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Institute of Hydrogeology, Engineering Geology and Applied Geophysics

Specification of the geothermic model in the environs of several selected boreholes

(Zpřesnění geotermického modelu v okolí několika vybraných vrtů)

MASTER'S THESIS

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Prague, 2013

Declaration:

I hereby declare that I am the author of this thesis and I have properly referenced all the relevant information resources used for its compilation.
I also declare that neither this thesis nor its substantial part has been submitted to fulfill requirements for another Master's or any other academic degree.

In Prague, 12th August 2013 Bc. Lucie Čápová

Acknowledgements:

I would like to thank to my supervisor, P. Dědeček, for his guidance and providing access to essential information as well as to the COMSOL software and thermal conductivity scanner without which the thesis could not be compiled. Many thanks are also due to my consultants, M. Kobr and J. Šafanda, as well as to Z. Kaláb for their advice and comments that helped to improve the manuscript. I would also like to thank Z. Mokrá, L. Hronec and L. Špičáková from the Geophysical Institute of the Academy of Sciences of the Czech Republic (AS CR) for passing to me their software skills and providing access to the Canvas software that helped me with construction of geological sections. Moreover, the help of D. Uličný from the Geophysical Institute of AS CR, D. Dolejš and K. Martínek from the Faculty of Science, Charles University in Prague and B. Mlčoch, V. Prouza and V. Rapprich from the Czech Geological Survey who contributed their valuable information on geological structure of the studied areas is gratefully acknowledged. J. Sedlák from Miligal, s.r.o. provided published and unpublished results of gravity surveys in the Krkonoše Piedmont Basin, for which I am really grateful. K. Kocourek from the Czech Geological Survey was a knowledgeable partner during collection and transport of drill core samples from the storage in Kamenná. I would also like to thank to P. Veselý and O. Šálek for information on well-logging results from the Bohemian Cretaceous Basin. Last but not least I would like to express my deep gratitude to my family for their patience and understanding and especially to my parents and my partner for careful proofreading and help with graphical editing.

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List of acronyms

AS CR - Academy of Sciences of the Czech Republic
BCB - Bohemian Cretaceous Basin
CGS - Czech Geological Survey
EGS - Enhanced Geothermal Systems
HDR - Hot Dry Rock
KPB - Krkonoše Piedmont Basin

1. Introduction

This thesis aims to summarize the basics of geothermic research including the principles of heat transfer and factors influencing the thermal conductivity and temperature gradient, give an introduction to the history of hot dry rock geothermal developments in Europe and the Czech Republic and then focus on several sites in the Czech Republic that have been recently subject to geothermal exploration and proposed for geothermal energy utilization. Extensive literature study of regional geology and well logging in some of the nearby boreholes and measurements of thermal conductivity on drill core samples are expected to help the author compile geological sections. On the basis of these, the author aims to construct geothermic models of the studied areas to verify their suitability for geothermal applications.

Study of heat flow and thermal properties of rocks has proven to play an important role as an additional discipline in reconstructions of Earth's thermal history, which lead to discovery of its composition and processes in the mantle and geotectonics. It provides countless valuable data in palaeoclimatic reconstructions and can be used as an auxiliary method in mineral exploration. However, in the first place, it has become an essential tool for geothermal exploration. Geothermal energy has been used for centuries in areas of increased volcanic and hydrothermal activity for district heating and baths and since the beginning of the 20th century it has become a source of electric power (the first geothermal power plant was established in Larderello, Italy, already in 1904). Nevertheless, geothermal power plants and district heating plants have been the province of areas with strong hydrothermal activity, only. Therefore, usage of geothermal power was long regarded as impossible in central Europe. With the advances of geothermal research and discovery of usability of hot dry rock environment, however, geothermics has become a vital discipline as the temperature in the reservoir is the crucial factor governing the efficiency of the whole system. In hot dry rock environments, the three most important parameters are: temperature, permeability of the reservoir rocks and fluid for extraction of heat. But permeability can be enhanced by hydraulic fracturing and fluid can be supplied, so the temperature is the principal factor to consider in feasibility studies. With further technological progress and advances in geothermal research, geothermal energy may soon become a marked source of power even in areas with older and cooler crust. This thesis aims to provide a general overview of geothermic conditions in the Bohemian Massif with relation to geological composition and tectonic setting, and then to further develop the topic on three selected localities (Litoměřice, Semily and Liberec), which have recently been chosen for geothermal utilization. After comparing well logging data with information on local geology and measurements of thermal conductivity on core samples, mathematical models of the thermal field on the selected sites are constructed. Based on those, conclusions are made whether these sites are suitable for building a geothermal power plant or a district heating plant or not and possible alternatives either of location or of the sort of application are proposed.

1.1 Past and present HDR projects in Europe

Hot Dry Rock (HDR) environment has been studied for geothermal applications in Europe since the 1980s. The first projects were launched for instance in Rosemanowes, Cornwall, UK (1984), Mayet de Montagne, France, Falkenberg, Germany and especially Soultz-sous-Forêts, Alsace, France.

The first HDR project in the UK was located in a former granite quarry in Rosemanowes, Cornwall and consisted of one injection well and one production well with a minimum distance of 133 m between them. The production temperature was 80°C and the chosen injection temperature was 25°C. The project aimed to study the reservoir's thermal and hydraulic performance, as well as the effect of hydraulic stimulation. It was suggested that with the injection temperature 40°C, the temperature of the rock 200°C and production flow rate of 75 $kg.s^{-1}$, the potential power plant would generate 50 MW_t with the thermal performance declining by 10% during its 25 year lifetime. However, the inclined wells had been drilled at unfavourable orientation to the regional stress – their azimuths were at the angle of 90° to the minimum horizontal stress in situ – which limited the amount of joints in which the brine could circulate. As a result, the available space was insufficient for the desired recovery of heat; the project was found economically unviable and was abandoned. However, the site does have a promising potential and now that the stress field on site is known, wells could be drilled in more favourable directions and better results could be achieved. (Richards, 1994)

The Soultz-sous-Forêts project is probably the best known geothermal project in Europe, providing countless amounts of valuable information on Enhanced Geothermal Systems (EGS) since 1987. The first borehole, GPK1, reached the temperature of 160°C at the depth of 3600 m. Another well, GPK2, was drilled in 1995 reaching the depth of 3878 m and in 2005 it was deepened to 5010 m. The temperature on its base was 203°C. Two more wells approximately 5 km deep had been drilled by then – GPK3 and GPK4. They were oriented in the favourable direction relative to the maximum horizontal stress and orientation of major joints, so that the constraints encountered in Rosemanowes were mitigated. GPK2 and GPK 4 are used as production wells, GPK 3 is used as an injection well (Gérard *et al*.,2006). Several circulation tests in the reservoir showed positive results and so a geothermal binary power plant could start its operation in 2008. Nowadays, it supplies the whole research centre with electric power and surplus is supplied to the nearby village.

In Germany, an "in situ downhole laboratory" was established in 2000 in a former gas exploration well in Gross Schoenebeck near Berlin. This original well has become the injection well of the new geothermal system. The reservoir is at the depth of approximately 4 km in a formation of volcanic Permian rocks that have been successfully stimulated to increase their permeability. Downhole temperature of the production well is 150°C. (Zimmerman, 2013, pers.comm.) A small functional power plant is installed on the site and was presented on the World Geothermal Congress in 2010. Even so, it is still being developed and its scientific contribution is remarkable.

Recently, Germany and France have become leading countries in the research and usage of Enhanced Geothermal Systems in Europe, systematically bringing out new information on hydraulic stimulation, thermal efficiency of the system etc. Outside Europe, significant advances in the EGS technology and usage are also made in the USA, Australia or Japan.

In the Czech Republic, several attempts for use of geothermal power from a deep geothermal system have been made, but so far none of them has been successful. The first geothermal exploration well was drilled in Litoměřice, North Bohemia, in 2006. However, due to complex geology in the basement, the borehole did not reach the desired depth of 2500 m. Although the project contributed greatly to the understanding of thermal properties of mica schists and quartz porphyry as well as to knowledge of regional geology, the budget was exhausted and the site abandoned for some time. Meanwhile, other projects have been proposed at a number of different sites, among others Semily, Benešov u Semil and Liberec and eventually, a new research project has been considered and proposed on the original site in Litoměřice. None of these projects, though, have progressed beyond preliminary exploration. Therefore, this thesis aims to study thermal conditions at these sites in detail and briefly evaluate geothermal potential of these areas.

2. Theoretical background

2.1 Basic equations

Heat transfer in the Earth's crust can be defined using the heat transfer equation (1):

(1) $$\rho c \frac{dT}{dt} = A - \int_V \nabla \vec{q}\, dV$$

where ρ is the rock's density, c is the rock's thermal capacity, T is temperature in K or °C, t is time, A is the rock's radioactive heat production, V is the volume of rock and $\vec{q}$ is the heat flux.

The heat flux on the Earth's surface is defined by Fourier's Law as (2):

(2) $$\vec{q} = -\lambda \nabla T$$

where λ is the rock's thermal conductivity. As most of the thermal energy on Earth is transferred from within, only the vertical direction is used, and minus is used as a convention to express that the heat flux is in the opposite direction than the temperature gradient. In this general case we consider heat flow in all directions.

For some applications, however, it is more convenient to introduce thermal diffusivity κ due to diffusive character of heat transfer as (3):

(3) $$\kappa = \frac{\lambda}{\rho c}$$

The transient heat transfer equation is defined as (4):

(4) $$\rho c \frac{\partial T}{\partial t} = div(\lambda\, grad\, T) + A$$

Thus, heat transfer via conduction is defined. However, heat transfer solely via conduction is not sufficient for geothermal applications. The most favourable geothermal reservoirs are situated in water or vapour-dominated environments, where heat transfer via convection takes place. Although in the Hot Dry Rock geothermal reservoirs only conduction takes place naturally, convective heat transfer must be forced in them by injection of brine in order to exploit the heat. Therefore, transient heat transfer equation considering fluid motion (5), (6) must be presented, too:

(5) $$\frac{\partial T}{\partial t} = -\vec{v}\nabla\mathrm{T} + \frac{\nabla.(\lambda\nabla\mathrm{T})}{\rho c} + \frac{A}{\rho c}$$

or using thermal diffusivity κ:

(6) $$\frac{\partial T}{\partial t} = -\vec{v}\nabla\mathrm{T} - \kappa\nabla^2 T + \frac{A}{\rho c}$$

where $\vec{v}$ is the velocity of the flowing fluid. Thus, the member with fluid velocity represents convection and the member with thermal conductivity or diffusivity represents conduction. Heat transfer via radiation is not mentioned as it only applies to higher temperatures than those encountered in the upper crust.

2.2 Variability of thermal conductivity

In the equations stated above, thermal conductivity is presented as a constant. However, this is not quite accurate as a number of factors can dramatically influence its value.

Thermal conductivity of rocks is influenced by their mineral composition, grain size, porosity, saturation with water or other fluids (air, hydrocarbons), mineralisation of water in the pores, as well as bedding and tectonic deformation, because rocks exhibit strong anisotropy of thermal conductivity. The effect of porosity and saturation has been discussed in a wide range of papers (e.g. Clauser, 2006, Robertson, 1988, Abdulagatova, Abdulgatov and Emirov, 2009 etc.). Due to the abovementioned factors, it is more accurate to determine thermal conductivity as a tensor, which is diagonal in the principal coordinate system (Jaupart and Mareschal, 2011) and not as a constant. However, for many rocks, anisotropy has minor effect in comparison with the uncertainty caused by variable mineral composition (Popov *et al.*, 1999). Varying thermal conductivity with mineral composition is shown in Figure 2. Last but not least, thermal conductivity is influenced even by temperature and pressure. Whereas thermal conductivity of various types of rocks can be generalised, providing the values for the rock in wet and dry state, the general relation between temperature and thermal conductivity remains uncertain as behaviour of crystalline rocks differs significantly from behaviour of sedimentary rocks. However, the study by Mottaghy, Vosteen and Schellschmidt (2008) reveals the relation for certain granitic rocks from the Kola Peninsula and from the Alps, which can be generally written as the equation (7) if thermal conductivity is only known at ambient temperature:

(7) $$\lambda = A\lambda(25°C) + 0.5\sqrt{B(\lambda(25°C))^2 - C\lambda(25°C)}$$

where A, B, C are empirical constants that are specific to each rock. These values from the Kola Peninsula and the Alps differ in the order of hundredths or tenths.

Abdulagatova, Abdulagatov and Emirov (2009) carried out a similar study focused on sandstone. They concluded that thermal conductivity of rocks with $\lambda < 2$ $\mathrm{Wm^{-1}K^{-1}}$ (at ambient temperature) usually increases with temperature whereas thermal conductivity of rocks with $\lambda > 2$ $\mathrm{Wm^{-1}K^{-1}}$ (at ambient temperature) tends to decrease with increasing temperature. They give examples of materials with conductivity increasing with temperature, such as feldspar aggregates, vitreous matter or marine sediments. Moreover, dependence of variability of thermal conductivity in sandstone on quartz content was highlighted in this paper.

These results correspond with the opinion published by Vosteen and Schellschmidt (2003) who studied samples of different types of rock under the temperature ranging from 0 to

500°C. These authors introduced the following equation (8) describing temperature dependence of thermal conductivity:

$$(8) \quad \lambda(T) = \frac{\lambda(0)}{0.99 + T\left(a - \frac{b}{\lambda(0)}\right)}$$

with different coefficients a and b for crystalline and for sedimentary rocks (for crystalline rocks, $a = 0.0030 \pm 0.0015$, $b = 0.0042 \pm 0.0006$).

Clauser and Huenges (1995) highlight an interesting fact that the influence of temperature on thermal conductivity of igneous rocks changes dramatically with different feldspar content. Whereas the conductivity of rocks rich in feldspar (e.g. syenite) decreases by no more than 10 % for the temperature of 300°C, conductivity of rocks poor in feldspars (granite, diorite, gabbro, peridotite etc.) decreases significantly, as apparent from Figure 1. This statement is in conformity with Robertson (1988) who revealed that thermal conductivity of plagioclase and microcline is roughly constant with temperature.

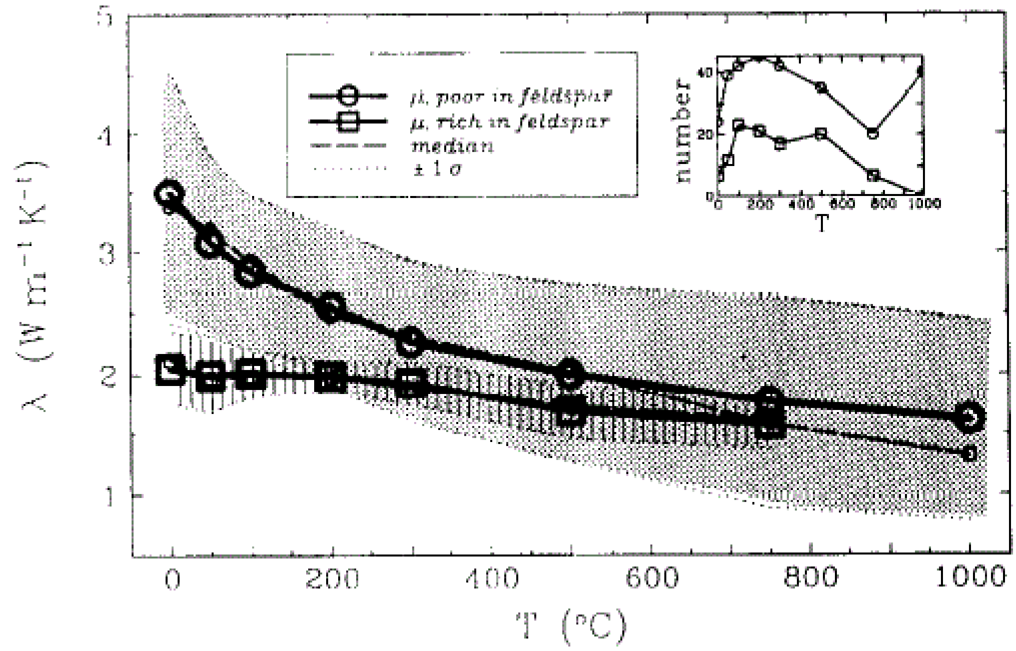


Figure 1 Dependence of thermal conductivity on temperature in igneous rocks. It is apparent that feldspar content plays a key role. Clauser and Huenges (1995)

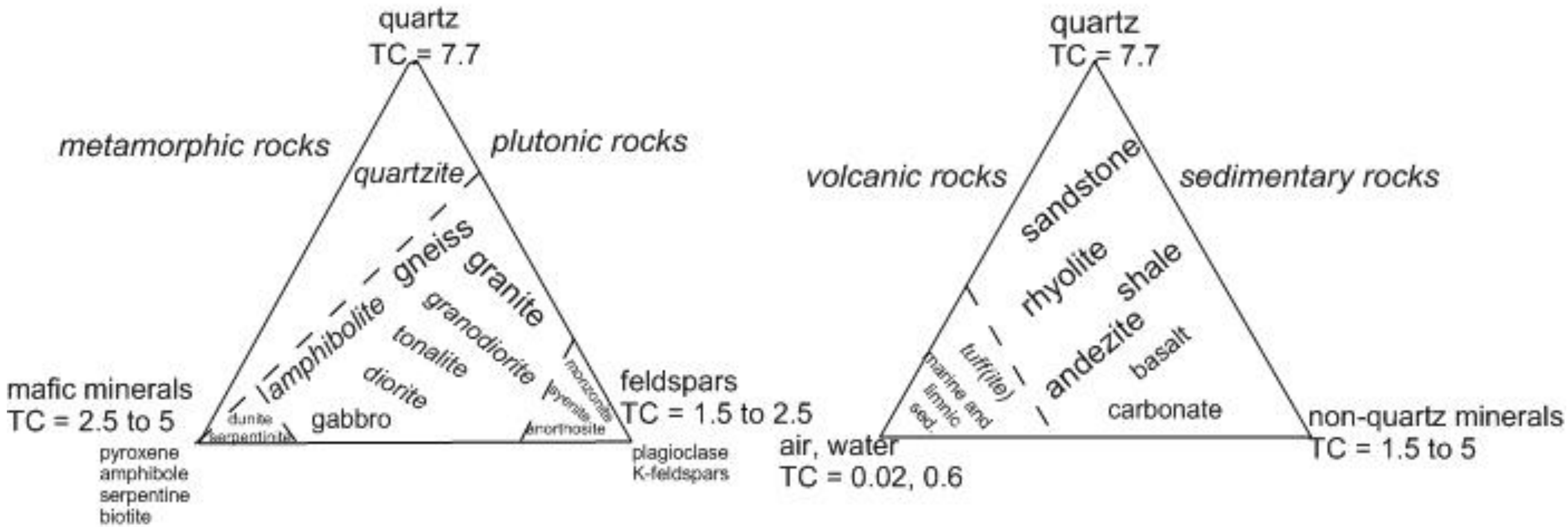


Figure 2 Thermal conductivity of various igneous, sedimentary and metamorphic rocks depending on their mineral composition. TC – thermal conductivity in $Wm^{-1}K^{-1}$. After Clauser and Huenges (1995)

These authors also use a simpler relation (9):

$$(9)\ \lambda(T) = A + \frac{B}{350+T}$$

Empirical constants A and B for crystalline rocks are stated in Table 1:

Rock type	T range	A	B
Acid rock	0 – 1400°C	0.64	807
Basic rock	50 – 1100°C	1.18	474
Metamorphic rock	0 – 1200°C	0.75	705

Table 1 Temperature range and constants A and B used in correction for temperature after Clauser and Huenges (1995)

Figure 3 shows the dependence of thermal conductivity of the three main rock types on temperature ranging from 0 to 200°C. The strongest influence is observed among granitic rocks in which thermal conductivity drops by almost 30%. Rocks that are least affected by temperature are mafic rocks, thermal conductivity of which decreases by less than 20%. Dependence of metamorphic rocks is more similar to acid than to basic rocks, but this information should be treated with caution as properties of metamorphic rocks are always related with the protolith.

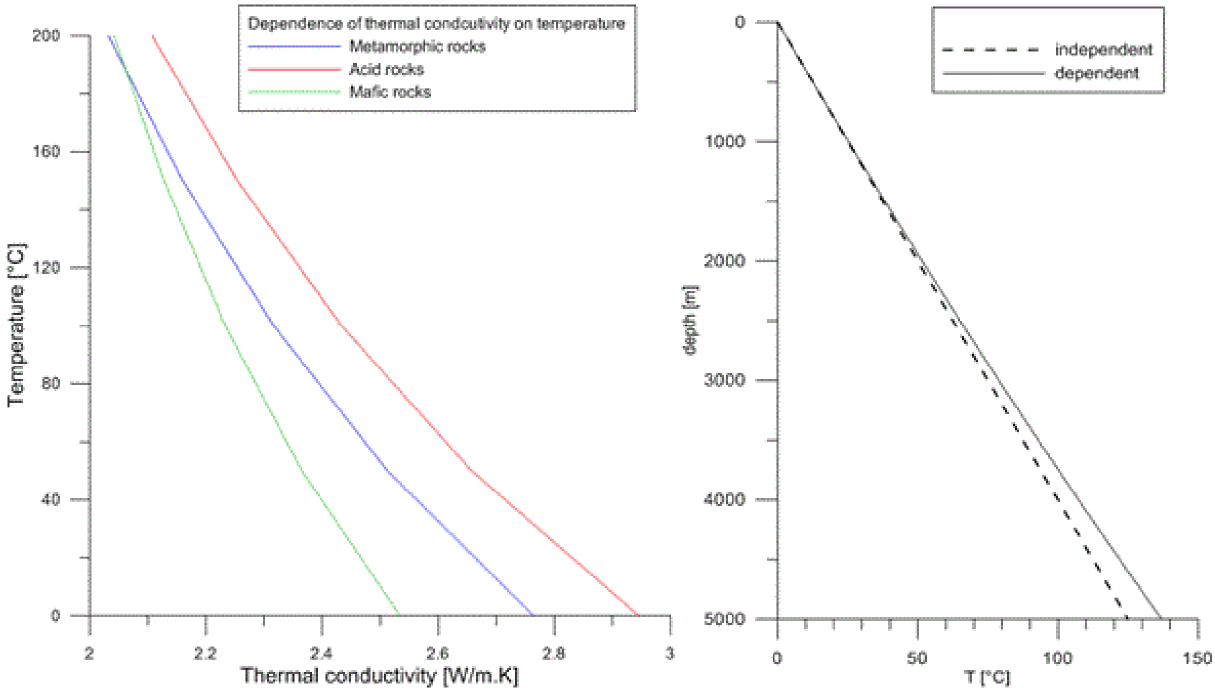


Figure 3 Dependence of thermal conductivity of different types of rocks on temperature. Acid rocks are most affected by temperature while the thermal conductivity of mafic rocks remains relatively stable. (Left)
The effect of such dependence is illustrated with the case of dependent and independent rock with the same thermal conductivity and heat flux. (Right)

The rock with dependence of thermal conductivity on temperature gives the temperature at 5 km depth higher by over 10°C than the rock with no dependence. Thermal conductivity at 0°C was chosen to be 3 $Wm^{-1}K^{-1}$ for both samples, and heat flux 75 $mW.m^{-2}$.

2.3 Measurements of thermal conductivity and diffusivity

To determine thermal conductivity and diffusivity of geological units present in the areas under investigation, samples of drill cores from the following boreholes were measured: Pé-1 (Prosečné), Kh-1 (Kruh), JB-3 (Jesenný) from the surroundings of Semily and Ub-7 (Rýdeč) and Br-1 (Brňany) from the surroundings of Litoměřice. These samples were taken from the rock sample storage in Kamenná with kind permission of the Czech Geological Survey. For more details on these boreholes see chapter 4.

The Lippmann&Rauen GbR Thermal Conductivity Scanner was used for the measurements. Glass with thermal conductivity 1.35 $Wm^{-1}K^{-1}$ and titanium with thermal conductivity 6.52 $Wm^{-1}K^{-1}$ were used as standards and for calibration of the device.

The principle of the method as described in detail by Popov *et al.* (1999) is based on comparison of the maximum measured temperature increase in the sample with the temperature increase in standards of known thermal conductivity as expressed in equation (10), where λ_s is the thermal conductivity of the sample, λ_R is the thermal conductivity of the reference standard, θ_R is the temperature rise in the reference standard and θ_s is the temperature rise in the sample:

$$(10) \quad \lambda_s = \lambda_R \cdot \frac{\theta_R}{\theta_s}$$

The device consists of a laser heat source and temperature sensors placed on a platform that moves under the samples and standards at constant speed. The layout is illustrated in Figure 4.

It is desirable that the measured samples' size in the direction of measurement is at least 3 cm and flat surface (roughness not exceeding 1 mm) of the measured plane is required. To ensure sufficient heat supply and minimize scattering and reflecting, both the samples and the standards are painted black along the surface exposed to the laser beam. Thermal effects of the paint are removed by calibration.

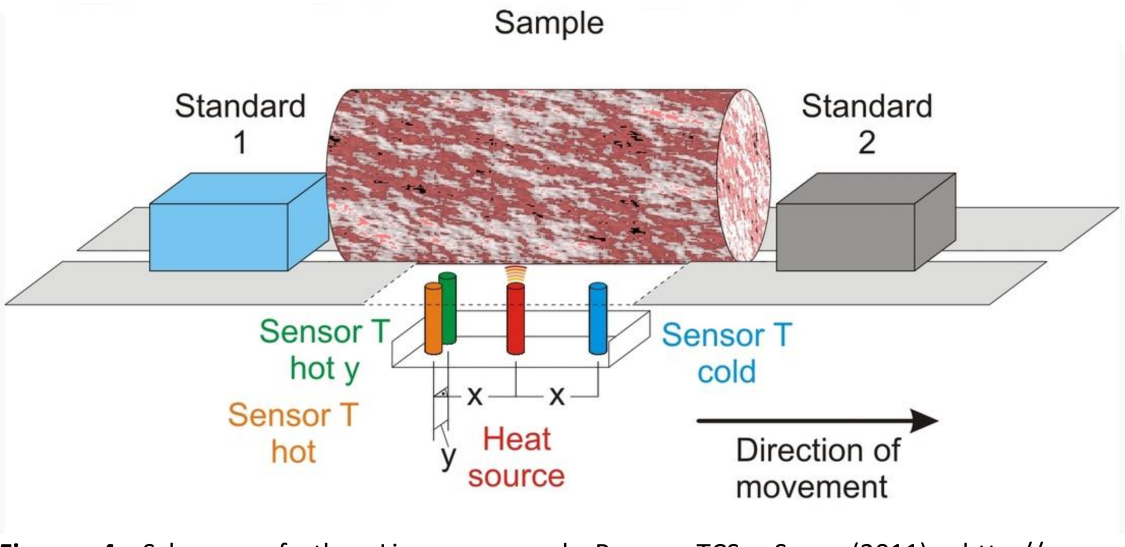


Figure 4 Scheme of the Lippmann and Rauen TCS. Sass (2011): http://www.geo.tu-darmstadt.de/fg/angeotherm/geotherm_forschung/TCS.en.jsp

Most of the cores that had sufficient size and quality were cut so that flat even surfaces were created in the directions parallel and perpendicular to the borehole axis. Phyllite samples that were not horizontally bedded were cut in the directions perpendicular and parallel to foliation. Some samples, however, would be destroyed by cutting, either because of poor consistency of the rock, because of swelling of clay minerals or because of their small size. Therefore, these samples were measured on the flattest planes that could be found on the samples and so the measurements of these might be less accurate due to the uneven surface. Moreover, some of the samples were smaller than the required 3 cm, which might also decrease the reliability of the measurement. Finally, another uncertainty in the measured values could be caused by measuring dry samples only, so that the effect of microcracks, which occur after relaxation of the core, could be enhanced, and the effect of groundwater and its mineralization is reduced. Therefore, the measured values may be lower than the actual values of thermal conductivity in situ.

All samples were measured in the direction of the borehole and in the perpendicular direction. A rectangular sample of marble of known thermal conductivity and diffusivity was measured along with all the samples so that the error of measurement was recorded and measured values could be corrected. It is a common practice that drill core samples are measured in two directions: vertical, i.e. parallel to the axis of the borehole, and horizontal, i.e. perpendicular to the axis of the borehole. In anisotropic rocks, such procedure is sufficient only for horizontally deposited layers and vertical boreholes. In case of inclined boreholes, cross-bedding or tectonically deformed rocks, the relationship between true and measured conductivities is described in the equation (11):

(11) $$\lambda_1 = \sqrt{{\lambda_x}^2 \cos^2\alpha + \lambda_x \lambda_z \sin^2\alpha}$$

$$\lambda_2 = \sqrt{\lambda_x \lambda_z}$$

where λ_1 (vertical) and λ_2 (horizontal) are apparent conductivities obtained by scanning, λ_x is the true horizontal thermal conductivity and λ_z is the true vertical thermal conductivity. α is the angle of bedding measured from the horizontal plane. This procedure was applied to several samples of phyllites that had undergone folding and faulting deformation.

If a drill core is not available, thermal conductivity can be estimated on the basis of well log data. A number of authors dealt with this issue in a number of papers, carrying out studies on the dependence of thermal conductivity on other petrophysical properties for both sedimentary and crystalline rocks, e.g. Sundberg *et al*. (2009), Hartmann, Rath and Clauser (2005) and others. Sundberg *et al*. (2009) suggest that in case of igneous rocks, thermal conductivity is proportional to density. Sedimentary rocks are more complicated as porosity and water saturation play a crucial role in determination of their thermal conductivity. Therefore, more geophysical logging methods must be involved. Hartmann, Rath and Clauser (2005) computed thermal conductivity of sedimentary rock samples using regression analysis of thermal conductivity, bulk density and sonic velocity. All authors agree that thermal conductivity of a rock can be calculated from known thermal conductivities of minerals, provided that mineral composition, porosity and saturation of the rock is known in detail and correct mixing law is chosen. Fuchs *et al*. (2013) conclude that geometric mean mixing model is the most suitable mixing model for most rocks.

2.4 Thermal gradient and its variability

Thermal gradient is the change of temperature with growing distance (usually only depth is considered in our calculations, as lateral change tends to be negligible or unimportant). It is closely dependent on thermal conductivity – the higher is the conductivity, the lower is thermal gradient. Change in conductivity is, therefore, responsible for change in thermal gradient.

The general statement above, however, is completely valid only in homogeneous isotropic environment with planar surface and where heat is transported solely by conduction. For example, presence of groundwater in porous rocks may drive convective heat transfer, in which case we cannot simply determine thermal conductivity as the only mechanism affecting thermal gradient. In environments with convective heat transfer, thermal gradient is significantly affected and can reach values near zero or, on the contrary, be increased as heat exchange within the fluid is even and efficient. Such mechanism is generally accepted in the Earth's mantle. However, the situation in the Earth's crust is more complicated because both convection and conduction are taking place and convection is driven by different mechanisms than in the mantle, where conduction takes place mainly due to adiabatic cooling. In the crust, the fluid that transfers heat via convection is usually groundwater flowing in porous rocks of sedimentary basins or in cracks in the near-surface crystalline rocks and the complex of factors that drive its flow are subject to hydrogeological research, which is beyond the scope of this paper. Overall, thermal gradient in the rocks under the groundwater table depends on the direction in which groundwater flows. At regional scale, temperature measurements have proven certain difference in temperature profiles in the areas of upwelling or in the areas of sinking, as presented in Figure 5.

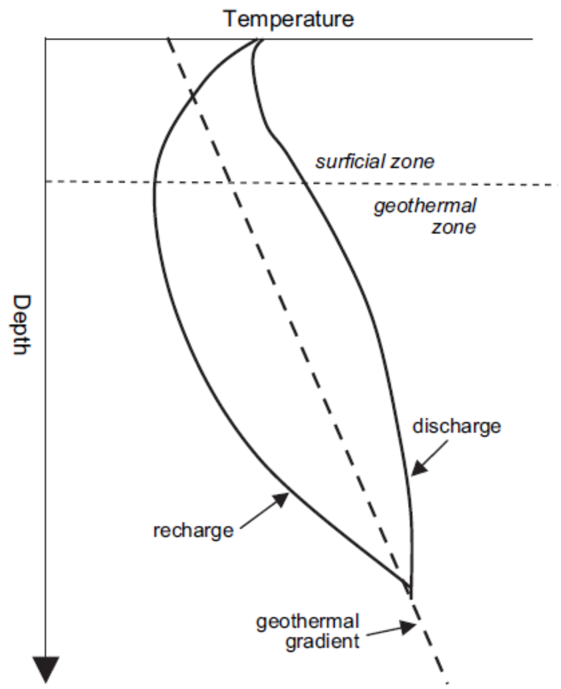


Figure 5 Temperature gradient in different hydrogeological regimes. Temperatures in the surficial zone are probably disturbed by seasonal variations, so only the temperatures in the geothermal zone are representative. Anderson (2005)

Another factor that has a great influence on temperature gradient is heat generation. Presence of rocks with high content of natural radioisotopes of ^{40}K, ^{235}U, ^{238}U and ^{232}Th that generate heat by radioactive decay can have a marked effect on the temperature gradient, as obvious from

Figure 6. For example, 1 km thick layer of granodiorite with thermal production of 8 μW.m^{-3} increases the local heat flux by 8 mW.m^{-2}. As apparent from Fourier's Law, in rocks with thermal conductivity 3 Wm^{-1}K^{-1} the temperature gradient would be 0.0027 °C.m^{-1} higher than in rocks without heat production. The contribution of heat production to heat flux causes a vast difference in temperatures at depth, as apparent from Figure 6.

Heat production of each rock can be determined from the equation 12 or 13 (Jaupart and Mareschal, 2011):

(12) $H = 10^{-11} (9.52 \cdot Q_U + 2.56 \cdot Q_{Th} + 3.48 \cdot Q_K)$

(13) $A = 0.257 \cdot Q_U + 0.069 \cdot Q_{Th} + 0.094 \cdot Q_K$

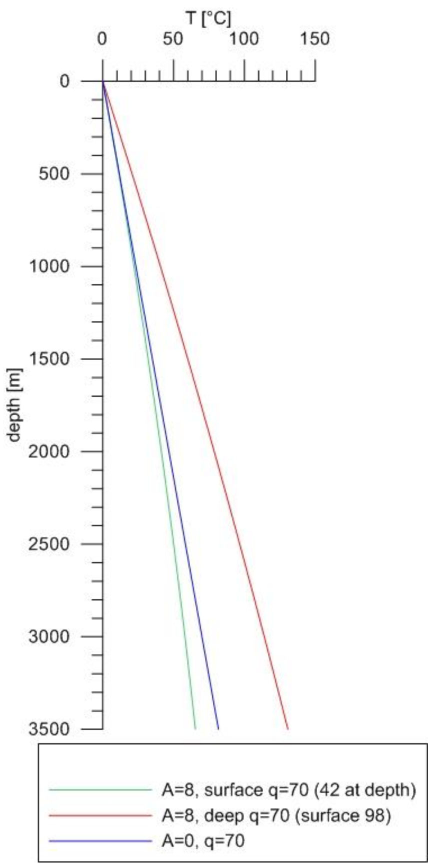


Figure 6 A 3.5 km thick mass of homogeneous rock. The surface heat flux 70 mW.m^{-2} was used for two cases (green and blue line). The red line represents the same value of heat flux at depth and its manifestation on the surface as well as increased temperature at depth).

where H is the bulk heat production in [W.kg^{-1}], and A is the heat production per unit volume in [μW.m^{-3}] defined as A=H.ρ where ρ is density (the average crustal density 2700 kg.m^{-3}), Q_U is concentration of uranium in ppm, Q_{Th} is concentration of thorium in ppm and Q_K is concentration of potassium in %. Concentrations of these elements can be determined by laboratory gamma-spectrometric measurements. However, relatively large volume of ground samples is required for such measurements. On the other hand, the measurement is essential as variations in heat production are significant even within a single rock type of a single geological unit. Extrapolation from one geological province to another is, therefore, impossible (Jaupart and Mareschal, 2011). If no samples are available, it is possible to use average values obtained from literature, provided that the significant uncertainty is taken into account.

Another factor that can have a strong influence on thermal gradient is topography, as demonstrated in Figure 7. It is obvious that topographic elevations that are further from internal heat sources of the Earth exhibit lower temperature gradient than depressions, in which the cool surface is nearer the hot masses beneath. This effect is stronger than the contradicting effect of decreasing surface temperature with increasing altitude.

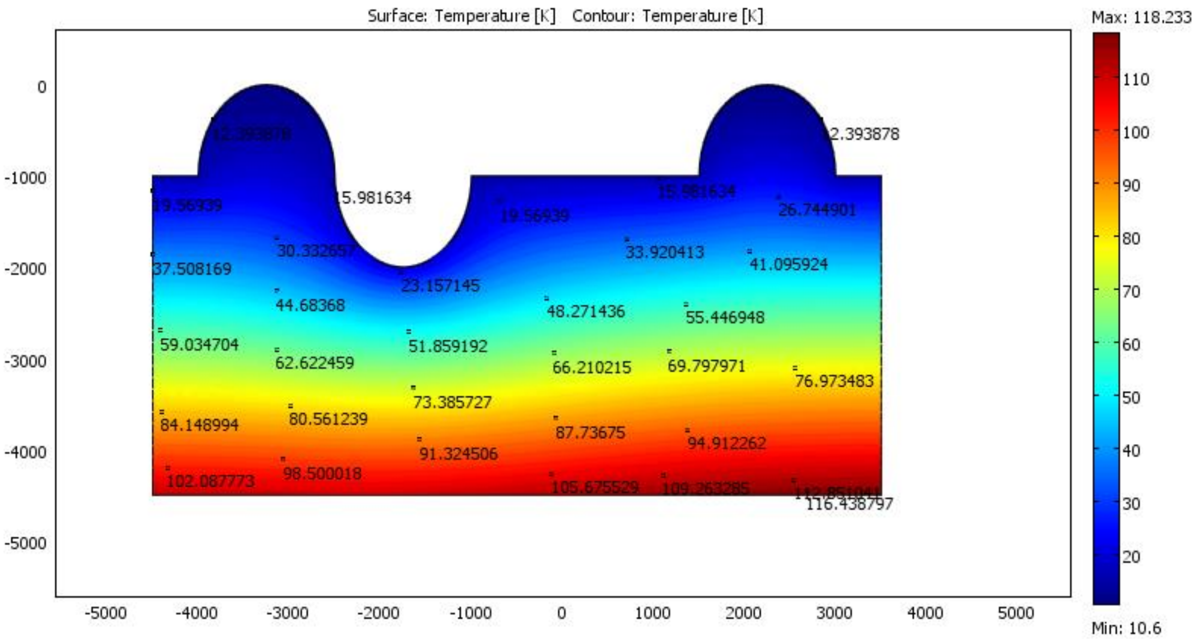


Figure 7 Effect of topography on temperature gradient (Temperature in °C).

Similar effect can be also reached in deeper geological units with palaeotopography or tectonic deformation, e.g. rift basins filled with sediments of different thermal conductivity.

In the near-surface layers, thermal gradient is affected by seasonality, as heat from the sun propagates deeper in the ground during summers and heat transfer to the surface increases during cold months. As demonstrated in Figure 8, seasonality mostly affects thermal profile in the first 10 m of depth, depending on the urbanization, vegetation, hydrology and geology of the place, and especially thermal properties of local rocks. Diurnal variations are negligible as they penetrate no deeper than approximately 1 m. Long-term climate changes, however, can be observed at great depths. The effect of the Little Ice Age is recorded in the depth up to 200 m and the effect of the last glacial period can be observed as deep as 2000 m (Jaupart and Mareschal, 2011). Therefore, the temperature data should be corrected for this effect during calculations of heat flow. The difference between the corrected and uncorrected heat flow is shown in the map (Figure 9). It is obvious that areas that were covered by ice-sheet are affected more strongly than the periglacial areas. In warmer climate zones, the effect is weak.

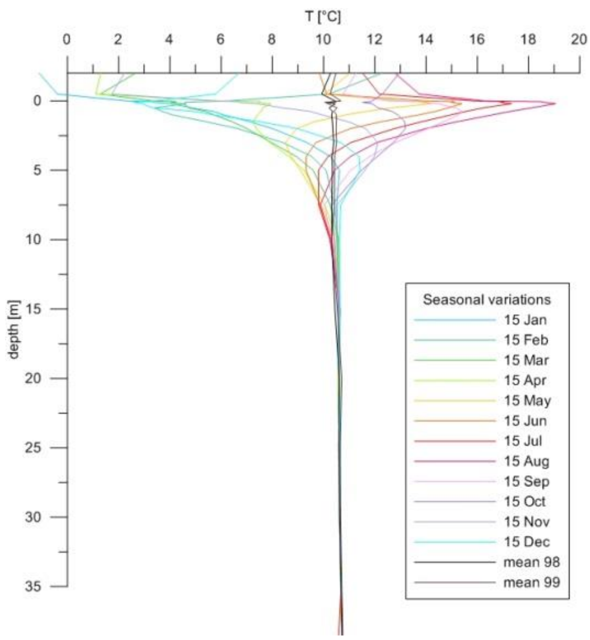


Figure 8 Seasonal temperature variations and their effect with depth. Data from the Geophysical Institute, AS CR, measured during 1998 and 1999 in Spořilov, Prague.

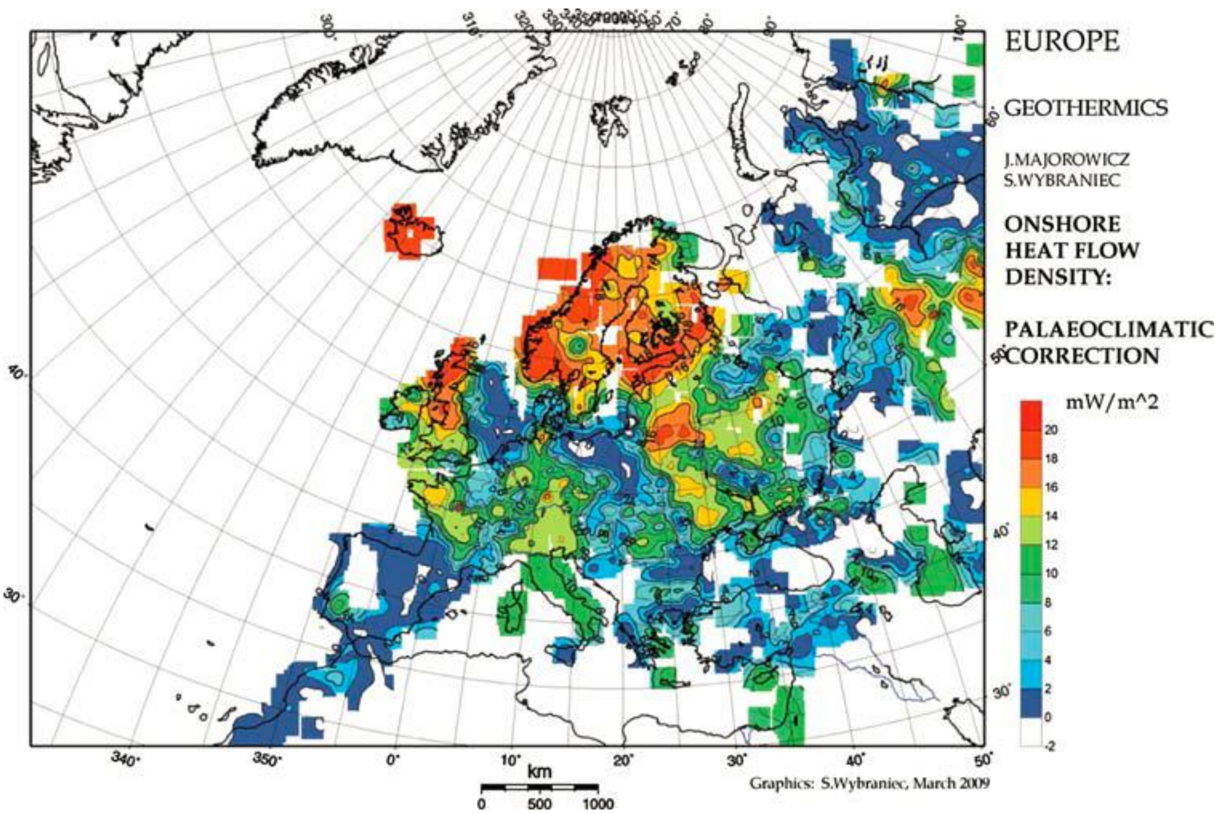


Figure 9 Difference between heat flux with palaeoclimatic correction and heat flux without the correction. Majorowicz and Wybraniec (2010)

2.5 Estimate of temperature in depth, calculation of heat flux, procedure of construction of geothermic models

Geothermic models are constructed as solutions of the heat transfer equation. For an accurate model it is vital to know the geological composition of the studied area in order to determine accurate values of thermal conductivity for each geological unit. In addition, some temperature measurements in boreholes are necessary for a valid estimate of thermal gradient in the area, so that heat flux can be calculated. With undisturbed temperature measurement in layers with known thermal conductivity, heat flux is calculated from the Fourier's Law.

It is common practice that average temperature on the surface is the Dirichlet boundary condition and heat flux is the Neumann boundary condition.

Simplified models are constructed for dry environments where only conductive heat transfer is considered. For more complex models involving convection, a number of hydrogeological parameters must be determined as well, usually requiring hydrogeological research carried out in the area of interest and detailed well-logging data that would determine porosity and transmissivity of the rocks and flow velocity of the fluid, so that other hydrogeological parameters can be calculated.

In the case of convective heat transfer, thermal conductivity of the rock is no longer sufficient as thermal properties of the fluid must be known as well. For undisturbed convection, specific heat of the fluid must be known.

In transient conditions, thermal diffusivity must be determined, for which knowledge of the material's density and thermal capacity is required as well (see chapter 2.1), unless rock samples are available for which thermal diffusivity can be determined by optical scanning together with thermal conductivity.

In conclusion, detailed well logging, geological and hydrogeological research must be carried out prior to construction of a working model. The knowledge of geological composition is essential for determination of geometry of units with different parameters (e.g. thicknesses of individual units for a 1D model). The parameters are either directly measured or calculated from other measured properties during the well-logging and hydrogeological interpretation.

By entering all the required parameters and boundary conditions in the heat transfer equation and finding its solution, the resulting temperature field in the defined geometry is acquired.

3. Geological settings

3.1 Relationship between regional geology and geothermic conditions

All the studied areas are found in the largest geological unit in the Czech Republic (see Figure 10) - the Bohemian Massif, which is a part of European Variscides that stretch across Germany and France to North Spain and southernmost parts of the British Isles. The central parts of Variscides consist of deeply metamorphosed rocks and granitic plutons. The map of European Variscides is in Figure 11. During the Carboniferous and Permian, numerous sedimentary basins were formed and filled with terrestrial clastic sediments. In the Cretaceous, especially during the Cenomanian transgression, the largest sedimentary basin in the Czech Republic was formed: the Bohemian Cretaceous Basin (BCB), which stretches over 200 km in the NW-SE direction. With three major aquifers it is a vital source of groundwater for the country. Its basement was studied in the 1960s using various geophysical methods including deep seismics, magneto-telluric method and gravity, as well as by drilling exploration boreholes. The results of the research are summarized in Malkovský *et al.* (1974). According to these authors, the basement is formed of Proterozoic rocks of the Teplá-Barrandian Unit or Variscan plutonic or metamorphic crystalline massifs (Krušné hory Crystalline Complex, Krkonoše-Jizera Crystalline Complex etc.), and Permo-Carboniferous terrestrial sediments of the Krkonoše Piedmont Basin, Mnichovo Hradiště Basin, Česká Kamenice Basin, Mšeno-Roudnice Basin and other local occurrences.

With the coming Alpine Orogeny in the Late Cretaceous and during the Tertiary, many fault structures in the Bohemian Massif were rejuvenated and a number of new faults were generated. Among the most important tectonic structures, the Elbe Lineament and the Eger Graben (or Eger "Rift") should be pointed out. Not only do these structures predefine the course of some of the Czech Republic's major rivers, they also exhibit increased heat flux causing increased temperatures at shallower depths (Figure 12).

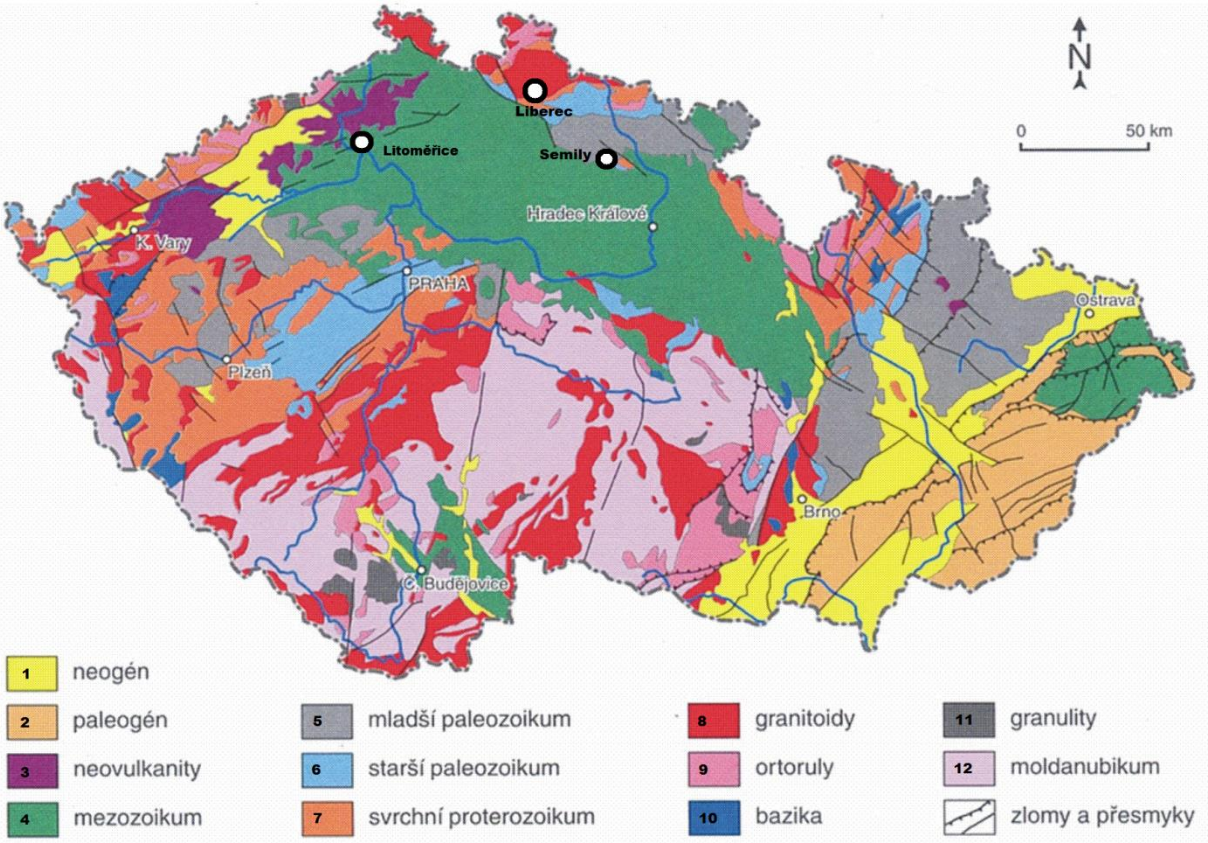


Figure 10 Simplified geological map of the Czech Republic by Chlupáč et al. (2002) with located areas of interest: Litoměřice, Semily and Liberec.
1 - Neogene, 2 - Palaeogene, 3 - Cenozoic volcanic rocks, 4 - Mesozoic, 5 - Upper Palaeozoic, 6 - Lower Palaeozoic, 7 - Upper Proterozoic, 8 - granitoids, 9 - orthogneisses, 10 - mafic rocks, 11 - granulites, 12 - Moldanubian unit. The last cell of the legend represents faults.

During the Cenozoic, volcanic activity was taking place in the west and north-west of the Bohemian Massif, namely in the volcanic complexes of České středohoří and Doupovské hory. Some post-volcanic phenomena can still be observed in those areas, such as thermal waters used by numerous spas, seismic swarms, leakage of CO_2 and, most importantly, increased heat flux, often exceeding 80 $mW.m^{-2}$. Some of these phenomena are mentioned in chapter 4.

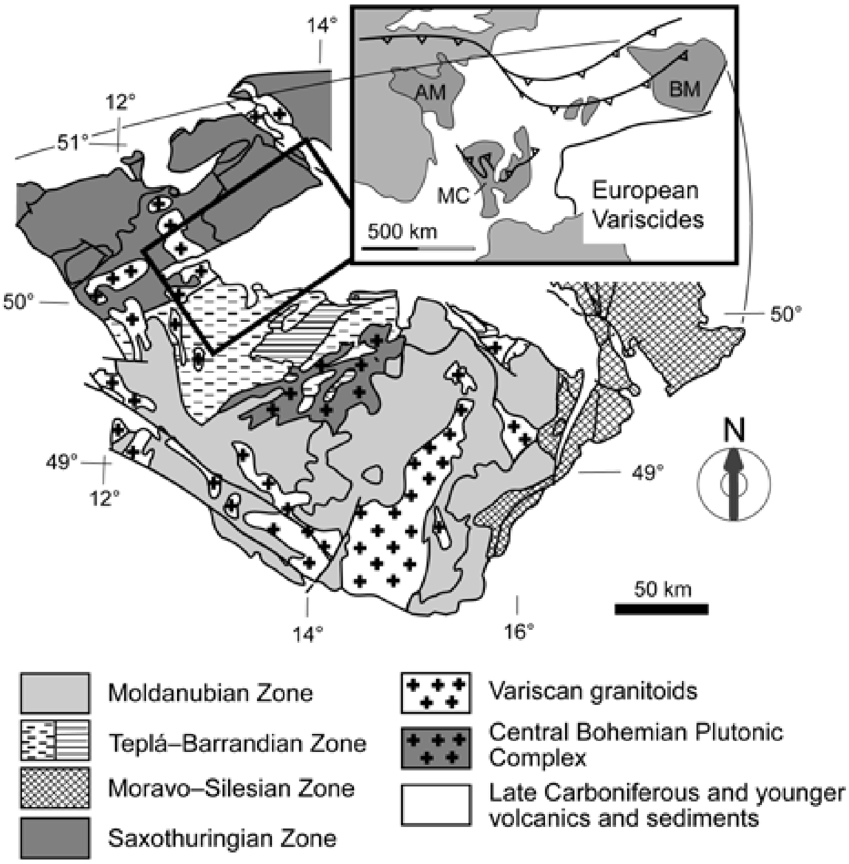


Figure 11 Schematic map of European Variscides and a detail of Bohemian Massif. Mlčoch and Konopásek (2010)

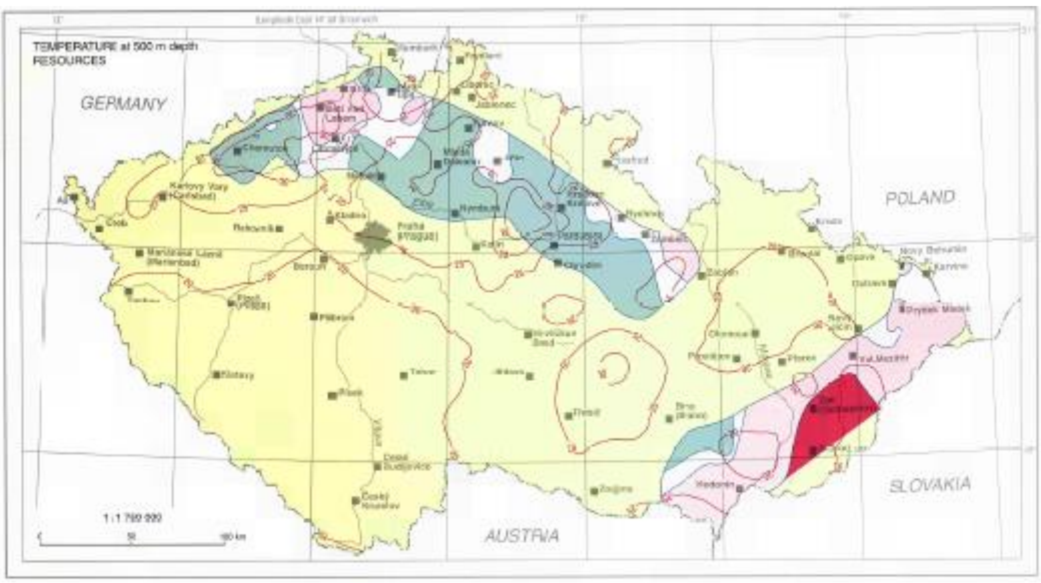


Figure 12 Map of isolines of temperature at 500 m depth. Bohemian Cretaceous Basin, North Bohemian Basin, Vienna Basin and Carpathian Foredeep are highlighted in colour, potential geothermal areas highlighted in red. Hurter and Haenel (2002)

3.2 Optimal geological environment for a HDR site

Examples of a very favourable (A), less favourable (B) and unfavourable (C) geological environment for a HDR site are given in Figures 13 and 14.

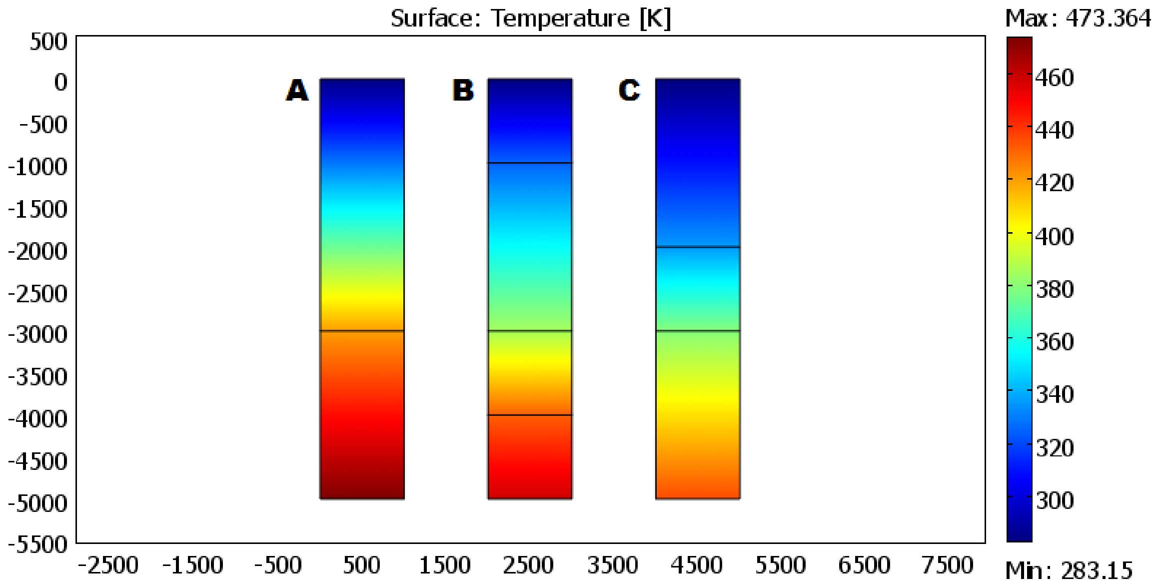


Figure 13 Examples of environments with q=75 mW.m^{-2}:

A: 0-3 km insulating anisotropic sediments - shales, λ_1=1.5, λ_2=2
3-5 km granite body, λ=2.8, A=6.5,
B: 0-1 km insulating shales, λ_1=1.5, λ_2=2
1-3 km limestone, λ=2.8
3-4 km volcanic rocks, λ=1.8
4-5 km plutonic body, λ=3, A=5,
C: 0-2 km sandstones, λ=3
2-3 km volcanic rocks, λ=1.8
3-5 km metamorphic rocks, λ_1=2.3, λ_2=2.8

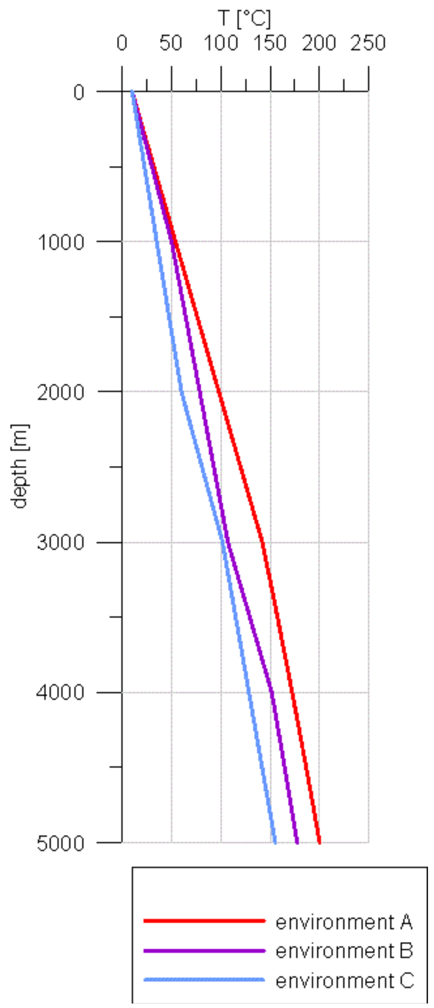


Figure 14 Temperature profiles of environments A, B and C.

It is apparent that the environment A represented by a granitic pluton overlain by shales is a very good environment for a HDR site, as the temperature of 100°C is reached at the depth of 2 km already. The temperature at the depth of 5 km reaches 200°C. On the other hand, the environment B consisting of shales, limestone, volcanic rocks and a granitic pluton seems less favourable, with the temperature lower by 25°C at 5 km depth than environment A. An unfavourable environment is represented by the example C. Sandstones and volcanic rocks with anisotropic horizontally foliated metamorphic rocks in the basement exhibit the lowest temperatures along the whole profile. It is interesting that the temperature gradient increases noticeably in the anisotropic layers of each environment. This fact corresponds with the idea presented by Ledru and Frottier in Huenges (2010) who point out that anisotropy renders vertical heat transfer while supporting the lateral heat transfer, thus causing accumulation of heat within these layers.

4. Geothermal exploration in the Czech Republic

An extensive geothermic study was carried out already in the second half of the 20th century. The first map of heat flow in former Czechoslovakia was published by V. Čermák in 1968. Since then, numerous papers on heat flow and geothermic properties of rocks have been published by researchers from universities and especially from the Geophysical Institute of AS CR. During the past decade, the global trend of search for green energy resources has roused special interest in geothermal energy. As a result, the first geothermal exploration borehole was drilled in Litoměřice in 2006 and Litoměřice has become the first site proposed for construction of a geothermal power plant or a heat plant in the Czech Republic. Several other sites have been explored afterwards for geothermal applications, such as Semily or Liberec. Nevertheless, more information on local geothermal conditions that would prove suitability of these areas for geothermal energy usage is needed in order to attract investors and launch the projects. Therefore, the author of this thesis has constructed geothermic models of these sites to verify their suitability for geothermal applications. The results of this research are summarized in this chapter.

4.1 Litoměřice

The town of Litoměřice is located in the north-western part of the Bohemian Cretaceous Basin (BCB) near the intersection of two largest deep-seated fault zones in the region: the Eger Rift and Elbe Lineament, and lies in proximity of the Cenozoic volcanic centre of České středohoří. Other two major faults in the area are the Litochovice Fault (which is a part of the České středohoří Fault Zone) and the Litoměřice Fault. Most major faults are extensional and run in the E-W direction, normal faults of mostly Late Palaeozoic age running in the direction parallel to the Krušné hory Mts., i.e. SW-NE direction, are common as well. Faults of the Elbe Fault Zone running in the NW-SE direction also occur in the area (Mlčoch and Konopásek, 2010). The Litoměřice Fault separates the horst of the Opárno Crystalline Complex from the "Eger Rift", locally reaching the throw of up to 100 m. The basement of the area is formed of Proterozoic migmatites and orthogneisses belonging to the Krušné hory Crystalline Complex and of the so-called "Teplice rhyolite" or "Teplice porphyry" of Variscan age. The basement is overlain by the sequence of Permo-Carboniferous sediments of the four major formations of the Mšeno-Roudnice Basin (Kladno, Týnec, Slaný and Líně formations) with typical alternating mudstones and siltstones with sands and conglomerates and several coal-bearing horizons. The Permian formations are covered with Cretaceous sediments of the Eger part of the BCB, consisting of mudstones, marlstones and argillaceous limestones in the south with increasing proportion of sandstones towards the north. Sedimentation of the Upper Cretaceous is almost horizontal, with a slight inclination towards the north. Some parts are overlain with Tertiary volcanites, mainly foidites, trachytes and trachytic basalts of the České středohoří Volcanic Complex (Domas *et al.*, 1988). On the other hand, Cajz and Valečka (2010) argue that the Litoměřice Fault forms the margin of the Mšeno-Roudnice Permo-Carboniferous Basin and Litochovice Fault delimitates the Opárno Horst.

This area exhibits increased heat flow (locally exceeding 80 $mW.m^{-2}$). It is subject to discussion whether such heat flow should be attributed to post-volcanic activity of the area, to the deep-seated faults, a granitic pluton with intensive radiogenic heat production or a combination of these. The geological composition of the area is complicated as two major Variscan terranes – the Teplá-Barrandian and Saxothuringian – meet here. Further to the south-west, in the Karlovy Vary Region that is located within the so-called Eger Rift, naturally occurring thermal mineral waters are used in numerous spas and several hot springs and mud volcanoes are subject to protection as a national natural heritage. As this area is located on the same deep structure of Eger Rift, connection including some communication of thermal waters is possible. In the town of Děčín, which is only 30 km far from Litoměřice, thermal waters are used for district heating in a part of the town.

Figure 15 Boreholes Br-1, GTPV LT-1 and Úb-7 (from south to north) and the position of the geological section running through them in the section of a geological map 1:50 000 published by the Czech Geological Survey.

4.1.1 Boreholes

The location of the boreholes and of the geological section is shown in Figure 15. General description of boreholes that have been used for construction of the model is given in the following paragraphs including lithology, stratigraphy and hydrogeology, as well as the outcome of thermal conductivity scanning on drill cores. For isotropic samples, i.e. those with thermal conductivity difference between the horizontal and vertical direction not larger than 10%, the average value of thermal conductivity is stated. For anisotropic samples, the average value of thermal conductivity in the direction parallel to bedding or foliation and in the direction perpendicular to bedding or foliation are stated. Thermal conductivity of crystalline basement samples was also corrected for temperature. In case of sedimentary rocks, such correction was not applied because the temperatures in the sedimentary cover are relatively low and the effect of temperature is negligible compared to the error induced by measuring dry samples instead of water-saturated samples.

Br-1 Brňany

The village of Brňany is located approximately 6 km south of Litoměřice. The position of the borehole is shown in Figure 15. The borehole was drilled during the research project on the basement of the BCB in the 1960s and reached the depth of 1388 m. Lithological description is given in Table 2.

Lithology and stratigraphy

0 - 8.5 m	Quaternary	
8.5 - 149.7 m	Cretaceous-Turonian	marlstones, calcareous siltstones
149.7 - 199.7 m	Cretaceous - Cenomanian	sandstones
199.7 - 1312.6 m	Permo-Carboniferous	199.7-846.7 m red siltstones and mudstones of the Líně Formation
		grey mudstones of the Slaný Formation (<100 m)
		arkoses, conglomerates and siltstones of the Týnec Formation (<100 m)
		siltstones and mudstones of the Kladno Formation, breccias on the base
1312.6 - 1388 m	crystalline basement	bluish siliceous diorite (plagioclase prevalent over orthoclase and quartz) alternating with phyllite

Table 2 Lithological and stratigraphical description of Br-1. After Macák *et al.* (1968)

Hydrogeology

According to hydrogeological research and resistivimetric and thermometric measurements, 5 inflows have been detected in the borehole and named using letters A – E (Jetel and Štefek, 1968):
A (1310 – 1384 m) – inflow of saline water into Proterozoic phyllites, horizontal flow
B (928 – 990 m) – inflow of hyperhaline water into Carboniferous sediments of the Týnec Formation, horizontal flow, very low permeability and filtration coefficient
C (663 – 812 m) – inflow of hyperhaline water into the lower parts of the Carboniferous Líně Formation, very low permeability and filtration coefficient
D (444 – 612 m) – inflow of mineral water into the Permo-Carboniferous Líně Formation, very low permeability and filtration coefficient
E (148 – 200 m) – Cenomanian aquifer (moderate permeability of sediments, filtration coefficient $2*10^{-6}$ m.s^{-1})

Thermal properties

Thermometric measurement was first carried out in February 1967 in the depth interval 10 - 857 m, later (May 1967) in the depth interval 120 – 1250 m. Figure 16 shows the temperature profile along the borehole together with variations in temperature gradient. Maximum measured temperature at the depth of 1250 m was 48.6 °C. The data from these two measurements for the same depths differ. The reasons for these variations might be as follows: a) measured too soon after drilling, b) measured too rapidly, c) incorrect calibration, d) temperature detectors with low resolution. All these factors are common among measurements performed in the 1960s and 1970s by industrial companies because the apparatuses were not as advanced as nowadays and neither was the knowledge of temperature field in the geological environment.

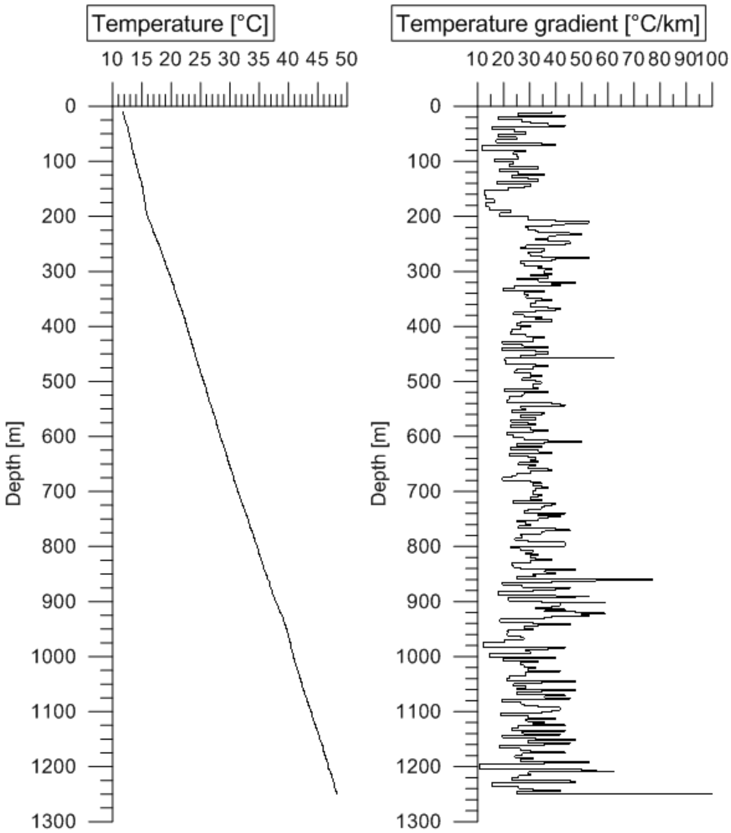


Figure 16 Temperature and temperature gradient in the borehole Br-1.

Heat flux was calculated from Fourier's Law from the mean thermal conductivity in all depth intervals where thermal conductivity had been measured (2.4 $Wm^{-1}K^{-1}$) and the mean temperature gradient (29°C/km). The average calculated heat flux in this borehole was 69 $mW.m^{-2}$. Horizons influenced by flowing water were excluded from the calculation.

Radiogenic heat production is calculated as mentioned above from the concentration of radioactive isotopes of K, U and Th in the rock. As the heat production of sediments is usually negligible, this would apply to igneous rocks. However, the granodiorite samples did not have sufficient volume for laboratory gamma-spectrometry. Therefore, their radiogenic heat production could not be determined.

Úb-7 Rýdeč

The borehole is located between the villages Rýdeč and Řetouň approximately 10 km northwards of Litoměřice, see Figure 15 for the location. It was drilled in 1965 and reached the depth of 588 m. Trachytic dikes and sills have been intersected in several parts of the hole, but their thickness was insignificant.

Lithology and stratigraphy

0 - 2 m	Quaternary	

2 - 525 m	Cretaceous	2 - 20.8 m Santonian siliceous sandstone with intercalations of calcareous mudstone and marlstone
		20.8 - 264 m Coniac (full thickness of the unit) calcareous mudstones and marlstones, calcareous and argillaceous sandstones near the roof
		264 - 488 m Turonian marlstones, calcareous mudstones and argillaceous limestones, argillaceous and marly sandstones in the lower parts
		488 - 525 m Cenomanian argillaceous sandstones, mudstones in the lower parts, conglomerate and sandstone on the base
525 - 588 m	crystalline basement	525 - 526 m reddish eluvium of granodiorite
		526 - 579 m hydrothermally altered granodiorite
		579 - 588 m granodiorite (rich in plagioclase and microcline, contains accessory zircon)

Table 3 Lithological and stratigraphical description of Úb-7 after Macák, Opletal, Shrbený (1969).

Hydrogeology

Hydrogeological testing and well logging was performed in the Cenomanian and Turonian aquifers. Porosity of sandstones was determined ranging from 21 to 24% (Macák, Opletal, Shrbený, 1969). All the studied horizons were found permeable, although their permeability was relatively low (filtration coefficient $1.64*10^{-6}$ - $5.30*10^{-7}$ $m.s^{-1}$ according to hydrogeological testing by Hazdrová – Database of Geologically Documented Objects- CGS-Geofond).

Thermal properties

Thermometric measurement was carried out in the depth interval 36.8 – 487.5 m. Figure 17 shows the temperature profile along the borehole together with variations in temperature gradient. Maximum measured temperature at the depth of 487.5 m was 26.3 °C.

Heat flux was calculated from Fourier's Law from the mean thermal conductivity from all depth intervals where thermal conductivity had been measured (2.1 $Wm^{-1}K^{-1}$) and from the mean temperature gradient (36°C/km). The average calculated heat flux in this borehole was 75.2 $mW.m^{-2}$. Horizons influenced by flowing water were excluded from the calculation.

As well as in the case of Br-1, the granodiorite samples had too small volume for laboratory gamma-spectrometry, so that their radiogenic heat production could not be determined.

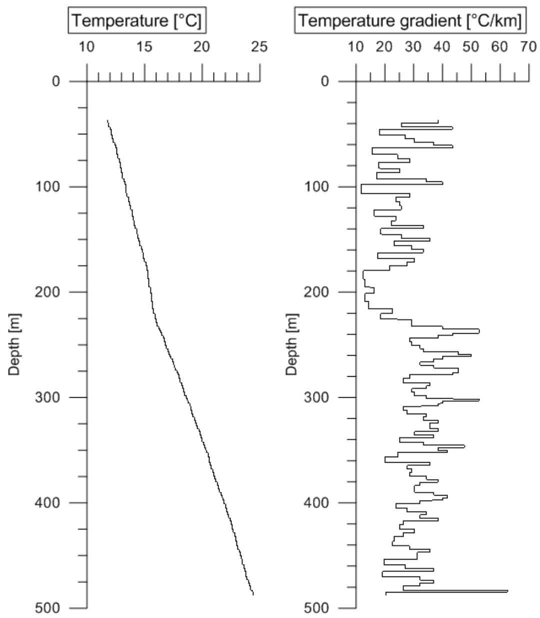


Figure 17 Temperature and temperature gradient in the borehole Ub-7.

GTPVLT-1 Litoměřice

The exploration well GTPV LT-1 is the first borehole in the Czech Republic drilled primarily for geothermal purposes. The drilling took place in years 2006-2007 and the final depth was 2110 m.

Lithology and stratigraphy

0 - 25 m	Quaternary	
25 - 165 m	Cretaceous - Turonian	
165 - 190 m	Cretaceous - Cenomanian	
190 - 780 m	Permo-Carboniferous	190 - 460 m Líně Fm.
		460 - 500 m Slaný Fm.
		500 - 600 m Týnec Fm.
		600 - 780 m Kladno Fm.
780 - 910 m	"Teplice porphyry"	Rhyolitic ignimbrite
910 - 942 m	?	base of Permo-Carboniferous unit
942 - 2050 m	Proterozoic crystalline basement	mica schist with interlayers of phyllite and actinolite-rich rock
2050 - 2110 m	Proterozoic crystalline basement	phyllite

Table 4 Lithological and stratigraphical description of GTPV LT-1 after Žáček and Škoda (2008).

Hydrogeology

The borehole was cased and sealed along the whole sedimentary sequence, so that the measurements would not be affected by flowing water from the overlying aquifers. Thermal water had been expected in the Teplice porphyry as it is the reservoir of thermal water in Teplice. However, the basement crystalline formations including the porphyry were found dry, lacking any hydraulic communication with the overburden. (Burda *et al.*, 2007)

Thermal properties

Thermometric measurement has been carried out repeatedly. In 2007 the temperature profile was as shown in Figure 18.

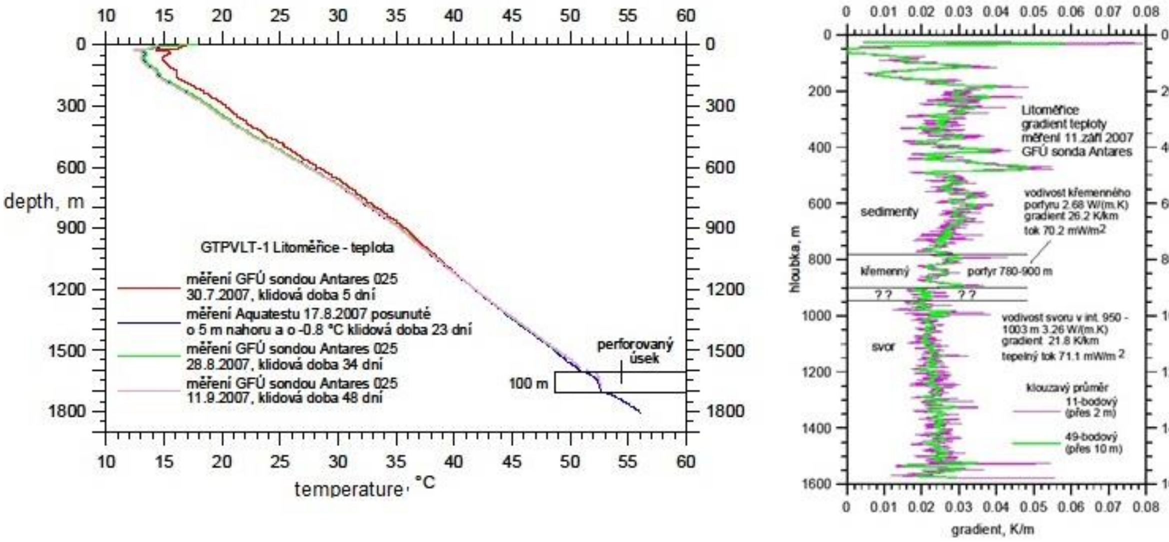


Figure 18 Temperature profile (left) and variability of temperature gradient in GTPV LT-1 (right). Šafanda *et al*. (2007). The temperature profile shows that the temperature at the depth of 1800 m is slightly less than 60°C.

The measurements were performed 5, 23, 34 and 48 days after drilling. Maximum measured temperature at the depth of 1800 m was 56.5°C (Myslil *et al.*, 2008).

Thermal conductivity could only be measured on samples of the quartz porphyry and mica schist because core from other parts of the borehole was not available. Therefore, the heat flux at the depth of 1800 m was extrapolated from values calculated in the horizons with known thermal conductivity and corrected for palaeoclimate. The estimate was given as interval 72 – 78 $mW.m^{-2}$ (Šafanda *et al.*, 2007).

4.1.2 Hydrogeology

Hazdrová (1967) pointed out that the basement on the map sheets of Litoměřice and Ústí nad Labem is penetrated by numerous cracks and water circulation may be taking place not only in the Cretaceous, but also in the Permo-Carboniferous and even in the Teplice Porphyry. However, Kobr (2013, pers.comm.) remarks that no vertical fluid motion has been recorded by well logging in the majority of the BCB in lower portions than Cretaceous. Nevertheless, water circulation within the Cretaceous aquifers can be significant. Jiráková *et al*. (2011) observed low temperature gradients in the area of Česká Lípa (NE of Litoměřice), which is the infiltration area of the aquifer and is influenced by precipitation, and increased gradient in Ústí nad Labem, where thermal waters from deeper structures accent and are utilised for balneology and heating. In general, the regional groundwater circulation has NE-SW direction. Even the shallow circulation might potentially affect the thermal field in Litoměřice, but portions where the shallow circulation is taking place were not incorporated in the presented studies.

4.1.3 Geological structure

A rough geological section was constructed on the basis of geological maps of the area and information from the boreholes. Previously constructed sections in the nearby areas were also placed alongside with background information, for example the section by Guy *et al*. (2011) – Figure 19- and the seismic profiles across the Mšeno-Roudnice Basin. The area of interest lies near the boundary between the Saxothuringian and Teplá-Barrandian units of the Bohemian Massif, but the exact position of the boundary is unclear.

Whereas the sediments of the BCB and the underlying Permo-Carboniferous formations have been studied in detail and are fairly well explored, the crystalline basement remains severely unexplored despite numerous research projects attempting to shed some light on this matter (e.g. Malkovský *et al*., 1974; Mlčoch and Konopásek, 2010 etc.). Deep boreholes such as Br-1, GTPV LT-1 or Úb-7 give a clue on the geological composition of the basement, but do not provide enough information for a valid interpolation of geological situation between them. Basement of both the Br-1 and Úb-7 is formed of plagioclase-rich granodiorite. The granodiorite from Úb-7 exhibits higher-temperature alteration than the granodiorite from Br-1, which is largely altered by chloritization (Dolejš, 2013, pers.comm.). The rock from Úb-7 is also more fine-grained than that from Br-1. Opletal (1968) classifies the rock from Br-1 as a quartz diorite and notes that two different types of this rock have been intersected in the hole – the sample from the depth of 1343.3 m appeared to be a normal granitic rock whereas the sample from the depth of 1362.7 m seemed strongly hybrid.

However, no granitic plutonic rock has been intersected in GTPV-LT 1. The rocks underlying the Permo-Carboniferous sediments in this borehole are the quartz "Teplice" porphyry and metamorphic rocks – mica schists and phyllites. A plutonic body is inferred at the depth of 2.3 km. The previous prognoses have considered either the occurrence of a granitic or a mafic body, but the possibility that the metamorphic rocks continue to the depth of 5 km and no plutonic body is present has also been taken into account (Myslil *et al*., 2008).

According to Mlčoch (2013, pers. comm.), the last possibility is the most likely. Research on the basement carried out especially by B. Mlčoch from the Czech Geological Survey found evidence that the basement is formed of metamorphic rocks of the Teplá-Barrandian zone, which is partly subducted under the Saxothuringian. According to this author, the granodiorite intersected in Br-1 is either an independent plutonic body or a part of the Čistá-Jesenice Pluton of Cambrian age, while the granodiorite intersected in Úb-7 most likely belongs to the Variscan zone of intrusives that formed along the boundary of the colliding units. This theory has been developed on the basis of information from boreholes as well as gravity survey in the north-west of Bohemia (see the gravity map - Appendix C). Distinct gravity highs are represented by the Bechlín Pluton located approximately 50°25' N, 14°22'30'' E, and by subducted masses approximately 8' north of this body. The Čistá-Jesenice Pluton appears as a relative gravity low among other masses of the Teplá Barrandian Unit. On the other hand, the masses of the Saxothuringian unit manifest as negative gravity anomalies, compared to their south-eastern neighbour. The interpreted basement by Mlčoch and Konopásek (2010) is presented in Figure 20.

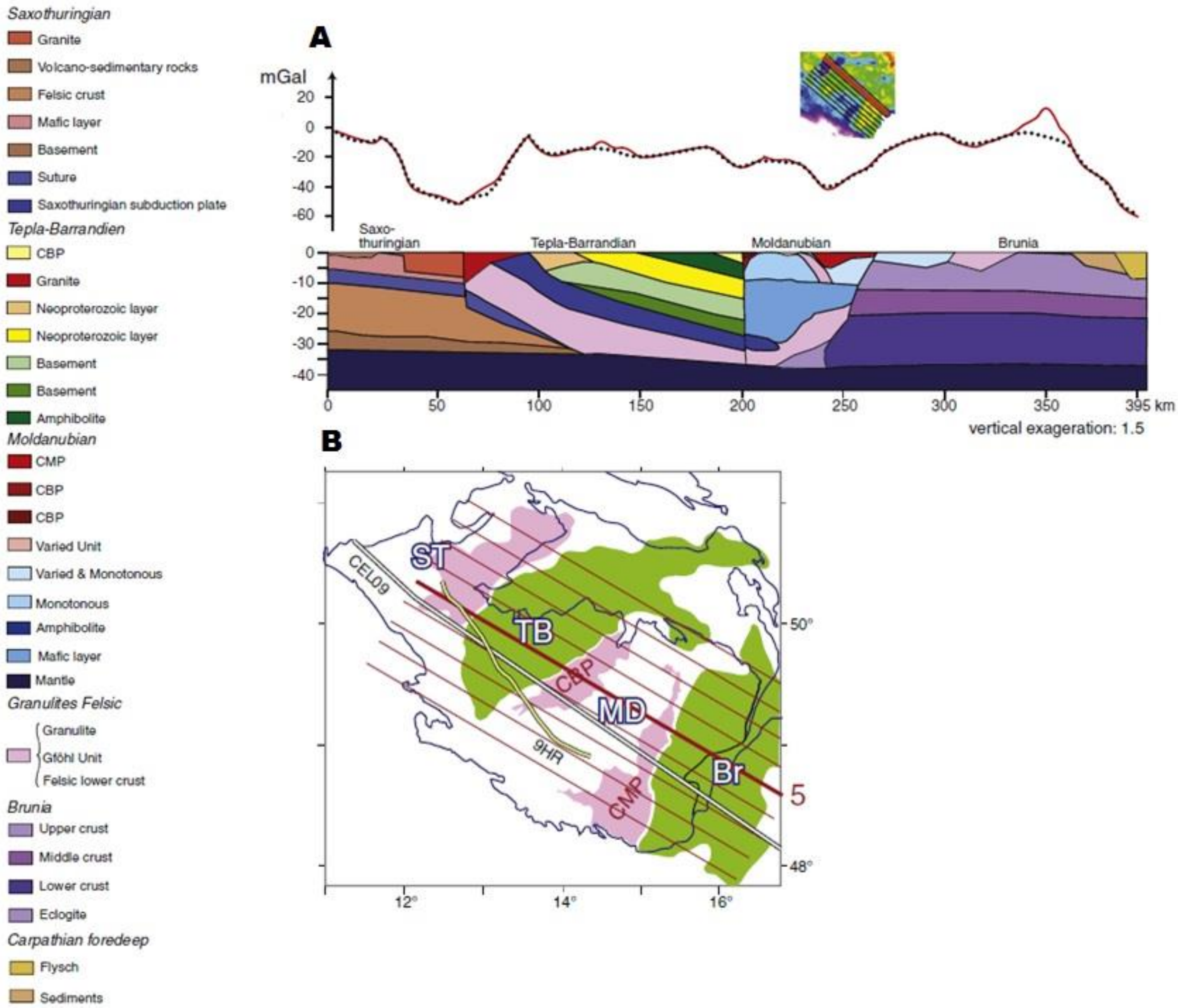


Figure 19 Geological section across the Bohemian Massif south of the area of interest. A – Gravity survey with location of the profile and interpreted cross section, B – orientation of cross sections within the Bohemian Massif (ST – Saxothuringian, TB – Teplá-Barrandian, MD – Moldanubian, Br – Brunia). Guy *et al*. (2011)

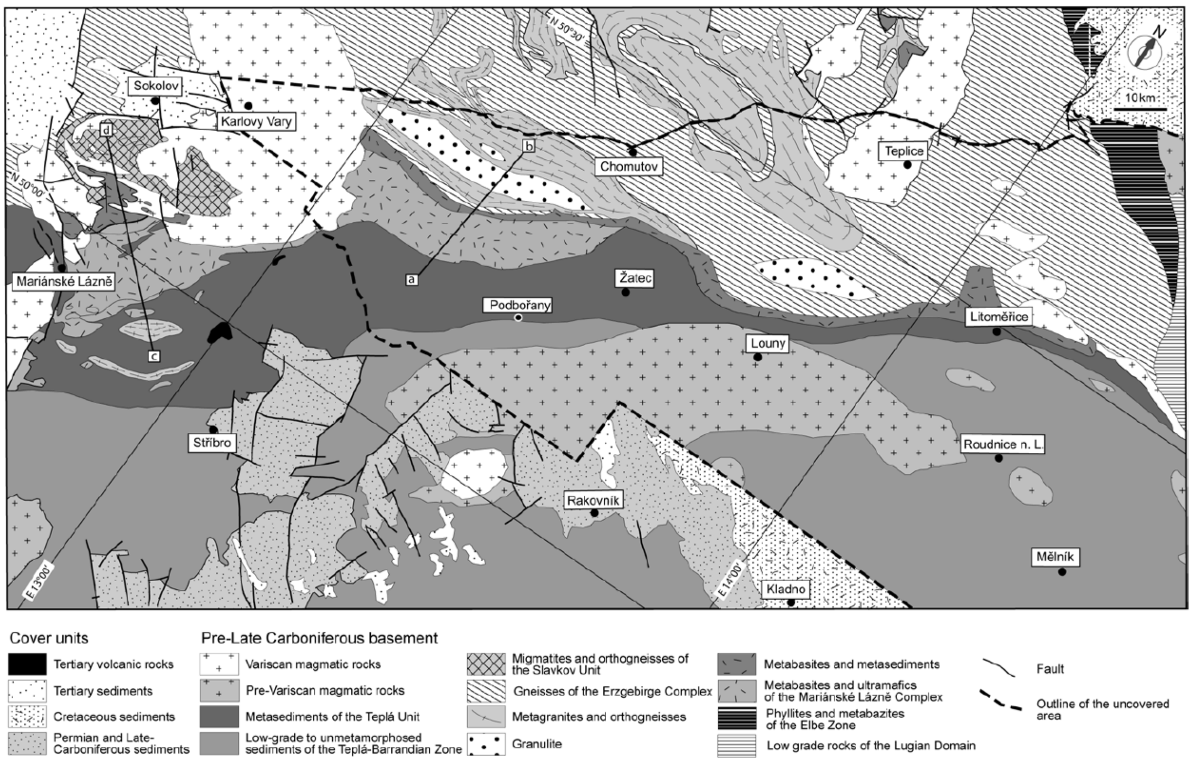


Figure 20 Basement of the Mšeno-Roudnice and Krušné hory Piedmont basins according to Mlčoch and Konopásek (2010). The town of Litoměřice lies upon metasediments of the Teplá Unit, Rýdeč well was drilled in one of the smaller Variscan plutonic bodies on the boundary of Saxothuringian and Teplá-Barrandian Units and Brňany is located on one of the pre-Variscan plutonic bodies, here represented by a single body, but may be a part of the Čistá-Jesenice-Louny Pluton.

Uličný (2013, pers. comm.) highlighted the importance of strike-slip faults in the direction of the Elbe Lineament, which are probably the deepest structures in the area. Unlike the Litoměřice and Litochovice faults, which are essentially abstract names for large-scale systems of smaller faults, following the principal tectonic directions, the dislocation on the Elbe Lineament faults could probably penetrate into deeper parts of the crust. An overview of the complex tectonic situation is given in Figure 21 in the map of the basement.

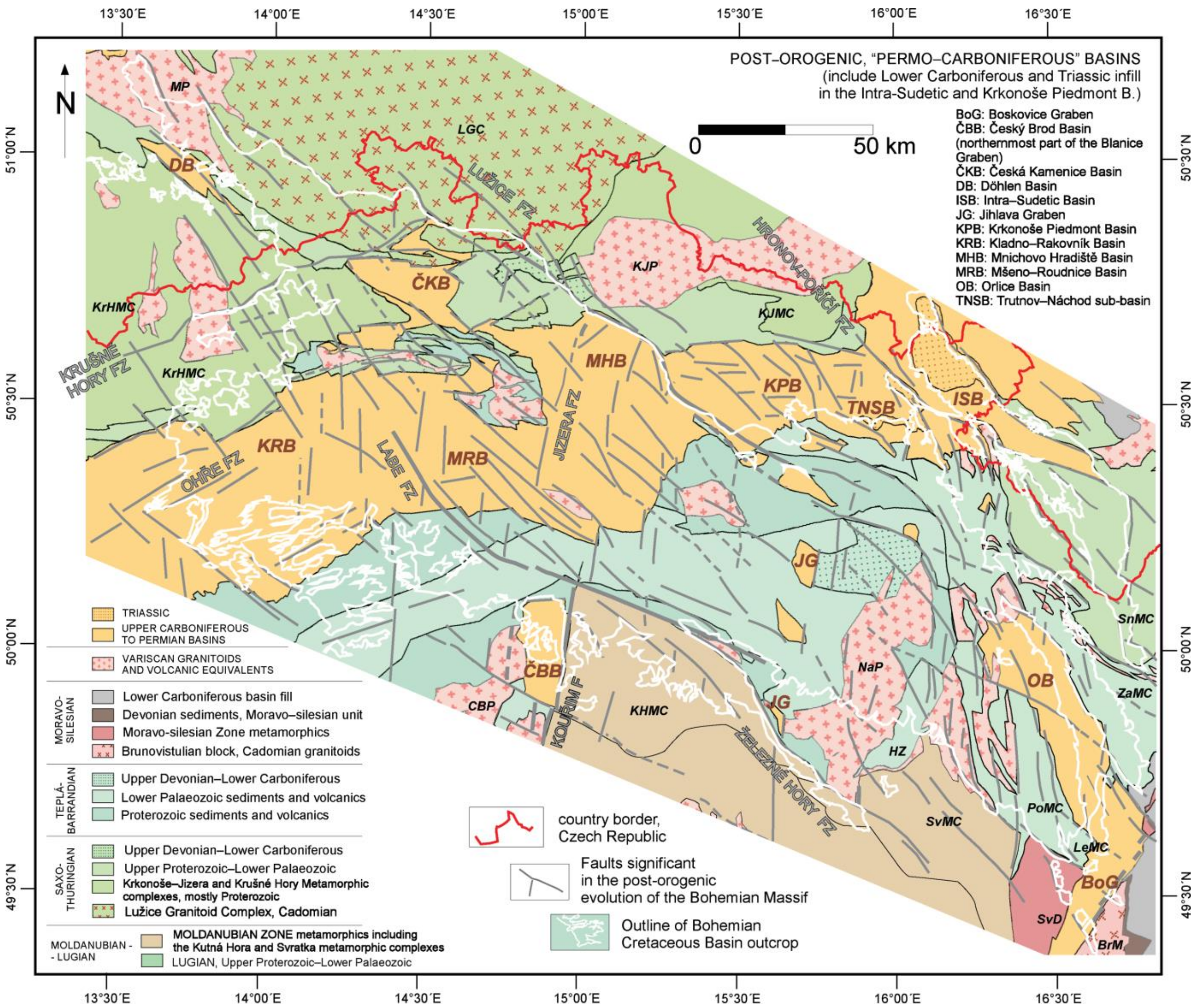


Figure 21 Map of the basement of the Bohemian Cretaceous Basin with all important tectonic lines, including the Labe (Elbe) Fault Zone and the Ohře (Eger) Fault Zone. Uličný *et al.* (2009)

The section below represents the author's personal opinion on the geological conditions in the area of interest. For accurate image of the geological composition of the basement, more research is vital, including reflection seismics and deep boreholes.

The greatest uncertainty lies between the plutons in Brňany and in Rýdeč. The likeliest possibility is the occurrence of metamorphic rocks of the Teplá-Barrandian Unit or possibly the contact with the Saxothuringian unit. Proximity of such tectonic contact is supported by the fact that the GTPV-LT 1 borehole intersected a horizon which had undergone cataclasis and is, therefore, a part of a fault zone (Burda *et al.*, 2007). However, it is subject to discussion, whether the entire basement is formed of mica schists that were intersected in the borehole or whether they are formed of rocks of a higher metamorphic grade. The first version of the model, considering geology as represented in the geological section, considers the option of presence of orthogneisses. The second model is computed with mica schist instead of orthogneiss.

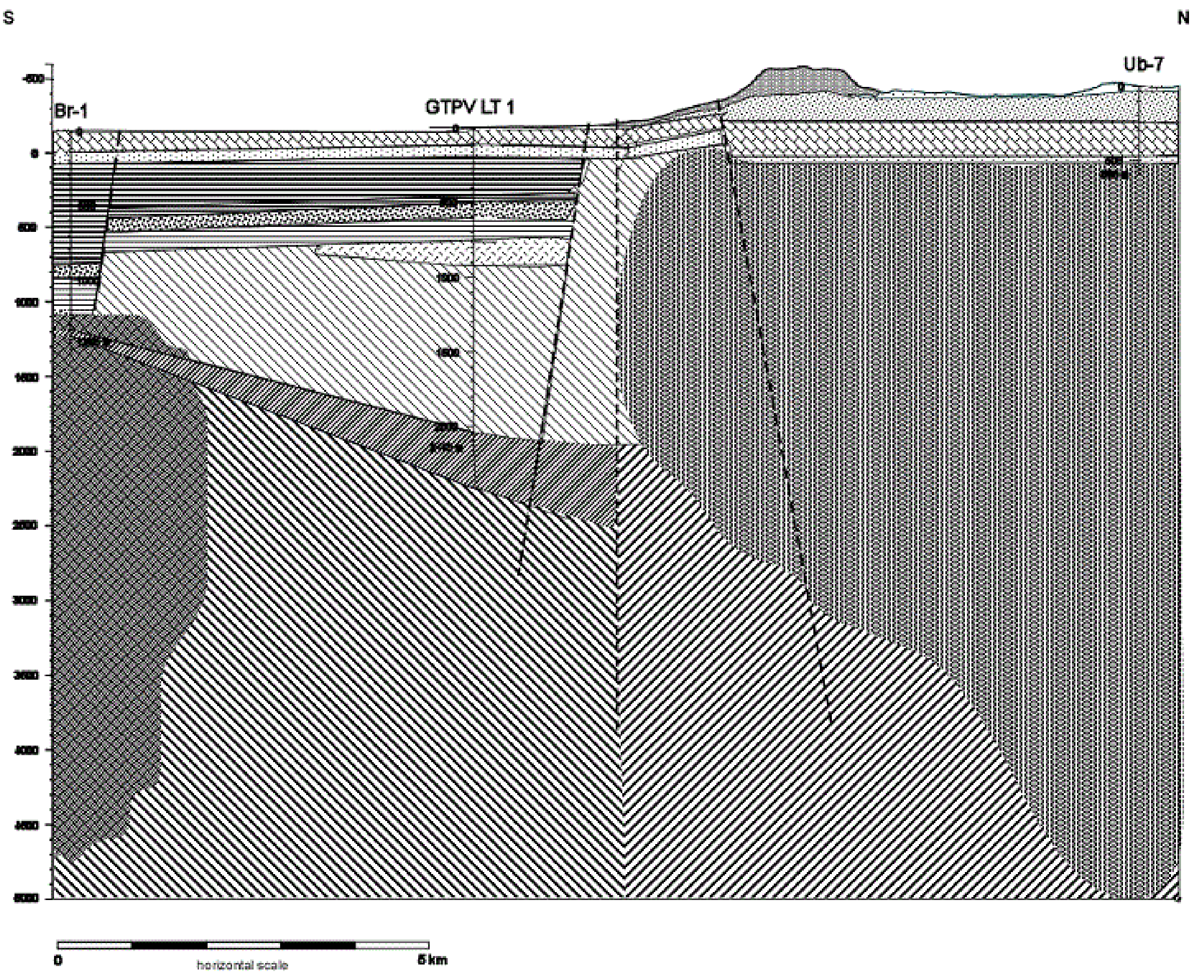


Figure 22 Geological section Brňany – Rýdeč. For full-sized section with a legend see Appendix A.

The geometry of the 2D models, as apparent from Appendix B, is based on the geological section presented in Appendix A or Figure 22. The geological units correspond with those presented in the geological sections and their properties are presented in Table 5. Models I and IV correspond precisely with the section, models II and III are modified. Mica schist is expected in the basement instead of gneiss.

The vertical line represents the boundary between the Teplá-Barrandian and Saxothuringian unit formed of strike-slip faults of the Elbe Fault Zone. However, as its character (geometry of the faults, thermal conductivity of the fill of the joints) is unknown, no effect on thermal field is considered.

4.1.4 1D model for GTPVLT-1 to 5 km depth

Models computed by Šafanda *et al*. (2007) take into account two possibilities of the basement in Litoměřice – presence of either granitic or mafic igneous body. With a granitic body, the average temperature inferred at 5 km depth is 140°C (± 8 °C), with a mafic body it is higher, reaching in average 146°C (± 7 °C). Temperature profiles of these models are presented in Figure 23.

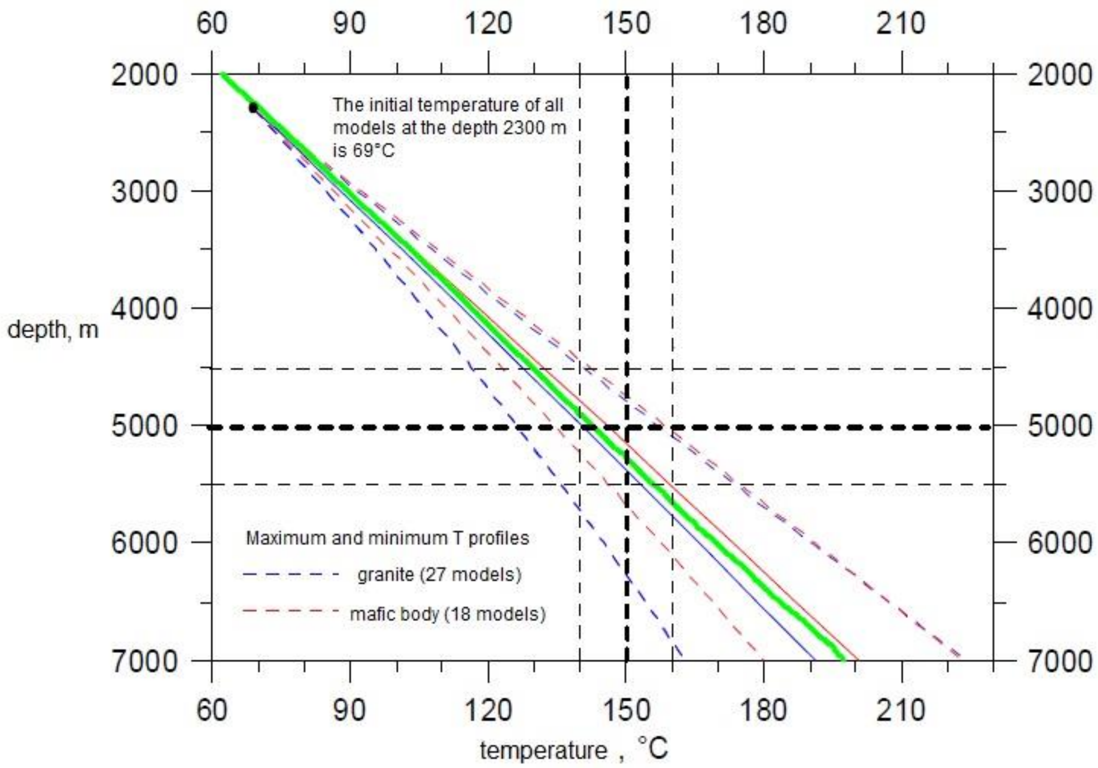


Figure 23 Temperature profiles of models computed by Šafanda *et al*. (2007) from the depth of 2300 m where an igneous body is expected. Red line: mafic body, blue line: granitic body, green line: temperature profile of the KTB deep borehole.

4.1.5 2D models along the section

Models were constructed to the 5 km depth using the COMSOL Multiphysics 3.5 software.

The geometry of the models is based on the geological section above, presented in Figure 22 and Appendix A. Each unit has been attributed average thermal conductivity based on the measurements or values from literature with correction for temperature applied to crystalline rocks using equation (8) after Vosteen and Schellschmidt (2003) (no temperature correction was applied to sediments as the error generated by measurements of dry samples is greater than the effect of temperature). The mean surface temperature is calculated using the Kubík's equation (14) and the heat flow has been calculated from temperature measurements in the depth intervals with known thermal conductivity, corrected for palaeoclimate and heat production.

(14) $T=10.6-4.7*0.001*h-0.33*(\phi-50°)$

where h is the altitude and ϕ is latitude.

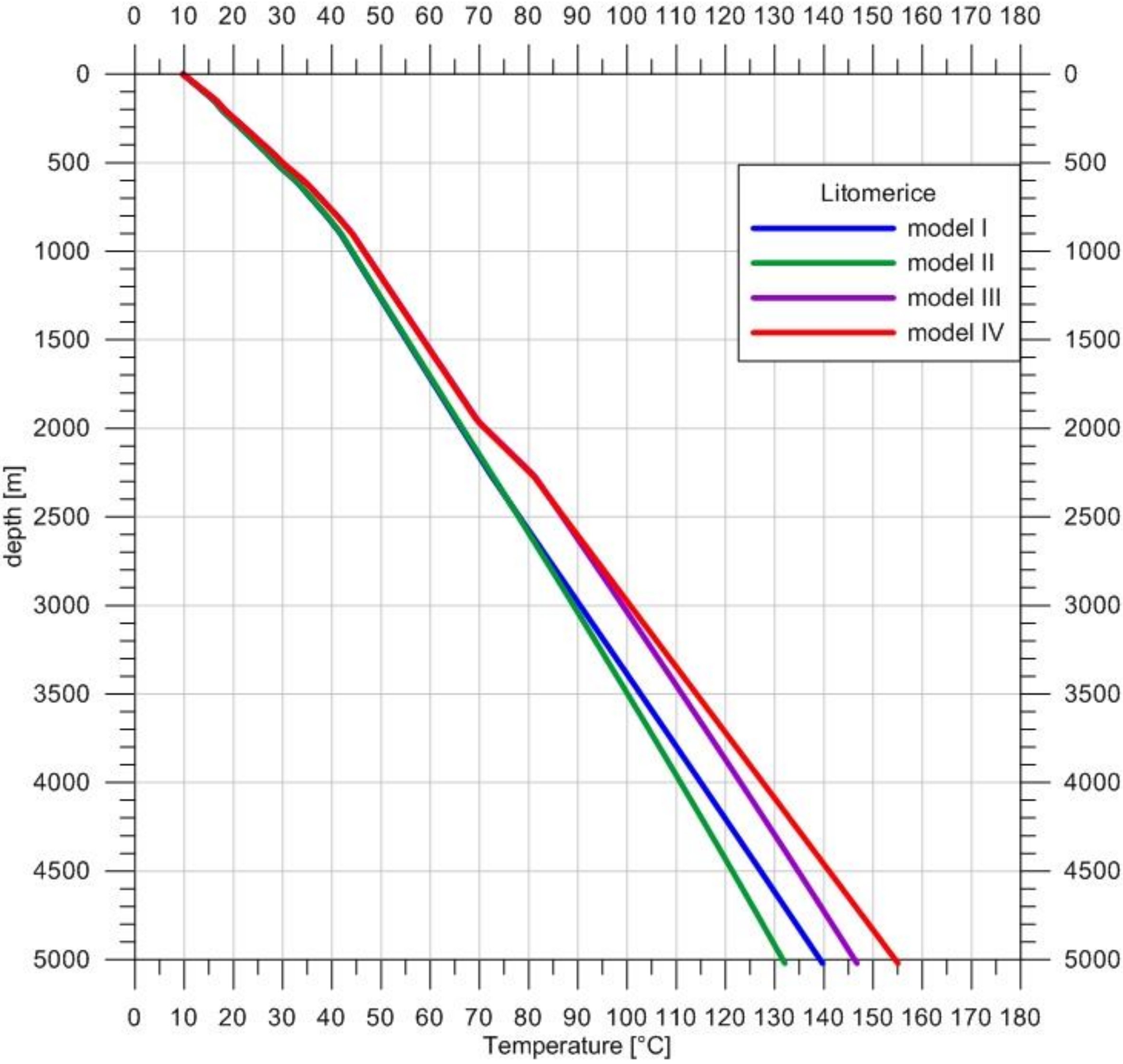


Figure 24 Vertical temperature profiles of models I – IV on the site of the GTPVLT-1 borehole. Models III and IV show higher temperature at the depth of 1500 m than was actually measured, so the situation illustrated in them is unlikely.

See the list of parameters in Table 5. As the heat production of granodiorite could not be measured, average values were used in the model. The value of thermal conductivity of the granodiorite in Rýdeč seems too low and it is likely, that the sample from depth 582 m was still slightly hydrothermally altered. Therefore, an average value of thermal conductivity of granodiorite was used as well. Although heat flux in Brňany and Rýdeč has been calculated, the temperature profiles in these wells were unreliable and therefore heat flux from Litoměřice is used in all models. As Šafanda *et al*. (2007) determined heat flux in Litoměřice as an interval 72 – 78 $mW.m^{-2}$, the lower value is used in models I and II, the higher value is used in models III and IV. Models II and III considered mica schist to be the prevalent rock in the basement. Models I and IV considered prograde metamorphism with gneisses underlying the mica schists as presented in the geological section (Appendix A).

Thermal conductivity [W/m.K]:	**isotropic**	**perpendicular**	**parallel**
Coniac (mudstones)		1.3	1.7
Turonian (marlstones and calcareous mudstones and siltstones)		1.9	2.5
Cenomanian and Santonian sandstones	2.8		
Líně Fm. (weighted average)		2.1	2.4
Slaný Fm. (weighted average)		2.4	2.6
Týnec Fm. (weighted average)		1.9	2.6
Kladno Fm. (weighted average)		2.5	2.6
basalt	1.6**		
hydrothermally altered granodiorite (Ub7)	2.0		
granodiorite	2.9**		
granodiorite Br1	3.2		
Teplice porphyry	2.7*		
phyllite	3.5		
mica schist		3.3*	3.6*
gneiss	3.1		
Heat flux [mW/m^2]:	**uncorrected**	**palaeo**	**heat**
Litoměřice min			72*
Litoměřice max			78*
Heat production [µW/m^3]:			
granodiorites	2.5**		
Teplice porphyry	13.3*		
gneiss	1.5**		
mica schist	3.5*		
Surface temperature [°C]:	T=10.6-4.7*0.001*h-0.33*0.53		

Table 5 Parameters entered in the models for Litoměřice. For isotropic samples, average thermal conductivity is determined. For anisotropic samples, thermal conductivity parallel and perpendicular to the bedding is stated.

* Šafanda et al. (2007)

**average values from Hellwege et al. (1982)

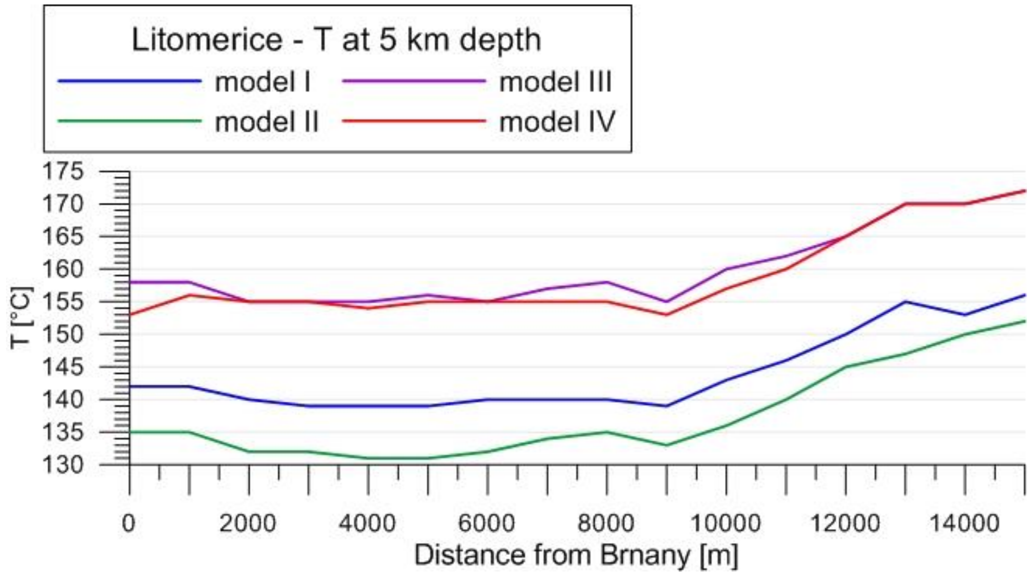


Figure 25 Temperature at the 5 km depth along the profile Brňany – Rýdeč . GTPVLT-1 is situated approximately 5 km north of Brňany, which corresponds with the minimum temperature.

Figure 24 shows vertical temperature profiles on the site of the Litoměřice borehole for different model parameters. Appendix B shows the 2D models between Brňany and Rýdeč. Figure 25 shows horizontal temperature profiles at the depth of 5 km to illustrate in which parts the highest temperature is reached. Surprisingly, the site of the GTPVLT-1 (5.5 km north of Brňany) seems the least favourable site along the profile. Higher temperature would be reached if the drilling site was moved further north where the volcanic rocks of the České středohoří Mountains form an insulating cap rock, causing the heat to accumulate beneath them.

4.1.6 Comments on the models

Some geological and hydrogeological features indicate that the area of Litoměřice could be a promising geothermal site, as shown in Figure 26. It is located in a region with higher heat flux and sedimentary formations involve some confined aquifers with hyperhaline water. Although the cap rock is not impermeable, its thermal conductivity is relatively low.

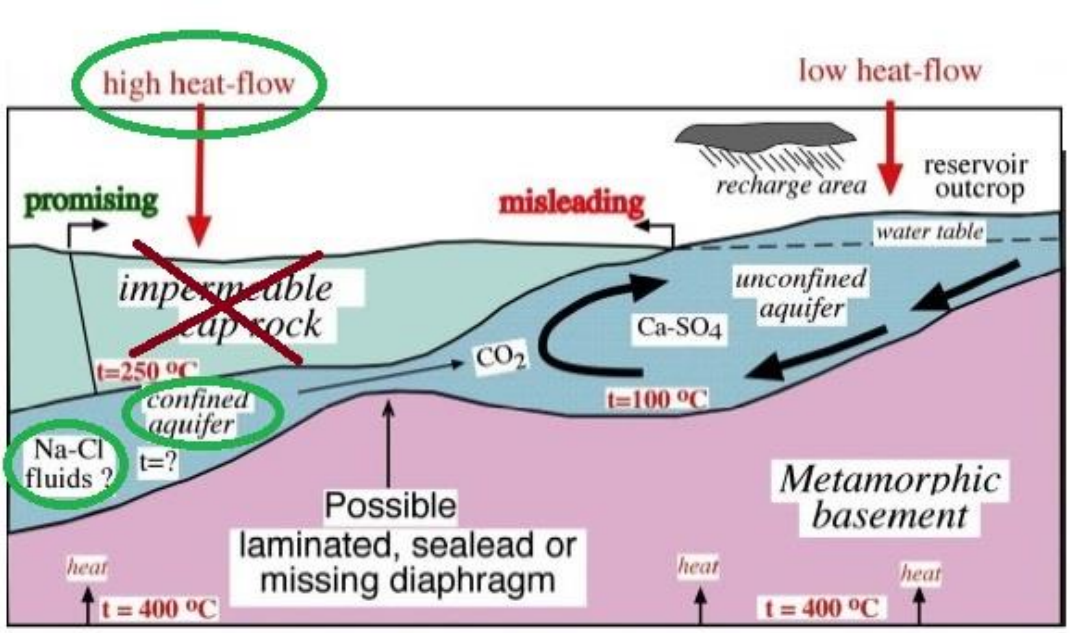


Figure 26 Illustration of geological environments promising or misleading for geothermal exploration. Promising factors encountered in the area are in green loop, misleading factors are crossed in red. Modified from Manzella *et al*. (2013)

The models, however, show a less optimistic situation. The least favourable scenario represented by model II finds the temperature on the site insufficient for feasible geothermal energy usage. The most favourable scenario represented by model IV, on the other hand, shows thermal conditions similar to those in Gross Schoenebeck. However, the temperature profile of the model IV does not correspond with the temperature profile measured in GTPVLT-1, so that such scenario is regarded as unlikely. The likeliest possibility is represented by model I as it exhibits the best fit with the temperature measurements in the borehole. With the downhole temperature reaching approximately 140°C, this scenario would be unviable for electric power generation but with good permeability and production rate the reservoir could serve for district heating of the town of Litoměřice. If another drilling site could be found approximately 6 km further north, the temperature would be high enough even for electricity generation.

Nevertheless, these models include several uncertainties in the entry parameters. The greatest of them is the value of radiogenic heat production in the basement rocks. The values included in these models had marked effect on heat flux. If the heat production of the basement is lower than average values for these rocks, the correction of heat flux for heat production will not cause a significant drop in the heat flux and the situation for model I would then be as presented in Figure 27.

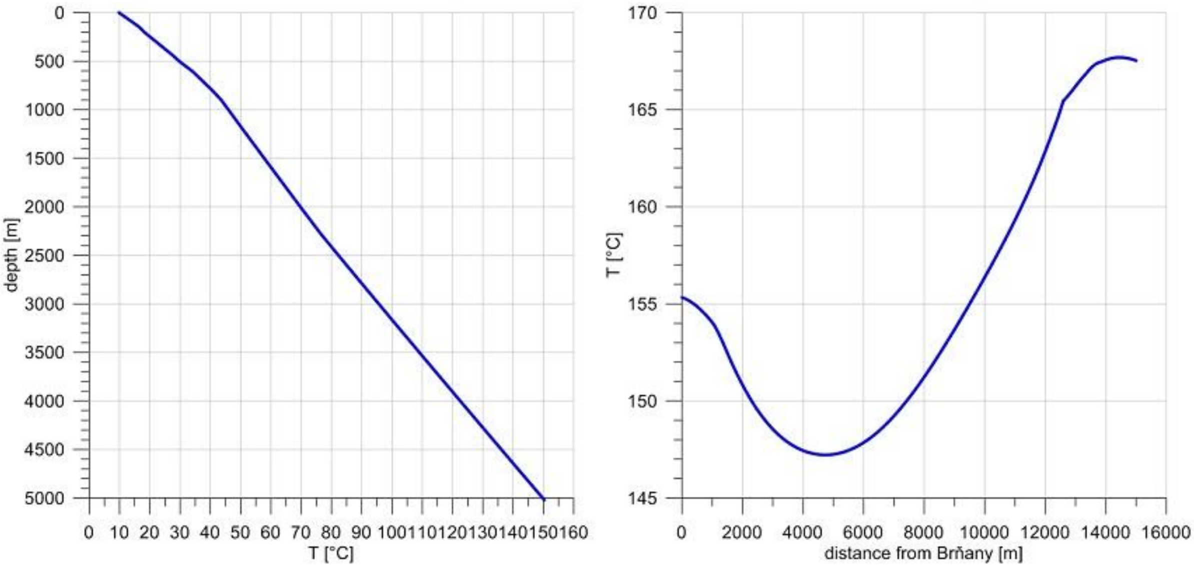


Figure 27 Temperature profile on the site of GTPVLT-1 for the case when heat production in the basement is negligible (left). Horizontal profile between Brňany and Rýdeč at 4.7 km depth below sea level for the same case (right).

In summary, models I – IV represent environments with factors that can have negative effect on heat flux and the whole temperature field. Thus, they show the least favourable conditions that can occur on the site. As shown in model I-A, without these factors the temperature at 5 km depth can be higher by 10°C, which makes the site much more promising even for electricity production.

4.2 Semily

The town of Semily is located in the north-east of the BCB in the Krkonoše Piedmont Basin (KPB) near its northern margin overlying the Krkonoše-Jizera Crystalline Complex (the Poniklá Series consisting of phyllites, greenschists and crystalline limestones). The boundary between the Teplá-Barrandian and Lugian zone is found beneath the basin. The fill of the Krkonoše Piedmont Basin consists of a sequence of Permo-Carboniferous sediments with similar lithology as those in the Mšeno-Roudnice Basin (see 4.1 Litoměřice). However, the fill is younger and its stratigraphical nomenclature is different. The oldest unit in the KPB comparable with the Kladno Formation of the Central and West Bohemian basins is the Kumburk Formation. The Slaný Formation coincides with the Syřenov Formation in the KPB and the youngest Central Bohemian unit – the Líně Formation – corresponds with the Semily Formation of the KPB. Unlike the Central and Western Bohemian Permo-Carboniferous basins, however, significant deposition of sediments continued in the KPB during Permian. The Semily Formation is overlain by Vrchlabí Formation that has transgressive character. The Prosečné Formation in its overburden consists of red siltstones and the stratigraphically important Kalná Horizon. The uppermost part of the sequence predominated by red sandstones and conglomerates is the Chotěvice Formation. (Chlupáč *et al.*, 2002)

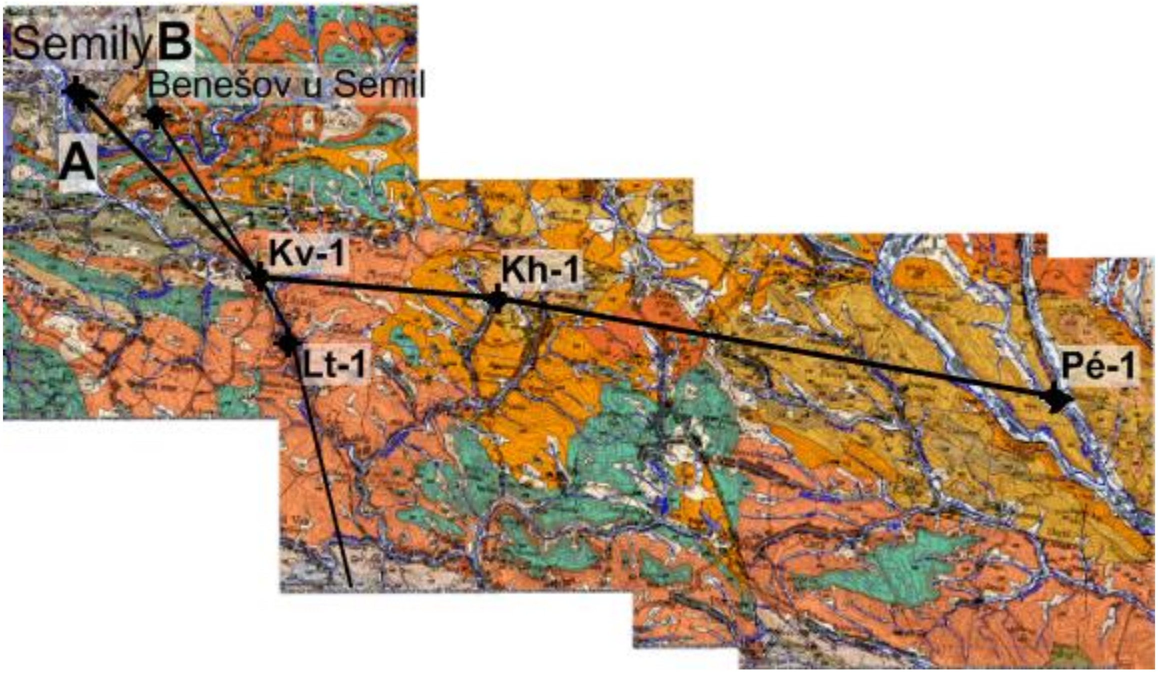


Figure 28 The town of Semily and boreholes Kv-1, Kh-1 and Pé-1 (from west to east) and the position of the geological sections A and B running through them in the section of a geological map 1:50 000 published by the Czech Geological Survey (composition from map sheets 03-41 Semily and 03-42 Trutnov).

During the Permian, the area was affected by volcanism, for which there is evidence in numerous tuffitic (rhyolite) or melaphyre horizons. In the southern part of the basin, the basement consists of a metamorphic volcanosedimentary complex of phyllites, greenschists, metadiabases, metagreywackes and metamorphic rhyolite and basaltic tuffs.

According to Malkovský et al. (1974), there is a significant tectonic boundary in the basement of the Krkonoše Piedmont Basin, separating the Palaeozoic Krkonoše-Jizera Crystalline Complex from Proterozoic rocks. North of the borehole of Prosečné Pé-1, Lower Palaeozoic and gneisses and migmatites of the Krkonoše-Jizera complex are expected, but already in the Pé-1, Proterozoic greenschists have been intersected in the basement of Carboniferous sediments.

Principal two tectonic directions are E-W and NW-SE. Faults of the E-W direction mostly occur in the central and western part of the KPB. The most important structure of this direction is the Kundratice-Javorek Fault, which has the downthrow of the northern block of almost 800 m near the village of Čikvásky and causes repetition of the sedimentary sequence in the west of the basin (Prouza and Tásler in Pešek *et al*., 2001). Another important fault of this direction is the Škodějov Thrust, forming the boundary of the Permo-Carboniferous basin with crystalline rocks in the north.

The NW-SE (Sudetian) direction is represented by the Hronov-Náchod-Poříčí Fault Zone, delimitating the KPB in the east. The Lužice (Lugian) Fault penetrates the KPB in its westernmost parts near Malá Skála.

The Krkonoše Piedmont Basin is a synclinorium with low amplitudes of folds. The axis of the central depression runs in the E-W direction. The basin is slightly asymmetrical, with the axis lying slightly more to the north, going through Kruh, Horní Kalná and Prosečné. The maximum thickness of the sedimentary cover reaching 1800 m is found near Prosečné.

Sediments are mostly horizontally bedded; only on the northern boundary of the basin the sedimentary beds in the overburden of the crystalline basement are inclined with the dip angle up to 30°.

During the Late Palaeozoic, the area exhibited great volcanic activity of mainly basic and intermediate character. Several basaltandesite (melaphyre) lava flows can be observed in the near environs of Semily and between Semily and Vrchlabí. More basic lavas have been found nearer to the central depression – a 100 m thick and about 8 km long basaltic sill has been intersected in the borehole in Košťálov. (Prouza and Tásler in Pešek *et al.*, 2001)

4.2.1 Boreholes

Pé-1 Prosečné

The village of Prosečné is located approximately 27 km east of Semily or 3 km north-west of Hostinné. The axis of the Krkonoše Piedmont Basin runs through this area, so that the sedimentary cover reaches its greatest thickness here. The hole was drilled in the 1960s under the terms of the project T-1-20 "Regionální geologický výzkum ČSSR" (Regional geological research of Czechoslovakia) and reached the depth of 1750 m.

Lithology and stratigraphy

<table>
<tr><td>0 - 8.5 m</td><td>Quaternary</td><td></td></tr>
<tr><td rowspan="9">8.5 - 1688.9 m</td><td rowspan="9">Permo-Carboniferous</td><td>8.5 - 301 m siltstones and mudstones</td></tr>
<tr><td>301 - 452 m purple-red sandstones and conglomerates</td></tr>
<tr><td>452 - 640 m red siltstones and mudstones</td></tr>
<tr><td>640- 700 m grey calcareous and bituminous siltstones and mudstones</td></tr>
<tr><td>700 - 919 m marlstones and siltstones</td></tr>
<tr><td>919 - 1263 m purple sandstones and conglomerates</td></tr>
<tr><td>1263 - 1356 m arkoses and grey siltstones and mudstones</td></tr>
<tr><td>1356 - 1689 m brown-red siltstones and mudstones with carbonate concretions, conglomerates on the base</td></tr>
<tr><td>1627 - 1634 m basaltic sill</td></tr>
<tr><td>1689 - 1750 m</td><td>crystalline basement</td><td>greenschist, diabase and metadiabase</td></tr>
</table>

Table 6 Lithological and stratigraphical description of Pé-1. After Tásler (1968).

Thermal properties

Thermometric measurement was carried out in the depth interval 137 - 935 m. Figure 29 shows the temperature profile along the borehole together with variations in temperature gradient. Maximum measured temperature at the depth of 935 m was 42.6 °C.

Heat flux was calculated from Fourier's Law from the mean thermal conductivity in all depth intervals where thermal conductivity had been measured (2.6 $Wm^{-1}K^{-1}$), and the mean temperature gradient (55.6°C/km). The average calculated heat flux in this borehole was 144 $mW.m^{-2}$. Horizons influenced by flowing water were excluded from the calculation. This value is very high and is probably influenced by previously unnoticed fluid motion in the intersected formations and therefore was not included in the models.

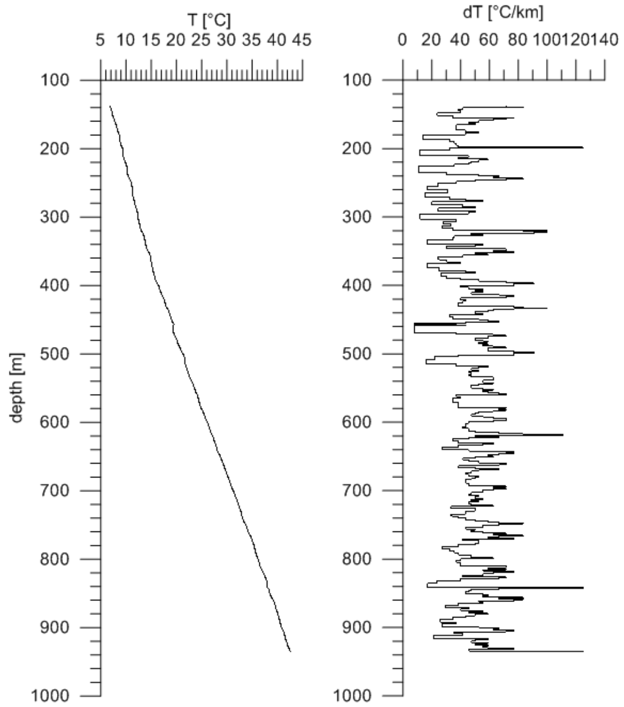


Figure 29 Temperature and temperature gradient in the borehole Pé-1.

Kh-1 Kruh

The village of Kruh lies approximately 11 km east of Semily or 4 km south-west of Jilemnice. The axis of the Krkonoše Piedmont Basin runs through this area, so that the sedimentary cover reaches its greatest thickness here. The depth of the borehole is 650 m.

Lithology and stratigraphy

0 - 346 m	Prosečné Formation (Permo-Carboniferous)	reddish siltstones and mudstones
		12 - 19 m limestones or bituminous sediments of the Kalná Horizon
		115 - 158 m siltstones and arkoses of the Arkose Horizon
		158 - 168 m melaphyres and tuffs of the Melaphyre Horizon
346 - 650 m	Vrchlabí Formation (Permo-Carboniferous)	siltstones and mudstones with interlayers of coarse sandstones

Table 7 Lithological and stratigraphical description of Kh-1. After Jelenová (1987).

Thermal properties

Thermometric measurement was carried out in the depth interval 100 - 637 m. Figure 30 shows the temperature profile along the borehole together with variations in temperature gradient. Maximum measured temperature at the depth of 635 m was 26.1 °C.

Heat flux was calculated from Fourier's Law from the mean thermal conductivity in all depth intervals where thermal conductivity had been measured (1.9 $Wm^{-1}K^{-1}$) and the mean temperature gradient (16°C/km). The average calculated heat flux in this borehole was 30 $mW.m^{-2}$.

It is obvious that the whole temperature measurement was severely affected by fluid motion in the well. Therefore, these values are unreliable and not incorporated in the models.

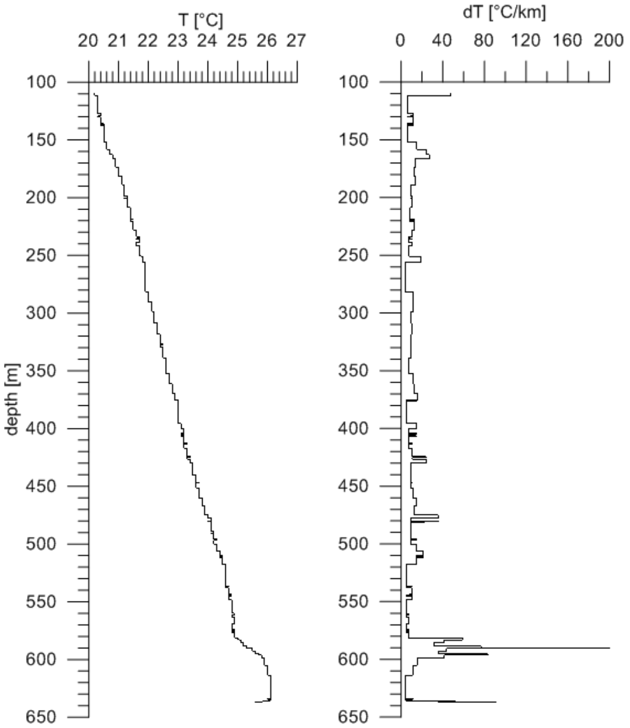


Figure 30 Temperature and temperature gradient in the borehole Kh-1.

KV-1 Košťálov

The village of Košťálov lies approximately 8 km south-east of Semily. The borehole, reaching the depth of 1125 m, is one of the boreholes that contributed greatly to the knowledge of the geological structure of the KPB and its basement.

Lithology and stratigraphy

0 - 145 m	Libštát Formation (Permian)	mudstones and siltstones with interbeds of sandstones
145 - 627 m	Semily Formation (Permo-Carboniferous)	siltstones, sandstones, conglomerates
		327 - 413 m melaphyre
627 - 856 m	Kumburk Formation (Carboniferous)	siltstones, conglomerates, mudstones, sandstones
856 - 1125 m	Proterozoic basement	856 - 876 m phyllite
		876 - 1125 m greenschist

Table 8 Lithological and stratigraphical description of Kv-1 from the Database of Geologically Documented Objects (Czech Geological Survey)

Hydrogeology

Three aquifers were identified in the borehole at depths 103-413 m, 550-645 m and 865-1125 m. All of them contain mineralised thermal water with the temperatures 21.6, 25.3 and 31.3°C, respectively. The uppermost aquifer has the $Na\text{-}Ca\text{-}SO_4$ type of mineralization, the other two are $Na-SO_4-HCO_3$ type. (Jetel, 1977, Database of Geologically Documented Objects, Czech Geological Survey)

However, the filtration coefficient in these water-bearing formations is low, so their influence on the temperature field is regarded as minor.

Thermal properties

Thermometric measurement was carried out in the depth interval 20 - 880 m. Figure 31 shows the temperature profile along the borehole together with variations in temperature gradient. Maximum measured temperature at the depth of 880 m was 37.2 °C.

Heat flux was calculated from Fourier's Law from the mean thermal conductivity in all depth intervals where thermal conductivity had been measured (2.9 $Wm^{-1}K^{-1}$) and the mean temperature gradient (29°C/km). The average calculated heat flux in this borehole was 83.7 $mW.m^{-2}$. Horizons influenced by flowing water were excluded from the calculation.

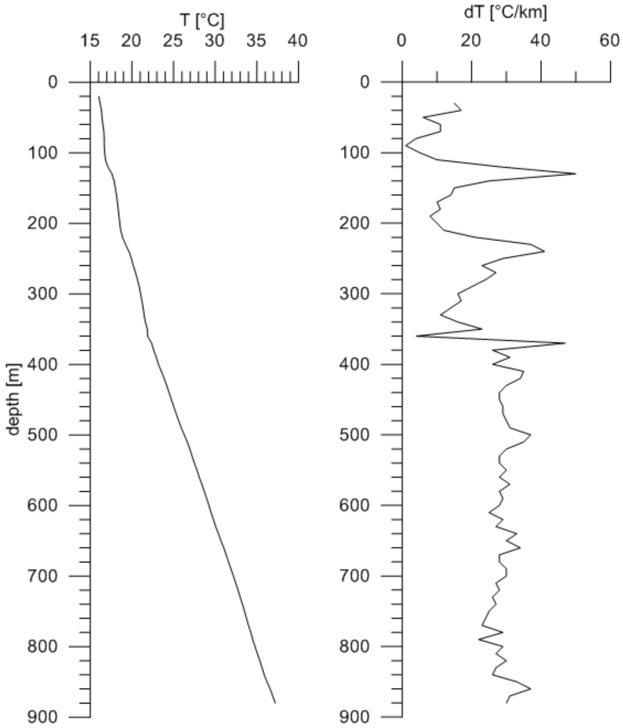


Figure 31 Temperature and temperature gradient in the borehole Kv-1

4.2.2 Hydrogeology

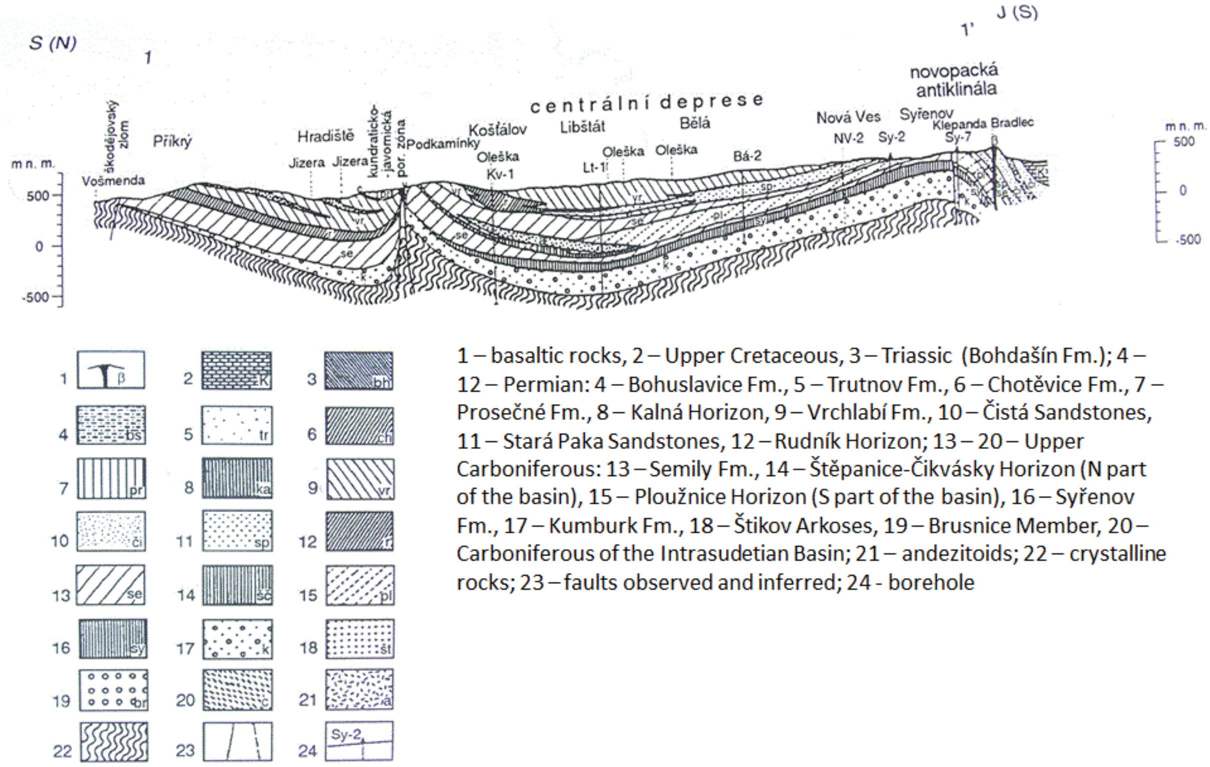
Thermal waters have been encountered in the east of the basin along the Hronov-Náchod Fault Zone. The temperature of the water in the well Ba-1 (Batňovice) was 45°C. General hydrogeological conditions in the area of interest are as follows: Transmissivity is generally low or moderate, chemical composition of groundwaters is usually sodium-sulphate-carbonate type, as observed in Kv-1. However, it has been observed that in the areas of infiltration, transmissivity is lower than in drainage areas. As majority of the formations are shaly, their porosity is low and therefore they are usually permeable only in fractured zones. Near the surface, groundwater flows in fracture systems. With increasing depth, velocity of the flowing fluid decreases. It is common that permeability decreases with depth, but there is an exception in Košťálov in the depth 341-361 m, where a formation with higher permeability was intersected. (Prouza and Tásler in Pešek *et al.*, 2001)

4.2.3 Geological structure

Section 1 after Prouza and Tásler in Pešek *et al.*, (2001) is oriented in the NW-SE direction and is heading from Košťálov on its SE end towards the town of Benešov u Semil, which is near the basin's margin. The section intersects the sediments of the Vrchlabí and Semily formations and melaphyres. The basement is formed of metamorphic rocks of the Krkonoše-Jizera Crystalline Complex comprising mainly greenschists and phyllites (these have been drilled in Kv-1). However, gravity survey by Sedlák *et al*. (2007) identified a body of mafic rocks, probably metabasites in the depth interval 1-3.5 km between Libštát and Košťálov (Sedlák, 2013, pers.comm.). As this gravity anomaly continues as far as Prosečné and Horní Kalná, where metadiabases and gabbros from the basement of Carboniferous sediments were drilled, it is likely that this gravity anomaly represents a single mafic body. According to (Sedlák, 2013, pers.comm.), this body is emplaced in the depth interval of 2 – 6 km between Jilemnice and Horní Kalná. However, metadiabase and metagabbro have been intersected in the borehole in Horní Kalná already at the depth of 1385 m (Prouza, 2013, pers. comm.)

Airborne and in situ radiometric measurements have shown increased contents of K, U and Th radionuclides in bituminous clays and phyllites. (Skácelová in Prouza *et al*., 2010). Therefore, their radiogenic heat production has been calculated and included in the models, although the thickness of the productive mudstones is not large (order of meters to tens of meters).

Prouza and Tásler in Pešek *et al*., (2001) constructed a geological section running through Libštát and Košťálov in the N-S direction from the Nová Paka Anticline to the northern margin of the basin. The section is presented in Figure 32. Benešov u Semil is located in the northern part of the section. The deeper structures were estimated based on the gravity survey and its interpretation by Sedlák *et al*. (2013) and is presented in Figure 33.



1 – basaltic rocks, 2 – Upper Cretaceous, 3 – Triassic (Bohdašín Fm.); 4 – 12 – Permian: 4 – Bohuslavice Fm., 5 – Trutnov Fm., 6 – Chotěvice Fm., 7 – Prosečné Fm., 8 – Kalná Horizon, 9 – Vrchlabí Fm., 10 – Čistá Sandstones, 11 – Stará Paka Sandstones, 12 – Rudník Horizon; 13 – 20 – Upper Carboniferous: 13 – Semily Fm., 14 – Štěpanice-Čikvásky Horizon (N part of the basin), 15 – Ploužnice Horizon (S part of the basin), 16 – Syřenov Fm., 17 – Kumburk Fm., 18 – Štikov Arkoses, 19 – Brusnice Member, 20 – Carboniferous of the Intrasudetian Basin; 21 – andezitoids; 22 – crystalline rocks; 23 – faults observed and inferred; 24 - borehole

Figure 32 Geological Section across the KPB after Prouza and Tásler in Pešek *et al*., (2001). Part of the section between Libštát and Vošmenda is used as profile B.

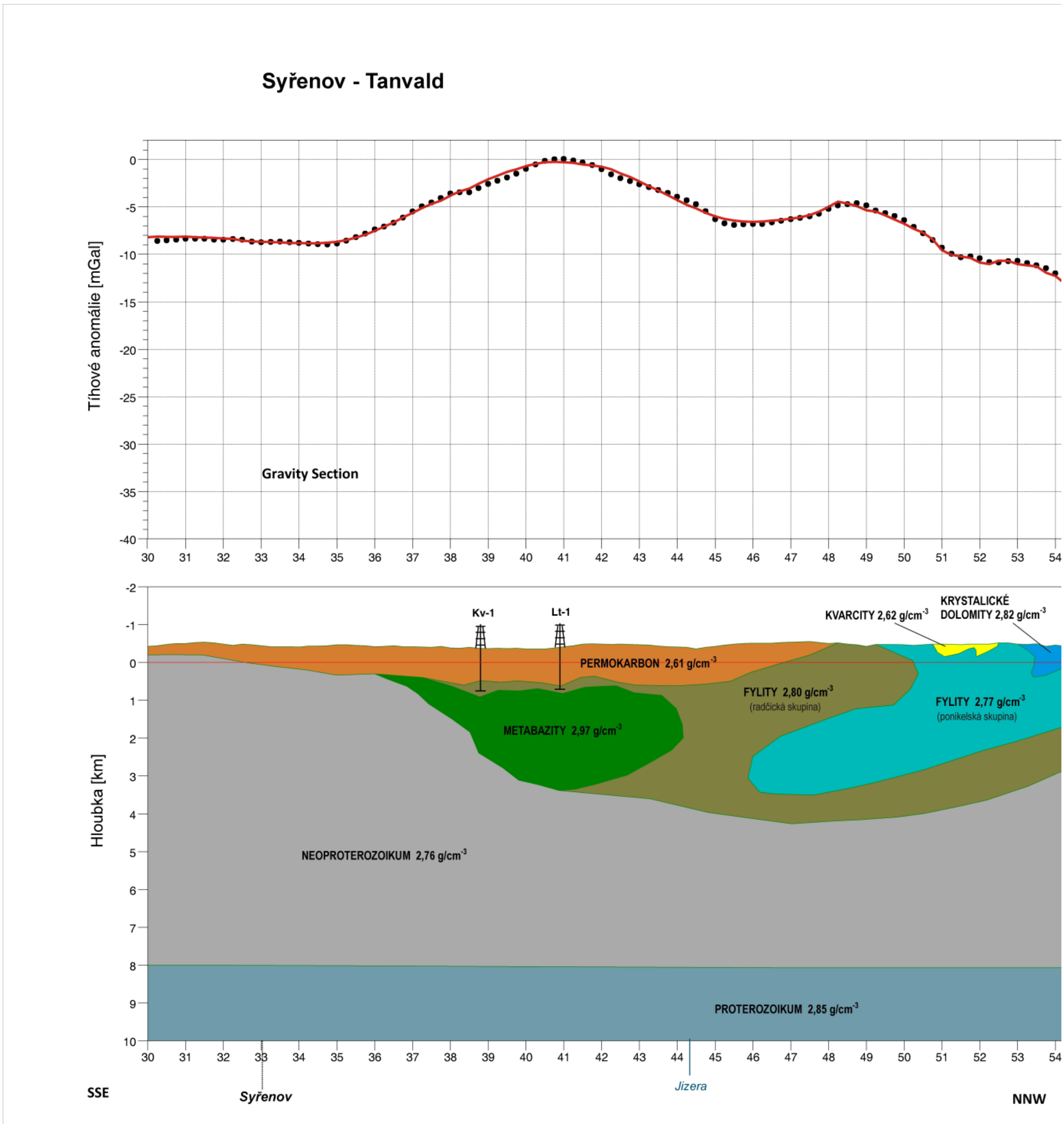


Figure 33 Geological model of the basement of KPB based on the gravity survey. After Sedlák (2013, pers. comm.)

4.2.4 2D model along the section

The same procedure as in the case of Litoměřice was used for construction of models in the Semily area. As two sites have been proposed for drilling, Semily and Benešov u Semil, two different geometries have been compiled. The NW part of one profile reaches Semily, the northern part of the other reaches Benešov u Semil. Both sections intersect near the borehole Kv-1 and data from this borehole are used because they seem to be most reliable of all the available boreholes. The data from Kv-1 are compared with data from the near borehole in Libštát to obtain more accurate image of the rock environment.

The section by Prouza and Tásler in Pešek et al., (2001) presented in Figure 32 is used for defining the geometry of the upper portions of the geological environment of Benešov u Semil and the section located in Figure 28 as section B. Concerning the basement, mafic body is inferred in the southern part of the profile. In the northern part, prograde metamorphism is expected. Therefore, the phyllites, the existence of which is confirmed, lie upon mica schists with enclosures of greenschists, which have been reported from outcrops of the Krkonoše-Jizera crystalline complex. In the lowermost parts of the section, orthogneisses of the Teplá-Barrandian unit are expected. For geometry of all the 2D models see Appendix B.

Geometry of the models for Semily (section A) is based on the geological section in Figure 34, see Appendix A for detail and legend.

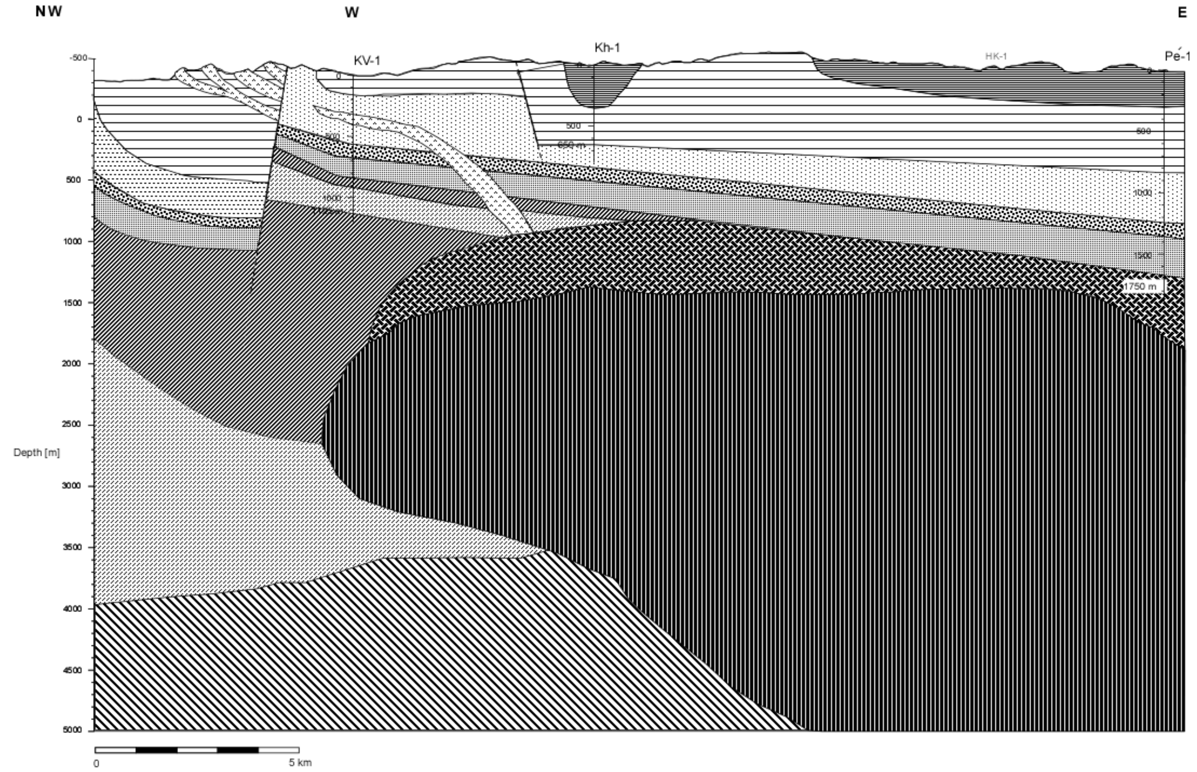


Figure 34 Geological section A: Semily – Prosečné as interpreted by the author. The town of Semily is located in the NW part of the section. For full sized section with a legend see Appendix A.

Benešov u Semil

The models for Benešov u Semil are constructed over the northern part of the geological section presented in Figure 32, from Libštát to the northern margin of the basin. Thus, Benešov u Semil is located approximately in the middle of the profile B.

Two parameters bring significant uncertainty to the model: heat flux and orientation of foliation of phyllites. Models I and IV use the value of heat flux calculated by Dr.Šafanda from the data in Libštát (Lt-1), which is, after applying the correction for heat production and palaeoclimate, 83.5 $mW.m^{-2}$. Models II and III use the value of heat flux based on measurements in Košťálov, introducing the value 86.5 $mW.m^{-2}$. Models V and VI use the average value between the abovementioned, i.e. 85 $mW.m^{-2}$. Due to significant anisotropy observed in phyllites from Jesenný (JB-3 borehole located in the Krkonoše-Jizera crystalline complex between Semily and Liberec), two extreme cases were considered. Models I, III and

V consider the possibility that phyllite is horizontally deposited as observed in deeper portions of JB-3. In this orientation, the anisotropy is strongest. Models II, IV and VI consider the possibility that foliation is dipping at the angle of 45° (as observed in shallower portions of JB-3), which causes phyllite to appear almost isotropic. Unlike the situation in Litoměřice where the resulting temperature field depends on heat generation in the basement, the principal factor affecting the temperature field in Benešov u Semil is anisotropy of phyllite.

Figure 35 shows temperature profiles of each model. The greatest temperature, over 190°C, is reached with horizontally bedded phyllite and the heat flux from Košťálov. The lowest temperature (slightly over 150°C), on the contrary, results from phyllite dipping at 45°C with the heat flux from Libštát.

Figure 36 shows how temperature at the depth of 5 km below surface changes along the profile. Anisotropy of phyllite is again the driving feature.

All models correspond with temperature measurements carried out in Košťálov.

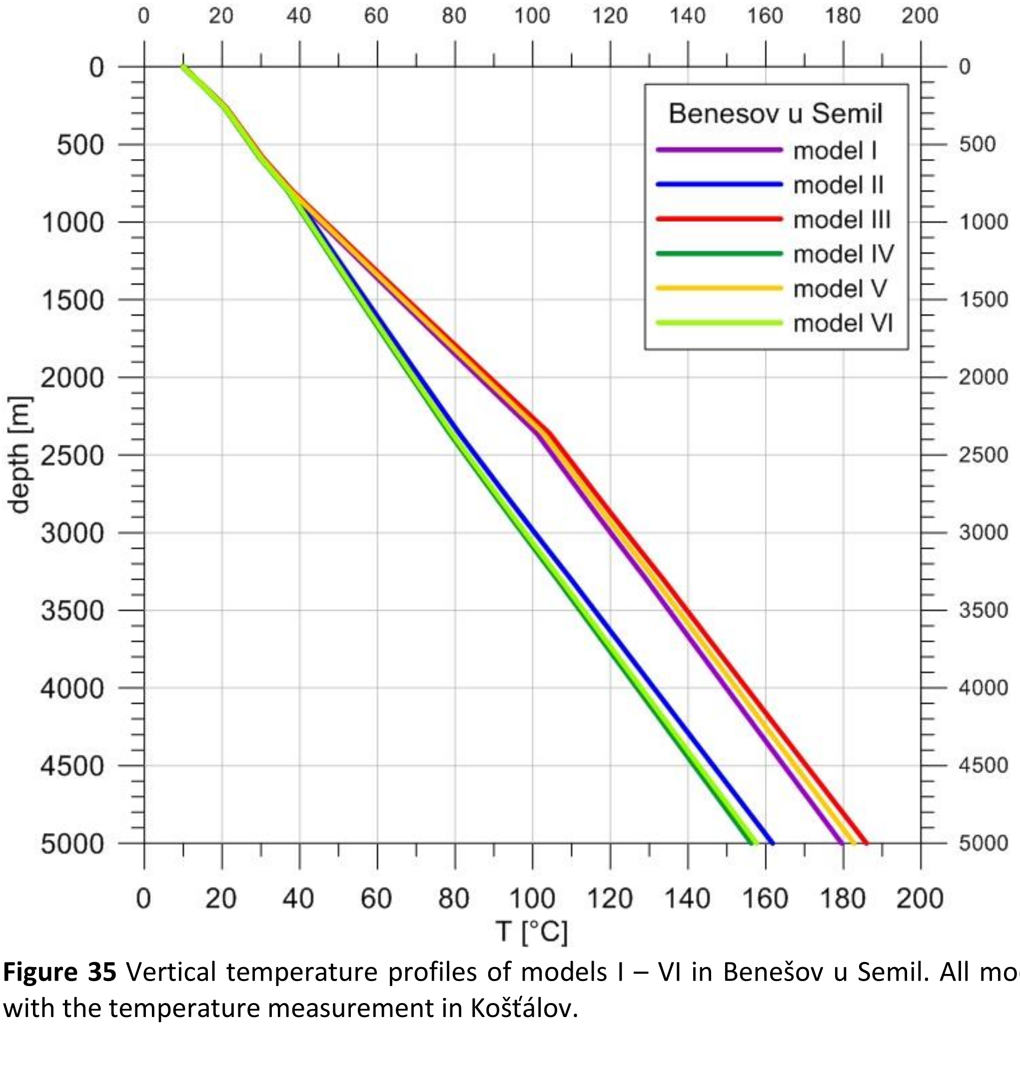


Figure 35 Vertical temperature profiles of models I – VI in Benešov u Semil. All models correspond with the temperature measurement in Košťálov.

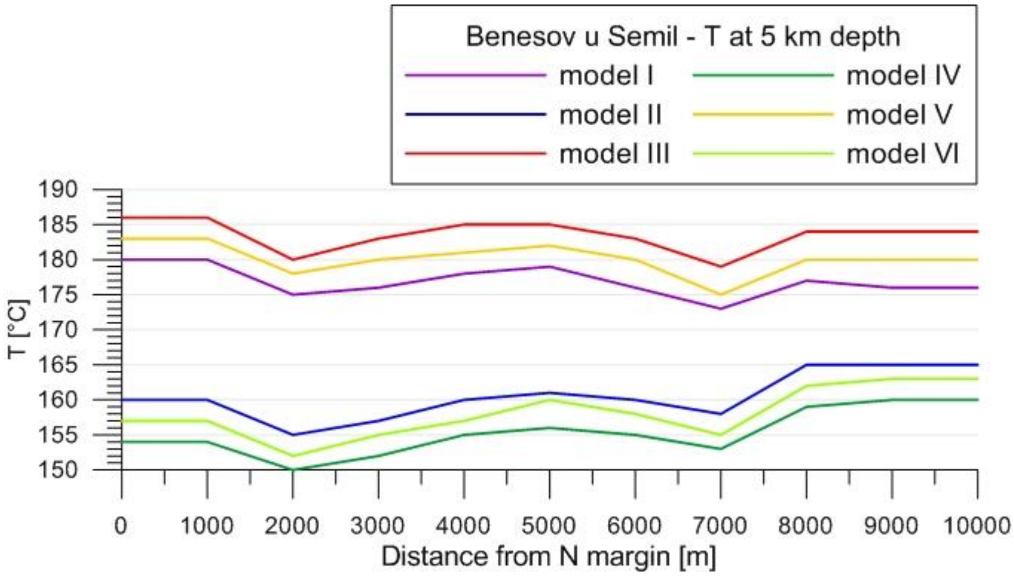


Figure 36 Temperature at the depth of 5 km along the section B. It is interesting that models with dipping phyllite exhibit greater temperatures in the southern parts of the profile, models with horizontal phyllite are the contrary. The difference at the northern edge of the profile reaches over 30°C.

Semily

The same parameters as in Benešov u Semil are used in the geometry for Semily as well. The geometry of the model is based on the geological section A as presented in Figure 34 and Appendix A. As temperature measurements from the boreholes Kh-1 and Pé-1 are unreliable, heat flux either from Košťálov or from Libštát is used again.

Models I and II use the heat flux from Libštát, models III and IV use the heat flux from Košťálov and models V and IV use the average heat flux from these boreholes. Models I, III and V include horizontal layers of phyllite, models II, IV and VI include phyllite dipping at 45°.

The town of Semily is located in the NW part of the section, i.e. on its left edge.

Figure 37 shows temperature profiles of each model. The greatest temperature, over 190°C, is reached with horizontally bedded phyllite and the heat flux from Košťálov. The lowest temperature (slightly less than 170°C), on the contrary, results from phyllite dipping at 45°C with the heat flux from Libštát.

Figure 38 shows how temperature at the depth of 5 km changes along the profile A. Anisotropy of phyllite is again the driving factor in the western and north-western part of the profile. In the eastern part of the profile, where a mafic body is emplaced instead of phyllite, temperatures at depth vary only with change in the heat flux. The temperature difference in Semily due to anisotropy of phyllite is over 20 °C.

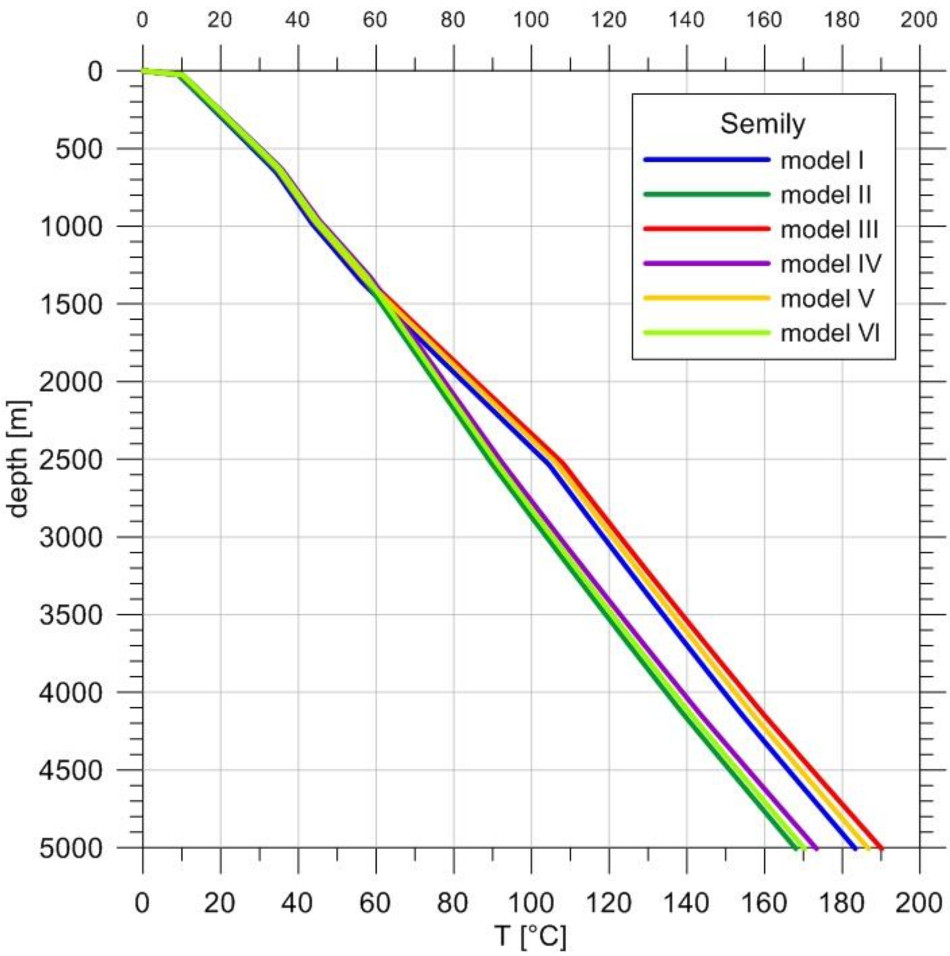


Figure 37 Vertical temperature profiles of models I – VI in Semily. All models correspond with the temperature measurement in Košťálov.

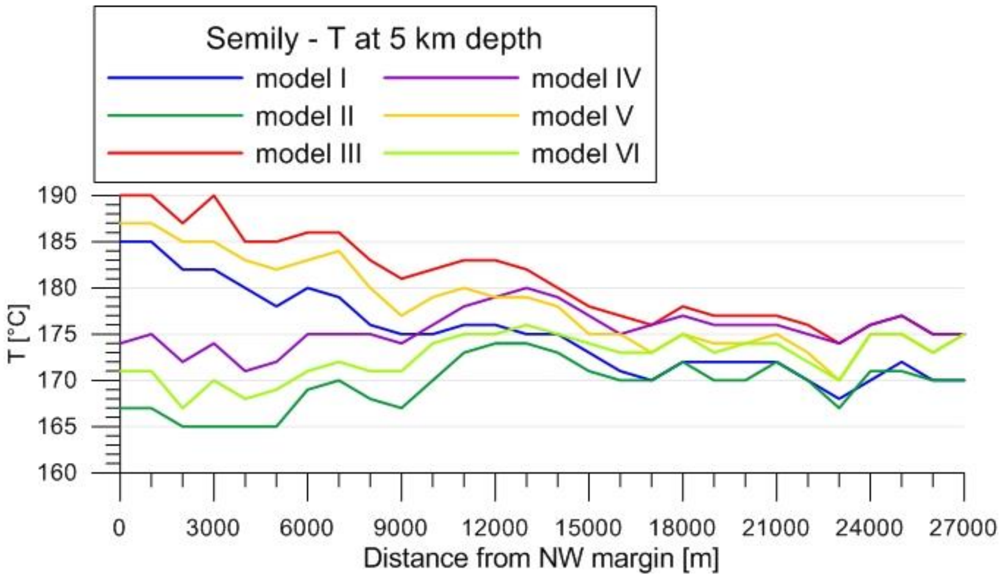


Figure 38 Temperature at the depth of 5 km along the section A. Different heat flux together with different structure of phyllite generate a difference of up to 25°C in the NW part of the section, i.e. on the investigated site. On the other hand, temperature difference in the east is only 5°C.

Determination of parameters for each unit

Thermal conductivity [W/m.K]:	isotropic	perpendicular	parallel
Prosečné Fm. (mudstones, siltstones)		2.1	2.2
Vrchlabí Fm. (all lithologies)		2.2	2.4
Semily Fm. (siltstones, marlstones, sandstones, conglomerates)		3.2	3.4
Syřenov Fm. (arkoses, siltstones, mudstones)	2.6		
Kumburk Fm. (siltstones and mudstones)	2.6		
metadiabase	2.6*		
melaphyre	2.2*		
phyllite	3.5	2.3	3.5
mica schist	2.8***		
gneiss	3.1		
gabbro	2.5**		
greenschist	3.4		
Heat flux [mW/m^2]:	**uncorrected**	**palaeo**	**heat**
Košťálov	83.7	93.7	86.5
Libštát	80.5*	90.5	83.5
Average from Košťálov and Libštát			85
Kruh	52.7	62.7	-
Prosečné	116.2	126.2	-
Heat production [µW/m^3]:			
mudstones of Vrchlabí Fm.	2.60		
gneiss	1.5***		
mica schist	1.5***		
Phyllites	2.05		
Surface temperature [°C]:	T=10.6-4.7*0.001*h-0.33*0.6		

Table 9 Parameters entered in the model. The mean surface temperature was determined using Kubík's empirical relation where h is altitude.

*Dědeček (2013, pers.comm.)

** ODP: average in holes 1275B and 1275D after Kelemen *et al*. (2004)

*** average values from Hellwege *et al*. (1982)

4.2.5 Comments on the models

According to the indicators suggested by Manzella *et al*. (2013) in Figure 39, the area may not be as promising as hoped for. Although the heat flux is high, groundwater in the sedimentary formations is of the type regarded as misleading. Due to fracture systems, the "caprock" formations are not impermeable, so that they do not preserve heat within but transfer it. Moreover, the high heat flux calculated from temperature data in Košťálov and Libštát can be influenced by thermal waters reported by Skácelová in Prouza *et al*., 2010 as well as Prouza and Tásler in Pešek *et al*., 2001 and identified in the Kv-1 borehole as recorded in the Database of Geologically Documented Objects of the Czech Geological Survey.

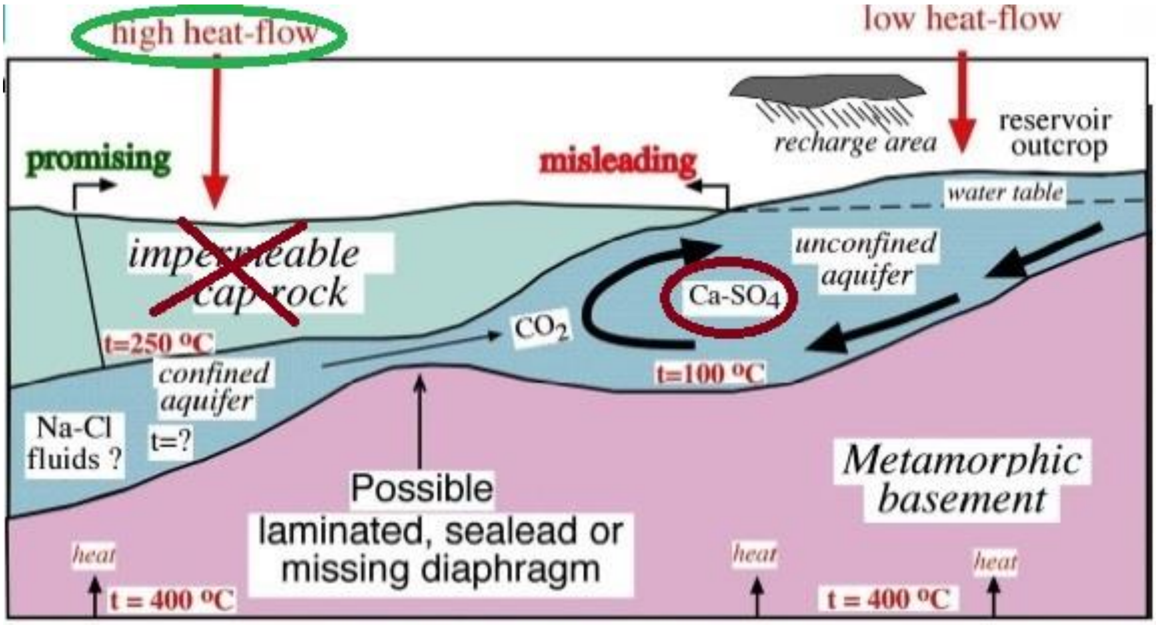


Figure 39 Illustration of geological environments promising or misleading for geothermal exploration. Promising factors encountered in the area are in green loop, misleading factors encountered in the area are in red loop and missing promising factors are crossed in red. Modified from Manzella *et al*. (2013)

The models, however, show a considerably more optimistic situation than in the case of Litoměřice. Both Semily and Benešov u Semil seem suitable for geothermal energy usage even for electricity generation as the lowest temperature computed for the least favourable conditions exceeds 150°C. This fact is driven by thermal properties of metamorphic rocks determined on the basis of measurements of drill core samples and extensive literature study. The other important factor is high heat flux encountered in most boreholes in the area. The origin of such a high heat flux is questionable and should be subject to further research. Thermal waters occur in a number of places in the Krkonoše Mts. piedmont, on the Polish side as well as on the Czech side. It should be examined whether these thermal waters can actually influence heat flux in the whole area or whether heat is transferred to the shallow parts of the crust via tectonic lines such as the Lugian Fault, faults related to the Elbe Lineament and others. It is interesting to point out that similar temperatures to those in Pé-1 have been measured in the same depths in Dolní Bouzov (DB-1 borehole), which is in the Mnichovo Hradiště Basin (Kobr, 2013, pers. comm.). The hint suggesting the origin of the high heat flux could thus be found in the common evolution of these basins.

4.3 Liberec

The city of Liberec lies on the Liberec Granite which is the part of the Krkonoše-Jizera Pluton, only its south-eastern parts reach the marginal parts of the Krkonoše-Jizera Crystalline Complex, consisting of Proterozoic phyllites, crystalline limestones, marbles, quartzites, mica schists, amphibolites and erlans. The grade of metamorphism increases toward east.

No deep boreholes have been drilled in proximity of Liberec yet. Therefore, the deeper structures of the basement remain subject to discussion and because of lack of deep boreholes with temperature measurements, heat flux can only be determined on regional scale from the map of heat flow. However, the Liberec Granite has been thoroughly studied in the tunnels in the Jizerské hory Mts., in shallow boreholes as well as in outcrops and its thermal properties are known. Thus, construction of a 1D model of temperature profile north of Liberec is simple, as we can infer uniform geology all along the vertical profile. For the case south of Liberec, the borehole Jesenný JB-3 has been chosen as a representative of the Krkonoše-Jizera Crystalline Complex for both the area of Liberec and Semily.

4.3.1 Considered environments

Borehole JB-3 Jesenný

The JB-3 hole lies approximately 30 km to the south-east of Liberec or 10 km north of Semily. It is situated in an intensively folded area in the centre of a Variscan synclinorium consisting of metamorphic rocks of the Krkonoše-Jizera Crystalline Complex.

Lithology and stratigraphy

0-118 m	alternating Quaternary sands with Silurian limestones
118 - 133 m	phyllite
133-143 m	alternating Quaternary sands with Silurian limestones
143 - 427 m	metamorphic Silurian limestone
427 - 506 m	phyllite

Table 10 Lithological and stratigraphical description of JB-3. After Krutský *et al.* (1968)

The geological situation is illustrated in the section (Figure 40) modified from Krutský *et al*. (1968).

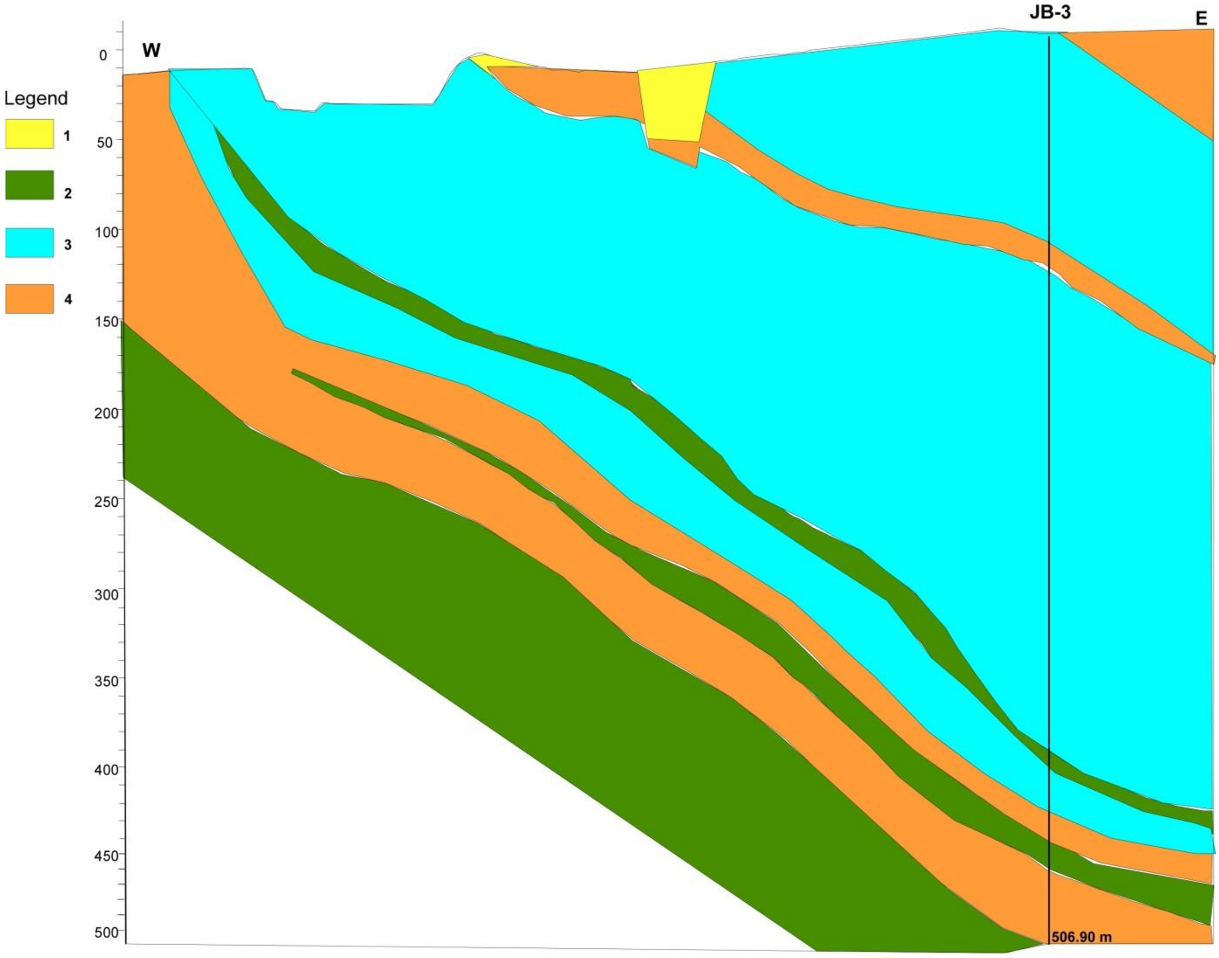


Figure 40 Simplified cross-section of the locality Jesenný-Bozkov modified from Krutský *et al*. (1968). 1 – quartzite, 2 – diabase, 3 – limestone, crystalline limestone or dolostone, 4 – phyllite.

The deeper basement can be subject to discussion. Generally it is accepted that the basement consists of Proterozoic metamorphic rocks: greenschists, phyllites or gneisses.

Hydrogeology

Krutský *et al*. (1968) reported aquifers in fracture systems of the E-W direction and karsting in the carbonates. These may bring uncertainty to the geothermic model as heat transfer via convection may be taking place there. However, as no data on these factors were available, they were not included in the models. Information acquired from the model should, therefore, be treated with caution.

Thermal properties (conductivity measurement, T logging, calculated heat flow)

Temperature measurements from the JB-3 were not available, so heat flux could not be accurately calculated. Therefore, two different values of heat flux were considered in the models (see below). Thermal conductivity scanning was performed on the core samples from JB-3, values of thermal conductivity and heat production in the Liberec granite were taken from the database of the Geophysical Institute, AS CR. The resulting values are stated in Table 11.

Liberec Granite

The Liberec Granite is coarse- to medium-grained biotite granite with marked phenocrysts of K-feldspar. Thermal properties of the Liberec Granite have been studied in detail in tunnels near the city by the staff of the Geophysical Institute AS CR (Dědeček, 2013, pers.comm.). However, no deep boreholes are present here, so two possibilities on heat flux are presented. The first possibility (model I) is taken from the map of heat flow with palaeoclimatic correction by Majorowicz and Wybraniec (2010) giving the value of 75 $mW.m^{-2}$. After applying the correction for heat production in the basement, the value is reduced to only 63 $mW.m^{-2}$ in the granite and to 67 $mW.m^{-2}$ in the Krkonoše-Jizera Crystalline Complex. The second option (model II) is using the average value from the Semily area, i.e. 82 $mW.m^{-2}$, which is reduced to 80 $mW.m^{-2}$ in granite and increased to 84 $mW.m^{-2}$ in the metamorphic complex after applying the corrections for palaeoclimate and heat production.

Determination of parameters for each unit

Thermal conductivity [W/m.K]:	**isotropic**	**perpendicular**	**parallel**
Liberec granite	3*		
mica schist	2.8***		
gneiss	3.1		
phyllite	3.5	2.25	3.49
crystalline dolomitic limestone	3.66		
Heat production [µW/m^3]:			
gneiss	1.5***		
mica schist	1.5***		
Liberec granite	5.7*		
Phyllites	2.05****		
Heat flux [mW/m^2]:	**uncorrected**	**palaeo**	**heat**
Semily	82	92	80 gr/84 met
Liberec	-	75**	63 gr/ 67 met
Surface temperature [°C]:	T=10.6-4.7*0.001*h-0.33*0.72		

Table 11 Determination of parameters entered in the models.
*after Dědeček (2013, pers.comm.)
** Majorowicz and Wybraniec (2010) map of heat flow, approximate value
***average values from Hellwege *et al*. (1982)
**** concentration of K, U, Th from Skácelová in Prouza *et al*. (2010)
gr – heat flux in the granite massif, met – heat flux in the metamorphic complex

4.3.2 1D model for each case

The case of Liberec Granite as a uniform homogeneous environment shows a very simple thermal profile that could only be disturbed by unexpected deep fracture systems with fluid circulation. However, the model could become more accurate if temperature measurements from deeper wells in the environment under investigation were available so that the in situ heat flux could be calculated.

On the contrary, the second model represents an extremely complicated environment with numerous uncertainties coming in play. The rich series of alternating metamorphic rocks of the Krkonoše-Jizera Crystalline Complex, i.e. phyllites, crystalline limestones and marbles, diabases and metadiabases, greenschists and quartzites, which differ in thermal conductivity and anisotropy from each other significantly, appears to be unpredictable. In this model, prograde metamorphism is considered. Phyllite is estimated to be the prevalent rock type in the basement of JB-3 to the depth of 2600 m, followed by mica schist (2600 – 4000 m) and gneiss (4000 – 5000 m). This assumption is based on the geology of the same unit in the area of Semily.

Temperature profiles of the four models are shown in Figure 41.

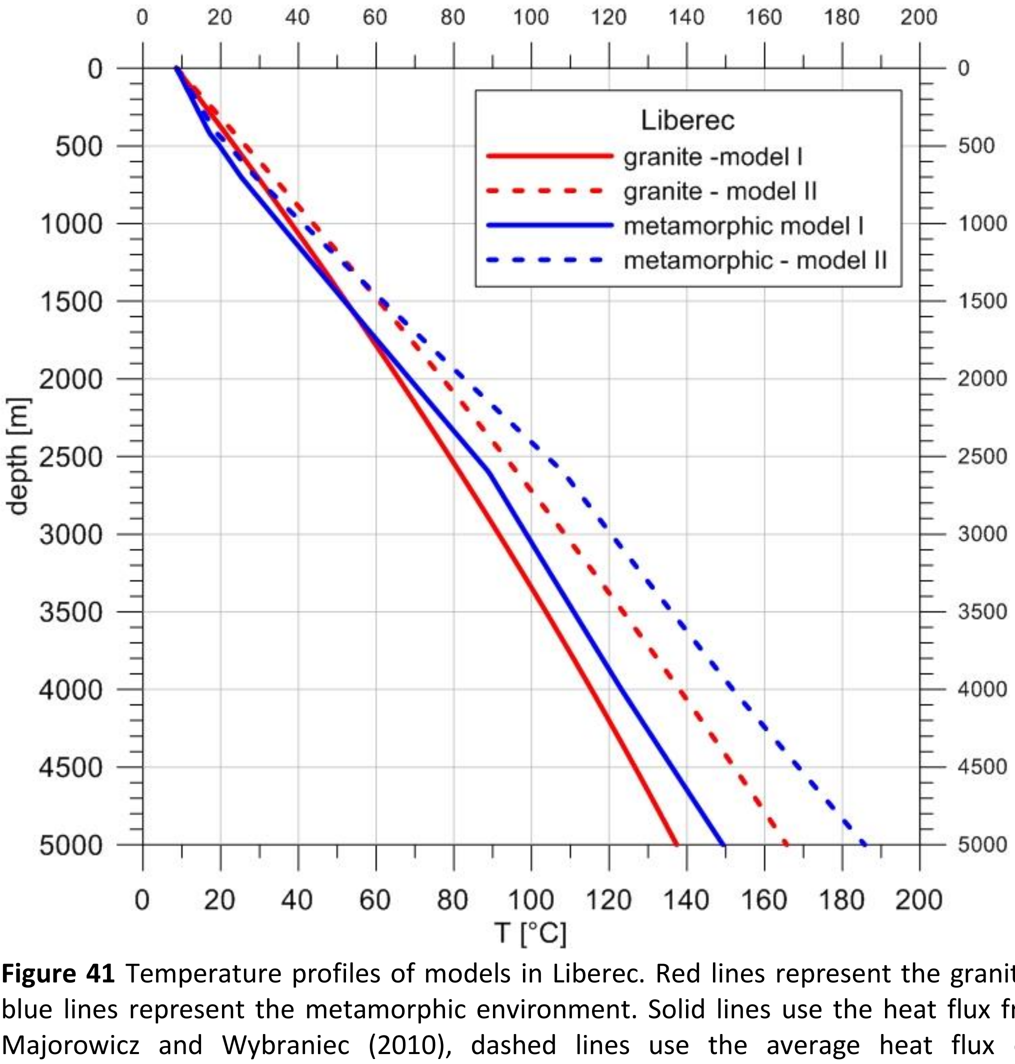


Figure 41 Temperature profiles of models in Liberec. Red lines represent the granitic environment, blue lines represent the metamorphic environment. Solid lines use the heat flux from the map by Majorowicz and Wybraniec (2010), dashed lines use the average heat flux calculated from temperature measurements in Košťálov and Libštát.

4.3.3 Comments on the models

Due to so many unknown parameters in this area, the models exhibit large variance in the resulting temperatures at 5 km depth – the least favourable possibility gives the temperature lower than 140°C, which is unsuitable for installation of a geothermal power plant. On the other hand, if the heat flux in the area proved to be higher than in the map by Majorowicz and Wybraniec (2010), the temperature is likely to exceed 150°C, which would increase the suitability of the site for geothermal energy usage.

5. Discussion

Very little is known about the basement at depths greater than 2 km. Numerous studies have used various geophysical methods including seismics and airborne gravity and magnetics to distinguish the most striking rock types, but even so the understanding of the deeper structures is relatively poor. This leads to a great uncertainty in the geothermic models as thermal conductivity of different crystalline rocks varies with mineral composition and so does its dependence on temperature. Due to large anisotropy of metamorphic rocks, knowledge of their foliation is necessary for correct determination of thermal conductivity. Moreover, so far undiscovered deep aquifers and fracture systems may occur in the studied areas and not be considered in the model. Therefore, the geological sections presented above show the author's interpretation of information acquired from literature or from discussions with experts in regional and structural geology. The geothermic models have been constructed on the basis of these sections and measurements which could attribute certain petrophysical properties to each unit. Their validity can be verified or denied after drilling deep boreholes in the investigated areas.

Reliable economic assessment of geothermal developments in each of the studied areas is impossible at this early stage of exploration. A thorough economic analysis can be provided using the HDRec software developed by Heidinger, Dornstädter and Fabritius (2006). However, it is essential to determine a number of more parameters in addition to temperature and geothermal gradient: wellbore geometry, borehole depth, rheology of the rocks and physical properties of the fractures, in situ stress field, type of fluid, production rate and expected production period. Although the depth and geometry of the boreholes is proposed, the stress field and deep hydraulic properties of the deep rock environment need to be studied so that a reliable feasibility analysis can be carried out. Nevertheless, the higher the temperature at depth, the more promising is the outcome. Based on this premise, Semily seems to be the best place for a pilot project as the highest temperature is expected here.

6. Conclusion

An extensive study of available information resources concerning regional geology of the studied areas brought valuable information on the geological structure, which was discussed with experts from the Czech Geological Survey, Geophysical Institute of the Academy of Sciences of the Czech Republic, Faculty of Science of the Charles University in Prague and Miligal s.r.o. (Ltd.), who have been studying these areas under the terms of numerous research projects. A review of results of this study is provided in this thesis. Even so, many outcomes remain questionable due to lack of deep boreholes and insufficient amount of deep-reaching seismic profiles. Obstacles have been encountered during study of older reports from the Czech Geological Survey (former Geofond) which were sometimes incomplete (missing maps and geological sections) or contained unreliable data (temperature logs measured under unsteady conditions).

Drill core samples from 5 boreholes were measured successfully using the Lippmann&Rauen GbR Thermal Conductivity Scanner. However, due to technical reasons and poor condition of the old samples (the studied boreholes were drilled in the 1960s), they were measured only in dry state. The true values of thermal conductivity could therefore be higher than stated.

Despite these constraints, the thesis provides a hypothesis describing thermal conditions in the studied areas. According to the models presented in chapter 4, the most promising area for geothermal energy usage is Semily. There, the lowest temperature at 5 km depth resulting from the least favourable conditions considered during construction reaches 166°C, which is higher than the temperature in Gross Schoenebeck where a working geothermal power plant has been installed successfully. If the most favourable conditions were encountered on the site, the temperature would be as high as 191°C. Benešov u Semil appears to be suitable, too, as it lies in proximity of Semily in similar conditions. There, the least favourable conditions still generate the temperature of 156°C at the 5 km depth in the presented model and thus ensure that the site is suitable for geothermal energy utilisation.

The models show that conditions in Litoměřice and Liberec are less promising. The models of Litoměřice generated similar results to the models presented by Šafanda *et al.* (2007), with the lowest temperature 132°C at 5 km depth and the highest temperature 155°C 5 km below Litoměřice. Suitability of this site for installation of a geothermal power plant is therefore considerably low. However, the 2D models suggest that greater temperatures would be encountered at the proposed depth if the drilling site was moved further to the north.

In case of Liberec, not enough information could be gathered for construction of a 2D model to the 5 km depth. However, the 1D models suggest that greater temperatures could be encountered in the metamorphic complex than in the granite massif. Whereas the lowest temperature computed for the Liberec granite is 137°C, the lowest temperature in the metamorphic complex with the same heat flux is 149°C. When higher heat flux was considered in the area, the temperatures at the desired depth rose to 165°C in the granitic massif or to 185°C in the metamorphic complex, respectively. Such conditions would be very favourable for geothermal energy utilisation. Therefore it is essential to carry out accurate thermometric measurements in boreholes near Liberec in order to determine the correct value of heat flux.

In conclusion, this thesis presents a compilation of varied geological and geothermic information and brings out suggestions for further research that could eventually lead to inception of geothermal power generation in the Czech Republic.

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8. Appendixes

Appendix A shows the geological sections from chapters 4.1 (Litoměřice) and 4.2 (Semily – section A) as concluded by the author. The composition of the basement is unknown, so the figures only represent one of the likeliest versions.

Appendix B shows the 2D models along the geometries defined by the geological sections: models of the area of Litoměřice are based on the geological section between Brňany and Rýdeč presented in Appendix A. The models of Benešov u Semil are based upon the geological section B presented in Figure 32. The models of Semily are based on the geology presented in Appendix A in the section A between Semily and Prosečné. The temperature variations are represented by a colour scale.

Appendix C shows the gravity map of NW Bohemia after Šrámek in Mlčoch et al. (2001)