity in the Neogene layers is assumed to be higher in the upper part. In the lower part of the Neogene layers, hydraulic conductivity has been set an order of magnitude lower. Vertical conductivity was set arbitrary at values 100 times lower than the horizontal. In the basement, hydraulic conductivity is assumed to be isotropic.

It is assumed that the crystalline rocks in the basement have a very low conductivity in general. However, their conductivity can be substantially increased in fault zones. To take this phenomenon into account significantly higher conductivity was incorporated along the Raba fault zone in the model that extends from north-eastern towards the south-western part of the pilot area (Figure 4).

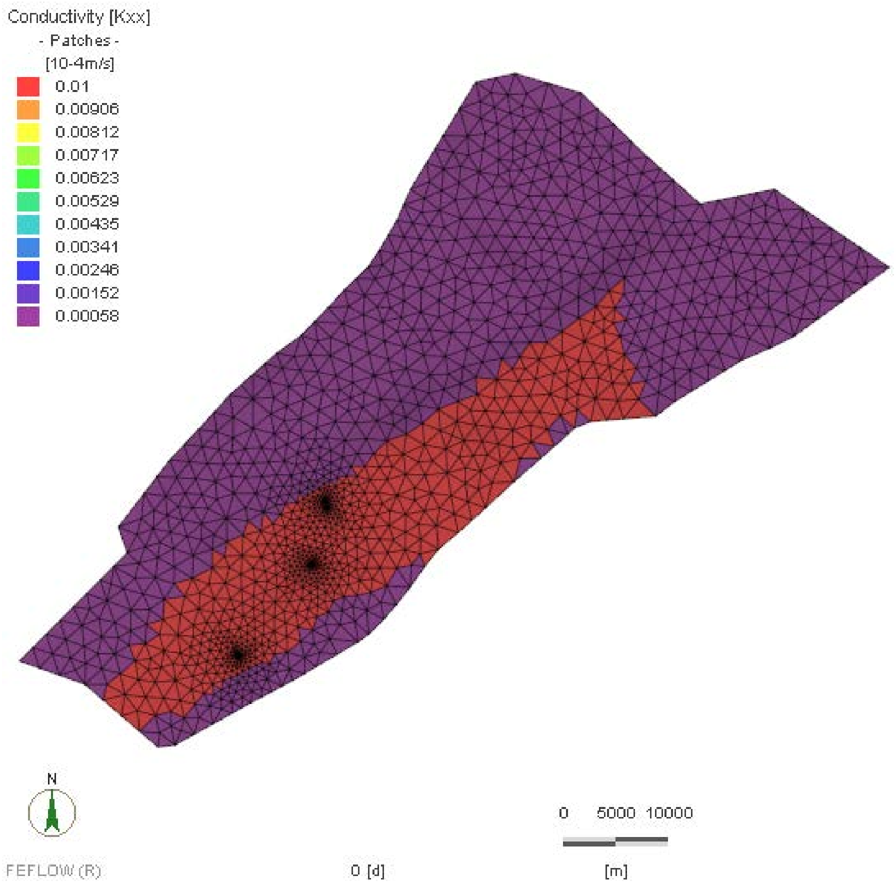

Figure 4. Conductivity values in slice 8 (base of Neogene). Higher values (red) are set for the Raba fault zone.

2.2.9 *Calibration and validation of the model*

Initial values of parameters were derived from T-JAM report (Rman et al., 2011) and further adjusted in the calibration process. According to the scarce piezometric head measurements in the Bad Radkersburg and Benedikt no long term declining trends of piezometric head levels are observed, which indicates a balanced aquifer system. This hydraulic equilibrium was a target of the calibration of the model parameters.

Calibration of geothermal parameters was based on temperature measurements in boreholes Peč-1, Kor-1gα and Be-2.

The thermal conductivity values in the model are derived from GeoZS internal database data (Rajver, 2012). They are based on core analysis and temperature data. Porosity in the basement has been set higher in the Raba fault zone than outside. Porosity values in the Neogene layers and basement outside the Raba fault zone have been set at 0.2 and 0.05 respectively.

Table 1 contains values of parameters, used in the pilot area model.

Table 1. Parameters used in the pilot area model.

Parameter	**Neogene**	**Basement**	
		Raba fault (RF) zone	**Outside RF zone**
Horizontal hydraulic conductivity [m/s]	1×10^{-6} - 1×10^{-7}	1×10^{-6}	5.8×10^{-8}
Vertical hydraulic conductivity [m/s]	1×10^{-8} - 1×10^{-9}	1×10^{-6}	5.8×10^{-8}
Porosity	0.2	0.2	0.05
Specific storage [1/m]	1×10^{-4}	1×10^{-4}	1×10^{-4}
Heat conductivity of solid [W/mK]	2	5	5
Heat conductivity of fluid [W/mK]*	0.65	0.65	0.65
Expansion coefficient [1/K]*	0	0	0
Volumetric heat capacity of solid [JK/m^3]*	2.52×10^{6}	2.52×10^{6}	2.52×10^{6}
Volumetric heat capacity of fluid [JK/m^3]*	4.2×10^{6}	4.2×10^{6}	4.2×10^{6}
Longitudinal dispersivity [m]*	5	5	5
Transverse dispersivity [m]*	0.5	0.5	0.5
Anisotropy of solid heat conductivity [W/mK]*	1.16×10^{-5}	1.16×10^{-5}	1.16×10^{-5}

* Default values in FEFLOW

3 RESULTS

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

3.1.1 Hydraulic head distribution

Due to the implementation of uniform recharge through infiltration, distribution of hydraulic heads in the model depends on boundary conditions and spatial distribution of hydraulic conductivities (Figure 5).

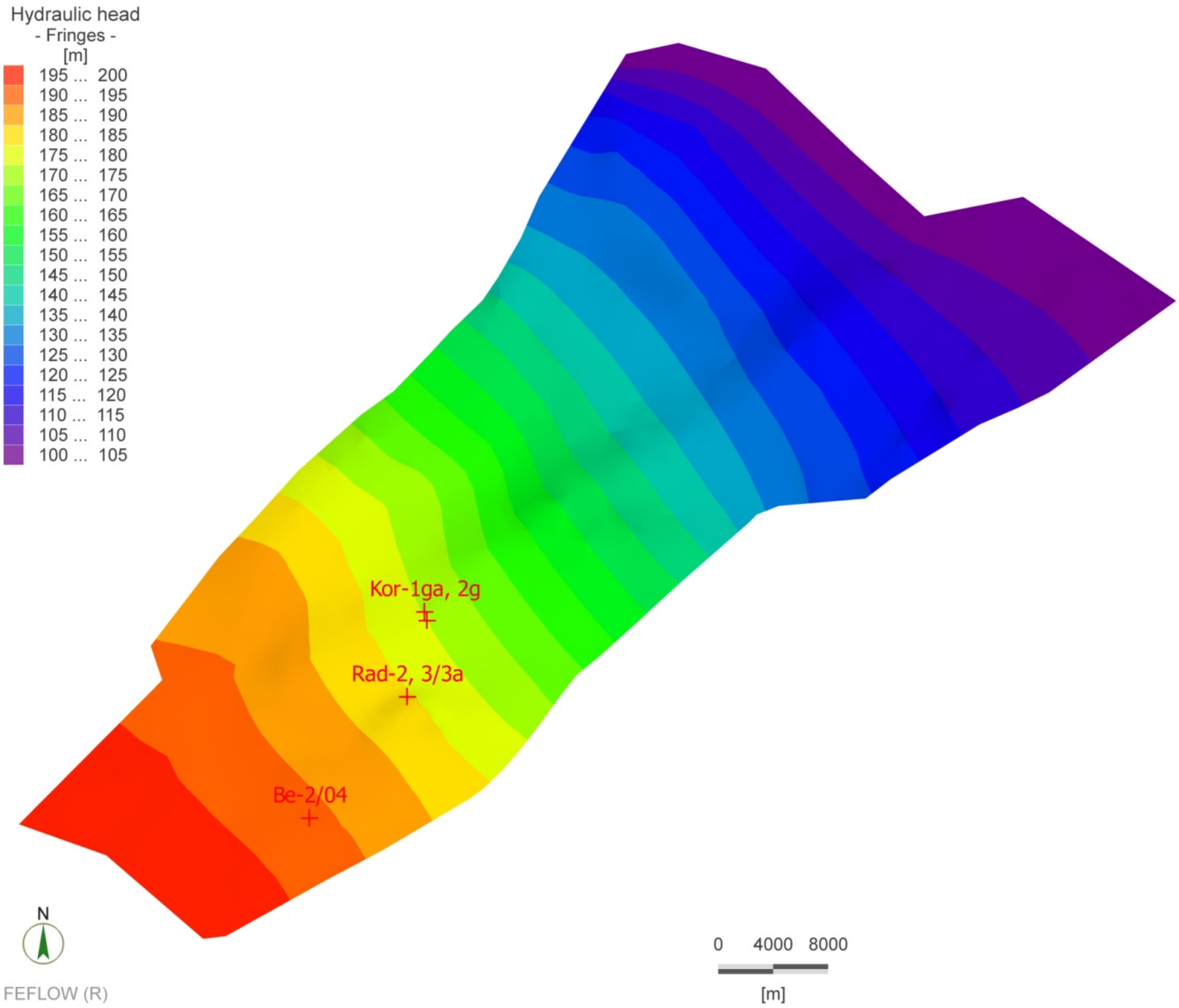

Figure 5. Computed hydraulic head distribution in slice 8 (base of Neogene).

3.1.2 Groundwater flow velocity

Figure 6 show the computed groundwater flow velocity – Darcy flux. The flow velocity is higher in the Raba fault zone, where the hydraulic conductivity is higher. Direction of groundwater flow is from SW towards NE. Outside the Raba fault zone, the groundwater flow velocity is below 1.18×10^{-5} m/d.

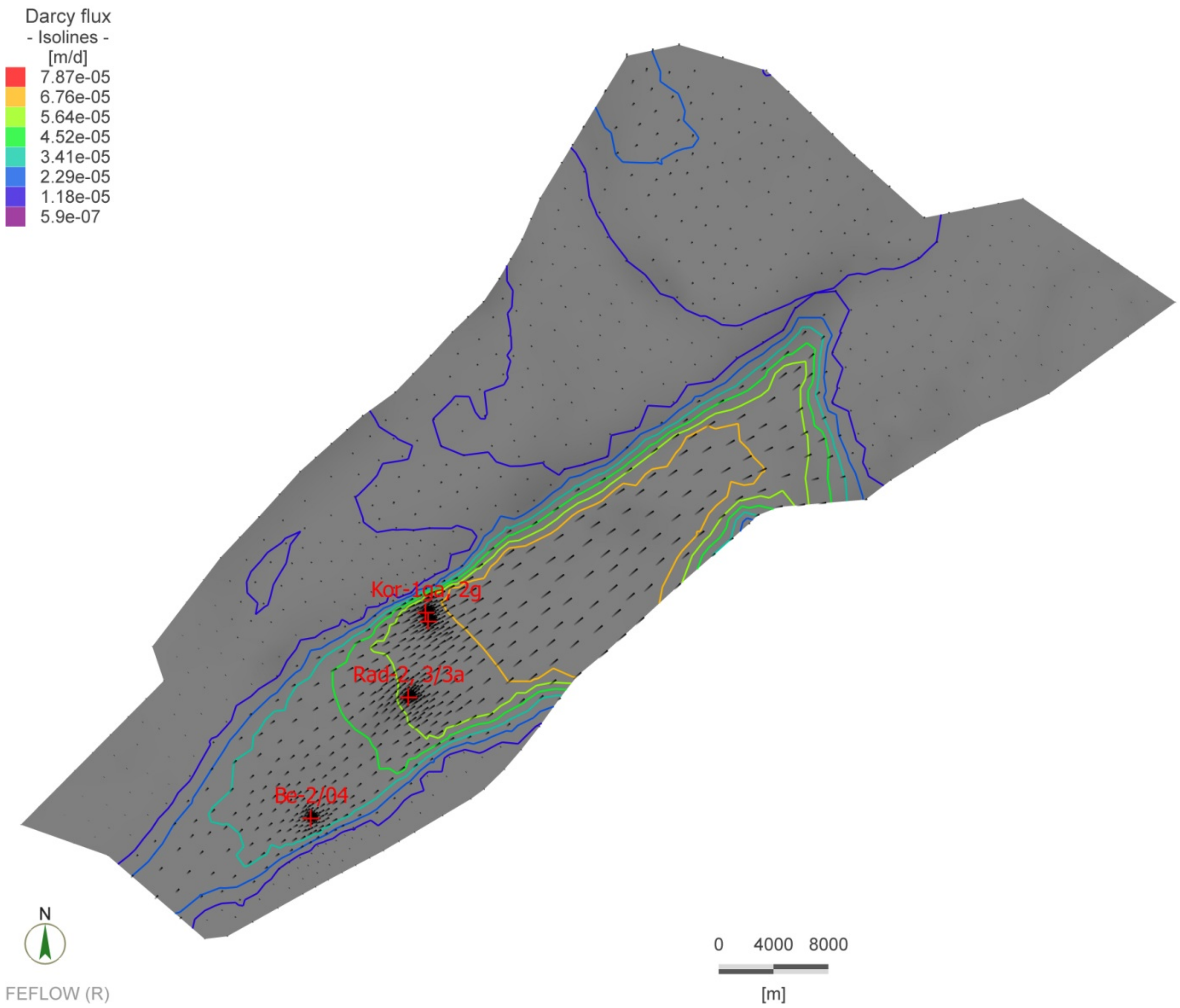

Figure 6. Computed groundwater flow velocity in slice 8 (base of Neogene). Black vectors show the direction of groundwater flow.

3.1.3 Temperature distribution

The main mechanism for heat transport in the regional model is conduction. Due to higher thermal conductivity in the basement layers, the temperature in the NE part of the area, where the thickness of the Neogene layers is greater, are higher (Figure **7** and Figure **8**). It is a manifestation of insolation effect of Neogene layers which slowing down the heat conduction.

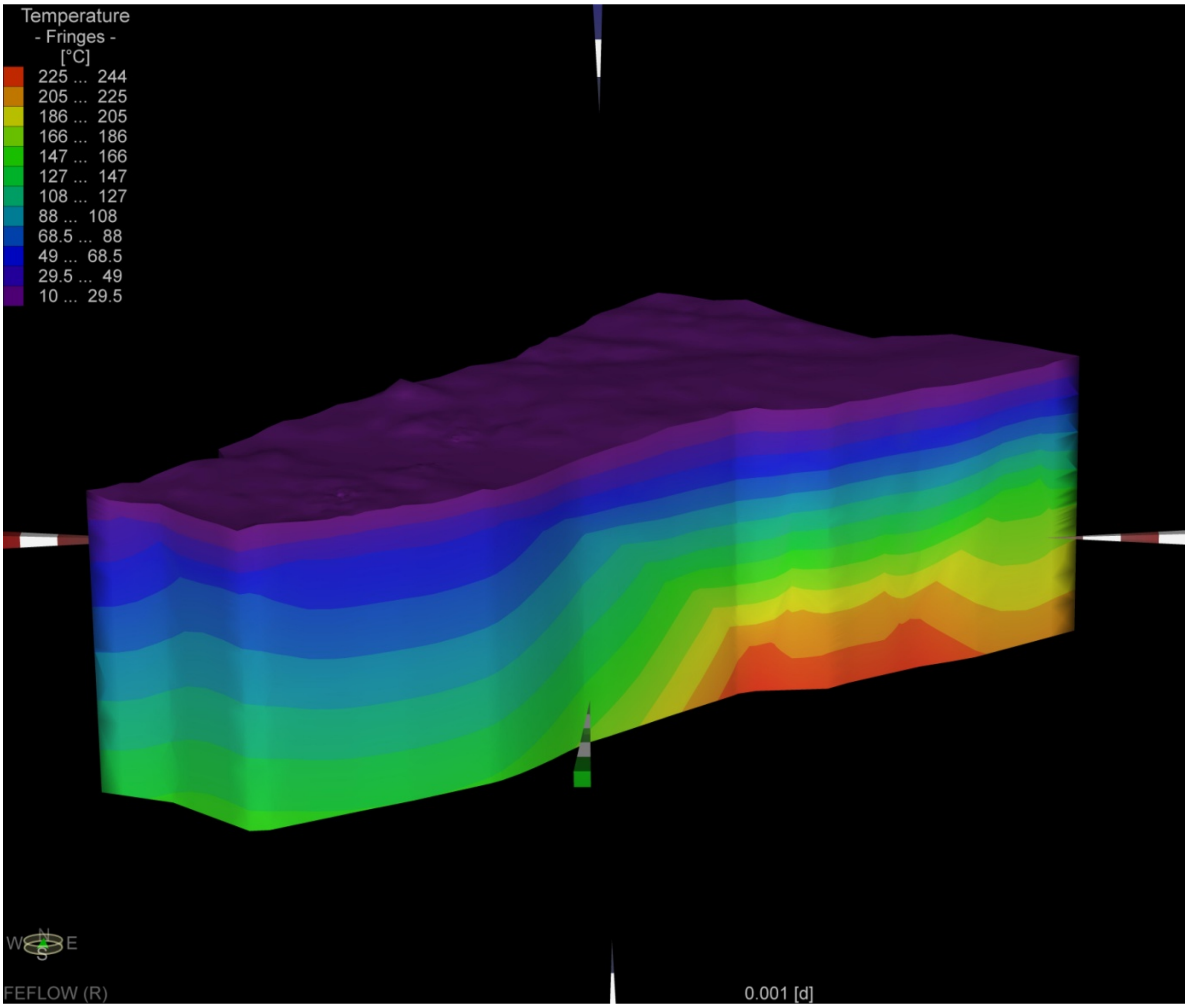

Figure 7. Temperature distribution in the model.

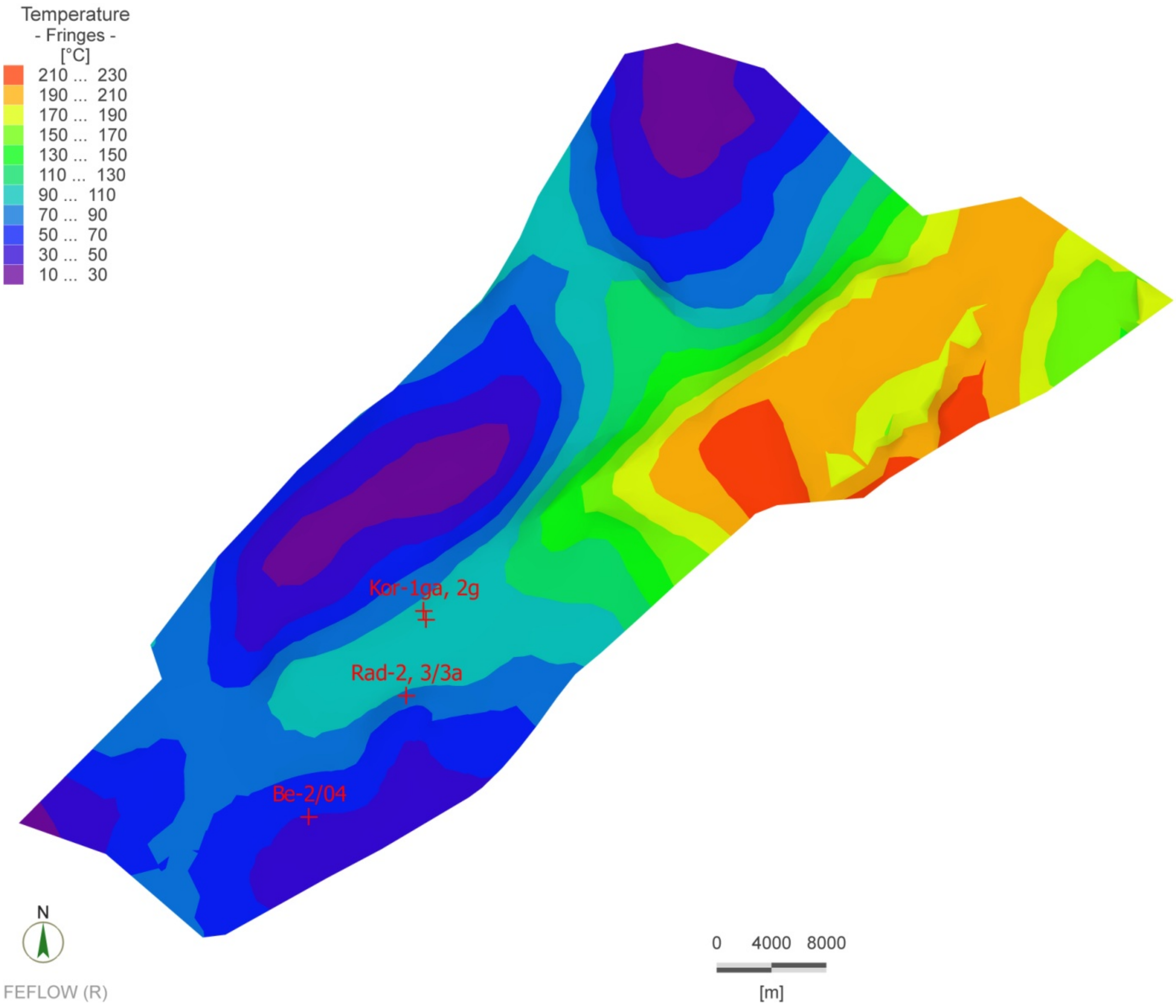

Figure 8. Temperature distribution in the base of Neogene (slice 8).

3.1.4 Temperature comparison

Figures Figure **9** and Figure **10** show the comparison between computed and measured temperatures in three deep boreholes, in Pečarovci, Korovci and Benedikt. The fit in the borehole Kor-1gα is very good. In the case of the borehole Peč-1 the fit is good in the upper Neogene layers, whereas in the basement rocks the computed temperatures are slightly higher than measured.

However, according to Gosar (1995) the Pečarovci antiform is a tectonically isolated structure. Several studies were performed for the gas underground gas storage in this area defining the faults acting as impermeable barriers. Therefore, the temperature measurements in borehole Peč-1 are not representative for the pilot area model.

The largest discrepancy between computed and measured temperature is observed in the borehole Be-2/04 (Figure 11). It indicates geothermal anomaly in the Benedikt area which cannot be simulated with the model on a pilot area scale. In order to simulate local geothermal conditions different modelling approach is used, which is described in chapter 3.2.

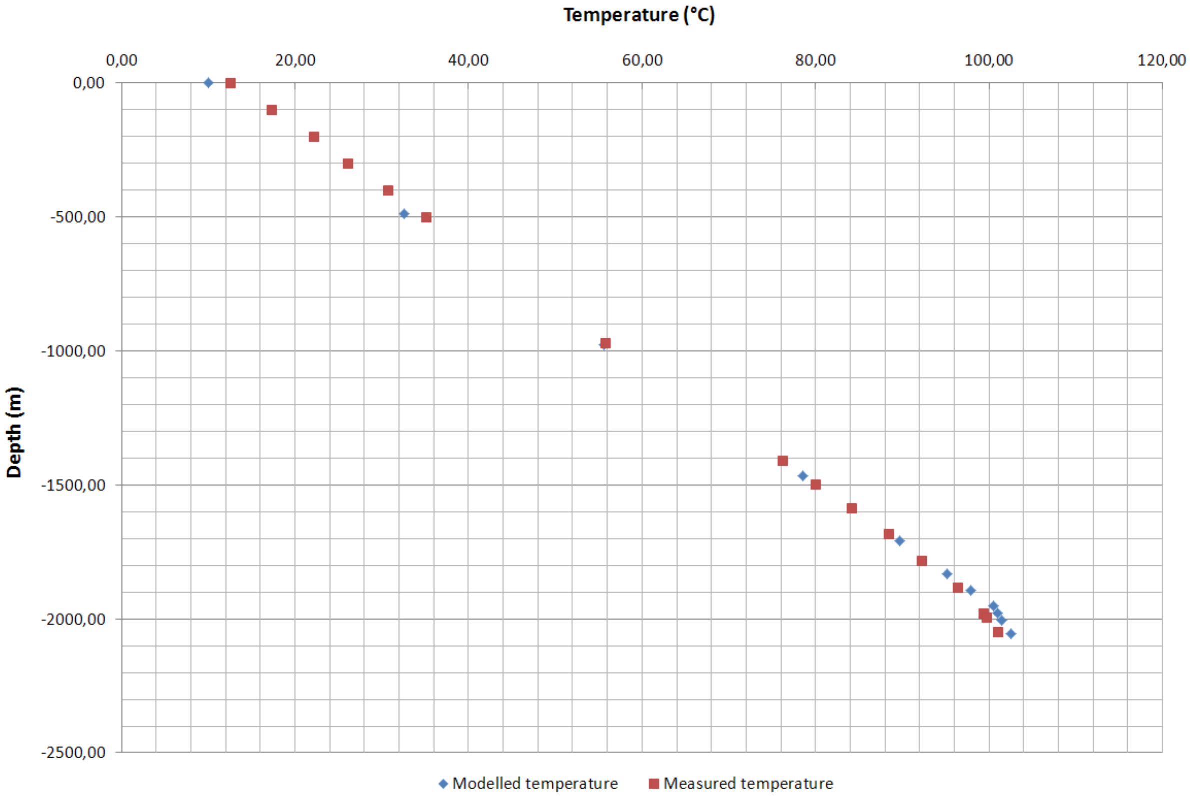

Figure 9. Comparison of computed and measured temperatures in Kor-1gα borehole.

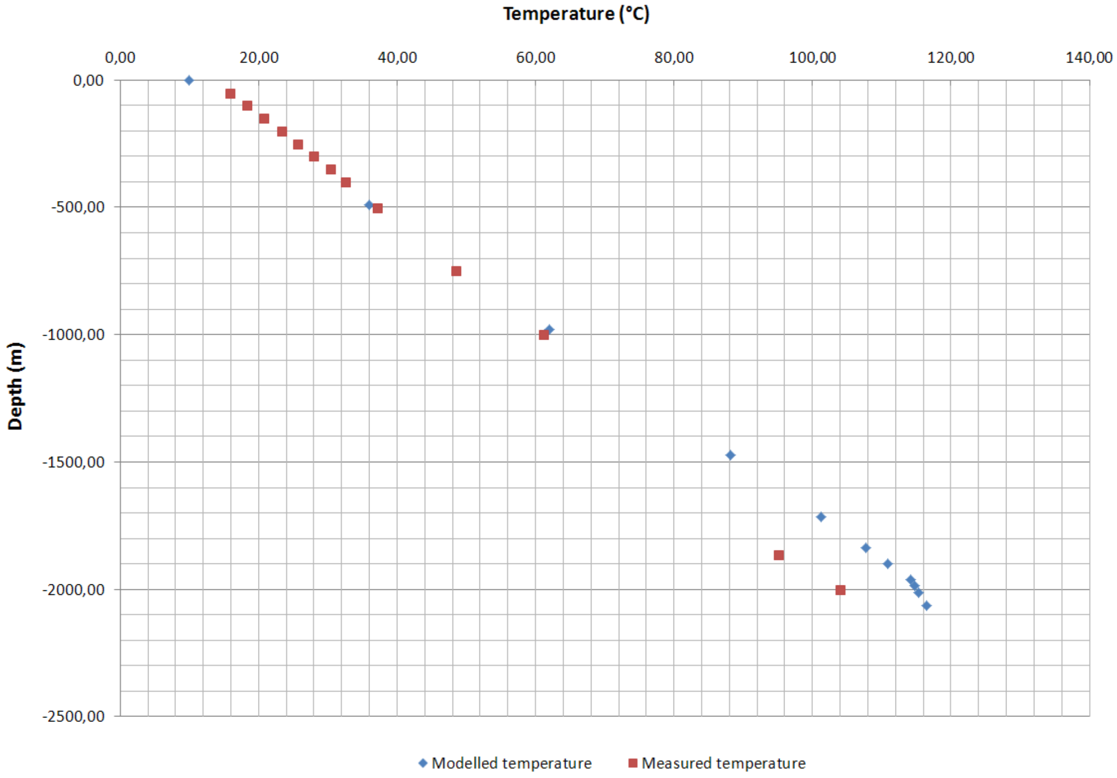

Figure 10. Comparison of computed and measured temperatures in Peč-1 borehole.

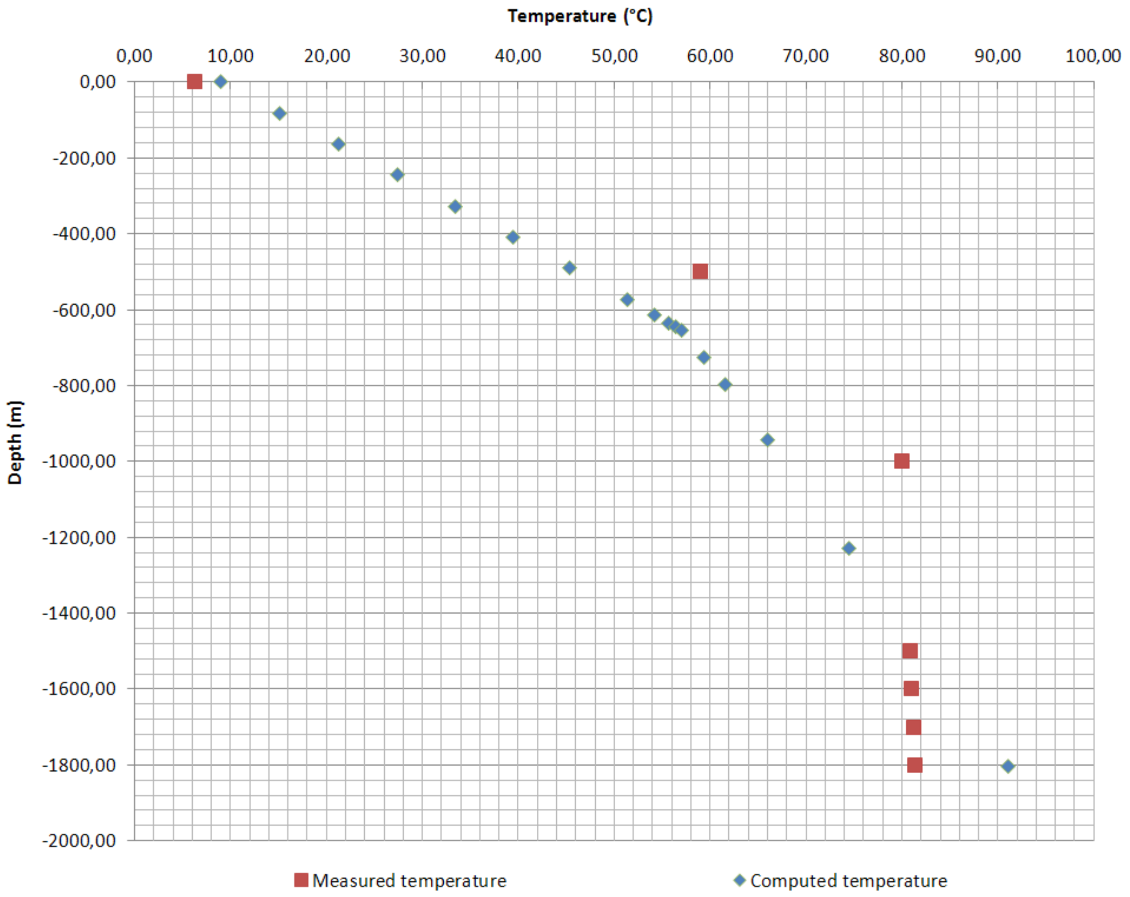

Figure 11. Comparison of computed and measured temperatures in Be-2 borehole.

3.2 The Benedikt local model

3.2.1 *Horizontal extent*

The local model area was defined in the SE part of the pilot area model, around the well Be-2/04 in Benedikt. It is a roughly square shaped and covers an area of 65 km^2.

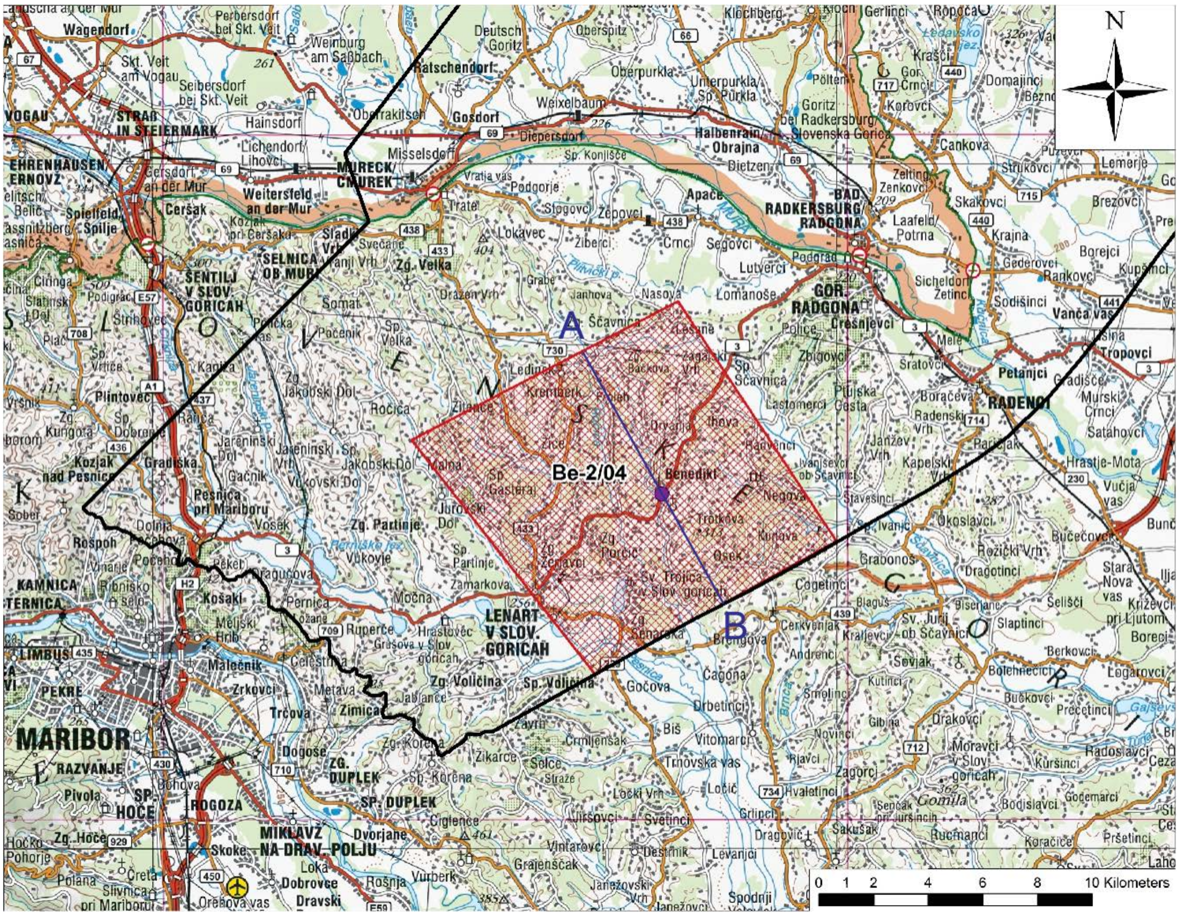

Figure 12. Local model area - red square, the black line delineates the pilot area model area, dark blue line – temperature cross section (Figure 17).

3.2.2 *Vertical extent*

The upper boundary is represented by the surface whereas the lower boundary is set at depth of 2 km in the Pre-Neogene basement rocks.

3.2.3 *Horizontal resolution*

The number of generated elements in the mesh is in total 3000 per each slice. The side length of triangular elements is around 200 m. Around the boreholes the mesh is refined (side length of elements around 50 meters).

3.2.4 *Vertical resolution*

The upper slice of the model is represented by the surface, while the lower slice is set at the depth of 2 km (distance from the surface). There are two geological layers, namely Neogene rocks and Pre-Neogene basement. Those two are further subdivided into several numerical layers (Neogene into 9 layers, Pre-Neogene basement into 8 layers).

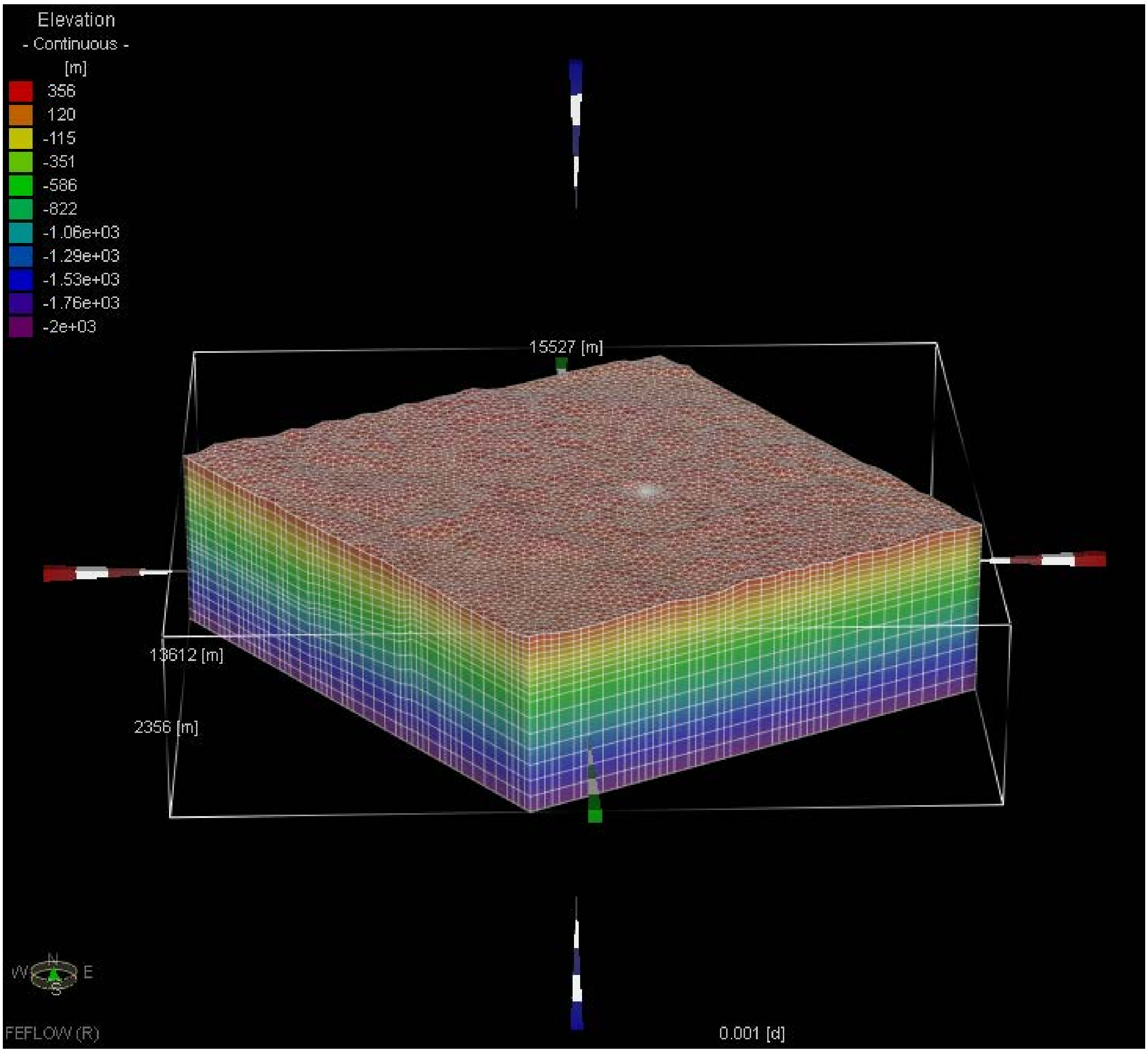

Figure 13. Geometry of the local model.

3.2.5 *Boundary conditions*

The SW in NE boundaries are set as fixed hydraulic head boundaries, at 200 m and 180 m.

The upper boundary of the model is set as constant temperature boundary at 10 °C (annual mean air temperature). The lower boundary is set as a constant temperature boundary at 82 °C which is the measured temperature at the bottom of the borehole Be-2/04.

All the other boundaries were set as no flow boundaries.

3.2.6 *Recharge*

The model is recharged at the SW boundary, due to hydraulic gradient, caused by hydraulic head differences at boundaries. Another source of recharge is infiltration. Same as in pilot area model, infiltration was set at 1.5 mm/year.

3.2.7 Discharge

There is no known natural discharge from the basement rocks in this area. Subsurface discharges in the model are simulated by the outflow at the NE boundary.

3.2.8 Material properties

In general parameters of the local model were derived from the pilot area model. However, some of the parameters were adjusted according to the local conditions and defined by calibration.

Table 2. Parameters used in the local model.

Parameter	**Neogene**	**Basement**	
		Raba fault zone	**Outside RF zone**
Horizontal hydraulic conductivity [m/s]	1×10^{-6}	1×10^{-5}	1×10^{-9}
Vertical hydraulic conductivity [m/s]	1×10^{-8}	1×10^{-5}	1×10^{-9}
Porosity	0.2	0.2	0.05
Specific storage [1/m]*	0.0001	0.0001	0.0001
Heat conductivity of solid [W/mK]	1.6	5	5
Heat conductivity of fluid [W/mK]*	0.65	0.65	0.65
Expansion coefficient [1/K]	0.0004	0.0004	0.0004
Volumetric heat capacity of solid [JK/m^3]*	2.52×10^{6}	2.52×10^{6}	2.52×10^{6}
Volumetric heat capacity of fluid [JK/m^3]*	4.2×10^{6}	4.2×10^{6}	4.2×10^{6}
Longitudinal dispersivity [m]*	5	5	5
Transverse dispersivity [m]*	0.5	0.5	0.5
Anisotropy of solid heat conductivity [W/mK]*	1.16×10^{-5}	1.16×10^{-5}	1.16×10^{-5}

* Default values in FEFLOW

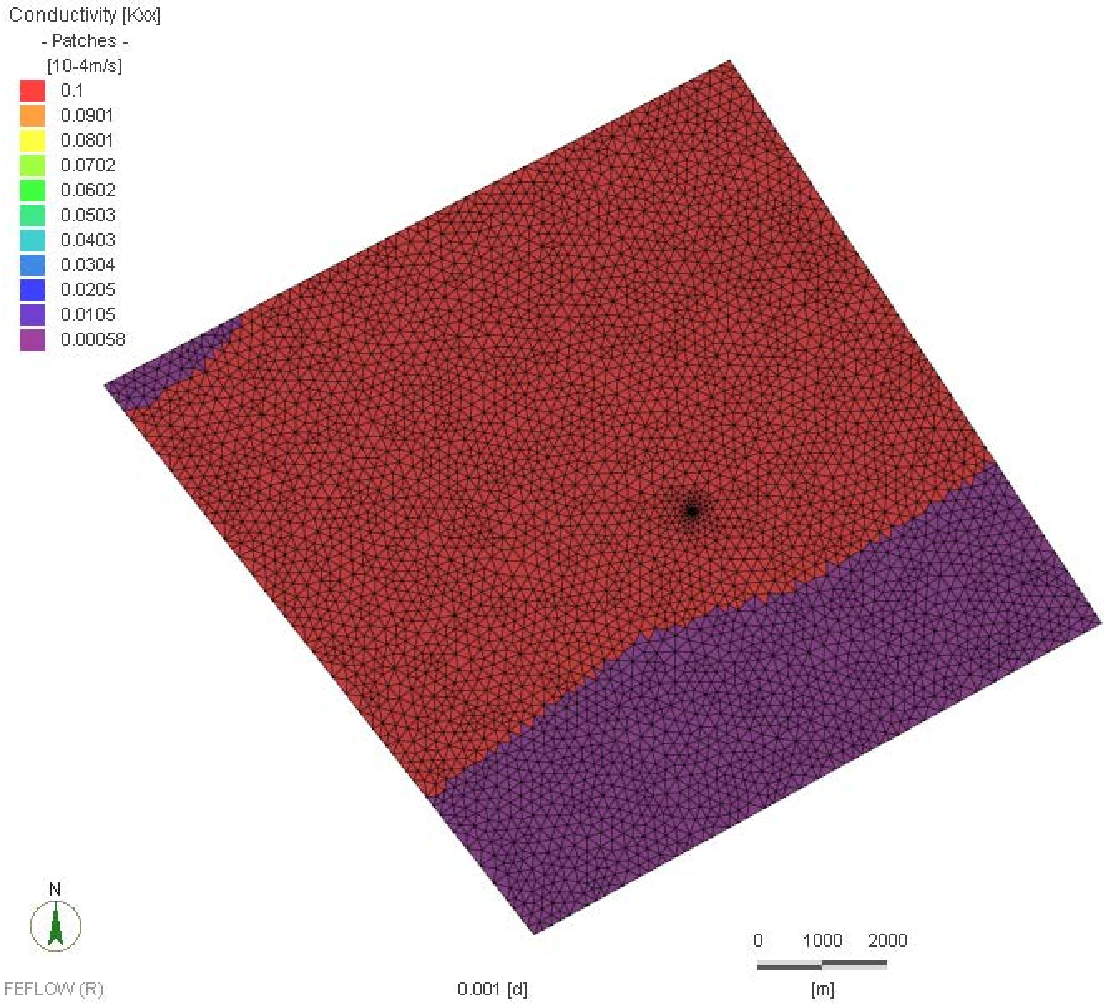

Figure 14. Distribution of the horizontal conductivity in slice 10. Red elements indicate higher conductivity in the Raba fault zone.

3.2.9 Results

Figure 15 shows the comparison between computed and measured temperatures in the well Be-2/04. Comparing to the results of pilot areal model (Figure 11), the fit is much better in the case of local model. This result indicates that temperature distribution in Benedikt can result from vertical groundwater movement in the fracture zone of Raba fault.

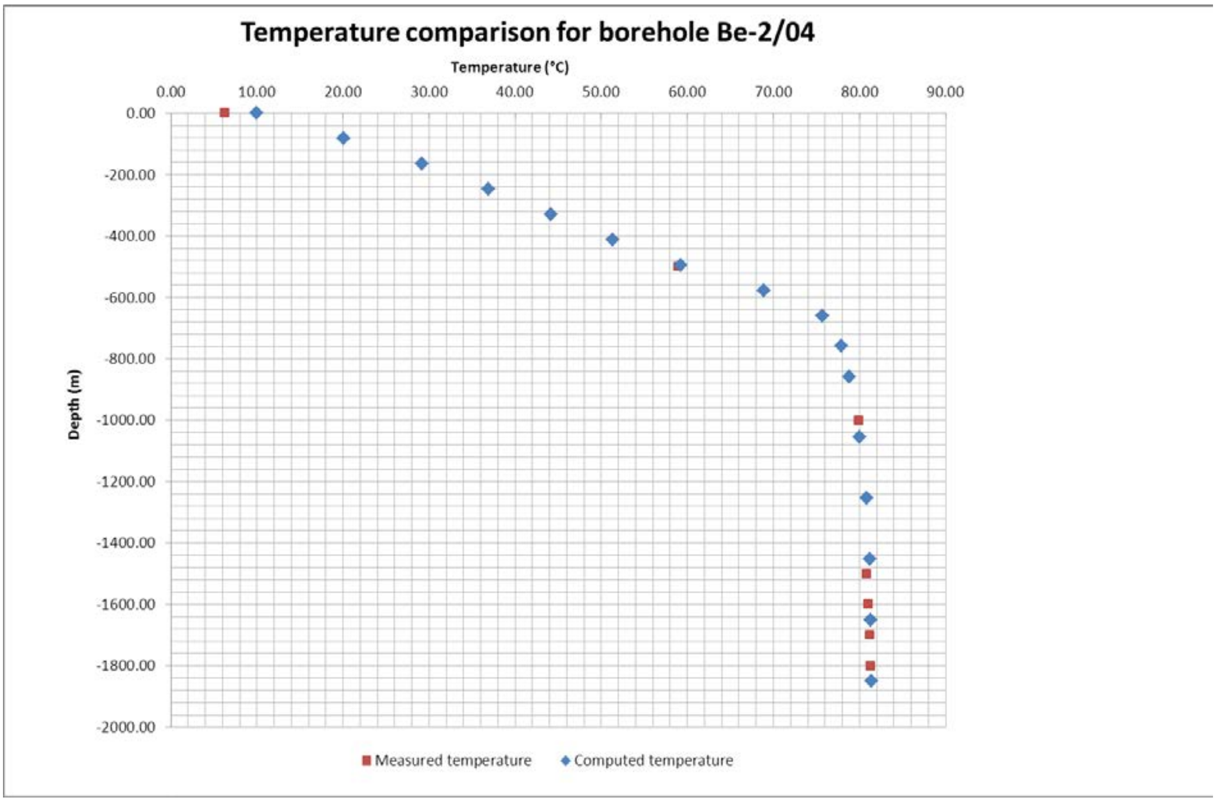

Figure 15. Comparison of measured and computed temperatures in well Be-2/04 in Benedikt.

Simulated convection cells, formed in the Pre-Neogene basement are presented in Figure 16. This effect caused the temperature distribution, presented in the cross section across borehole Be-2/04 (Figure 17). A temperature anomaly can be seen in the middle, extending approximately in the E-W direction. This anomaly is caused by ascending warmer waters due to convection. The thermal convection is caused by buoyancy force that arises from lower density of warmer water. In the model this phenomenon is controlled by thermal expansion coefficient.

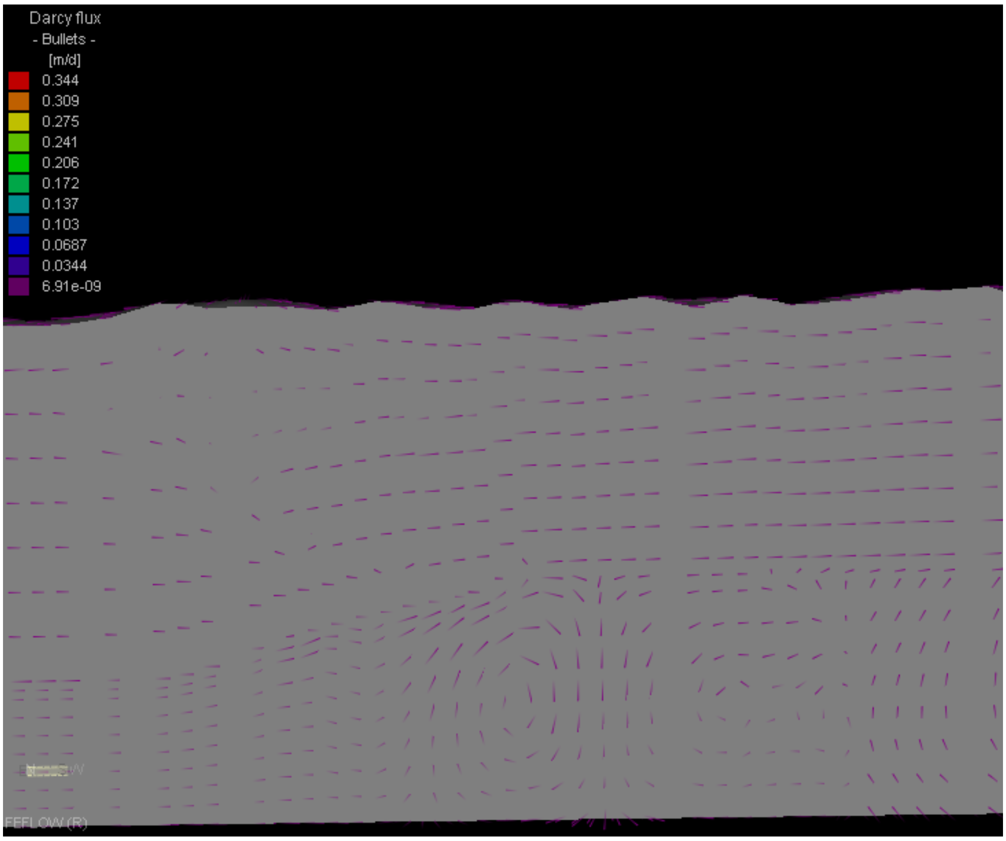

Figure 16. Groundwater flow in the northwest boundary of the model.

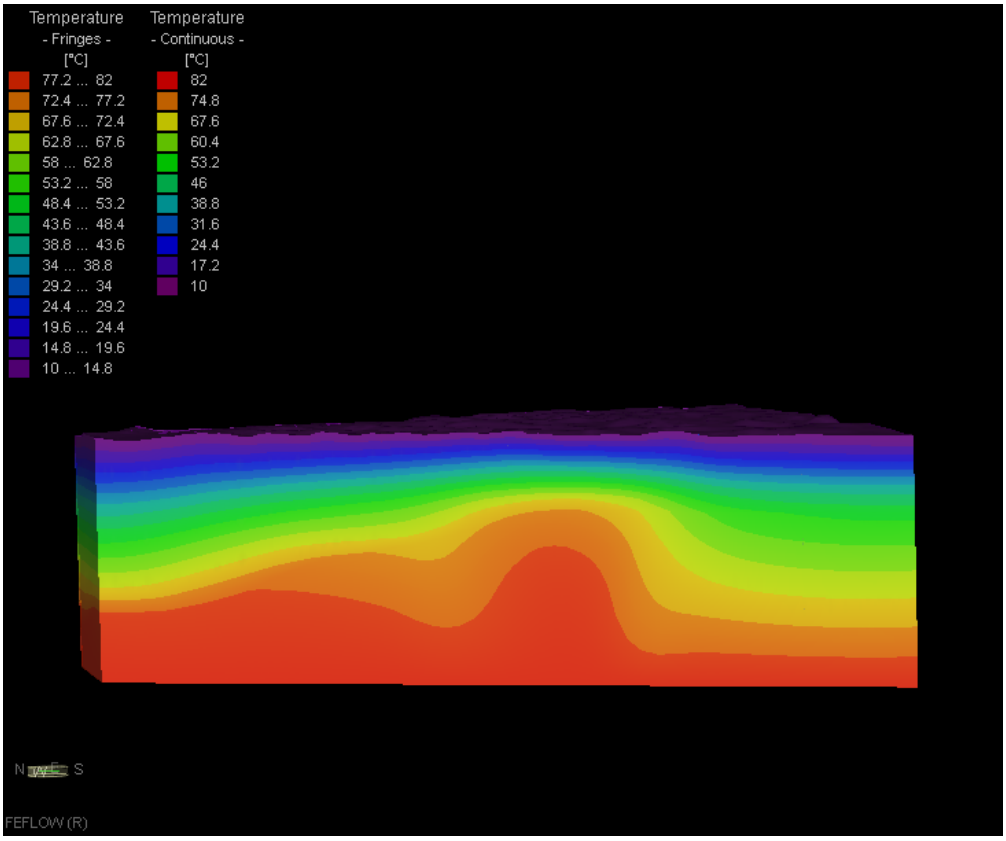

Figure 17. Temperature distribution in the cross section across borehole Be-2/04 in the N-S direction.

4 CONCLUSIONS

The modelling of the Bad Radkersburg – Hodoš pilot area was focused on deep geothermal aquifer in the Pre-Neogene basement. The constructed models enable simulation of natural hydrogeological and geothermal conditions in the pilot area. Good fit of computed and measured temperatures confirmed the assumption that conductive heat transfer is characteristic in most of the pilot area. However, positive geothermal anomaly in Benedikt had to be modelled separately and confirmed that it is related to convection flow.

Presented regional steady state modelling provides framework and initial conditions for scenario modelling which will be performed to evaluate the potential impacts of production in Korovci on the nearby thermal wells in Bad Radkersburg.

It has to be emphasised that preferential flow paths (open fissures, faults and channels) are characteristic for fissured aquifers such as the investigated one in the Pre-Neogene basement rocks, therefore the intergranular porosity model has strong constraints in describing the actual state and future predictions. Detailed geological structure and its hydrogeological characteristics have to be known much better than currently to ensure higher reliability of the numerical model. In presented case very scarce datasets were available, therefore uncertainty of the model is high. It can be diminished with additional measurements which enable better quantification of relevant geological, hydraulic, geochemical and geothermal processes. Measurements of equilibrated static hydraulic and geothermal conditions in all wells perforated in the basement rocks should be performed first to determine horizontal and vertical pressure gradients in the aquifer. Therefrom flow direction and magnitude could be estimated. Hydraulic tests are needed secondly, to determine its hydraulic conductivity and specific storage plus the main flow zones which control the production possibilities. Chemistry and isotopic composition of water and gas should be investigated in details, to determine the water origin, mean residence time and prevailing geochemical processes. Hydraulic connection between different sites can be interpreted by these methods also. High mineralization of thermal water and very high gas content should be accounted for when designing and executing all tests as they severely impact the wellhead measurements. Consequently, transducers have to be installed in the main production zone in the perforated sections in wells (Pivot point if possible) to ensure reliable results.

5 LITERATURE

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