

3D Modeling of Geothermal Reservoirs

Case Study from Subtatric Basin in Western Carpathians,
Slovakia

Lucia Hlaváčová



UNIVERSITY OF ICELAND



University
of Akureyri

3D MODELING OF GEOTHERMAL RESERVOIRS

Case Study from Subtatric Basin in Western Carpathians, Slovakia

Lucia Hlaváčová

A 30 credit units Master's thesis

Supervisors:

Dr. Juraj Janočko (Professor, Technical University of Kosice, Slovakia)

Dr. Axel Bjornsson (Professor, Univ. of Akureyri)

Dr. Hrefna Kristmannsdottir (Professor, Univ. of Akureyri)

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RES | the School for Renewable Energy Science
Solborg at Nordurslod
IS600 Akureyri, Iceland
telephone: + 354 464 0100
www.res.is

ABSTRACT

Geothermal energy is a potential renewable energy source that should be taken into account by the Slovak government. To aid geothermal exploration, 3D modeling is a very useful tool. The objective of this project was to model Poprad basin and the northern part of Hornad basin, in the Inner Carpathian system in Slovakia, to assess future prospective geothermal areas. These two are considered active geothermal areas. The main aquifers are built by Triassic carbonates – dolomites and limestones of Choc and Krizna nappe. In the central part of the Poprad basin, on the basis of seismic interpretation, Choc nappe thicknesses from 200 to 1100 m were obtained. Larger nappe thicknesses from 1200 to 1500 m were obtained on the east and southeast part of the studied area. The average value of the temperature gradient reaches $32.6 - 34.5^{\circ} \text{C/km}$ and the average value of the heat flow density was estimated on 67mW/m^2 . Temperatures on the top of the Pre-Paleogene basement reach $50 - 85^{\circ} \text{C}$. In this work the geologic structure of the Gerlachov area, which is situated in the northwestern part of Poprad Basin, was also interpreted. From a geothermal point of view the formations with the most potential are Mesozoic units represented by Choc and Krizna Nappes underlying Paleogene rocks. Based on the geologic composition of Choc Nappe, the existence of very good conditions for a geothermal water reservoir can be expected. Krizna Nappe has less positive conditions for geothermal waters exploitation. General discharge of groundwater in Choc Nappe should be more than 22 l.s^{-1} . The temperature in Choc Nappe is between 35 and 45°C .

PREFACE

This thesis is submitted to RES | The School for Renewable Energy Science as partial fulfillment of the requirements for the M.Sc. degree. The work presented here is the product of three months of data gathering and 3D modelling. The work was conducted in the Department of Geosciences in the Technical University of Košice in Slovakia.

This M.Sc. work is focused on the 3D modelling of geothermal reservoirs in Subtatric basin in Western Carpathian area in Slovakia. Modelling was specialized on reservoirs in Poprad basin and the northern part of Hornad basin.

These three months started with collecting data from the study areas, followed by work with this data and preparing it for 3D modelling software. I am very grateful to Ing. Miloš Varga PhD. for helping me with data processing. I am also very grateful to Prof. Ing. Juraj Janočko CSc., Dr.scient. for all the time, guidance and support given to me during the elaboration of this thesis.

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Lucia Hlaváčová, Akureyri, Iceland 18th of February 2009

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1 INTRODUCTION

Renewable energy sources are domestic energy sources which help to increase the safety of energy supply and diversification. In addition, utilization of renewable energy sources usually fulfils the conditions of environmental acceptability. An increase in renewable energy utilization, through heat and electricity production is one of the EU strategies for dealing with current climatic changes because, for example, they contribute to reducing the emission of green house gases. Also, renewable energy sources play an important role in the area of local and regional development and employment.

In the year 2001, the European parliament and European Council directive announced the objective of reaching 20% of energy consumption from renewable energy sources by 2020. The directive confirmed the EU priority of increasing the utilization of renewable energy sources till 2010.

The new conception of renewable energy source utilization was approved by decree of the Slovak government No. 282/2003. Technically available potential of renewable energy sources, according to Energetic conception of the Slovak republic, is from biomass (46,7 % , 60,458 TJ), geothermal (17,5%, 22,680 TJ), solar (14,5 % , 18,720 TJ), waste (9,8 % , 12,726 TJ), biological fuels (6,9 % , 9,000 TJ), small water power plants (2,9 % , 3,722 TJ), wind (1,7 % , 2,178 TJ). In total there is energy potential of 129,484 TJ that can be extracted from renewable energy sources (Decree of the Slovak Government No. 282/2003)

Geothermal energy is a promising option. Its energy is derived from the heat contained within the earth. It is a form of renewable energy and has proved to be reliable, economic, environmentally friendly and sustainable. The use and study of geothermal energy was greatly improved in the 1990's in order to supply reusable energy for the increased worldwide energy demand (Dickson and Fanelli 2004). Geothermal resources are found in all types of rocks: sedimentary, metamorphic and volcanic. On average the formation temperature increases by about 30°C/km, which means that temperatures of about 100°C can generally be found at depths of 3 to 4 km. It is not enough to find temperatures suitable for utilization. Locations must be found where water is present at a suitable depth, and the local permeability is sufficient to absorb heat stored in the rocks and carry it up to the surface.

Several geological surveys showed that Slovakia is relatively rich in geothermal sources. The water temperature of these sources varies between 75 and 130°C. The Slovak economy is 90% dependent on imported energy sources; therefore utilization of this non-traditional renewable energy source is imperative. The current utilization of geothermal energy in Slovakia is only about 6 % of the country's renewable energy production.

2 PROJECT OUTLINE

The main objective of this project is to characterize the geothermal potential of the Subtatric region, as it is a vital part of a long-term governmental plan for the use of renewable energy sources, mostly for heating and electrical production. The whole study is subdivided in the following partial items:

- **Geological analysis** - The study area covers the Paleogene depressions known as Subtatric depression and extends further to the southeast, to the Hornad Depression. The great advantage for the proposed project is a large number of older hydrogeological and geothermal wells in the area providing huge amounts of data needed for the planned analysis. The geological analysis will be devoted to the evaluation of the lithology of potential reservoir rocks and the role of tectonics in exploitation of the reservoir rocks.
- **Data available for the thesis:**
 - Para-3D seismics, locality Gerlachov, Subtatric depression
 - Several 2D seismic profiles from the Subtatric depression
 - Geological map from the Subtatric and Hornad depressions at scale 1:50 000
 - Interpreted gravity data showing basement of the Subtatric depression, 5 geothermal wells from Subtatric depressions showing lithology, stratigraphy, hydrogeology and some of the geothermal parameters
- **Hydrogeological analysis** - In this part the hydrogeological units made of different potential reservoir rocks will be evaluated. The hydrogeological parameters will be obtained from existing archive manuscripts and published papers. This part will also include petrophysical analysis (porosity, permeability, type of hydrogeological reservoir, circulation etc.) of the evaluated rock units.
- **Geothermal conditions** - Based on archive works and wells, geothermal characteristics of the selected region will be presented.

3 BACKGROUND INFORMATION

The modeled geothermal reservoir is situated in Inner Western Carpathians, Slovakia. The studied area is shown in Figure 3.1.

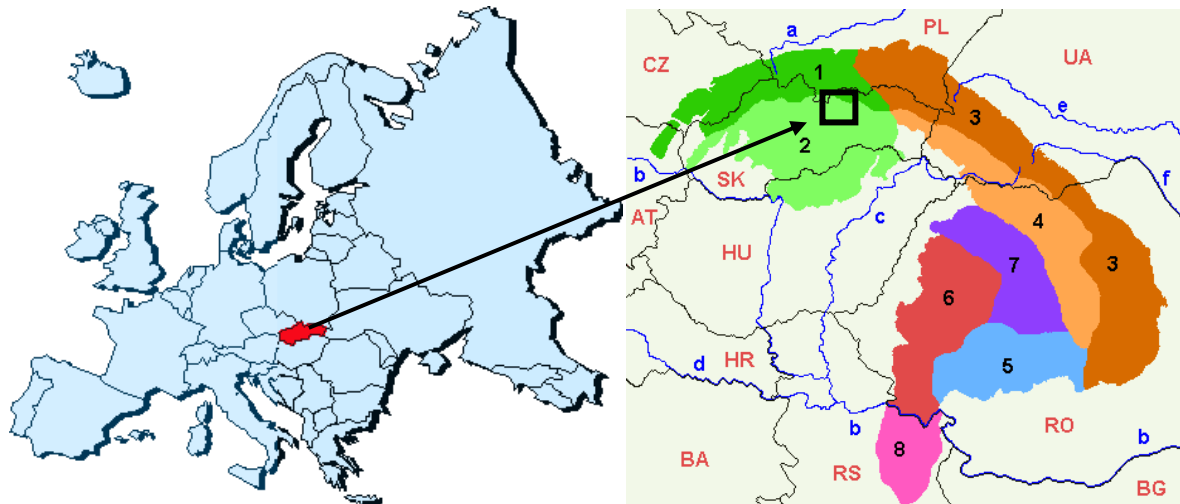


Figure 3.1 - Map of Carpathian region: studied area located inside the black box

Legend: Location of Slovakia in Europe, Division of the Carpathians: 1-Outer Western Carpathians, 2-Inner Western Carpathians, 3-Outer Eastern Carpathians, 4-Inner Eastern Carpathians, 5-Southern Carpathians, 6-Western Romanian Carpathians, 7-Transylvanian Plateau, 8-Serbian Carpathian

3.1 Geologic background

The geological structure of the Western Carpathians in Slovak territory and favorable geothermic conditions create a suitable setting for the occurrence of geothermal energy resources. The Western Carpathians are classified according to the age of development of the Alpine nappe structure as the Outer, with Neo-Alpine nappes, and the Inner, with Paleo-Alpine and Pre-Paleogene nappe structures. The Klippen Belt marks the boundary between them (Fig. 5). The structure of the Western Carpathians is characterized by zoning. The Mesozoic and Tertiary formations, arrayed in a series of arched belts, have been tectonically transformed from qualitatively and temporally different sedimentary basins into the fold-nappe ranges, which may either be composed of sedimentary filling alone, or may include the original basement (Biely Ed. 1996). The geological setting is favorable for the occurrence of geothermal waters with temperatures higher than 20°C only to the south of the Klippen Belt. Geothermal waters are largely associated with Triassic dolomites and limestones of the Križna and Choč nappes (Fatricum and Hronicum), less frequently with Neogene sands, sandstones, conglomerates, andesites and related pyroclastics. A map with the geologic formations in the Slovak Republic is shown in Figure 3.2.

3.2 Geology of Inner Carpathians

The characteristic feature of this zone is the pre-Senonian (Mediterranean) age of nappe thrusting, manifestations of Alpine metamorphism and magmatism and large areal extent of post-nappe sedimentary and volcanogenic formations. The pre-Senonian nappe structure

consists of two kinds of nappes. The first type is composed of the pre-upper Carboniferous fundament overlain by Late Paleozoic and Mesozoic in normal position. This nappe group includes the Tatricum, Veporicum and Gemericum. The second type comprises rootless nappes composed of Mesozoic and sometimes Late Paleozoic rocks which are entirely separated from their substratum. This type includes nappes in the Fatricum, Hronicum and Silicikum.

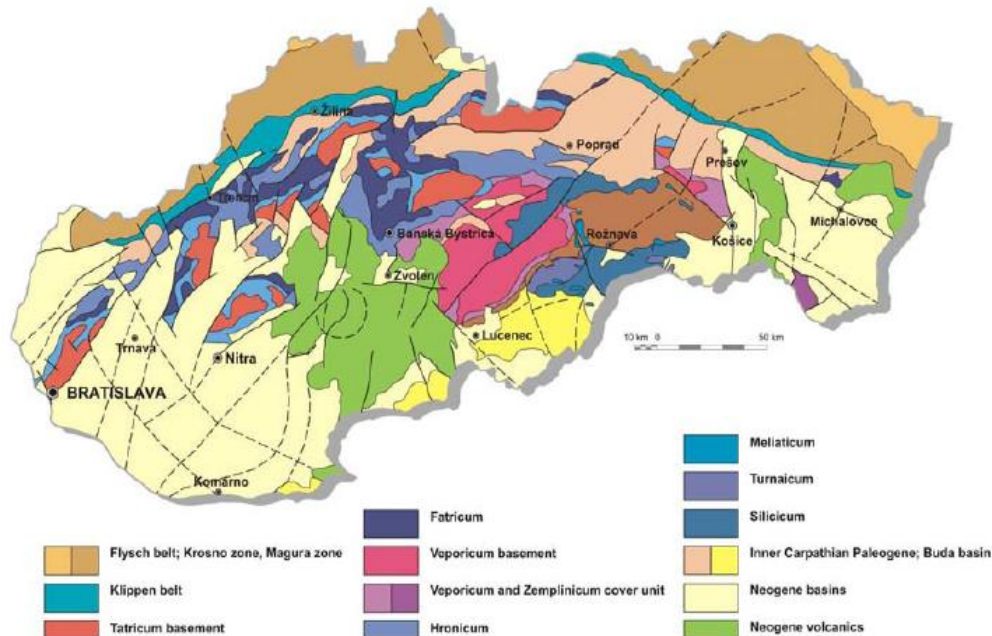


Figure 3.2 - Tectonic map with geologic formations of the Slovak Republic (Biely Ed., 1996)

Tatricum

Tatricum is widespread in the core mountains (Malé Karpaty, Považský Inovec, Strážovské vrchy, Malá Fatra, Tatry, Veľká Fatra, Nízke Tatry, and Branisko) in the outer section of the Inner Carpathians. It is dominated by crystalline schists, granitoids and the envelope which in some mountain chains starts with Permian continental sediments. The Tatric Mesozoic sediments range in age from the Lower Triassic to cenomanian in the Tatry Mts. to the Lower Turonian. The Mesozoic succession of strata is interrupted by hiatuses in the Upper Triassic and Lower Cretaceous. It is dominated by carbonate rocks except for the Lower and Upper Triassic where detrital sediments prevail.

Veporicum

Veporicum also consists of crystalline schists, granitoids and the Late Paleozoic and Mesozoic envelope. It is fringed by the Čertovica line in the north and the Lubeník-Margecany line in the south. The envelope of the crystalline formations was preserved mostly in the northern Veporic subzones where its Lower Triassic – Neocomian succession of strata is similar in character to the Fatricum. The Mesozoic rarely occurs in the southern subzones. The Late Paleozoic formations have a detrital character. The whole envelope is mildly metamorphosed. The Veporicum is overthrust onto the Tatricum.

Gemicum

Gemicum is widespread in the Inner Carpathians' southern tract. This term now refers only to the Paleozoic part of the originally larger unit. It comprises the Early Paleozoic Gelnica Group dominated by flysch rocks with abundant acid effusive volcanics and the Rakovec Group composed of flyschoid and mafic effusive volcanic rocks. In addition it includes Upper Carboniferous detrital sediments, Permian continental sediments with acid effusive volcanics and, in the south, Permian marine detrital sediments are also present. In the Alpine period, the Early Paleozoic sequences were intruded by granitoids.

The Meliaticum and Tornaicum in the southern Inner Carpathians, which were formerly assigned into the Gemicum, are now regarded as separate units. Their areal extent is very small, and their mutual relationships and position have not yet been cleared up sufficiently. The Gemicum is overthrust onto the Veporicum.

Fatricum

Fatricum consists of rootless nappes overlying the Tatricum (Křížna and Vysoká nappes). It is a succession of strata ranging from the Lower Triassic to Cenomanian. Only in the Staré Hory area the Křížna nappe includes earlier rocks which are Permian and crystalline. The Fatric basin of deposition is likely to have been situated between the Tatricum and Veporicum.

Hronicum

Hronicum is made up of higher rootless nappes resting on the Fatricum largely in the Tatric and partly also in the Veporic area. The nappe rocks are Carboniferous to Neocomian in age. Permian continental sediments are accompanied by mafic volcanics. The Triassic in the Choč nappe has a variegated marine carbonate character whereas the Šturec nappe is essentially dolomitic. The Hronicum basin of deposition was probably situated south of the Gemicum.

Silicikum

Silicikum (Mesozoic of the Slovak Kras, Galmus, Muráň, Plateau, Drienok nappe, etc.) is the highest group of rootless nappes composed of Lower Triassic shale facies but mainly Middle to Upper Triassic carbonates. They were probably deposited in the same sedimentary area as the Hronicum.

The Middle Cretaceous Inner Carpathian tectogenesis is characterized by the complete reduction of the crystalline basement which originally underlay the rootless nappes. After the nappes were overthrust, this area was partly inundated by a Senonian sea whose sediments were preserved only very rarely. In the Paleogene, the Inner Carpathians became a basin of deposition. Thick flysch formations, the Inner Carpathian Paleogene, were deposited in the northern section. The Buda- (Pannonian) facies Paleogene was laid down in the south. Late tectonic and post-tectonic molasse basins evolved in the inner Carpathians after the Sava folding, a process accompanied by intensive volcanism. The filling of these basins is dominated by brackish and freshwater sediments. The Neogene tectonic regime crushed the Inner Carpathians into blocks. Tectonic activity of the blocks resulted in the ascent of

magma, particularly along the block limits. The volcanics belong to the effusive series rhyolite-andesite-basalt, and the intrusive rocks in the granite-granodiorite group.

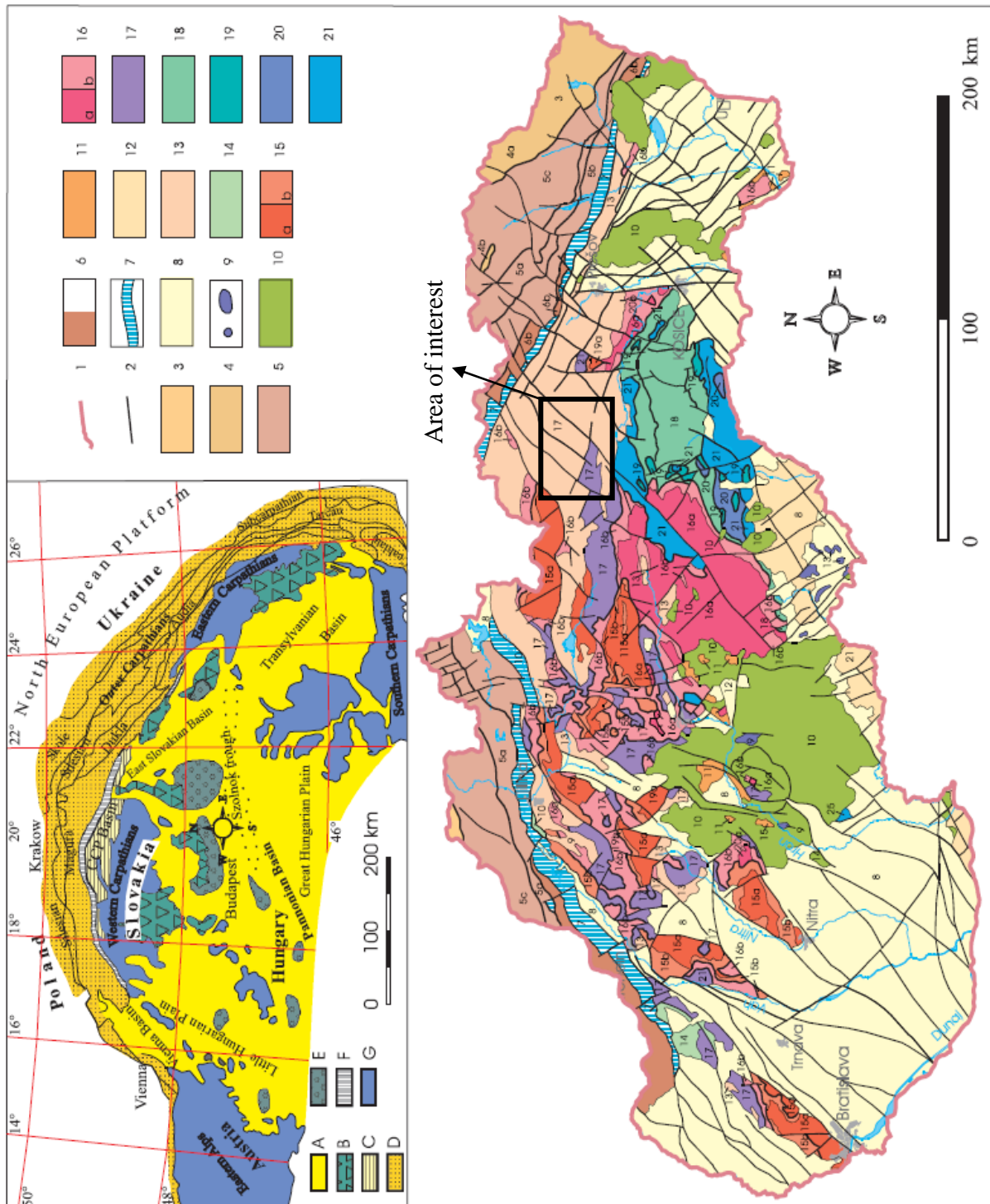


Figure 3.3 - Position of Western Carpathians in the Carpathian Mountain system

Legend: A - Neogene Sedimentary rocks, B - Neogene volcanics, C - Inner Carpathian Paleogene basin, D - Outer Flysch belt, E - Neogene volcanic rocks, F - Pieniny Klippen Belt, G - Inner units of Carpathians 1 - State border, 2 - faults, 3 - Silesian nappe of the Outer Carpathian Flysch belt (OCF belt), 4 - Foremagura units of the OCF belt: 4a - Dukla unit, 4b - Grybow unit, 5 - External Magura nappes of the OCF belt: 5a - Bystrica unit, 5b - Lrynica unit, 5c - Raca unit, 6 - Internal Magura nappes of the OCF belt: 6a - Biele Karpaty unit, 6b - equivalents, 7 - Pieniny Klippen Belt, 8 - Neogene and Quaternary rocks, 9 - Alkali basalts, 10 - Andesitic volcanic rocks (Neogene), 11 - Rhyolitic volcanic rocks (Neogene), 12 - Eocene to early Miocene sediments of

the Hungarian (Buda) basin, 13 - sediments of the Inner Carpathian Paleogene basin, 14 - sediments of the Gosau, Myjava, and Hricov groups, 15 - Tatricum: 15a - crystalline basement, 15b - sedimentary cover, 16 - Veporicum, Zemplinicum: 16a - crystalline basement, 16b - sedimentary cover and Križna nappe, 17 - Hronicum, 18 - Gemericum, 19 - Meliaticum, 20 - Tornaicum, 21 - Silicicum (Janočko et al. 2006)

3.3 Geothermal energy of the Slovak Republic

The geothermal fields in the West Carpathian area are very variable. Their regional character and spatial distribution of geothermic activity are controlled mainly by:

- different deep structure of West Carpathian neotectonic blocks, mainly different from the earth's crust thicknesses and irregular introduction of heat from the mantle,
- course of principal discontinuities and fault lines seated deep in the earth's crust
- spatial distribution of Neogene volcanism,
- distribution of radioactive sources in the upper sections of the earth's crust and
- hydrogeological setting.

The thermal field, at depths up to 3000 m, is controlled to a great extent by hydrogeological conditions. Its local variations result from the surface morphology, shallow, thermally active tectonics, local manifestations of Neogene volcanism and different thermal conductivities. The thermal field at depths greater than 3000 m, however, reflects geothermic activity of deeper morphologic structures of the earth's crust.

From a geothermic point of view, the West Carpathians may be divided into two parts which differ considerably in their geothermic activities and spatial distribution of the earth's heat. Relatively low temperatures and slight surface heat flow are characteristic of the central and northern sections of the Inner Carpathians and the western section of the outer Flysch Belt. In contrast, high subsurface temperatures and high heat flow are typical of the Inner West Carpathian Neogene basins and volcanic mountains. These two geothermally different regions are separated from one to another by zone of intensive horizontal thermal gradients, at the contact between the volcano-sedimentary complex and pre-Neogene units of the West Carpathians. Transient geothermic activity occurs in the Inner Carpathian Paleogene and the eastern section of the Outer Flysch Belt.

The maximum differences in mean surface heat flow density in individual West Carpathian structural-tectonic units reach as much as 55 mW.m^{-2} (between the Eastern Slovakian and Vienna basins). The differences are a result of the different structure and dynamics of basic neotectonic blocks. High heat flows are associated with weakened sections of the earth's crust whereas low heat flow typically occurs in thick crust.

Heat flow density in the West Carpathians is highly variable and regionally falls from the Inner Carpathians towards the outer arc. The highest values between 82 and $121,6 \text{ mW.m}^{-2}$, averaging $110,9 \text{ mW.m}^{-2}$, have been recorded in the Eastern Slovakian Basin. The heat flow density pattern corresponds to the basin's deep structure and spatial distribution of centers of deposition which characterize its geodynamic history. This basin is regarded as a tectonically reworked basin of thermal origin formed by lithospheric extension. Its geothermal activity was further increased by huge volcanism. High heat-flow densities in this area occur in a place where the earth's crust was thinned at the expense of thermally predisposed lithosphere and where more heat ascends from the upper mantle.

Areal distribution of heat-flow density at the Mohorovičič discontinuity (division between the earth's crust and upper mantle) suggests major differences between the deep geological structures of individual tectonic blocks in the West Carpathians. It has turned out that different surface heat –flow densities in individual main structural-tectonic units in the West Carpathians can only be explained by different introduction of heat from the upper mantle. This important source of heat varies from one area to another. Regional difference in heat-flow densities at the core / mantle boundary below the Neogene depressions and Outer Carpathians attains as much as 50 – 55 mW.m⁻². These great differences are of prime importance for the geodynamics of the whole Carpathian system and mobility of the neotectonics of the whole Carpathian system and mobility of its neotectonic blocks. They cause differences of 400 – 500°C at the base of the earth's crust underlying the Eastern Slovakian Basin and Outer Flysch Belt. Such big temperature differences over a relatively small area give rise to intensive horizontal thermal gradients, also at great depths, which in turn may cause thermoelastic stresses, increased seismic activity and tectonic instability of the area concerned (Franko et al. 1995)

3.3.1 Hydrogeothermics

Thermal springs as manifestations of geothermal energy also occur outside active volcanic zones (seismic zones). Areas richly endowed with these waters also include young orogenic belts, such as the Alps and Carpathians (Franko, O. 1990).

The assessment of geothermal activity of a given territory is based on generally valid criteria (Franko, O. 1979; Remšík, A. 1987a):

- geothermic activity equal or higher than world average (heat-flow density $q = 70$ mW.m⁻²; geothermic gradient $Gg = 30$ K.km⁻¹),
- extensive spatial distribution of suitable geothermal aquifers.

The most extensive geothermal aquifers are Triassic dolomite-limestone complexes in the Inner West Carpathians. The above-mentioned springs are associated with these carbonates. Some other significant aquifers are neogene sands and clastics followed by andesites and related pyroclastics. Because of their lithology, the Flysch Belt (alternating sandstones and claystones) and Klippen Belt (limestones and flyschoid sediments) are virtually devoid of geothermal waters.

The main geothermal aquifers are Triassic dolomites and limestones, basal Paleogene conglomerates and breccias of Inner Carpathian nappes and envelope units, as well as Eastern Alpine nappes (Vienna Basin). They are widespread in inter-mountain depressions. The thickness of the aquifers varies from one nappe or envelope unit to another, For example, in the Krížna nappe, where these aquifers have fissure and fissure-karst permeability.

Transmissivity coefficients T in individual tested aquifers vary from 6,7.10⁻⁶ to 2,3. 10⁻² m².s⁻¹ averaging 3,08.10⁻³ m².s⁻¹.

The relationship between geothermal waters and these aquifers is best indicated by natural thermal springs. The springs result from the fold-nappe structure of Mesozoic formations with extensive folds plunging from mountain slopes to substantial depths and from longitudinal and transverse faulting. The catchment areas are connected with transit-accumulation areas through large fold flanks while longitudinal and transverse faults or their

intersections allow the waters to rise onto the surface through a Tertiary and Quaternary cover. This is particularly the case in inter-mountain depressions.

Geothermal waters are also bound to aquifers without natural springs as is the case in the hydrogeothermal structure of the Danube Basin central depression. They can also be hosted by aquifers lacking catchment areas, such as deep geothermal aquifers in pre-Tertiary substratum of lowlands. Prospecting for geothermal waters is focused mainly on aquifers without natural springs. Further significant, although less widely distributed, aquifers are Miocene and Pliocene sands. They can be found in the Danube and South Slovakian basins. In the former basin the sands alternate with clays (Franko, O. et al. 1985) while in the latter the sands form a more or less single layer (Franko, O. et al. 1967). The aquifers have intergranular permeability.

Andesites and related pyroclastics in the Eastern Slovakian Basin are less important geothermal aquifers. These Miocene aquifers contain geothermal waters because they are at substantial depths and are faulted (Rudinec, M. 1989).

In Slovakia three types of geothermal waters have been classified (Franko, O. 1985; Franko, O. et al. 1986, Remšík, A. 1987a):

- high-temperature waters whose surface temperature exceeds 150°C (aquifer temperature exceeds 180°C)
- medium-temperature waters whose surface temperature is 100 – 150°C (aquifer temperature is 130 – 180°C)
- low-temperature waters whose surface temperature is less than 100°C (aquifer temperature is below 130°C).

Low-temperature waters can be tapped by wells 3000-4000 m deep. Medium-temperature waters are widespread in seven areas, the most favorable of which, at depths 3000-4000 m, are the Košice Basin, Beša–Čičarovce structure and central depression. The high temperature waters occur in four areas and, except in the Beša – Čičarovce structure, at depths greater than 4000 m.

Based on chemical composition, three basic genetic types of geothermal waters have been classified (Bodiš D. – Franko, O. 1986):

Geothermal waters with marinogene mineralization, which include:

- connate waters whose mineralization corresponds to the paleo-salinity of their aquifers and which were metamorphosed only in the water-rock system and/or by CO₂ addition,
- connate waters infiltration-, biogenic-, or petrogenic-degraded to various degrees and at different periods,
- highly mineralized geothermal waters formed through halite dissolution by sea water or through local thickening of sea water;
- Geothermal waters with petrogenic mineralization whose T.D.S. does not exceed 5 g.l⁻¹ exemplified by meteoric waters of fairly deep or deep circulation;
- Geothermal waters of mixed origin and complex chemistry.

3.3.2 Geothermal resources and potential

In Slovakia geothermal resources were documented by wells in 26 prospective areas. In total, 117 geothermal wells are registered in Slovakia, 5 of them were negative. The amount of app. 1690 l/s of geothermal water were documented by geothermal wells. The temperature on the well head reaches 18 – 129°C (Figure 3.4).

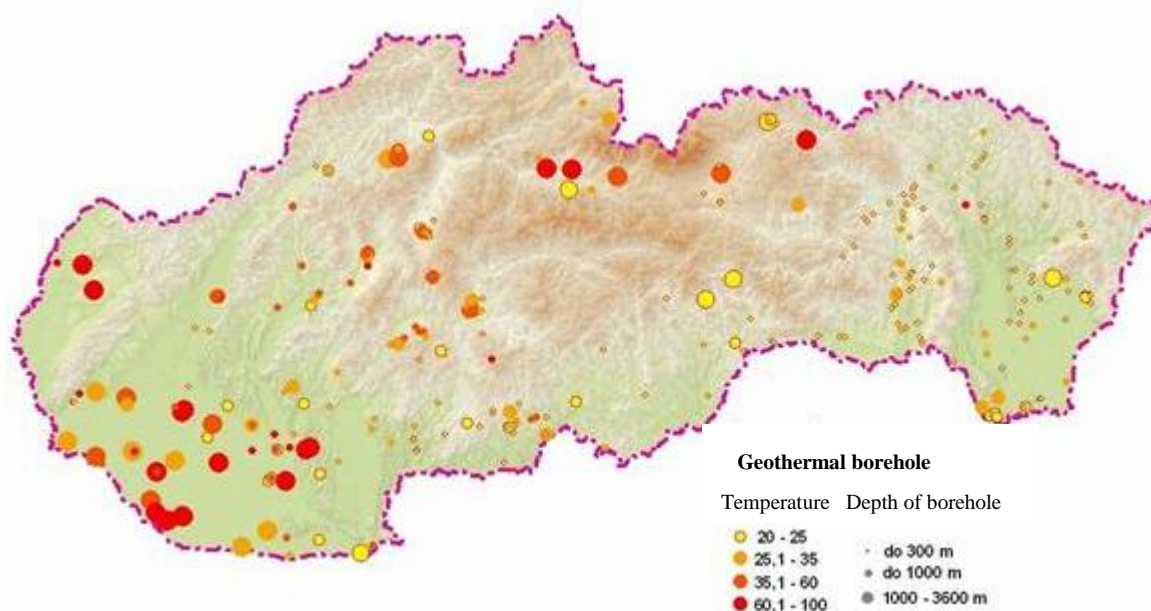


Figure 3.4 - Geothermal boreholes and their temperatures characteristics in Slovakia

Geothermal waters are largely bound to Triassic dolomites and limestones of the Krížna and Choc nappes, and less frequently to Neogene sands, sandstones, conglomerates, andesites and related pyroclastics.

Geothermal waters were reached by wells 92 – 3616 m deep. Free outflow of the wells ranged from 0.1 up to 100 l/s, Na-HCO₃-Cl, Ca-Mg-HCO₃ and Na-Cl chemical type of water with the T.D.S. value of 0.4 – 90.0 g/l prevails (Fendek and Fendekova, 2005).

The history of utilization of geothermal energy in the Slovak Republic is mainly the history of utilization of the thermal springs. Many archeological finds discovered at the site and the surrounding thermal springs indicate that man was attracted to settle in these friendly areas. The first utilization of geothermal waters for energetic purposes is connected with space heating in spas and can be dated to the year 1958. Three systems of direct utilization of geothermal waters were tested (Uhliarik, 1977):

- direct space heating
- utilization of heat pumps
- space-heating and heating of hot service water through heat exchangers

These first steps created conditions for more extensive research on the field of geothermal energy utilization for direct use in the Slovak Republic.

Geothermal resources in Slovakia are recently used in agricultural farms, for space heating, fish farming and recreational purposes (swimming pools). In 12 agricultural farms

geothermal water is used for greenhouse and soil heating. This allows the early production of vegetables and flowers. The total area covered by greenhouses is about 25,86 hectares. The number of locations where geothermal water is used for space heating has increased significantly from 6 in 1999 to 13 in 2004. This type of heating is used to heat hotels, blocks of flats, a hospital, and a sport hall. Eight geothermal heat pump installations are reported with a total installed capacity of 1,4 MWt and producing 12,1 TJ/yr of heat. A total of 32 individual projects using thermal energy are reported for the Slovak Republic, with a major district-heating project being proposed for the eastern city of Košice. The individual direct-heat uses are: district heating (31,6 MWt and 576,9 TJ/yr); greenhouse heating (31,8 MWt and 502,3 TJ/yr); fish farming (4,6 MWt and 72,4 TJ/yr); and bathing and swimming (118,3 MWt and 1,870.3 TJ/yr); for a total, including heat pumps, of 187,7 MWt and 3,034.0 TJ/yr (Lund 2005). Total thermal installed capacity in MWt: 187,7, direct use in TJ/year: 3,034, direct use in GWh/year: 842,8 , capacity factor: 0,51. Geothermal power plants have not been installed in Slovakia in the meantime.

Based on existing research the most prospective spots for geothermal energy usage would be the Neogene basins and depressions: Vienna, Danube and East-Slovakian Basins, south-Slovakian depressions and intermountain depressions in the Western Carpathians (Figure 3.5). Eastern Slovakia is among the areas with the most geothermal potential in Central Europe. This is evident by both the thermal regime of the region, related to the mantle upheaval in the Pannonian domain, as well as to geological structure of the region; the Mesozoic carbonate complexes overlain by thick shale-to-sand sedimentary cover are the best water reservoirs in the area.

As was mentioned before, geothermal resources can be classified, according to their temperature, into three types:

- **Low temperature sources** - Areas which contain low temperature sources (20 – 100°C) in Slovakia are: Komarno high block, Danube basin central depression, Bánovce basin, Topolčany embayment, Trnava embayment, Piešťany embayment, Central Slovakian Neogene volcanics (NW part), Central Slovakian Neogene volcanics (SE part), Upper Nitra Basin, Levoča Basin (W and S parts, Horne Strhare – Trenc graben, Rimava Basin, Trenčín Basin, Ilava Basin, Levice marginal block, Komarno marginal block, Vienna Basin, Komjatice depression, Levoča basin (N part), Humenné ridge, Košice Basin, Beša-Čičarovce structure, Dubník depression (Fig.3). All determined areas have favorable conditions for low temperature geothermal waters occurrence at depths of 150 – 3500 m.
- **Medium temperature sources** - Areas with medium temperature sources (100 – 150°C) are Beša-Čičarovce structure, Košice Basin, Danube Basin central depression, Humenné ridge, Levoča Basin (N part), Žilina Basin, Trnava embayment, Piešťany embayment, Central Slovakian Neogene volcanics (NW parts), Vienna Basin. Favorable conditions for medium temperature geothermal waters occurrence are at depths of 2500-4500 m.
- **High temperature sources** - Areas with water temperatures higher than 150°C are: Beša-Čičarovce structure, central Slovakian Neogene volcanics (NW part) and in Vienna Basin at the depth of 3500 – 5500 m (Fendek and Fendekova, 2005).

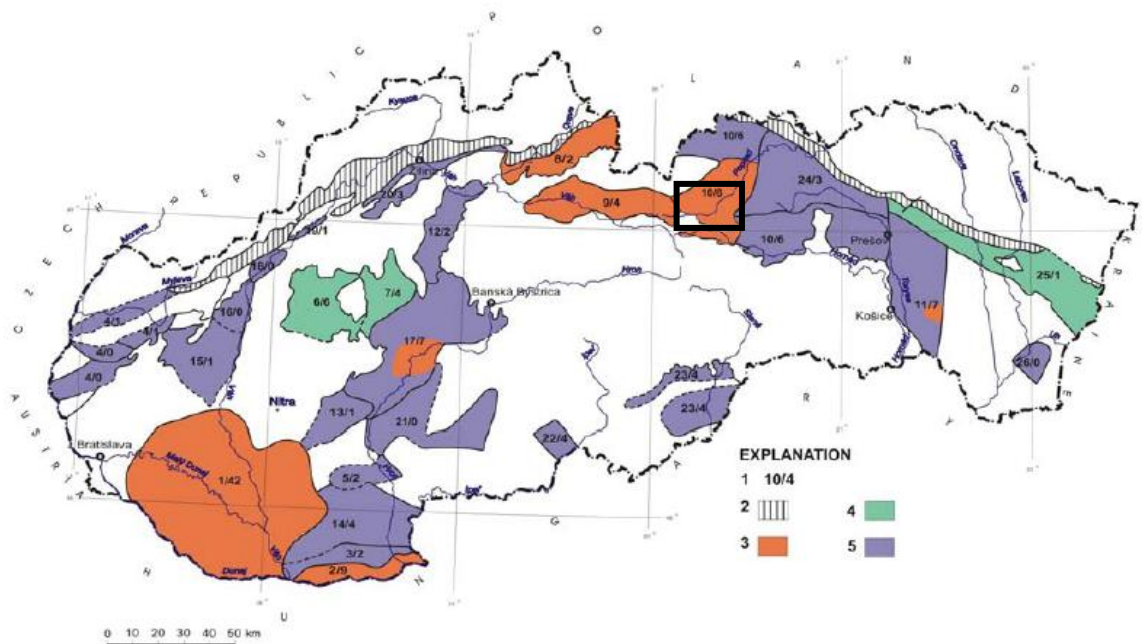


Figure 3.5 - Potential geothermal areas and structures of the Slovakia

Legend: 1 - serial number of the prospective area or structure/number of drilled geothermal wells, 2 – Klippen Belt, 3- prospective areas with geothermal water verified by geothermal wells, 4 – prospective areas geologically assessed for the purpose of prospecting and exploration of geothermal waters, 5 prospective area with assumed occurrence of geothermal waters (based on general knowledge of geological conditions).

List of prospective areas: 1-Danube Basin central depression, 2-Komarno high block, 3-Komarno marginal block, 4-Vienna Basin, 5-Levice marginal block, 6-Banovce Basin and Topolcany embayment, 7-Upper Nitra Basin, 8-Skorusina Basin, 9-Liptov basin, 10-Levoca Basin (W and S parts), 11-Košice Basin, 12-Turiec Basin, 13-Komjatice depression, 14-Dubník depression, 15-Trnava embayment, 16-Piestany embayment, 17-central Slovakian neogene volcanics (NW part), 18-Trencin Basin, 19-Ilava Basin, 20-Zilina Basin, 21-Central Slovakian Neogene volcanics (SE part), 22-Horne Strhare – Trenc graben, 23-Rimava Basin, 24-Levoca basin (N part), 25-Humenne ridge, 26-Besa – Čičarovce structure (Fendek and Fendekova, 2005)

3.3.3 Košice Basin

Ďurkov area (Vranovská et al., 1999) is located in the south-eastern part of the Košice Basin, bordered in the East by neovolcanic rocks of Slanske vrchy Mts. Three geothermal wells GDT-1, 2 and 3 were drilled, cased and tested throughout 1998 and the first half of 1999. Their vertical depths were 2252 - 3210 m.

A reservoir of geothermal waters is located at a depth of 2000 – 3500 m. The most important inflow zones were identified on the top of the Triassic dolomites of the Veporicum unit, having fissure and fissure-karst permeability. Free outflow of the wells reached 50 – 65 l/s during performed short-term hydrodynamic tests. The temperature on wellheads varied from 123 up to 129°C. Measured temperature in the bearing at the depth of the 3000 m reached 143°C. Average heat flow density value was estimated at 94.4 mW/m².

The Ďurkov area is typical, with its complicated system of water – water vapor – solid phase. The value of TDS varies in the range of 25 – 32 g/l. Chemical composition is of distinct Na-Cl type with the low presence of Na-HCO₃ component.

The available amount of geothermal energy was estimated to be 92.63 MWt based on the results of mathematical modeling.

3.3.4 Poprad Basin

Geothermal water aquifers (Daniel et al., 1998) are built by Triassic carbonates of the Choc and Križna nappes located under the Tertiary strata. The thickness of the Choc nappe sequences reaches 200 – 1100 m in the central part of the Poprad basin. Unusually thick – 1200 to 2000 m - are Choc nappe sequences to the east and south-east of the Vrbov fault at the point of contact between the basin and the Levoča Mts.

The average value of the temperature gradient reaches 32.6 – 34.5°C/km and the average value of the heat flow density was estimated to be 67mW/m². Temperatures on the top of the Pre-Paleogene basement reach 50 – 85°C.

The value of the specific thermal-energy potential varies from 0.023 to 10.007 GJ/m². Geothermal water is of Ca- Mg-HCO₃ SO₄ chemical type. The value of TDS ranging from 2.9 to 4.1 g/l. CO₂ prevails in gas composition.

The total amount of natural geothermal waters in Poprad basin was estimated to be 216.2 l/s. This amount represents 33.884 MWt of thermal energy.

3.3.5 Liptov Basin

The pre-Paleogene basement of the Liptov basin (Remšík et al., 1998) is built by Choc and Križna nappe sequences. It can be divided into some depressions and elevations according to its morphological structure. Paleogene sediments are the most thick in Liptovska Mara depression – up to 2200 – 2300 m.

The thermal field of the basin is very variable. It is disturbed by convective heat transport in the Kokava depression and in the Besenova elevation. Temperatures at the depth of 1000 m range from 29 to 46°C, and at the depth of 2000 m they range from 46 to 76°C. The average value of the geothermic gradient at depths of 2000 – 2500 m reaches 17.8 – 31,9°C/km for Paleogene and Mesozoic rocks. Heat flow density varies from 52,0 do 71,7 mW/m². According to values of the geothermic gradient and heat flow, Liptov basin can be divided into two geothermically different areas – the western, with higher geothermic activities, and the eastern, which has distinctly lower geothermic activities. Hydrogeothermal structures of the Choc nappe (Ivachnova depression, depression of the Liptovska Mara, Demanova depression, Vavrisovo-Kokava depression and Biely Vah depression) are typical for the occurrence of geothermal waters at temperatures of 20 – 90°C at depths of 500 – 3000 m. Chemical composition represents Ca-Mg-HCO₃ but also Ca Na-Mg-HCO₃-SO₄ type with the amount of TDS ranging from 0.35 to 5.0 g/l. CO₂ is the dominant gas in all morphological structures of the Liptov basin. All these structures can be characterized as semi-open hydrogeothermal structures.

Hydrogeothermal structures of the Križna nappe (Kokava depression, Besenova elevation, structures in the area of the Liptovska Mara depression, and Ivachnova depression) bear geothermal waters at depths of 900 – 3500 m with water temperatures of 30 – 100°C. Chemical composition is represented by Ca-Mg-HCO₃-SO₄, and Ca-Mg-SO₄-HCO₃ type of water, and the amount of TDS ranges from 3 to 5 g/l. Structures can be characterized as open or semi-open hydrogeothermal structures.

The total natural amount of geothermal waters was estimated to be 248 l/s, which represents the total amount of thermal energy of 34.589 MWt. This estimate is in quite good accord with the results of the geothermic balance (30.103 MWt). However, the geothermic balance seems to be underestimated because it does not take into account the infiltration area of the Earth's heat (Fendek and Fendekova, 2005).

3.3.6 Skorusina depression

The Skorusina depression is built by Central-Carpathian Paleogene sequences with thicknesses of 200 to 2600 m, underlain by Choc and Križna nappes, an envelope unit and a crystalline core. Geothermal waters are bound to Triassic dolomites of the Choc and Križna nappes. Their thickness ranges from 300 to 600 m, with the maximal depth of -3600 m a. s. l. in the north-eastern part of the depression. Depending on the depth of aquifer occurrence, the water temperature ranges from 25 to 125°C. Four geothermal structures were identified in the Skorusina depression (Bajo et al., 2004). The largest and most prospective is the Zabiedovo structure, built by Križna nappe sequences, which has the shape of a syncline with a depth ranging from -1400 up to 1600 m a.s.l. Temperatures on the top of carbonates reach values of 60 – 120°C. The adjacent structure is called the Dolny Kubin structure, creating an elevation located in the central part of the Skorusina basin. Carbonatic aquifers in its south-western part are developed at depths of 0 to – 800 m a.s.l., and temperatures increase from 30 to 45°C. In the north-eastern part, carbonates lay at depths of -600 up to 1200 m a.s.l. and water temperatures vary between 40 and 55°C. The third structure, named Velicne structure, is located roughly between Parnica and Oravska Poruba villages. Carbonates building the structure are developed at depths of -400 to -1800 m a.s.l. and temperatures vary from 35 to 70°C. The structure of Male Borove is built by Triassic carbonates of the Choc nappe. Carbonates can be found at depths of +800 up to -600 m a.s.l. and the temperature at their bottom is 10 – 50°C.

Value of the free outflow, documented by long-term hydrodynamic test performed on OZ-2 Oravice geothermal well, reached 86.8 l/s with a water temperature of 52.5°C on the well head. The exploitable amount was estimated using the mathematical model of 65 l/s by the maximum depression of 0.331 MPa. Natural resources of the geothermal energy represent 24.0 MWt, from which 4.0 MWt are bound to the Choc nappe, representing 48 l/s of geothermal waters with the temperature of 28 – 35°C on the well head. The remaining 20 MWt are bound to Križna nappe, representing 118 l/s of geothermal waters with temperatures of 43 – 60°C on the well head.

3.3.7 Central depression of the Danube basin – Galanta area

The central depression of the Danube basin – Galanta area (Bondarenkova et al., 1998) is represented by Galanta depression and its closest surroundings. It stretches to Senec and Zlate Klasy surroundings in the West, and down to the connection line Zlate Klasy – Horne Myto – Kralov Brod in the South. The eastern border is delineated by villages Ziharec, Selice, Trnovec and Dlha nad Vahom and the northern border continues from Vahovce through Dolna Streda, Majcichov and Cataj up to Senec.

Two depth intervals 1200 – 1600 and 1600 – 2100 m differ by qualitative parameters of geothermal waters bearing in aquifers. The first level consists of sequences of the Pontian up to the upper Pannonian sediments. They are built of sands, partially by clayey sands. The total thickness of the sediments is 400 m. Layers decline in the southern to southwestern direction. The total area of aquifers is 322 km². The second group of aquifers consists of sequences of the lower Pontian up to the upper most Sarmatian ages. Aquifers are built by fine to middle grained sands, locally by weakly cemented sandstone. The total thickness of the sequence reaches up to 500 m.

Petrogenic geothermal waters occur in the area. They are of Na-HCO₃ type with the value of TDS up to 1g/l, or Na-Cl type with TDS up to 10 g/l (Fendek and Fendekova, 2005).

The Galanta area can be characterized as an area with high geothermic activity. The average value of the temperature at a depth of 1000 m is 50.3°C, at a depth of 1500 m it reaches 69.6°C, at a depth of 2000 m up to 88.5°C and at the depth of 2500 m up to 106.0°C. The average value of the geothermic gradient was estimated to be 40°C/km, and the main part of the area can be characterized by the heat flow density value of 78 MW/m². The value of the heat flow density varies in the interval of 71,4 – 81,6 mW/m² with an average value of 76,8 mW/m².

The value of the specific thermal-energy potential of the natural amount of groundwater at a depth of 1200 m varies, ranging from 0.420 to 4.288 GJ/m² with a mean value of 2.074 GJ/m². At a depth of 1600 m the value ranges in the interval 0.747 – 3.809 GJ/m² with an average value of 1.161 GJ/m².

The total exploitable amount of geothermal water was estimated using a mathematical model. The total withdrawal of geothermal water (taking into account also existing geothermal wells) has the value of 176.0 l/s which represents 39.77 MWt of thermal energy. Results of the model and performed geothermic balance estimation were in agreement.

3.3.8 Ziar basin

A geological-geophysical interpretation of the latest results gained by geothermal investigation in the Ziar basin (Remšík et al., 2000) was used for compilation of a new morphological-tectonic and geological scheme of the Pre- Tertiary basement. A map of the surface and thicknesses of the Choc nappe carbonates, Velky Bok series and Krížna nappe was compiled as well. Pre-Tertiary basement is built by Choc nappe sequences. In the south-eastern and northwestern parts Triassic carbonates prevail, in the central part Ipolica series (shales, sandstone) is a main building element. In the deeper part, under the Choc nappe, Mesozoic sequences (Triassic-Cretaceous) of the Velky Bok series and Krížna nappe are developed. Heat flow density ranges in the interval between 80–100 mW/m², with a characteristic value of 95 mW/m². A large (central) part of the Pre-Tertiary basement of the basin can be characterized by temperatures of 100°C and higher at depths of -2100 m a.s.l. and deeper. The highest temperatures are in the central part of the basin in a partial depression between Lovca and Ziar nad Hronom where at depths from -3400 to -3500 m a.s.l. the temperature is about 130°C.

The upper hydrogeothermal structures are built by Triassic carbonates of the Choc nappe. It is supposed that they contain geothermal waters with reservoir temperatures of 20–150°C at depths from 200 up to 4100 m a.s.l. Triassic carbonates of the Velky Bok series or Krížna nappe built the lower hydrogeothermal structures where, at depths from 600 up to -4700 m a.s.l., geothermal water with reservoir temperatures from 30 up to 160°C could be reached. The chemical composition of geothermal water in the Ziar basin is probably of Ca-Mg-SO₄, and Ca-Mg-SO₄- HCO₃ type with the amount of TDS 2 – 4 g/l. CO₂ or H₂S gases could be present as well. The specific thermal-energy potential of the natural geothermal water for Triassic carbonates of the Choc nappe was estimated to be 0.091 – 6.307 GJ/m², with an average value of 3.251 GJ/m². For Triassic carbonates of the Velky Bok series and Krížna nappe it was estimated to be 0.329 – 3.658 GJ/m² with an average value of 2.357 GJ/m².

The amount of natural geothermal water with a temperature of 60°C (Sklene Teplice structure) and 110°C (Ziar structure) represents 65.3 l/s, which is equivalent to 22.296 MWt of prognostic geothermal energy from the natural resources (Fendek and Fendekova, 2005).

Table 1 – Summary of geothermal areas in Slovakia

| Locality | Aquifers | Depth of perforated intervals [m] | Discharge [l/s] | Water temp. [°C] | Heat power [MWt] | T.D.S. [g/l] | Chemical type of waters |
|-----------------------------|---|-----------------------------------|-----------------|------------------|------------------|--------------|--|
| Komarno block | Triassic dolomites, limestones, Neogene sandstones, conglomerates | 77-1761 | 5,5-70 | 20 -56 | 0,12-7,33 | 0,7-90 | Ca-Mg-HCO ₃ -SO ₄ Na-Cl , mixed type |
| Central depression | neogene sands, sandstones, conglomerates | 276-2487 | 0,3-25 | 23-91,5 | 0,13-6,80 | 0,5-8,3 | Na-HCO ₃ , Na-HCO ₃ -Cl |
| Dubník Depression | Badenian sandstones, conglomerates | 745-1905 | 1,5-15 | 52-75 | 0,25-2,40 | 10-30 | Na-Cl, Na-SO ₄ -Cl |
| Levice Block | Badenian clastics, Triassic dolomites | 995-1740 | 28-53 | 69 - 80 | 6,3-14,42 | 19,2-19,6 | Na-Cl |
| Komjatice depression | pannonian sands, sandstones | 1509-1700 | 12 | 78 | 2,5 | 20,1 | Na-Ca-Cl-HCO ₃ |
| Bánovce basin | Triassic dolomites | 1512-2025 | 2,0-17 | 40-55 | 0,33-1,78 | 0,7-6,0 | Na-HCO ₃ -Cl-SO ₄ , Na-Cl |
| Upper Nitra basin | Triassic limestones, dolomites | 1677-1851 | 26,9 | 66 | 4,85 | 0,93 | Ca-Na-Mg-HCO ₃ -SO ₄ |
| Liptov basin | Triassic dolomites, limestones | 1315-286 | 6-31 | 32-62 | 0,43-5,89 | 0,5-4,8 | Ca-Mg-HCO ₃ -SO ₄ , Ca-Mg-HCO ₃ |
| Poprad basin | Triassic dolomites | 835-1983 | 20-33 | 46- 59 | 2,58-6,08 | 3,0-4,0 | Ca-Mg-HCO ₃ -SO ₄ |
| Skorusina Mts. | Triassic dolomites | 950-1565 | 100 | 54 | 16,3 | 1,2 | Ca-Mg-HCO ₃ -SO ₄ |
| Viena basin | Triassic dolomites, limestones | 1242-2570 | 12-25 | 73- 78 | 2,91-6,59 | 6,8-10,9 | Na-Ca-Cl-SO ₄ , Ca-Mg-HCO ₃ |

4 CHARACTERISTICS OF STUDY AREA: POPRAD BASIN

4.1 Geomorphologic classification

The Subatric basin is a geomorphological unit situated in northern Slovakia. It is part of province Western Carpathians, sub-province Inner Western Carpathians (Figure 4.1) and Fatra-Tatric area. The Subatric basin is one of the high laid basins in Slovakia.

It is bound on all sides to geomorphological units. In the North they are the Choč mountains, Tatra mountains and Spiš Magura, in the East the Levoča mountains, in the Southeast is the Hornad depression, in the South are the Kozie chrby and Nízke Tatry mountains and in the West the Veľká Fatra mountains.

The Subatric basin is divided into two units: the Liptov basin in the West and the Poprad basin in the East. The study area is situated mainly in the Poprad basin, more to the southeast near the Hornad depression (Figure 4.1)

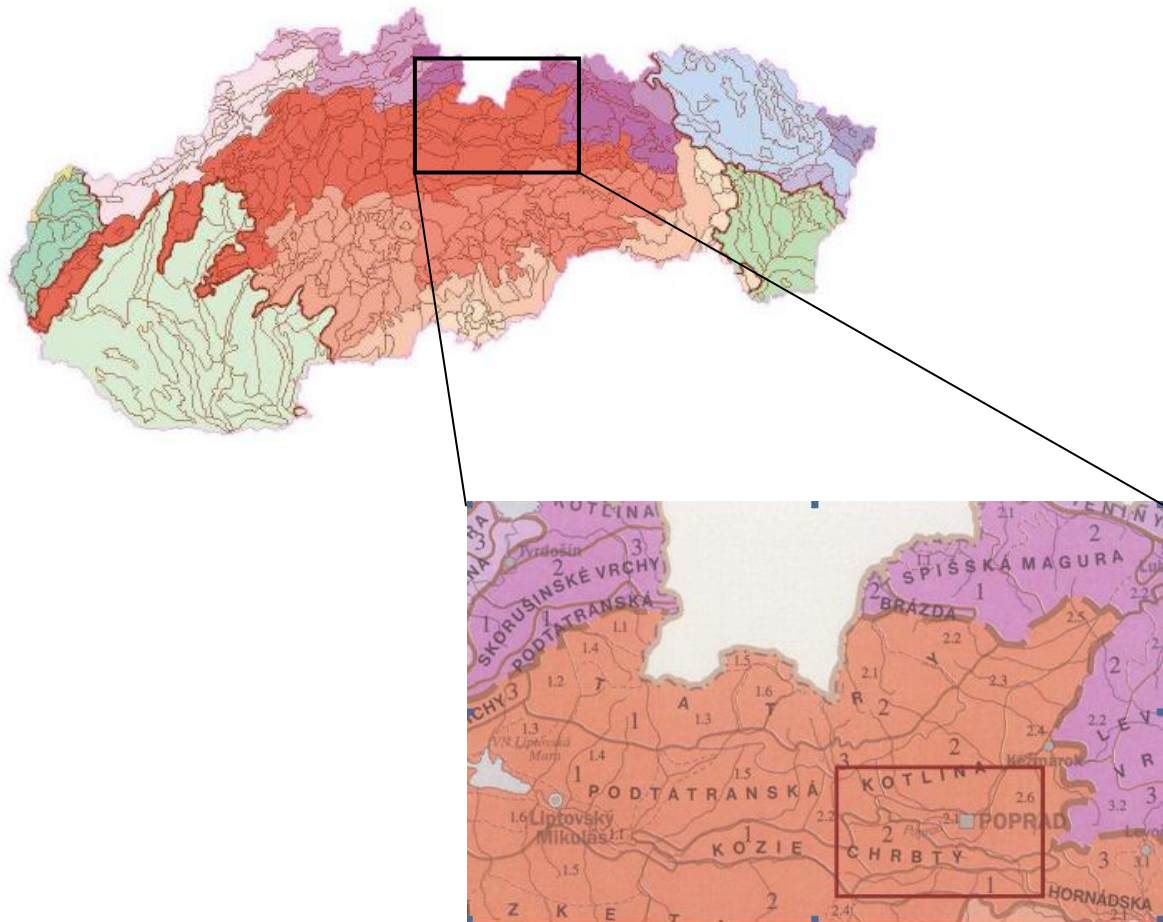


Figure 4.1 - Location of study area in geomorphological units in Slovakia (Mazúr and Lukniš, 1986)

4.2 Climatic conditions

From a climatic point of view, the Poprad basin area, the west and central part of the Hornád basin, belongs to a temperature zone with western air flow. It is a mildly warm area, mildly humid with cold winters characteristic of valleys.

In terms of climatic-geographic types, this area has a mildly warm to mildly cold basin climate. Annual average air temperature is $6,4^{\circ}\text{C}$. Global sun radiation is $104 - 106 \text{ kcal.m}^{-2}$. In the summer it is typically $41 - 42 \text{ kcal.m}^{-2}$ and in winter it is usually around 10 kcal.m^{-2} . Relative sun outshine is $44 - 46 \%$.

The number of summer days with a max. temperature $> 20^{\circ}\text{C}$ is $20-40$. The area has around $130 - 136$ frost free days. The number of days in which the average temperature is under 0°C is roughly $98 - 115$. Heating season starting on 15.9. and is $238 - 250$ days long. The warmest month is July and the coldest is January. Mountain influences in annual temperatures mean that autumn is warmer than spring. Daily temperature (the difference between maximum and minimum temperature) is highest in the end of the summer and reaches 16°C ; in December it drops to 7°C .

4.3 Geologic characteristics

Poprad basin is, from a geological standpoint, Inner Carpathian Paleogene (Figure 4.2). In the North the basin is Inner Carpathian Paleogene, with sharp bounded elevations of the West Tatra Mountains, which are created by crystalline units (Kryštalinikum). In the South it is Inner Carpathian Paleogene, bounded by the Low Tatra Mountains, which have similar sharp boundaries like those in the North.

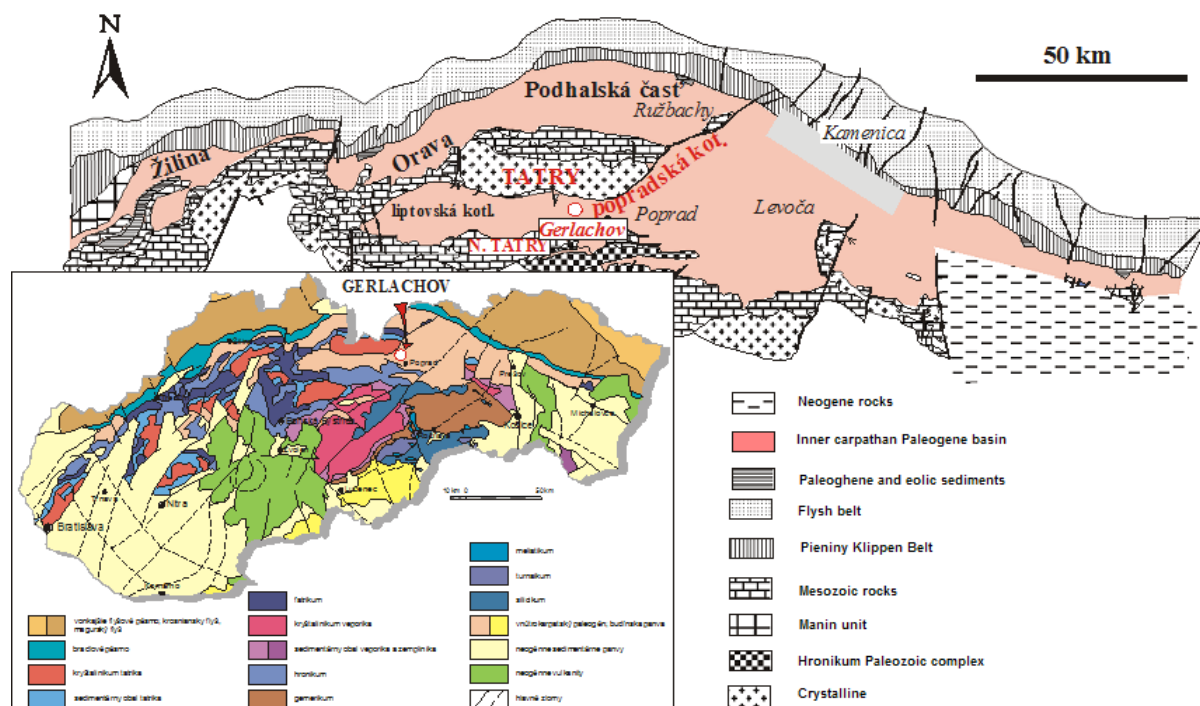


Figure 4.2 – Geologic position of the Inner Carpathian Paleogene basin, location of Poprad basin and Gerlachov area

Stratigraphic units in the studied area are: upper unit, which is for geothermal exploitation, with a negligible layer of Post-Tertiary sediments. Under this layer is a thick unit created by

Paleogene sediments made up of claystones and sandstones. Under this unit are Mesozoic sediments which are created by carbonate rocks,—in this unit carbonates are geothermal deposits. The Mesozoic unit is divided into 3 base units in this area: Choč nappe, Križna nappe and the envelope Mesozoic. All units have complicated tectonic structure, which influences the property of geothermal deposits. The undermost unit is basement, crystalline rock.

In this work two 3 D reservoir models will be designed. One is a model of Poprad basin and the northern part of Hornad Basin, and the second is a detailed model from Gerlachov area, which is situated in Poprad basin (Figure 4.4) The geologic composition of Gerlachov is showed in (Figure 4.3).The highest unit is the Post-Tertiary sediments unit, which is not important for this research. Under this unit is thick Paleogene sedimentary filling, made up of claystones and sandstones rocks. Under this unit is a layer of Mesozoic sediments. Those are built mainly by carbonate rocks, where a geothermal deposit is expected. The Mesozoic unit is divided into three subunits, which make up the study area: Choc nappe, Križna nappe and Mesozoic envelope. The lowest unit is Crystalline basement. All units in the studied area are described in the next chapter.

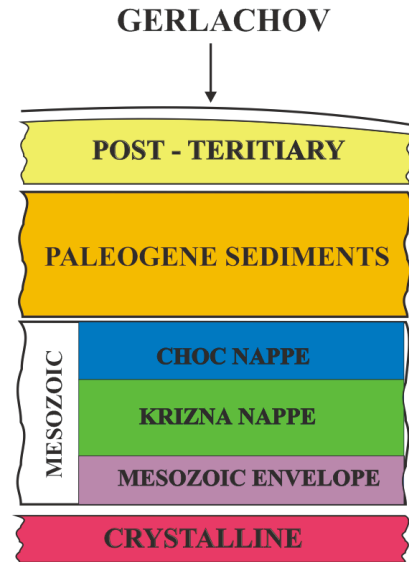


Figure 4.3 - Geologic composition of Gerlachov area

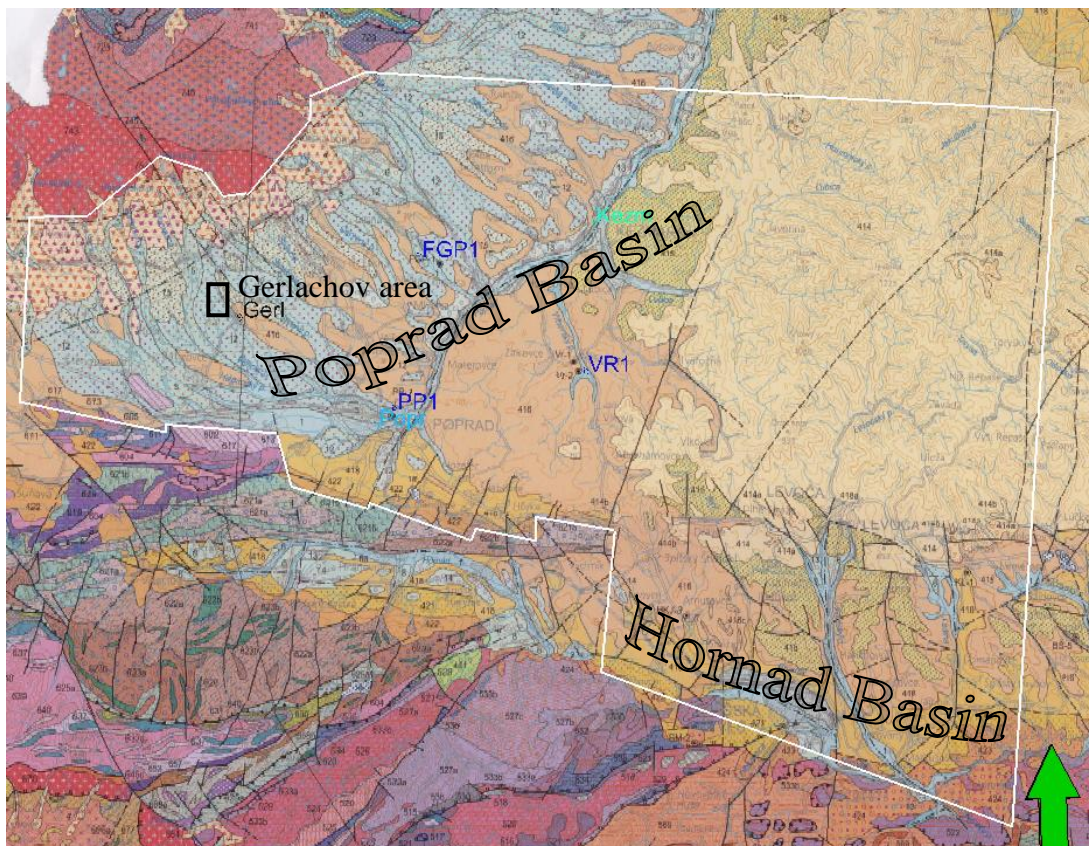


Figure 4.4 - Geological map of study area: Poprad basin, North part of Hornad basin and Gerlachov area (Polák et.al.,2008)

4.3.1 Geologic composition

In the area of the Poprad Basin, rocks of following geological units and formations are found:

- Post-Tertiary
- Paleogene
- Choc nappe of Hronicum
- Younger Paleozoic of Hronicum
- Krížna nappe
- Mesozoic of Tatricum envelope
- Crystalline of Tatricum

In the area of Hornad Basin, rocks of the following geological units were found and assumed:

- Post-Tertiary
- Paleogene
- Vernar nappe of Silicum
- Muran nappe of Silicum
- Younger Paleozoic of Gemericum
- Choc nappe of Hronicum

Post-Tertiary

Sediments of the Post-Tertiary unit overlap the Paleogene basin's fill as well as older units on the border of the basin.

The biggest representation is seen in moraine. They are augmented from the Tatra foothills to the Poprad Basin in the form of flat glaci-fluvial cone.

Glacial moraines are gravel-boulder sediments with thicknesses of 63–92 m. Glaci-fluvial cones with thicknesses up to 20 m are represented by thick layers of boulders and gravel. The composition of the sediments is mainly granitoids of Tatricum. The sediments are old to young Pleistocene, less than Holocene age. The rest of the Poprad Basin, the Post-Tertiary unit is represented mainly by deluvial, loam waste Paleogene sub-base. This is shown in Figure 4.5. The Pre-Tertiary unit of Hornad Basin has the same evolution as that of Poprad Basin.

Paleogene

The Paleogene rock sequences of Poprad Basin are quite large, and they overlap geothermal aquifers. Paleogene (upper Lutet–lower Oligocene) in both basins is built by Borovske, Hutianske and Zuberecke groups of strata.

In Borovske group of strata, on the base of Paleogene we can see the composition of rocks and how they were deposited. On Choc Nappe, mesozoicum is a group of strata created by carbonates breccias, conglomerates, sandstones and in Western part of Poprad Basin, limestones. In this case, because of the permeability of cavern faults, groups of strata can indicate a geothermal aquifer. In the upper part of the strata are sandstones and claystones giving way to small grainy conglomerates. Thicknesses of Borovske strata in Poprad Basin

are from 5 m (HV-3) to 14,5 m (Vr1). In the Southern part of basin are thicknesses of 10 – 50 m. In Hornad Basin, thicknesses from 29 (HKJ-4) to 114 m (HKJ-2) were documented.

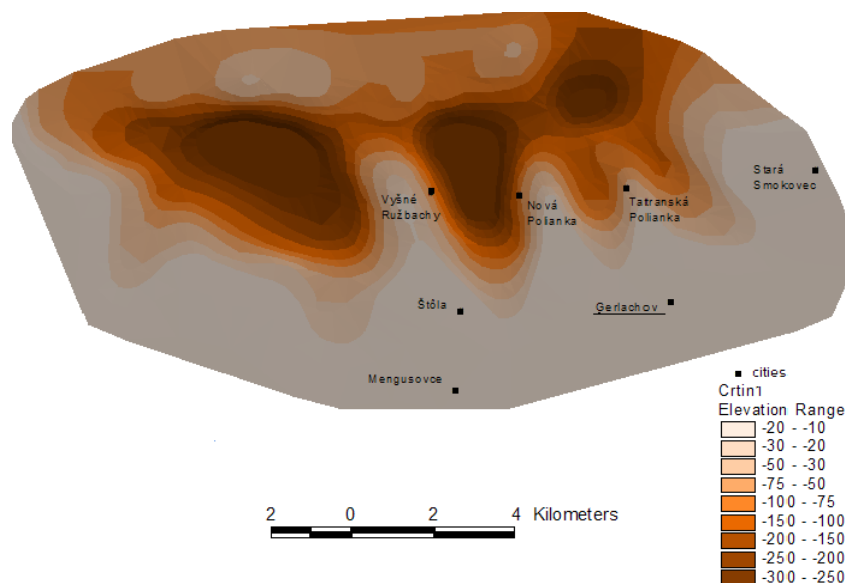


Figure 4.5 - Post – Tertiary thicknesses around Gerlachov

Hutianske group of strata have similar lithologic composition in both basins. In this strata are claystones and siltstones of gray and dark gray colors. In some places sandstones can be found. Thin layers of Mn-ores are evolved in the southern part of Poprad Basin. Thicknesses of strata between the basins are different. The following thicknesses can be found in boreholes in Poprad: FGP-1– 525 m and Vr-2 – 773 m, PP- 1 - 423 m. Thicknesses of Hutianske strata in Hornad Basin are smaller: borehole BS-3 -67 m, HKJ-3 -186 m and in DH-1 -490 m.

Zuberecke group of strata is characterised by alternating gray and dark gray claystones, siltstones and sandstones. Sandstones are fine-grained to coarse-grained. Usually muscovite is found in sandstones, and micro-layers of coal are locally found in claystones and siltstones. In Poprad Basin the largest thicknesses are found in boreholes Vr-2 –708 m and FGP-1 –880 m. In Hornad Basin, smaller thicknesses are found: borehole DH-1 –260 m, BS-3 –187 m, HKJ-3 –156 m.

Hutianske and Zuberecke stratas, because of their composition and thicknesses, are creating ideal isolators for aquifer horizons of geothermal waters – the rock sequences of Choc and Križna nappe, which lie in the background of these stratas.

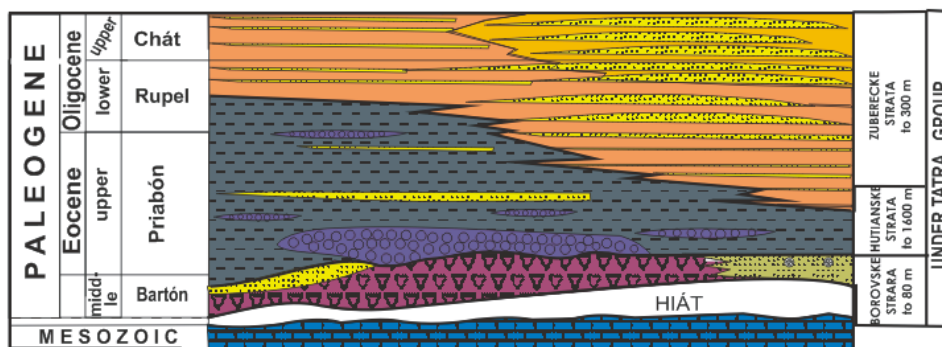


Figure 4.6 - Lithostratigraphic column of Paleogene sediments in interested area

Choc nappe

In the studied area, the rock sequences of Choc nappe contain the main geothermal aquifer. Nappe with rock filling are known from surface data of the middle and western parts of the Kozie Mts. and from boreholes in Poprad Basin. Carbonate rocks of nappe are only found in the northern part of Hornad Basin.

In Kozie chrby, on the border of Poprad Basin, the main rocks of the nappe are gray colored dolomites. Dolomites are fine-grained sludges, and are rarely crystalline. In tectonics zones dolomite breccias are common. Foliation and lamine beddings are common in upper Triassic dark dolomites, while at another site they are rare in middle Triassic brighter dolomites. Layer inclination is, on average, 20–50° to the north, north-east. They belong to the main dolomite (karn – norik) and dolomite of Ciernovazska facial zone (anis-norik). Thicknesses are 400–500 m, and in some places up to 1000 m. Other important stratigraphic layers have gutenstein layers (limestones with dolomites parts, breccias thickness to 250 m). Less important layers have reiflings limestones and lunske layers (shales and sandstones).

For the characterization of Choc nappe filling, 4 boreholes are important: FGP-1, Vr-2, Vr-1 and PP-1. Choc nappe rocks which were documented in the mentioned boreholes include:

Table 2 - Choc nappe borehole descriptions

Borehole FGP-1 Stara Lesna

| Depth (m) | Thickness(m) | Rocks type, geologic age |
|------------------|---------------------|--|
| 1440-1730 | 290 | Main Dolomite – norik |
| 1730-1820 | 90 | Reiflings limestones – ladin – spodný karn |
| 1820-1865 | 45 | Ramsau dolomites – upper anis – ladin |
| Together | 425 | |

Borehole Vr-2 Vrbov

| Depth (m) | Thickness(m) | Rocks type, geologic age |
|------------------|---------------------|--|
| 1488-1951 | 463 | Compact dolomite, light-gray to brown-gray, flawed by tectonics, calcite within faults |

Borehole Vr-1 Vrbov

| Depth (m) | Thickness(m) | Rocks type, geologic age |
|------------------|---------------------|--|
| 1495-1640 | 145 | Crystalline dolomite, strong fissured, karsified – upper trias |
| 1640-1725 | 85 | Black claystones with thin carbonate layers, Lunske layers, Karn age |
| 1725-1742 | 17 | Crystalline dolomite – middle trias |
| Together | 247 | |

Borehole PP-1 Poprad

| Depth (m) | Thickness(m) | Rocks type, geologic age |
|------------------|---------------------|--|
| 643,3-823,4 | 180,1 | Dark-gray and gray fine-grained dolomites and breccias dolomite, often decaying to pieces and brash, upper trias |
| 823,4-836,4 | 13,0 | Dolomite brash with dolomite pieces and dark shales – lunzke layers, karn age |
| 836,4-1155 | 18,6 | Gray and light-gray fine-grained dolomite |
| 1155-1193 | 38,0 | Dark-gray cavernous dolomite limestones with calcite grains |
| 1193-1205 | 12,0 | Light-gray fine-grained dolomites and brash. From 836,4 m middle trias |
| Together | 261,7 | |

Younger Paleozoic of Hronicum

Rocks of this unit are present up to the Paleogene level in the southern part of Poprad Basin in Kozie chrby. Younger Paleozoic rock has been associated with the Bocky nappe of Hronicum. In the area of Kozie chrby these rocks belong to the Ipoloticka group, generated by the Maluzina group of strata (perm) and also Niznobocianske strata (upper carbon). Perm rock sequences are predominant, with thicknesses of 1,5 - 2 km and they are made by colorful conglomerate sandstones, shales, and locally by evaporites, alkaline rocks and puff-stones. Stratas and layers are in an east-west direction, with 10°– 40° incline to the north.

Krížna nappe

Nappe rock fillings are known from surface data in Belianske Tatry , Ruzbassky ostrov and from boreholes FGP-1 and Vr-2 in Poprad Basin.

In the Belianske Tatra Mts., rocks are over 1500 m thick. The main rocks are ramsau dolomites, limestones of Jura age, keuper layers and dark Triassic limestones. The incline of the layers is around 30° to the north.

In Ružbašský ostrov part have nappe sequence to 950 m thicknesses. Dominant rocks (approx. 859 m, 90%) are various dolomites, breccia dolomite, less limey claystone and claystones. Some less frequently found rocks in the area are quartz sandstones and quartzite.

Krížna nappe sequences of Poprad basin were documented in two boreholes. Borehole FGP-1 bore the nappe to the Mesozoic strata of the Tatricum envelope, and borehole Vr – 2 ended in Krížna nappe.

Figure 4.7 shows a Litho-stratigraphic table of Krížna nappe

Table 3 - Křížna nappe borehole descriptions

Borehole FGP-1 Stara Lesna

| Depth (m) | Thickness(m) | Rocks type, geologic age |
|-----------------|--------------|--|
| 1865-2138 | 273 | Low sandy limestone, back, organodetric limestone with shale layers, apt – low alb age |
| | 292 | Limestone in fragments, marly, black, marly shale, Barém - Valangin age |
| 2430-2525 | 95 | Marly limestone, Titón - Berias |
| 2525-2560 | 35 | Limestone, low marly, fine-grained, fragments of red shales, Kimeridž age |
| | 95 | Sandy limestone, organodetric, fine-grained, shales, dark gray, black |
| 2835-3310 | 475 | Carpat keuper – norik Group of strata |
| Together | 1445 | |

Borehole Vr-2 Vrbov

| Depth (m) | Thickness(m) | Rocks type, geologic age |
|-----------------|--------------|---|
| 1951-2083,5 | 132,5 | Limey claystone, faulted by tectonics, with coal mass, calcite within faults, lower Krieda - Neokom |
| 2083,5-2321 | 237,5 | Compact dolomite, gray, flawed by tectonics, calcite within faults |
| 2321-2502 | 181,0 | Limey claystone, dark gray, faulted by tectonics, with coal mass, calcite within faults, |
| Together | 551,0 | |

Mesozoic of Tatricum envelope

Rocks of the Tatricum envelope were documented in the northern part of the basin, in the Belianske Tatras Mts. The envelope documented by borehole FGP-1 is in the middle part of the basin.

In an envelope in the Belianske Tatras Mts. can be found quartzite, conglomerates, silicious-sandstones and shales and, in a few isolated cases, gutenstein layers – dark limestones and bright dolomites. In borehole VRS-1 are non-carbonate rocks– sandstones, silicious-sandstones, quartzite in absolute superiority. They are assigned to the Triassic age. A deeper group of strata is composed of colorful shales, wacke sandstones, conglomerates and belongs to the lower Trias to Perm.

In the Tatricum envelope, Carbonatic rocks have been found in very small concentrations; therefore we can say that this area is not suitable for geothermal water circulation. The Tatricum envelope is documented by borehole FGP-1 and has the following structure:

Table 4 - Tatricum envelope borehole description

Vrt FGP-1

| Depth (m) | Thickness(m) | Rocks type, geologic age |
|-----------------|--------------|---|
| 3310-3320 | 10 | Limestone, shale, light siliceous – Doger age |
| 3320-3450 | 130 | Limestone, shale, marly, black – upper Lias age |
| 3450-3510 | 60 | Limestone, shale, sandy, black, dark gray, lower Lias - Ret |
| 3510-3616 | 106 | Quartzite, pink, gray – lower Trias |
| Together | 306 | |

| ÚTVAR-ODD-STUPEŇ | LITOLÓGIA | SÚVRSTVIA - VRSTVY | FOSÍLIE |
|-----------------------|-----------|--|---|
| K R I E D A | ALB | | |
| | APT | škvrité slie | Halicoryne nerea Clypeina nigra Salpingoporella muehlbergii |
| | BARÉM | koscieliské súvrstvie | Quinqueloculina minima Gaudryina tuchaensis Tintinnopsella carpathica Tintinnopsella longa |
| | HOTERIV | 100-150 m | |
| | VALANGIN | | |
| | BERIAS | | |
| | TITÓN | svetlé pelitické vápence (majolica, biancone) 50-80 m slie s aptychmi a sakokómami | Remaniella cadischiana Calpionella alpina, C. elliptica Saccocoma sp. |
| | KIMERIDŽ | červené hľuznaté vápence | Saccocoma sp. Lamellaptychus sp. |
| | OXFORD | | Lamellaptychus cf. lamellosus |
| | KELOVEJ | radiolárové vápence a radiolality | Bositra, Globochaete alpina |
| J U R A | BAT | 20-50 m | |
| | BAJOK | | |
| | ÁLEN | | |
| | TOARK | algäuske vrstvy | Hildoceras bifrons |
| | PLIENSBAH | 50-500 m | |
| | SINEMÜR | adnetské a hierlatzské vápence 10-15 m | Echioceras faricostatum |
| | HETANŽ | kopiencké vrstvy | Isopodichnus, Planolites |
| | RÉT | falranské súvrstvie 10-60 m | Retisphyllia clathrata, Pamirosaris rectilamellos |
| | NORIK | karpatský keuper pestré bridlice, pieskovce, zlepenca a dolomity 0-300 m | Agathammina austroalpina Clasacopollis sp. Gliscopollis sp. |
| | KARN | ramsaukské dolomity | |
| M E Z O Z O O I K U M | LADIN | 200-250 m | |
| | ANIS | guttensteinské súvrstvie: tmavosivé lavicovité vápence, dolomity, bazálne brekie 0-200 m | Encrinurus liliformis Terebratula vulgaris Spiriferia menzeli Spiriferia trigonella |
| | SKÝT | verfenské súvrstvie 0-100 m kremence a kremenné pieskovce 10-20 m | Triletes polonicus Puzosporites populosus |

Figure 4.7 - Križna nappe Litho-stratigraphic table

Crystalline of Tatricum – basement

Close to the High Tatras are two dominant rock groups: biotite granodiorite, with tonalities passing to muscovite-biotite granitoids. We can assume that there is continuation in the Poprad basin mesozoic envelope. Tatricum crystalline reach to the south is not known, but it can be assumed that in the southern part of the basin these crystalline formations have contact with veporic crystalline formations.

4.4 Tectonic composition

In the studied Poprad basin area, on the beginning of Miocene were moving processes with folded and faulted structures starting. It started structures with East-West direction form:

- Tatra mega-anticlinal
- Poprad basin synclinal
- Low Tatra mega-anticlinal

Tatra mega-anticlinal have asymmetric form, with steep inclination to the south totaled by crystalline. Choc-under Tatra fault bonded crystalline formations with Mesozoic envelope areas and nappes to south. In Poprad basin this fault is generated by a 3-5 km wide parallel faults system with 50 – 60° incline to the south and southeast. From the Baden age to now there has been an intensive uplift of the Tatra Mts. and a relative drop of the Poprad basin. It is expected that the uplift will reach approx. 5000 m.

The syncline of the Poprad basin has a west-east direction with a twist to the northeast.

The oldest faults are situated in a deep Paleogene base filling. Sub-horizontal border lines of Choc nappe, Križna nappe and Mesozoic envelope make tectonic nappe surfaces. These are documented in boreholes FGP-1 and VR-2 (Choc and Križna nappe contact), VRS-1 (Križna nappe and Tatricum envelope contact).

Poprad basin is bounded by a fault under the Tatra in the North and North-West. In the South this basin is bounded by west-east faults parallel with Kozie chrby. In the south-eastern part of the basin is the 0,5 km wide Vrbov fault zone. The fault zone starts from Kozie chrby, lies on the east side of Vrbov and goes to the north-east. The fault has a rapid incline to the northwest and borders the Choc nappe Mesozoic. Inside the Poprad basin, between Under Tatra and Vrbov fault, the fault system was interpreted. The faults have north-east directions and drop characters, which is the reason for the elevations and depressions form of the basin's sub-base. In the West, between Tatranska Strba and Gerlachovo, the sub-base drops 1000 m.

The western part of Hornad Basin is situated on the mega-anticline Spis-Gemer Rudohorie. In this basin, Paleogene and sub-base structure three fault systems are formed. In the North are west-east faults, which follow the elevation of Kozie chrby. The most common are southwest–northeast direction faults in the western part of the Hornad basin. Under the most important Muran fault is Paleogene contact with younger Paleozoic strata of Hronicum with dolomites of Vernar nappe. Blocks of basin filling are drooped on the faults to the East.

4.5 Hydrogeological characteristics

Based on hydrogeological regionalization of Slovakia (Šuba et al., 1984) the studied area belongs to the following hydrogeological zones (Figure 4.8):

- PQ 115 Paleogene of Hornad and Poprad Basins
- P 119 Paleogene of Levoča Mts.
- QG 139 Crystalline of High Tatras and their Post-Tertiary foreland

Partially intervened to this area are the following hydrogeological divisions:

- MG 116 Mesozoic of Slovensky raj and Havranie Mts. with Paleozoicum
- M 140 Mesozoic of Kozie chrbty part

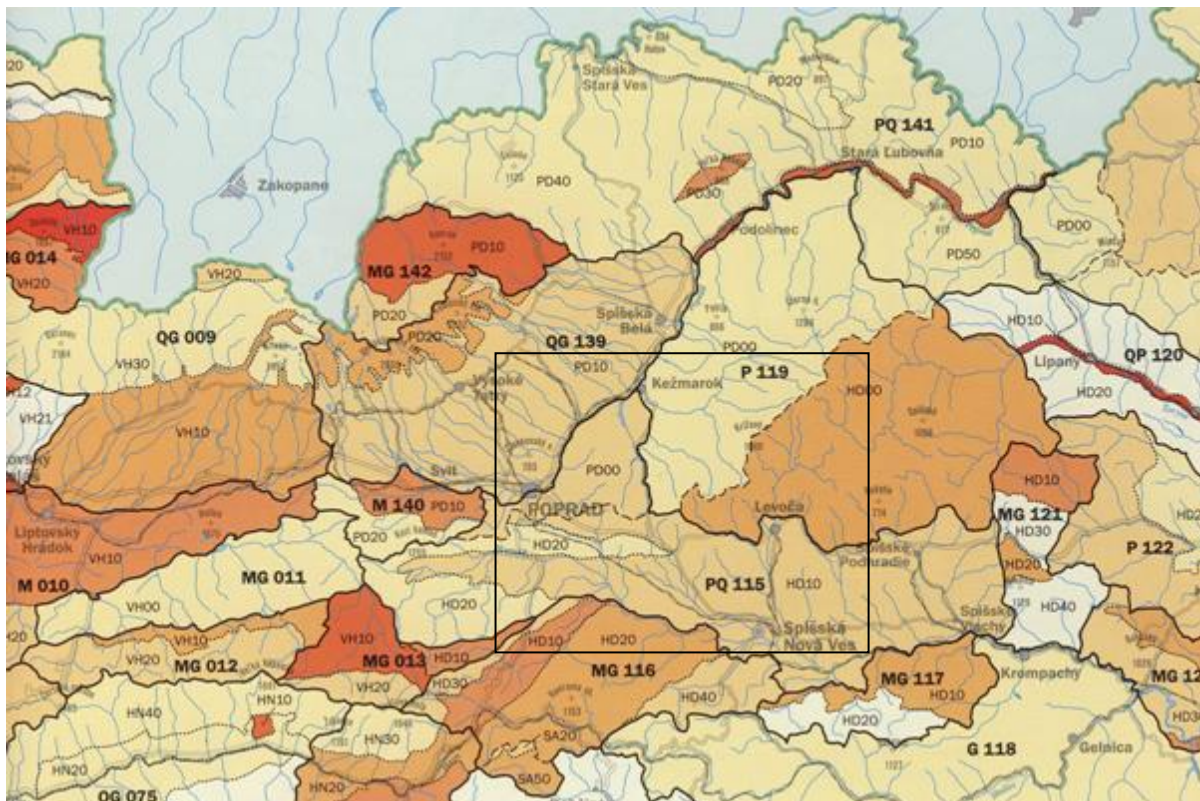


Figure 4.8 - Hydrogeological regionalization of Slovakia (Šuba et al., 1984)

PQ 115 Paleogene of Hornad and Poprad Basin

This area is divided into a subarea of Paleogene in the Hornad Basin and a subarea of Paleogene in the Poprad Basin. Special attention will be given to a partial area in the south-western part of PQ 115 that contains a “melaphyre series”.

This hydrogeological area is constructed of low watered claystone (Hutianske) and sandstone (Zuberecke) groups of strata of the Under-Tatra Mts. group (Gross et al., 1984), which have low permeability. The partial area of “melaphyre series”(ipolitic group – Vozárová - Vozár 1981) contains sandstones, shales, melaphyres and arkose outcroppings of Permian age on the

surface. Cyclic changing of claystones with sandstones leads to the aversion of ground water infiltration.

Areas of tectonic failures and zones of subsurface rocks have relatively favorable conditions for the accumulation of ground water. Rocks in the partial area of “melaphyre series” have low permeability and only permit a low infiltration of atmospheric precipitations.

P 119 Paleogene of Levoča Mts.

The hydrogeological area is built of sandstone (Bielopotocke) groups of strata from the Under-Tatra Mts. Group (Gross at al., 1984).

Predominantly, sandstone groups of strata are found above claystones with a layer of conglomerates. This group of strata is formed after tectonic movement gently deformed to flat synclines and anticlines bending to the south, southeast. All the lithologic and tectonic conditions which were mentioned made that sandstone group of strata drain mainly in the eastern and south-eastern part of mountains.

The main aquifer of Paleogene is fixed in the zone of slope sediments. The thickness and nature of aquifers change with lithologic composition of rocks, tectonics deformations and morphologic changes. Aquifers created by drainage through fractures and fractured talus yield from 0,01 to 0,3 l.s⁻¹.

QG 139 Crystalline of High Tatras part and Post-Tertiary theirs foreland

In Poprad Basin is an hydrogeological area built by glacial, glaciofluvial and fluvial sediments (partial area of Post-Tertiary of High Tatras and Poprad Basin).

Local glacial sediments are situated close to the end of mountain valleys near Poprad Basin. The granulometric composition of sandstones between boulders of the moraine is important for the permeability of glacial sediments.

Glaciofluvial and fluvial sediments cover a large area of Poprad Basin. Mostly there are sandstone, stony sediments of Wurm age and sandstones, loamy sand of Mindel age. The thickness of glaci-fluvial sediments ranges 25 to 80 m (Maťuš, 1991). The index of filtration in glaci-fluvial sediments is $10^{-4} - 10^{-8} \text{ m.s}^{-1}$.

Fluvial deposits of alluvium in the Poprad river have a maximum thickness of 7,0 m and index of filtration varies from $9,8 \cdot 10^{-4}$ to $6,7 \cdot 10^{-5} \text{ m.s}^{-1}$ (Haluška, 1968).

Important accumulations of groundwater are found in places where glaci-fluvial sediments fill the depressions.

MG 116 Mesozoic of Slovensky raj and Havranie Mts. with Paleozoicum

In studied area is hydrogeological zone represented mainly by Mesozoic and Paleogene rocks. Slovensky raj area is built by massive permeable rocks complex, mainly Triassic limestones and dolomites. They are lying on impermeable Paleozoic bedrock.

M 140 Mesozoic of Kozie chrbty part

The hydrogeological zone is made up of shale, sandstones with alkaline vulcanites (“melaphyre zone”) complex, which is impermeable. For accumulation of ground waters, middle and upper Triassic dolomite complexes are important; less important are limestones of Choc nappe of Hronicum.

Drain of the interested area

Outflow of the water from Poprad and Hornad Basins is realized by the Poprad and Hornad rivers. The Poprad river is fed by runoff from the Poprad Basin and flows to the Baltic sea and the Hornad river is runoff from the Hornad Basin and flows to to the Black sea.

Poprad river

The Poprad river is 169 km long and surface 1 889,2 km² all of river-basin in Slovak area. Runoff largely comes from the southern and south-eastern slopes of the High Tatras, the Belianske Tatras, Spis Maruga and Lubovinianska highlands, the Levoca Mts., the Cergov north-western slopes and the Poprad Basin. In the gauging station Strazky (670 km²) the average annual flow is 9,03 m³.s⁻¹, max. 383 m³.s⁻¹, and the minimum average daily flow is 1,38 m³.s⁻¹.

Hornad river

The Hornad river stretches 186,3 km through the Slovak area. The river is fed by runoff from the Levoca Mts., Branisko, Cierna mount, part of the Saris highlands, Cergov and Slanske Mts., the eastern part of Slovenske Rudohorie, and the Hornad and Kosice basins.

In the gauging station Kysak average annual flow is 19,4 m³.s⁻¹. Documented maximum flow is 689 m³.s⁻¹ and minimum flow is 2,5 m³.s⁻¹.

4.6 Hydrogeothermal characteristics

The main area of interest in terms of existent geothermal waters is the Levoča basin (Franko, 1979), mostly its western and south-western parts.

The term “Levoča basin” was introduced by Franko (1979) as it contains geothermal aquifers (Triassic dolomites and limestones) in basined position. The vast Levoča basin is separated by faults from the Klippen Belt in the north and northeast and borders the Tatry in the northwest, as well as eastern tracts of the Nízke Tatry, Slovenské Rudohorie and Čierna hora Mts. in the south. The western branch of the Hornád fault separates it from the northern Košice Basin. The Branisko horst is confined by faults in the west and east, and stretches from the Slovenské Rudohorie northward, and also into the Levoča Basin. The Ružbachy inlier rises from the substratum of the Paleogene between the Spišská Magura and Levočské vrchy Mts. In the southeast, the inlier is lined by a fault representing a continuation of the Subtatric fault.

The basin is filled with the Inner Carpathian Paleogene, composed of a tens-of-meters thick basal conglomerate formation and an overlying flyschoid formation up to 4000 m in thickness.

The Pre-Tertiary substratum of Levoča basin has a few characteristic features. The Ružbachy elevation stretches between the Tatry and Ružbachy and a similar one extends in the south as a continuation of the Vikartovský chrbát Ridge and as far as the Branisko Mts. The substratum surface between these two elevations declines from the Štrbský chrbát Ridge (separating the Liptov Basin from the Levoča Basin) in the northeast to a depth of more than 2500 m south of Stará Ľubovňa, from where it continues to decline in a narrow belt along the Klippen belt to a depth of 4000 m north of Prešov. A shallow trough (Hornád trough) has evolved between the Vikartovský chrbát Ridge in the north and Nízke Tatry and Slovenské Rudohorie in the south. From the edge of the Čierna hora, the Pre-Tertiary substratum

plunges to the northeast, first gently, then steeply towards the Klippen Belt. The Pre-Tertiary substratum of the Spišská Magura dips gently from the Tatry and Ružbašský chrbát Ridge towards the northeast to a depth of 2000 m.

The geologic structure of the pre-Tertiary substratum includes all tectonic units of the Inner West Carpathians. The Gemeric Paleozoic and Mesozoic complexes of the Galmus and Stratenská hornatina Mts. extend into the southern tract of the Spiš Basin below the Paleogene. To the north the pre-Tertiary substratum consists of a wide belt of the Choč nappe, which stretches as far as north of the Branisko. Tertiary rocks of the Šarišská Vrchovina rest on the Permian-Mesozoic envelope. It is assumed that Paleogene in the Levoča basin, i.e. the Spišská Magura, Levočské vrchy and a whole belt along the Klippen Belt as far as Prešov, is underlain mostly by the Križna nappe. The Ipoltica Group and a part of the Choč nappe in the south of the basin rest on the Mesozoic envelope of the Veporic crystalline (Veľký Bok series), whereas the Križna nappe in the central and northern sectors overlies the Tatric envelope Mesozoic. The Mesozoic complexes in different units reach different depths. The southern Šarišská Vrchovina and Klčov area at a depth of 1000 m are dominated by the crystalline unit (crystalline schists, granitoids) whose extent grows with depth. The Ružbachy elevation at 3000 m is presumably also composed of granitoids, while the southern and central sectors of the basin at this depth are filled with the veporic and Tatric envelope Mesozoic. The Križna nappe is expected at this depth in a belt fringing the Klippen Belt and a depression south of Stará Ľubovňa. At 4000 m the basin is dominated by the crystalline unit, while Mesozoic elements are probably confined to a belt along the Klippen Belt and to the Vikartovský chrbát Ridge area. At 5000 m the whole Levoča Basin is underlain by the crystalline unit except for a narrow strip along the Klippen Belt.

Geothermal activity in the area (Fendek et al. 1992, Franko et al. 1994a) is medium and ranges from 61,8 to 77,0 mW.m⁻², averaging 66,8 mW.m⁻². Activity in the geothermal field rises from the margins of adjacent mountains towards sunken sectors of the basin. It exceeds 70 mW.m⁻² in the Spišská Magura area, 65 mW.m⁻² in the Levočské vrchy, and 75 mW.m⁻² along the Klippen Belt towards the southeast. The temperature field has a similar pattern, with temperatures ranging from 30 to 45°C. Geothermal aquifers, i.e. Triassic carbonates of the Tatric and Veporic envelope units, as well as Križna and Choč nappes, reach depths of 1000-4000 m where aquifer temperatures vary from 37 to 109°C. In the depth interval 2000-4000 m the temperatures range from 61-109°C.

Evidence of geothermal activity in the area concerned includes natural thermal springs at Gánovce (Struňák, 1994), Baldovce (Haluška-Petrivalský, 1994), Lipovce (Malík, 1994) and Vyšné Ružbachy (Mlynarčík-Petrivalský, 1990). The springs at Baldovce (including Sivá brada) are recharged from carbonates of the Tatric and Veporic envelope units, those at Vyšné Ružbachy from Križna nappe carbonates, and those at Gánovce and Lipovce from Choč nappe carbonates. The existence of the waters at these localities has been proven by shallow wells. Deep wells have proven geothermal water occurrences in the above tectonic units at Klčov (Biely et al. 1965), Lúčka (Haluška-Petrivalský, 1994), near Baldovce (Tatric and Veporic envelope units), at Plavnica, Lipany, Šariš (Fendek et al. 1992, Križna nappe), Vrbov (Fendek et al. 1992), Poprad (Choč nappe, Daniel, 1994, pers. comm.), Arnutovce and Letanovce (Vernár nappe, Jetel et al. 1990). Waters from springs and shallow wells are 13,6-26,7°C and those from deep wells 19-107°C. The transmissivity coefficient T of Vernár nappe carbonates intersected by these wells is $1,4 \cdot 10^{-3} - 8,8 \cdot 10^{-4} \text{ m}^2 \cdot \text{s}^{-1}$, the coefficient in wells Vr-1 and Vr-2 in the Choč nappe is $1,2 - 6,4 \cdot 10^{-4} \text{ m}^2 \cdot \text{s}^{-1}$, in Križna nappe carbonates intersected by wells VRŠ-1, Vr-2, 5 and 9 at Vyšné Ružbachy $2,2 - 2,3 \cdot 10^{-5} \text{ m}^2 \cdot \text{s}^{-1}$.

Geothermal waters hosted by Vernár nappe carbonates are of Ca(Mg)-HCO_3 type and those bound to Choč nappe carbonates discharged by shallow and deep wells alike are of Ca(Mg)-HCO_3 type. Waters bound to Križna nappe carbonates and discharged by natural springs are of Ca(Mg)-HCO_3 type and those from deep wells are of Na-HCO_3 , $\text{Na-Ca(Mg)-HCO}_3\text{-Cl-SO}_4$ and Na-Cl types. Waters hosted by carbonates in the Tatric and Veporic envelope units are of Ca(Mg)HCO_3 type. Genetically, the waters are atmospherogenic with petrogenic mineralization. Aside from their chemistry, this origin is suggested also by $\delta^{18}\text{O}$ content in well Vr-2 at Vrbov, which oscillated around -13‰ . This attests to the infiltration of extremely “light” precipitation waters from all wells, except for those at Gánovce and Vyšné Ružbachy, which tapped natural springs, and have a marinogenic component seeped from Paleogene sea. Water from well Šariš-1 is of marinogenic origin.

Waters in the Levoča Basin typically have strong incrustation properties. Oversaturation with free Ca^{2+} ions at well top attains $80\text{-}90\text{ mg.l}^{-1}$ (wells Pl-1, Pl-2 at Plavnica). Sulfates (over 1000 mg.l^{-1}) and free CO_2 (about 600 mg.l^{-1} in wells Vr-1 and Vr-2 and about 1300 mg.l^{-1} in Pl-1 and Pl-2) are likely to cause strong sulfate and carbonate corrosion on those sections of installations which are not covered with incrustations. Fe contents from $0,9$ to $1,9\text{ mg.l}^{-1}$ would give rise to brown precipitation.

The probable recoverable amount of renewable geothermal energy in the western and southern sectors of the basin is $75,4\text{ MW}_t$ and the probable nonrenewable amount in the northern tract is 1316 MW_t (Franko et al. 1995).

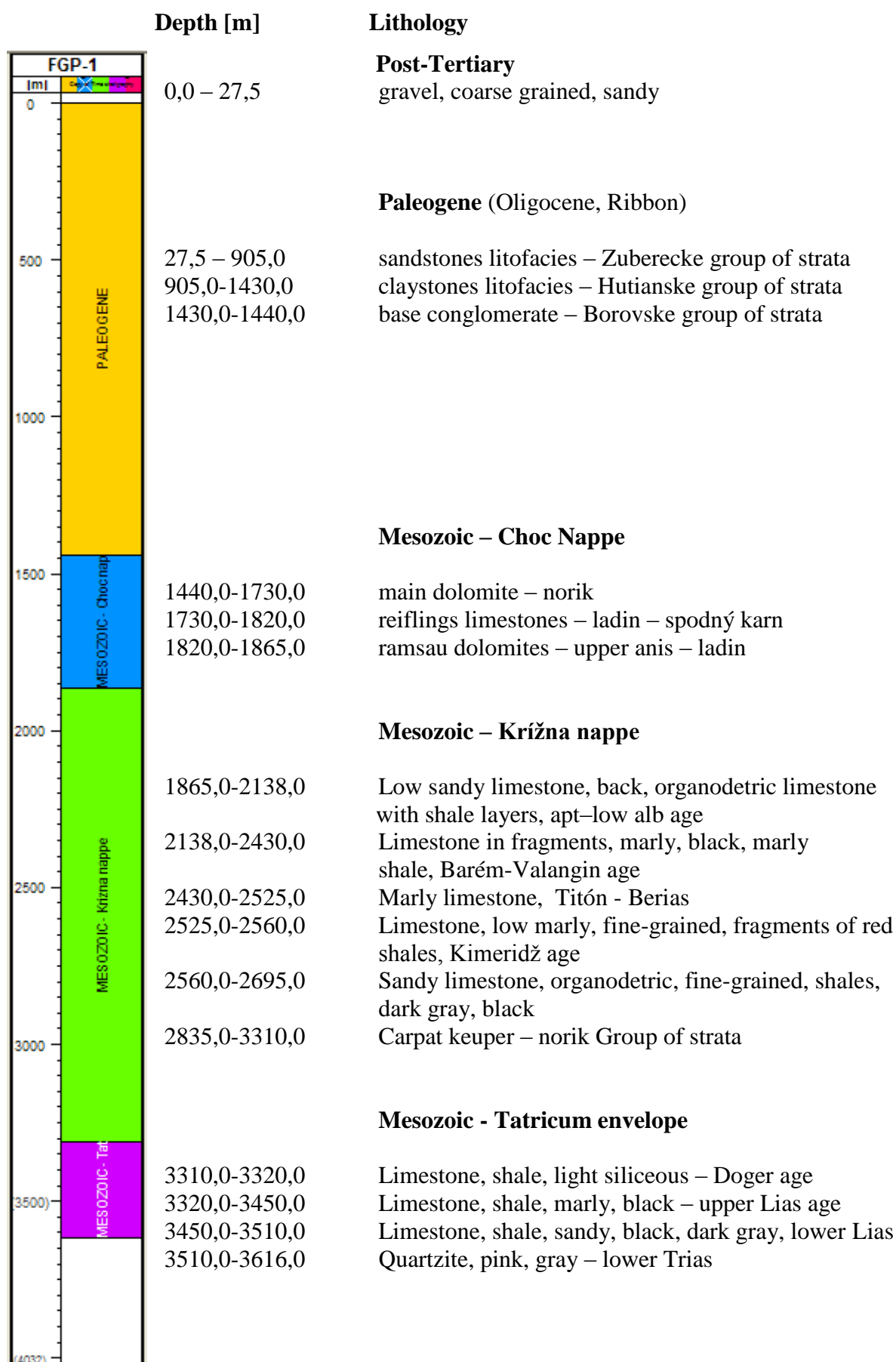
4.6.1 Depth composition and characterization of geothermal boreholes



Figure 4.9 - Boreholes location in study area; Gerlachov village location

In Poprad basin few deep boreholes were drilled. They provided important information and data for this work. From a geothermal point of view, the most important boreholes are: FGP-1 Stara Lesna, PP-1 Poprad, VR -1, VR-2, VR-2A, and HV3 in Vrbov. Close to the study area, Gerlachov, are boreholes FGP-1 and PP-1. Geological composition can be very similar to the Gerlachov area. The model will represent the whole basin, so boreholes FGP -1, PP-1 and also VR 2 will be described in more detail.

Hydrogeothermal borehole FGP -1 Stara Lesna



Hydrogeology and geothermal characteristic of borehole FGP-1

Borehole yield at the well bottom was measured to be 22,2 l/s with a temperature of 58°C. Hydrostatic pressure before the hydrodynamics test was 0,181 MPa on the surface and 13,866 MPa at a depth of 1400 m.

In borehole FGP-1, geothermal waters of Ca-Mg-HCO₃ type with a general mineralization of 3,1 – 3,3 g/l were found. The main gas elements in the water are CO₂ (97%) and N₂ (2,8 %).

Geothermal waters are mainly found in Triassic dolomites of Choc nappe. The hydraulic properties of aquifers are characterized by a coefficient of absolute flow capacity of $2,696 \cdot 10^{-11} \text{ m}^3$, a coefficient of flow capacity of $5,406 \cdot 10^{-4} \text{ m}^2/\text{s}$, a coefficient of permeability of $5,392 \cdot 10^{-13} \text{ m}^2$ and a coefficient of filtration of $1,081 \cdot 10^{-5} \text{ m/s}$.

The Choc nappe average geothermal gradient is 21,9°C/km and the density of thermal flow is 69,3 mW/m², given for borehole FGP-1.

Based on a more complex interpretation of the borehole, the maximum flow of useful geothermal waters is 40 l/s using a pump. The temperature on the well bottom is 58°C and the maximum thermal power is 7,1 MWt.

Hydrogeothermal borehole PP-1 Poprad

| Depth [m] | Lithology |
|------------------------------|---|
| PP-1 | |
| [m] | |
| 0,0 – 10,5 | Post-Tertiary loam, clay with rocks fragments |
| Paleogene | |
| 10,5–556,0 | dark gray claystones with gray fine-grained sandstones layers |
| 556,0–559,2 | tectonic claystones with claystones fragments |
| 559,2–609,0 | light gray lime siltstone |
| Mesozoic – Choc nappe | |
| 609,0–643,3 | tectonic area represented by claystone, sandstone, siltstone, claystones and carbonates |
| 643,3–823,4 | dark-gray and gray fine-grained dolomites and breccia dolomite, often decaying to pieces and brash, upper trias |
| 823,4–836,4 | Dolomite brash with dolomite pieces and dark shales lunzské layers, karn age |
| 836,4–1155 | Gray and light-gray fine-grained dolomite |
| 1155–1193 | Dark-gray cavernous dolomite limestones with calcite grains |
| 1193–1205 | Light-gray fine-grained dolomites and brash. From 836,4 middle trias |

Hydrogeology and geothermal characteristic of borehole PP-1

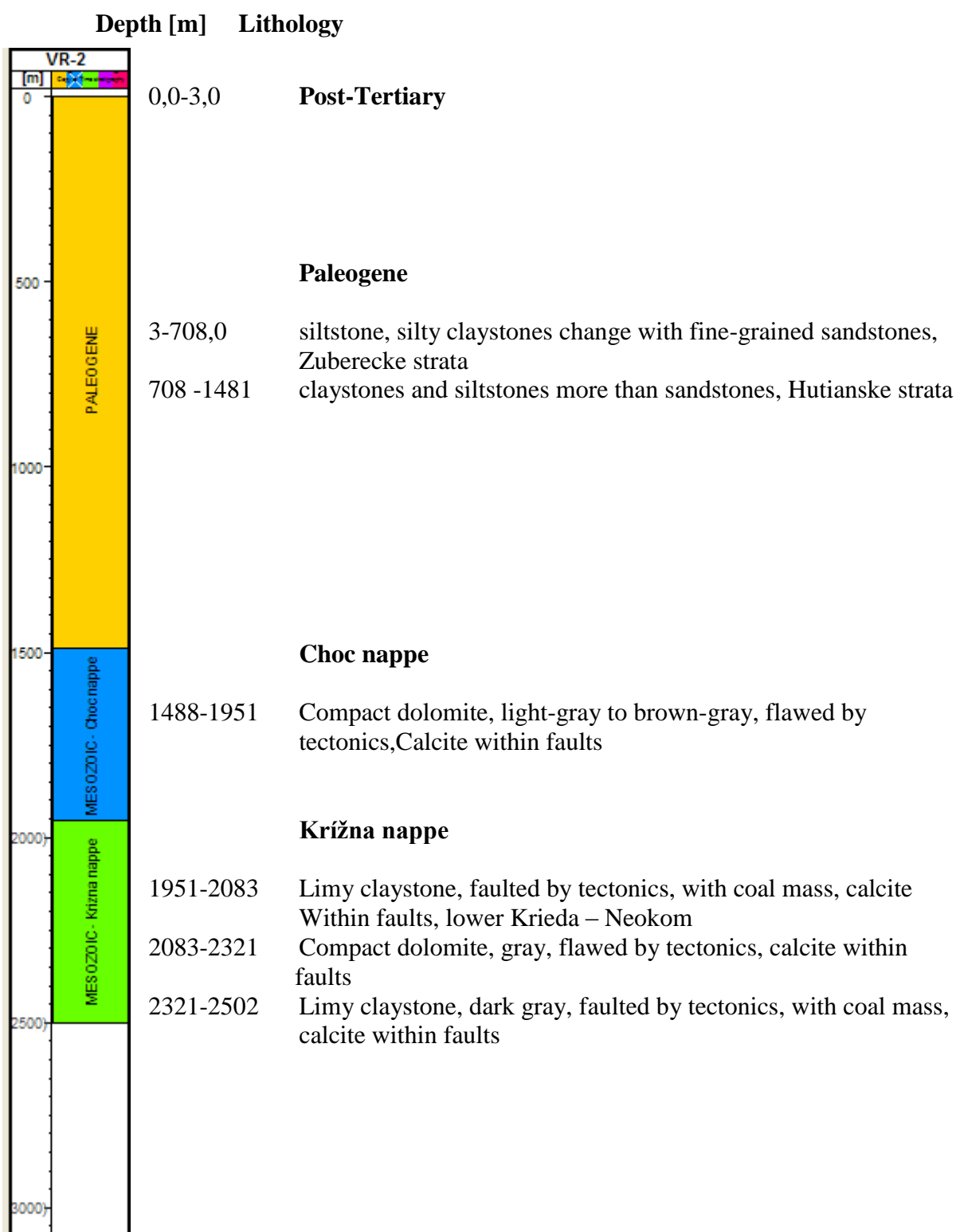
Based on logging measurements, productive sectors were specified and are shown in Table 5.

Table 5 - Productive sectors in borehole PP-1

| Productive sectors in PP – 1 Poprad borehole | | | |
|---|---------------------------|--------------------------|-----------------------------|
| Interval | Discharge | General discharge | Water temperature in |
| [m] | [l.s⁻¹] | [%] | inflow depth [°C] |
| 635-660 | 7,76 | 12,68 | 48,2 |
| 695-700 | 1,06 | 1,73 | 48,2 |
| 745-790 | 14,52 | 23,73 | 48,2 |
| 835-900 | 18,32 | 29,73 | 49,0 |
| 910-921 | 2,34 | 3,84 | 49,1 |
| 931-935 | 9,11 | 14,89 | 49,7 |
| 970-990 | 2,94 | 4,80 | 50,0 |
| 1090-1105 | 5,14 | 8,40 | 50,5 |

The geothermal water supply of borehole PP-1 was specified to be 48,2 l.s⁻¹ and the temperature on the well bottom is 48°C. The static pressure on the well bottom is 0,51 MPa. The geothermal water amount with this temperature has a thermal power of 6,647 MWt. The main aquifers are Triassic dolomites of Choc nappe faulted by tectonics. Geothermal waters of Ca-Mg-HCO₃ type with a general mineralization of 2,88 g/l⁻¹ and pH=6,21 were found.

Hydrogeothermal borehole Vr-2 Vrbov



Hydrogeology and geothermal characteristic of borehole VR-2

The geothermal water supply of borehole VR-2 was specified to be 33 l.s^{-1} and the temperature at the well bottom is 50°C . The main flows were localized in Mesozoic Choc unit in interval 1918 – 1972 m, lower in some intervals from 1488 to 1972 m.

The hydraulic properties of aquifers are characterized by a coefficient of absolute flow capacity of $1,061 \cdot 10^{-10} \text{ m}^3$, a coefficient of flow capacity of $2,4 \cdot 10^{-3} \text{ m}^2/\text{s}$. Thermal water is of Ca-Mg(SO₄)-HCO₃ type and mineralization of 3891 mg.l^{-1} . The pressure on the well bottom is 500 kPa.

The thermal power at a temperature drop to 35°C is 4,6 MWt.

4.6.2 Geothermic conditions

From a regional point of view, the Poprad and Hornad basins have the characteristics of a depression. Both depressions are bounded mainly by faults from the surrounding mountains. Geothermal waters are fixed in carbonate rocks which are under the Paleogene filling of both basins.

Thermal conditions

Temperatures have relatively stable character without strong temperature anomaly. The average temperature at a depth of 1000 m is $40,2 \pm 1,5^{\circ}\text{C}$ in Poprad basin and $35\text{--}40^{\circ}\text{C}$ in Hornad basin. At 2000 m depth, the average temperature is $66,8 \pm 2,3^{\circ}\text{C}$ in Poprad basin, and in the north the temperatures are around 60°C . At 2000 m the typical temperature is 55°C in Hornad basin. At 3000 m, in the Poprad basin, the central area has an average temperature of $92,2 \pm 1,7^{\circ}\text{C}$ and the border region to the south and southwest the temperatures are between $80\text{--}85^{\circ}\text{C}$. In Hornad basin temperatures of $75\text{--}80^{\circ}\text{C}$ are typical at 3000 m depth. At 4000 m depth the Poprad basin temperatures are between $110\text{--}117^{\circ}\text{C}$ and in Hornad basin they are $105\text{--}110^{\circ}\text{C}$.

Documented thermal gradients in the Poprad basin Paleogene group of strata are $32,6$ to $34,5^{\circ}\text{C}/\text{km}$, and Choc nappe dolomites are characterized by gradients of $19,8$ to $21,9^{\circ}\text{C}/\text{km}$. Križna nappe has a $24,6$ to $29,8^{\circ}\text{C}$ geothermal gradient. Geothermic data documented in Poprad basin deep boreholes are in Table 6.

Table 6 - Geothermic data of Poprad basin deep boreholes (Daniel et al. 1998)

| Temperature in depth | Boreholes | | |
|--|-----------|--------|--------|
| | FGP - 1 | VR - 2 | HV - 3 |
| $T_{500} \text{ } [^{\circ}\text{C}]$ | 24,4 | 22,3 | 23,7 |
| $T_{1000} \text{ } [^{\circ}\text{C}]$ | 41,5 | 38,6 | 40,5 |
| $T_{1500} \text{ } [^{\circ}\text{C}]$ | 58,5 | 54,7 | 57,3 |
| $T_{2000} \text{ } [^{\circ}\text{C}]$ | 68,4 | 65,1 | - |
| $T_{2500} \text{ } [^{\circ}\text{C}]$ | 81,2 | 80 | - |
| $T_{3000} \text{ } [^{\circ}\text{C}]$ | 93,4 | - | - |
| $T_{3500} \text{ } [^{\circ}\text{C}]$ | 104,7 | - | - |
| Geothermal gradient | FGP - 1 | VR - 2 | HV - 3 |

| | | | |
|-----------------------------|------|------|------|
| G Paleogene [°C/km] | 34,5 | 32,6 | 33,5 |
| G Choc nappe [°C/km] | 21,9 | 19,8 | - |
| G Krížna nappe [°C/km] | 24,6 | 29,8 | - |
| G Mesozoic envelope [°C/km] | 25,2 | - | - |

The temperature profile from borehole VR-1 Vrbov is not available, but during hydrodynamic tests the temperature was 55°C, measured on the Paleogene base at 1495 m depth. On the well bottom at 1730 m depth the temperature was 61,9°C. In the PP-1 Poprad borehole in the depth interval 1090–1105 m the temperature was 50,5°C. This temperature is higher because of flowing groundwater coming from deeper formations through fault dislocations. Geothermal temperature at 1000 m depth is approximately 40°C.

The Hornad basin temperature field is represented by data from HKJ-3 Arnutovce and HKJ-4 Letanovce boreholes. Data are shown in table below.

Table 7 - Geothermic data of Hornad basin deep boreholes (Daniel et al. 1998)

| Temperature in depth | Boreholes | |
|------------------------------|-----------|-------|
| | HKJ-3 | HKJ-4 |
| T ₂₀₀ [°C] | 13,9 | 14,1 |
| T ₄₀₀ [°C] | 20,7 | 20,7 |
| T ₅₀₀ [°C] | 23,5 | 23 |
| T ₆₀₀ [°C] | 25,7 | 25,2 |
| T ₈₀₀ [°C] | 30,1 | - |
| T ₁₀₀₀ [°C] | 34,5 | - |
| Geothermal gradient | HKJ-3 | HKJ-4 |
| G Paleogene [°C/km] | 33,3 | 33 |
| G Paleogene sub-base [°C/km] | 22 | 22,5 |

In the southern area of Hornad basin temperatures are lower. The relevant area in this work is the northern part of the basin; the southern part will not be described. In boreholes HKJ-3 Arnutovce and HKJ-4 Letanovce, Triassic breccias dolomite and dolomite breccias (Jetel et. al., 1990), which are characterized by a geothermal gradient of 22 to 22,5°C/km in the Paleogene sub-base were documented.

Temperatures of the Paleogene sub-base in Poprad and Hornad basins confirmed that those areas have potential for geothermal water exploitation. In Poprad basin, with its carbonate base, it is possible to reach a maximum ambient temperature of approximately 85°C in 3200 – 3300 m depth in Spišská Bela. In the biggest part of the basin temperatures of more than 50°C at 1500 m depth can be found. This shows that the considered area belongs to high potential areas for geothermal water exploitation.

The potential for low temperature sources exploitation is also found in the Hornad basin, in areas where temperatures are 30–35°C in Mesozoic carbonate aquifers.

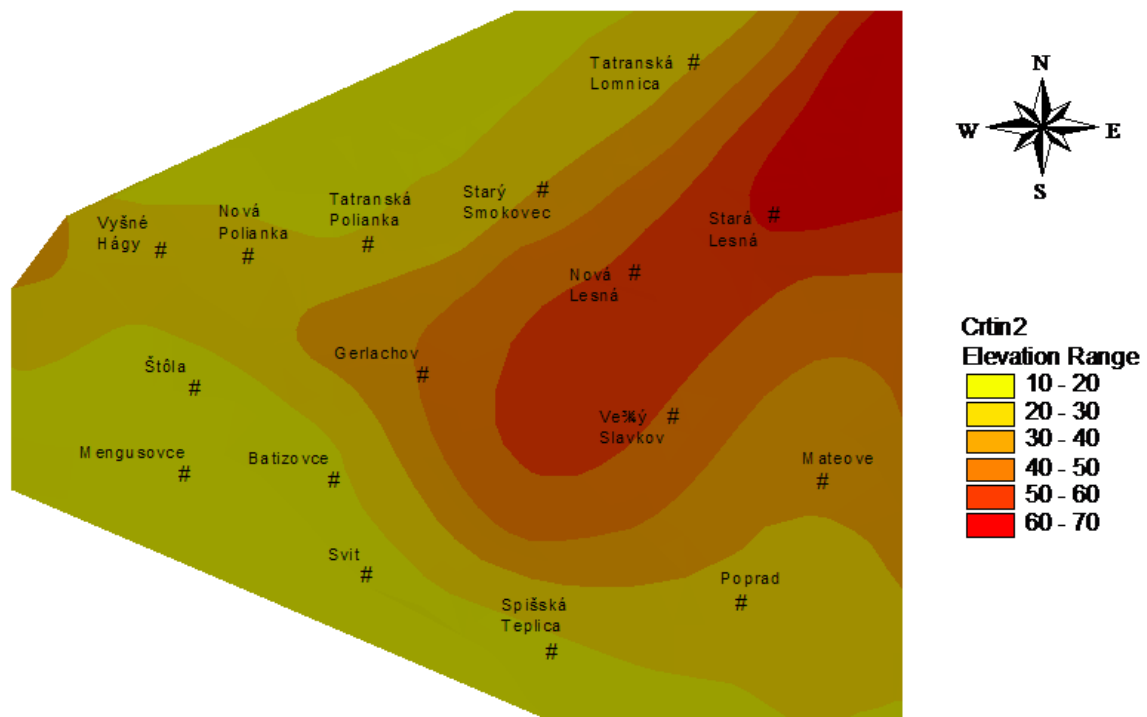


Figure 4.10 - Isothermal lines in interested area

5 3D GEOTHERMAL RESERVOIR MODELING APPROACH

A 3D model of the geothermal reservoir was made in the modeling program Petrel, Version 2008.1. After a description of the observed area, data were collected from existing wells and from geologic reports. This was a base for the characterization of the stratigraphy, spatial distribution, and depth of the analyzed reservoirs and petro physical properties of geothermal reservoirs. The next step was the modeling of reservoir rocks and making a 3D model of the study area. In this work two models based on two different types of data were submitted. The first model is from the whole Poprad Basin and the northern part of Hornad Basin, and the second model is from a small area situated close to the village Gerlachov. Gerlachov is in the Poprad Basin and is situated in northwest part of the basin (Figure 4.4). The modeling in the Poprad Basin was based on analysis of bitmaps (in jpg format) of seismic profiles from this area. The modeling in the Gerlachov area was based on digital seismic data in SEG Y format.

The main advantages of 3D modeling when compared to 2D modeling are:

- More reliable data for the interpretation of geological and tectonic structure
- Geological risk evaluation
- Economic assesment, feasibility study
- Image – higher chance to convince potential partners

5.1 Petrel background

Petrel is a PC-based workflow application for subsurface interpretation and modeling. It allows users to perform all manner of workflows, from seismic interpretation to reservoir simulation. Geophysicists, geologists and reservoir engineers can move across domains, rather than applications, through the Petrel integrated toolkit.

Benefits of the program include:

- All tools from seismic interpretation to simulation are integrated in one application, eliminating import and export problems and promoting collaboration.
- Strong visualization capabilities give instant QC of all data in 3D.
- Models can be updated instantly when new data arrives, allowing the user to make quick and reliable decisions.
- All results can be copy and pasted to any Windows application, making it quick and easy to report and present your latest results.
- Petrel has a familiar Windows user interface, undo/redo functionality, and stores modeling history, making it easy to use and learn (Petrel 2008.1—What's New).

5.1.1 Geomodeling

Geological models are created for many different purposes, but common to all of them is the desire to build a representation of the subsurface. Depending on the purposes, different aspects of the model may be important.

In the case of a regional exploration model, the shape of the structures may be most important. Geological models may be used to achieve accurate volume calculations or to test the effect of different depositional regimes against observed data. With simulation models, the size and complexity may be the limiting factor in creating a model that achieves a good

history match. Petrel uses a 3D grid to supply the building blocks with which the user can recreate representations of reality (Petrel 2008.1—What's New).

5.2 Process resolution and methodology of seismic interpretation – Poprad basin

Before working in Petrel program it was necessary to prepare all the data from the investigated area. Data were collected from geologic, geophysical and hydrogeological reports stored in the Slovakian state geological archive GEOFOND at the State geological institute of Dionyz Stur (ŠGÚDŠ) in Bratislava. Based on this data, the geological, tectonics, hydrogeological and hydrogeothermal situation were described in the study area. The main goal was the geologic interpretation of seismic profiles that are located in the interested area that represent a main proxy for the definition of geothermal reservoirs in the area. The interpretation was focused on the identification of the following main surfaces:

- pre-Tertiary (Paleogene) surface
- interpretation of the Paleogene fill thickness of Poprad Basin and the northern part of the Hornad Basin
- the interpretation of the base of the Mesozoic Choc Nappe
- the interpretation of the base of the Mesozoic Križna Nappe
- interpretation of the tectonic structure (fault analysis)

For this purpose the following seismic profiles were interpreted: 750/92, 751/93, 752/93, 753/93 and 756/93. Those seismic profiles were made in the years 1992 – 1995 by the survey “Flysch of East Slovakia – geophysics, study”.

5.2.1 Analysis of seismic profiles

The analyzed seismic sections from the Poprad Basin and the northern part of the Hornad Basin were reprocessed profiles of medium quality. This also influenced the resolution of my interpretations. The base of Paleogene fill, represented by high amplitude reflectors, is very distinct in all seismic sections. Below this, two complexes separated by an unconformity were also interpreted. The upper complex represents Choc Nappe, the lower one the Križna Nappe, both assigned to the all Mesozoic units covering the crystalline basement and, occasionally, the Upper Paleozoic–Mesozoic envelope unit of so called Tatricum.

Seismic profile 750/92

The profile 750/92 passes in a northeast–southwest direction toward the southern margin of the basin and approximately in the middle part it bends northwest–southeastward, towards Spišská Magura Mts. and it ends near the Klippen Belt on the border with Poland. In the southern part it records the so called Vikartovce ridge consisting of the Permian rocks of Choc nappe. Further on it continues across the Poprad Depression to the High Tatry Mts. separated by a sub-Tatric fault. In the northern part it records the striking elevation of the Mesozoic Ružbachy Island and the partial Spišská Magura Paleogene Basin.

Seismic profile 751/93

The profile begins approx. 2 km west of Markušovce village and continues along Levoča town to the north where the profile changes its direction to the northeast. Visible on this profile are the crystalline rocks in the lowermost part overlain by the Krížna Nappe (Mesozoic rocks) and Choc Nappe. The whole sequence is topped by the Paleogene rocks.

Seismic profile 752/92

Profile 752/92 has an approximately west–east orientation and is located more or less in the central part of Levočské vrchy Mts. In the eastern part of the profile the front of Choc Nappe, overthrust by Krížna Nappe (or Mesozoic sediments of Krížna type), is visible. In the easternmost part of the profile an elevation of the Paleogene base elevating the Mesozoic rocks of Krížna Nappe is well recorded. This structure was also confirmed by the borehole Sariš – 1.

Seismic profile 753/93

Profile 753/93 has northwest-southeast orientation from the margin of the High Tatra Mts. to the southern boundary of the basin. In the northwestern part it records the foothills of the High Tatra Mts. with reduced, probably only envelope, Mesozoic of Tatricum, and a system of listric sub-Tatric faults. The profile passes southeastward across the Poprad Depression toward the southern margin of the basin and it records Mesozoic units in considerably greater thicknesses, which were also confirmed by drills. An obduction of Veporicum crystalline complexes over Tatricum complexes can be assumed in greater depths in the southeastern part of the profile.

Seismic profile 756/93

The profile runs parallel with the southeast margin of the High Tatra Mts. and Ružbachy Mesozoic Island over the deepest part of the sub-Tatric fault system. Beneath the Paleogene base the profile interprets Choc Nappe underlain by the Krížna Nappe and Mesozoic envelope. The lowermost part is formed by the crystalline rocks of the Tatricum.

5.2.2 Import data

Data which can be imported into Petrel are lines/point data, 2D grids (isochors, depth and time grids, 2D trends, etc.), seismic interpretations, seismic (SEG-Y), wells and well tops, and more. Before importing data it is necessary to know the formats of the imported data and the formats that are supported by Petrel. An important part of importing data into a new project is to check the quality of the input data.

In this case 2D data was available. It was 5 seismic profiles in jpg format from the studied area (Figure 5.1). Before importing profiles into the program it was necessary to prepare bitmaps of those seismics and define the coordinates of the seismic profiles.

The entire process consists of the following steps: It was needed to find the real co-ordinates X,Y in the Slovak JTSK system (geodetics X,Y, co-ordinates). An situation map of seismic profiles (lines) was imported to the MicroStation program with a map of Slovakia and geodetical points. X,Y coordinates of the profiles were defined for the imported profiles (Figure 5.1). The coordinates represented the beginning and end X,Y points of profiles. Certain profiles had two different orientations. In these cases the profiles were subdivided

into two segments and each segment was treated as an individual profile. The tables with points were prepared for every profile in txt format for importing the lines into the program.

The next step was preparing the pictures in jpg format for importation to Petrel. It was necessary to fit each profile to the same depth and start from zero level ($Z=0$). Every 6 profiles were cut off to zero level and the co-ordinate for Z – depth was assigned to -5000 m.

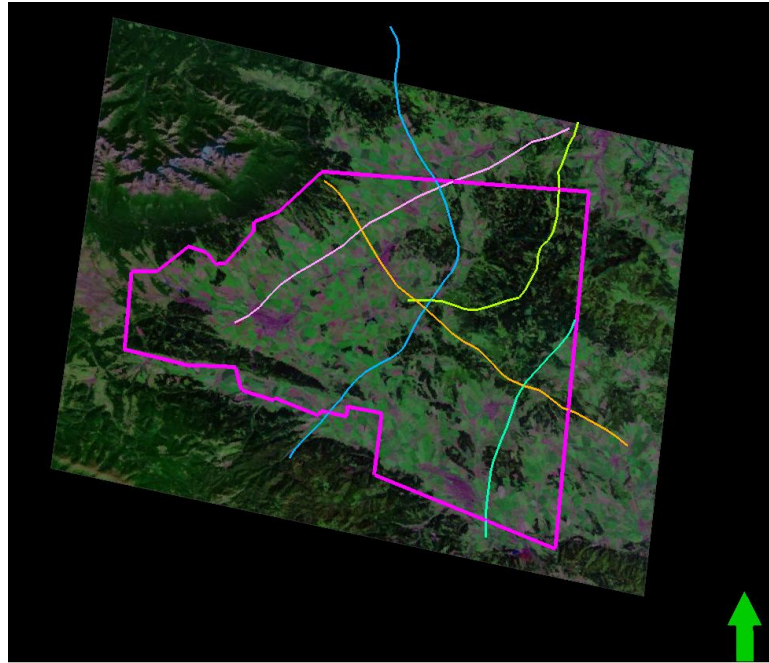


Figure 5.1 - Location of seismic profiles in studied area

After preparing bitmaps and co-ordinates data was imported into Petrel. It was made by polygons (line) from founding co-ordinates X , Y , Z and then importing the bitmaps with seismic to the program (Figure 5.2)

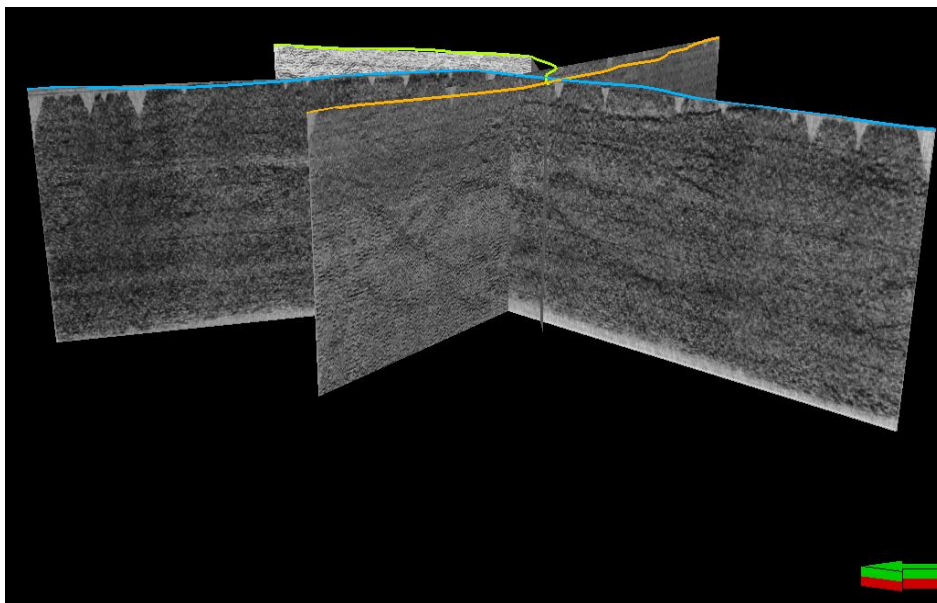


Figure 5.2 - Imported seismic profiles

Import well data

Petrel handles two types of well data: well tops (points) and well trajectories, with or without logs. When importing well data in the supported well formats, Petrel automatically saves the data in appropriate folders and sub-folders in panes. The general workflow for importing well data into Petrel is: import of well heads, insert well path/deviation data and add logs to the wells (Figure 5.3).

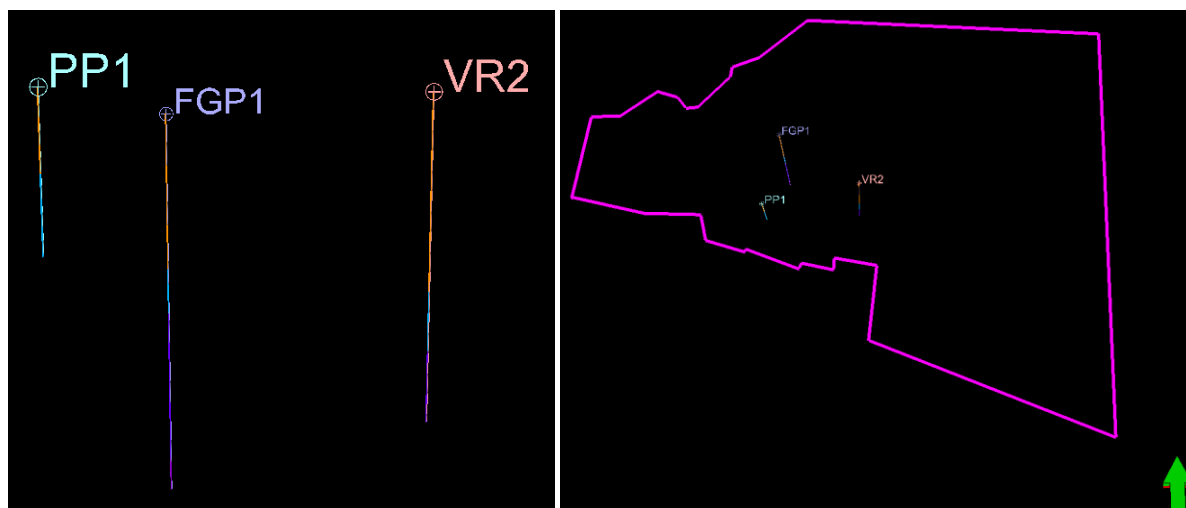


Figure 5.3 - Imported boreholes

This system ensures flexibility and accuracy in the import. The procedure allows for multiple well imports, easy updating of previously imported wells, and the option to further organize the imported wells into sub folders.

Well trace and well logs are stored independently, which allows logs with different sampling intervals to be attached to the same well trace. This may have an effect when using the calculator (Petrel Manual).

Well co-ordinates and lithology from the interested area were known from the collected report. It was prepared with tables in txt format with co-ordinates and names of wells. The locations of cities were imported the same way.

Time stratigraphy was prepared in the Templates panel - Discrete property templates in Time stratigraphy. In a copy of the time stratigraphy the names and colors for stratigraphy zones, which are present in studied area and were documented in wells, were prepared (Table 8).

Table 8 - Statigraphy table

| Code | Name | Color |
|------|------------------------------|-------|
| 0 | PALEOGENE | |
| 1 | MESOZOIC - Choc nappe | |
| 2 | MESOZOIC - Krizna nappe | |
| 3 | MESOZOIC - Tatrucum envelope | |
| 4 | BASEMENT | |

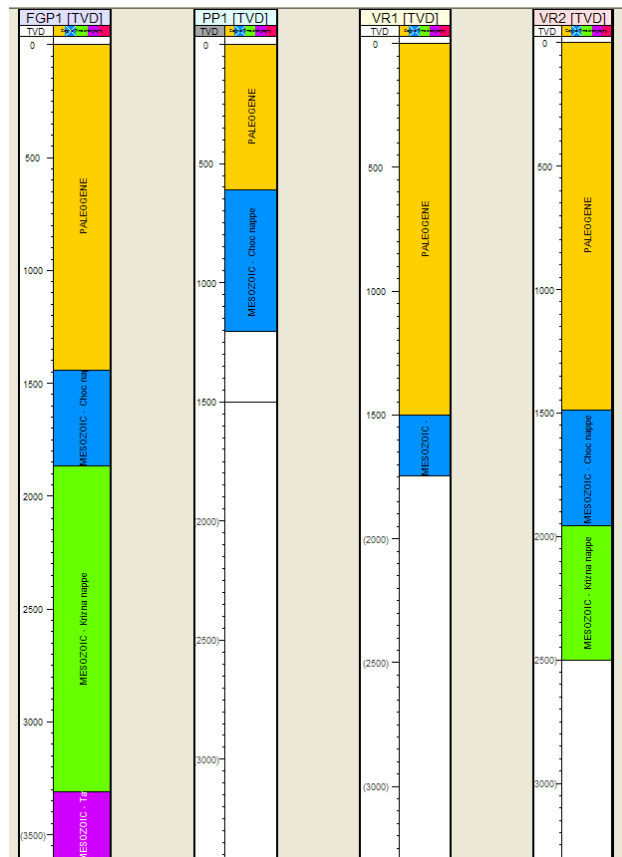


Figure 5.4 - Well stratigraphy

5.2.3 Seismic interpretation

Seismic interpretation was made straight on imported bitmaps with seismics. Faults were interpreted straight on the pictures one by one on profiles.

Horizons were interpreted as polygons. It was not possible to interpret horizons in the geophysics panel by interpreting grid horizons function. Normal seismic diagrams were not available, only the bitmaps of profiles. Horizons were interpreted manually by polygons in Utilities – Make edit polygons. Three polygons were interpreted on each profile: base of the pre-Tertiary (Paleogene) polygon, base of Choc Nappe and base of Križna Nappe polygons (Figure 5.5). Those polygons were then used as input for the formation of surfaces (Figure 5.6)

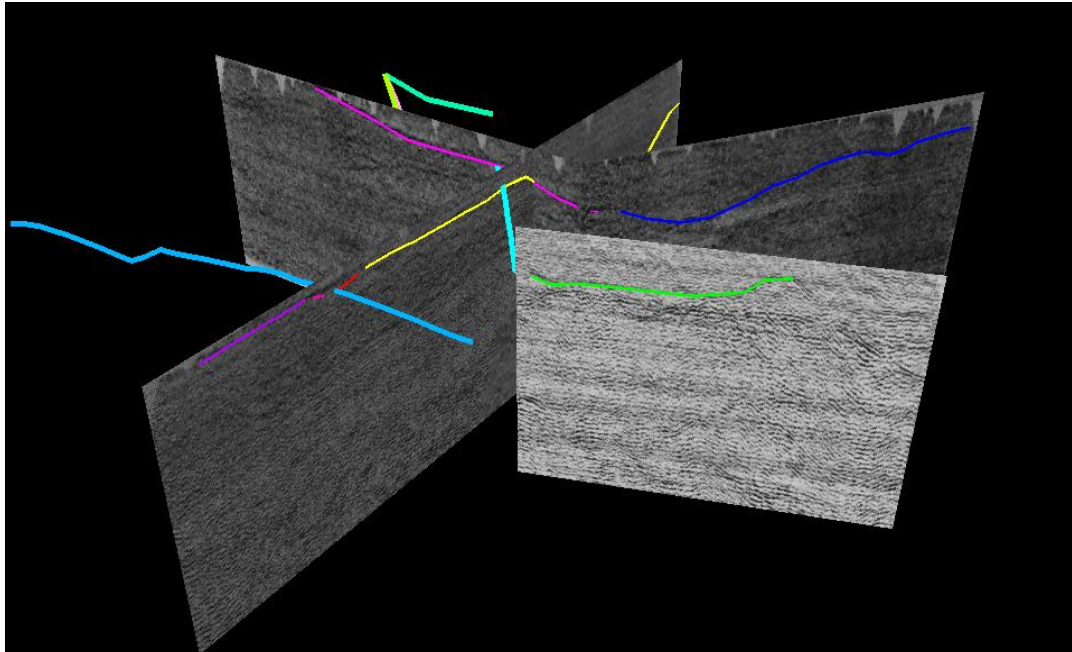


Figure 5.5 - Polygons of Paleogene base

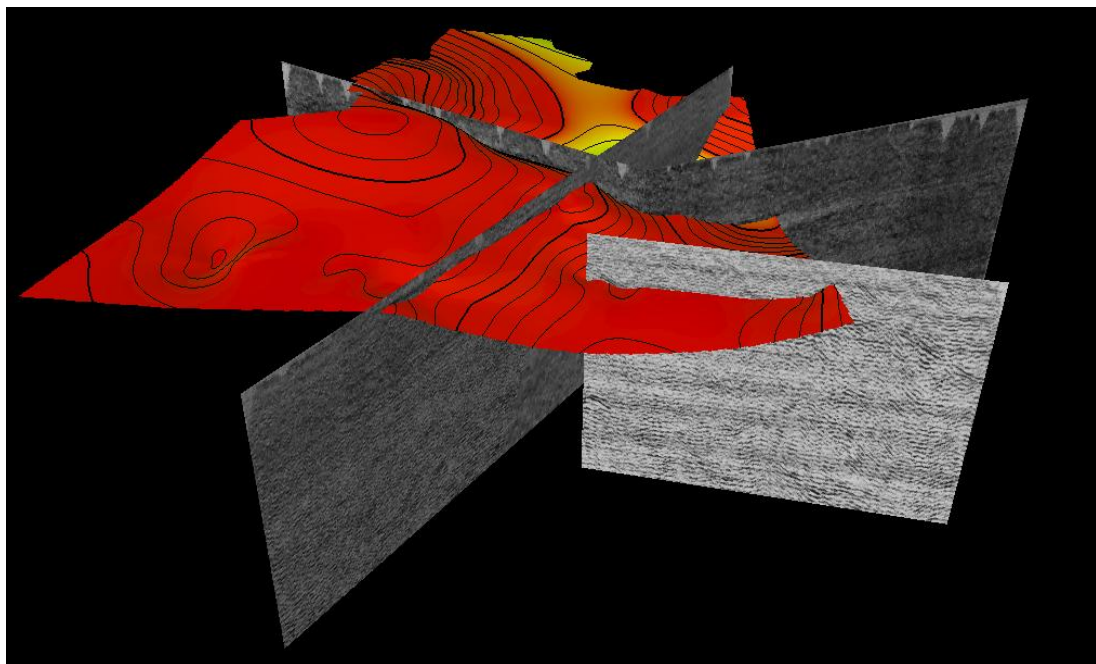


Figure 5.6 - Surface of Paleogene base

5.2.4 Structural Modeling

Structural modeling in Petrel is subdivided into three processes:

- Fault modeling
- Pillar gridding
- Make horizons

Fault Modeling

Fault modeling, which defines the faults in the geological model, forms the basis for generating the 3D grid. These faults define breaks in the grid, lines along which the horizons inserted later may be offset. The offset which occurs is entirely dependent upon the input data, so modeling reverse faults is just as easy as modeling normal faults. All pillars in the 3D grid are extended to meet the top and base of the horizons defining the grid. This was done in Make Horizon, so it was necessary to make sure that all fault models were modeled above the top and base horizon. A modeled fault must never cross another fault without being connected (Petrel Manual).

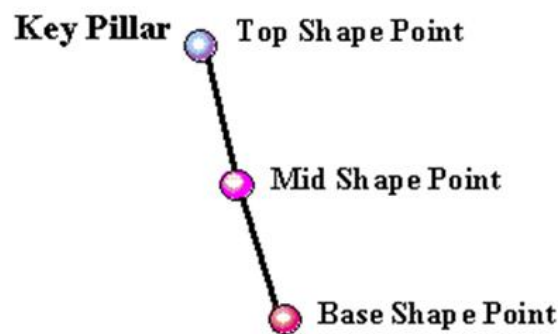


Figure 5.7 - Key pillar representation

Faults are built using Key Pillars. A Key Pillar is a vertical, linear, listric or curved line described by two, three or five so called Shape Points; two for vertical and linear, three for listric and five for curved. Several Key Pillars joined together by these Shape Points define the fault plane (Figure 5.7).

When building a structural model in Petrel, fault modeling is the first step. It was needed to create Key Pillars along all the faults to incorporate them into the model (Figure 5.8).

Pillar Gridding

Pillar gridding generates the grid from the fault model. Limits on the geometry or the grid can be defined during the process so it is easy to generate two grids from the same fault model, one designed for geological modeling and another optimized for simulation.

The process of Pillar Gridding consisted of generating the 3D grid from the fault model. Pillar Gridding is the process of making the 'Skeleton Framework'. The skeleton is a grid consisting of a Top, a Mid and a Base skeleton grid (Figure 5.9), each attached to the Top, the Mid and the Base points of the Key Pillars (the fault model). In addition to the three skeleton grids, there are pillars connecting every corner point of every grid cell to their corresponding corners on the adjacent skeleton grid(s).

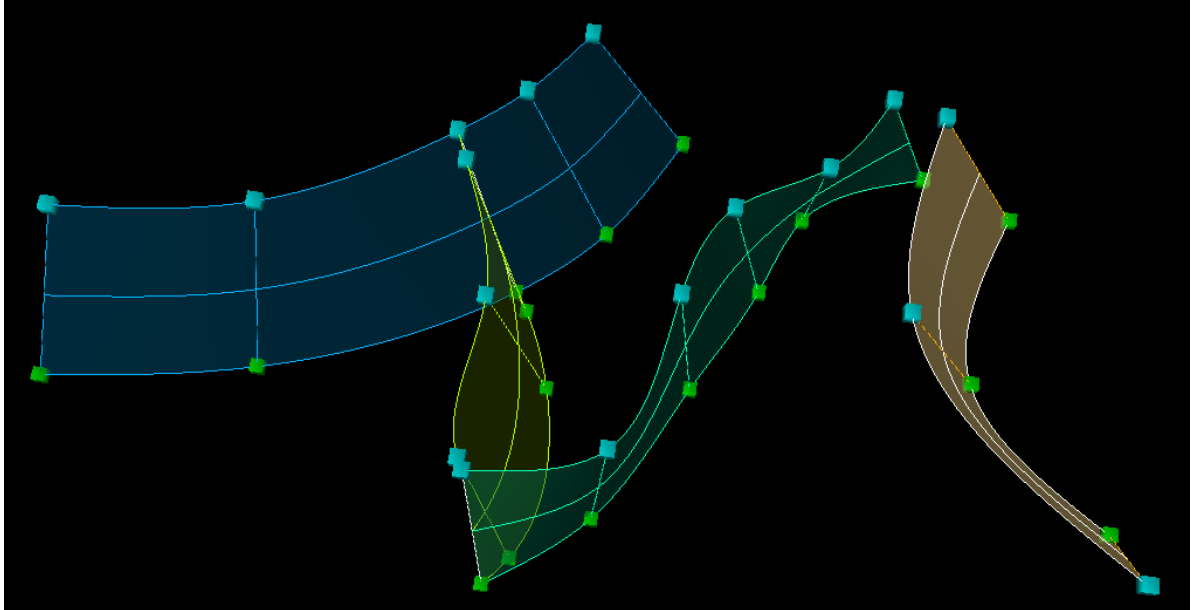


Figure 5.8 - Fault modeling

When the skeleton grid was being created it was working with the Mid Skeleton grid. The Mid Skeleton grid is the grid attached to the mid-lines that connect the Key Pillars. The purpose is to create a grid that looks correct at the midpoint level, with respect to the grid cell size, orientation and appearance of the cells. The next step was to extrapolate this Mid Skeleton grid upwards and downward in order to create the Top and Base skeletons.

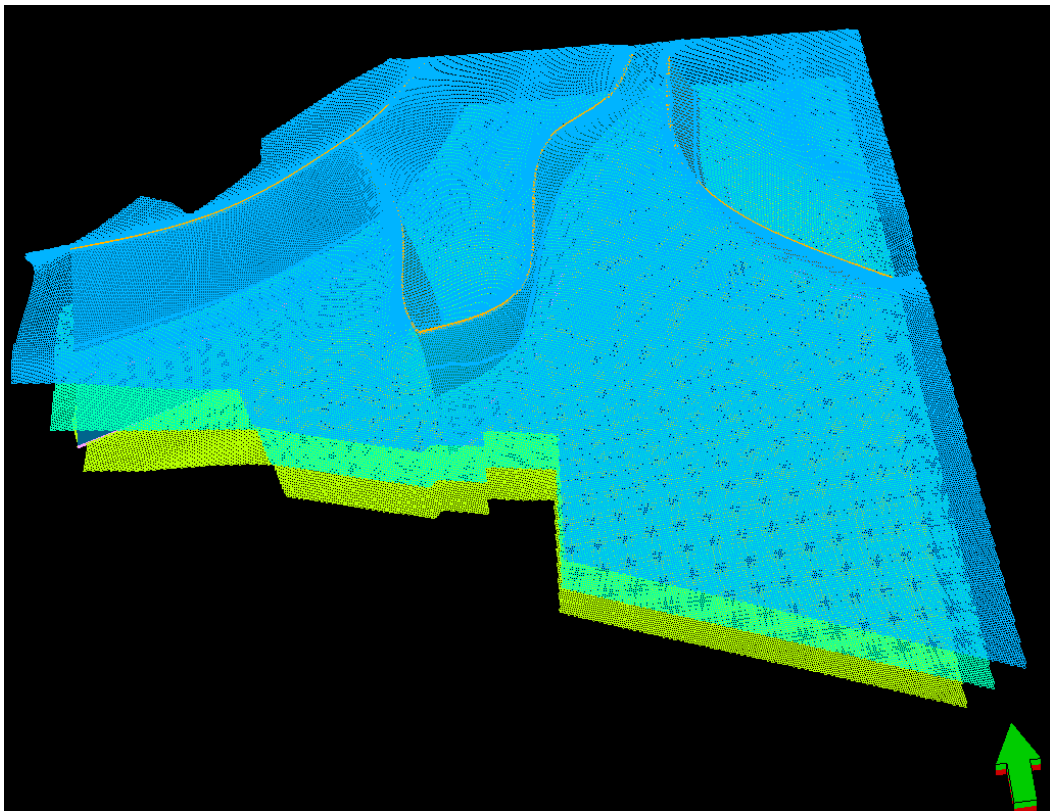


Figure 5.9 - Skeleton grid

Make Horizons

The Make Horizons tool is used for building the vertical layering in the model. It is here that the offset on the faults is defined. Make Horizons generates independent geological horizons from XYZ input data. To generate additional horizons using relative distance to existing horizons, Make Zones must be used. These two processes are used to create the geological zones within the model. It is expected that each zone will have similar petrophysical properties and can therefore be modeled using a single set of input data. (Figure 5.10 and Figure 5.11)

These three processes should always be considered together and it is possible go back and forth between them. Problems with the fault model will often not be obvious before Pillar Gridding begins, and problems with the pillar grid may not be obvious before horizons are built. Similarly, many problems identified when using Make Horizons will require an edit of the pillar gridding options or even the fault model (Petrel Manual).

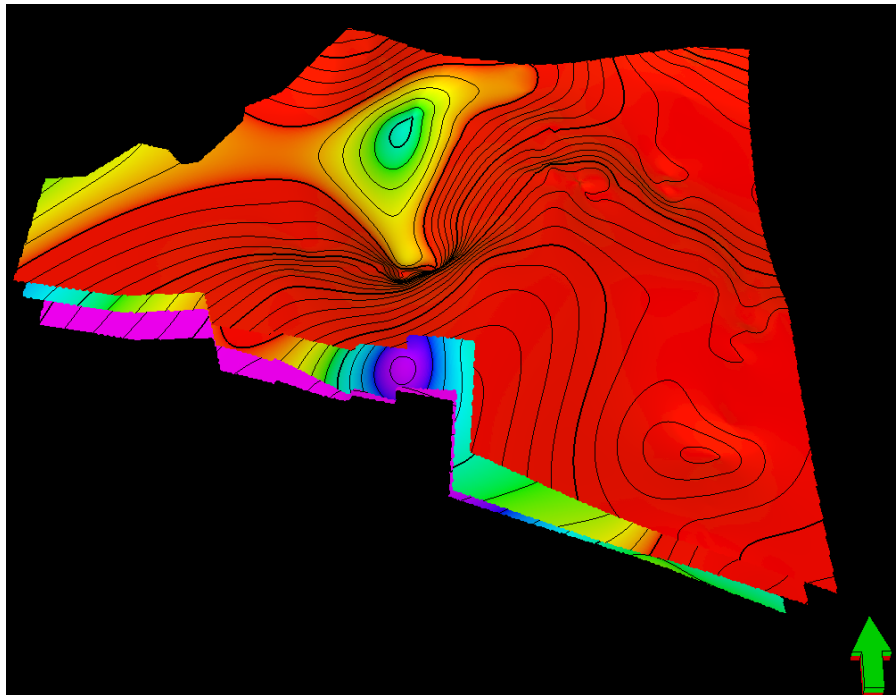


Figure 5.10 - Interpreted horizons

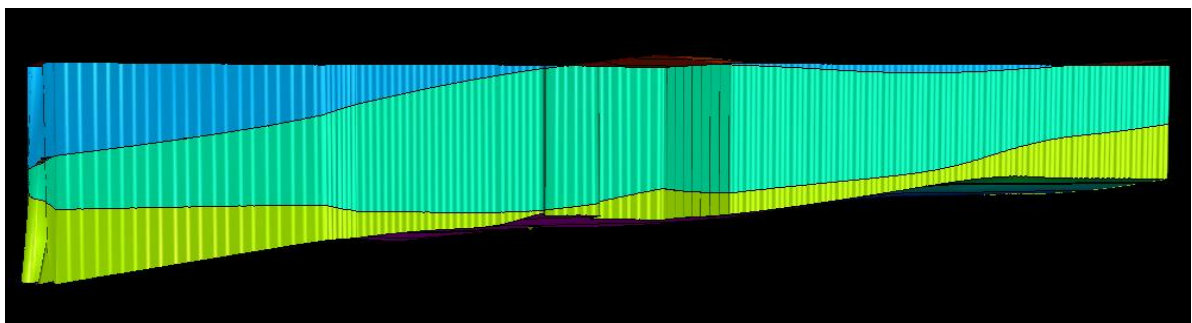


Figure 5.11 - Interpreted zones

5.3 Process resolution and methodology of seismic interpretation – Gerlachov

This studied area is situated on the western border of Gerlachov village. The area is characterized by thick Paleogene rock complexes mainly consisting of claystones and occasional sandstones underlain by Mesozoic and crystalline rocks. . The Mesozoic rocks form the Choc Nappe underlain by the Krizna Nappe. The Mesozoic envelope of Tatricum is expected below the Krizna Nappe. The crystalline rocks are composed of similar rocks to those that are exposed in the neighboring Tatra Mts.

In the study area 73 seismic profiles were made covering an area stretching in a northwest–southeast direction with approximately 25 m distance between them and approx. 1.8 – 3.0 km in length (Figure 5.12). Only 35 profiles were useful for interpretation. All the others were either too small or were not clear enough for interpretation. The realized seismic research had “pseudo – 3 D” seismic status. Data from field measurements were then processed by 2D seismic profiles methodology. Each seismic profile was interpreted. Interpretation was made in 2D diagrams imported to the Petrel in SEGY format.

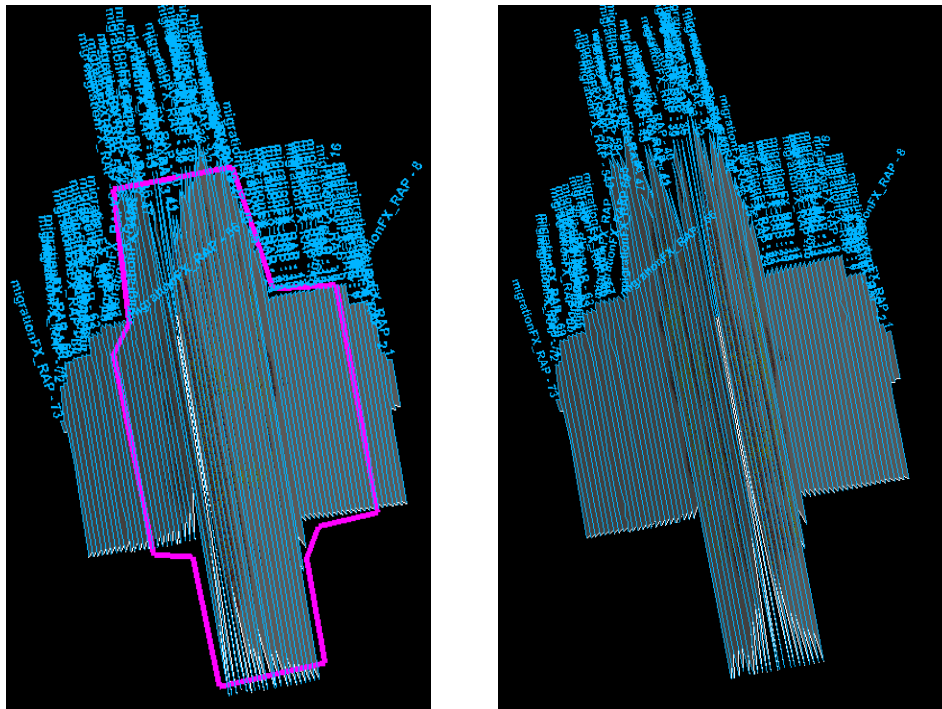


Figure 5.12 - Situation of imported 2 D diagrams, polygon for surfaces creating

After data import to the Petrel program the profiles suitable for interpretation were selected. Altogether 35 profiles were selected. Those profiles were interpreted in the interpretation folder by manual interpretation. The process panel was used for seismic interpretation from the geophysics menu. The seismic horizons and faults were interpreted manually.

5.3.1 Fault Interpretation

There are two ways to interpret faults in Petrel: classical interpretation (drawing fault segments) in the seismic interpretation and by modeling faults directly on the seismic in 3D through the Fault modeling process.

Classical interpretation gives all the flexibility of traditional interpretation together with the added clarity of fault planes triangulated in 3D.

The advantage of using the fault modeling process is that after the interpretation, the model is ready for gridding as soon as the interpretation is complete. Furthermore, the interpreter is forced to solve problems regarding fault hierarchy and connections during interpretation, thus avoiding the need for reinterpretation before fault modeling.

Fault segments are interpreted simply by digitizing directly on a seismic intersection. To start a new fault interpretation, right click on an existing interpretation folder (or if needed insert a new interpretation folder first) and select Insert fault. Then, select Interpret faults or press F and begin digitizing. The new fault object has appeared in the interpretation folder with a name in bold, indicating that it is the active fault.

Faults are digitized in segments (lines), which are automatically triangulated in Petrel to give a fault surface (Petrel Manual).

5.3.2 Horizons interpretation

Horizons were interpreted in the Seismic interpretation process in the Processes pane. Interpretation tools were available on the toolbar to the right of the Display window. The Horizon Interpretation icon in the tool bar must always be depressed to perform horizon interpretation of any kind. The short cut key H will toggle this on automatically. To be able to do any horizon interpretation, a seismic horizon must exist and be active. It is needed to Insert seismic horizon, or left click on an existing horizon to activate it (name in bold text).

Auto tracking settings for each of the interpreted horizons are held in the settings for that horizon. To begin a new interpretation, it must be added to an interpretation folder if one is not already present in the project, (Insert, New Folder, New Interpretation Folder), then select Insert seismic horizon. In the settings dialog for the new horizon is an Auto tracking tab function, this holds the autotracking settings for that horizon (Petrel Manual). An example of Faults and horizons interpretation is shown in Figure 5.13. For visualization, surfaces were made. In the Utilities menu a polygon was prepared for making boundaries of the interested area. To make surfaces, 4 horizons were inserted one by one within the boundaries of the polygon.

5.3.3 Make Surfaces

The Make/Edit Surface utility can be used to construct a surface (grid) from different types of input data. This can also be used to make trend surfaces for the property modeling task and to make fault surfaces.

Once a surface has been constructed using the make surface operation, it can be updated, taking account of any changes in input data, boundaries, trends etc. by selecting regenerate from the right mouse button options. An image can be used as the main input.

Surfaces were made in the Process diagram - the Make/Edit Surface process dialog (Petrel Manual).

In the Execute tab, input data were entered into the Main input area. The area of the new surface was limited by a boundary; boundary data was entered into the Boundary area. In the Output data, was entered an existing surface in the Surface area.

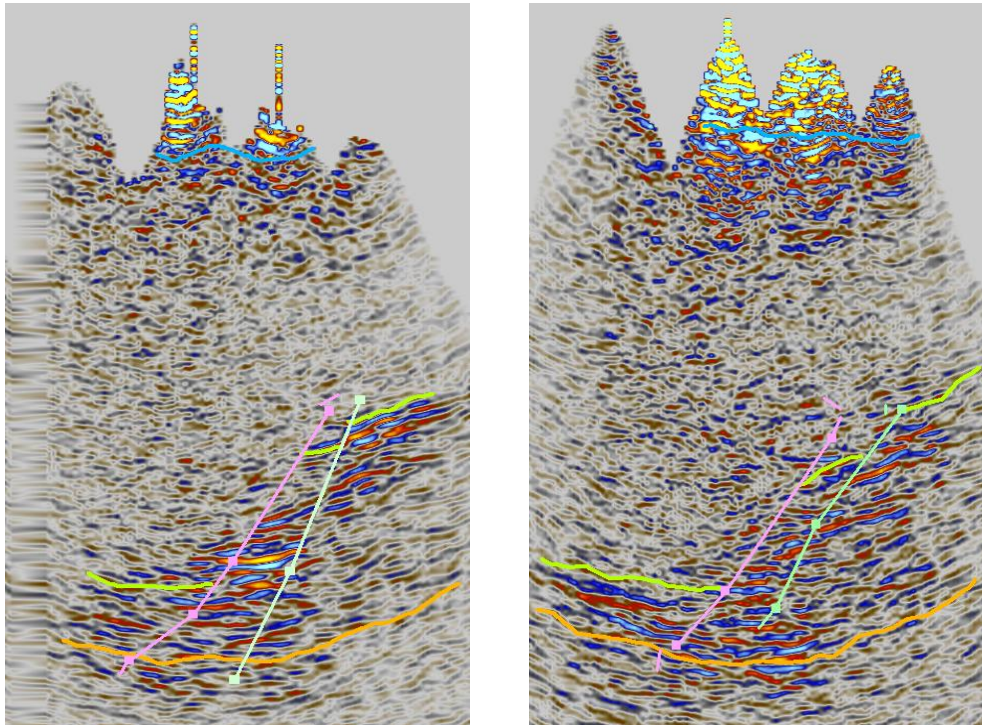


Figure 5.13 - Faults and horizons interpretation on seismic section Nr. 30 and 40

The type of input data was selected from the pull-down menu and the Suggest method and the settings tab was pressed.

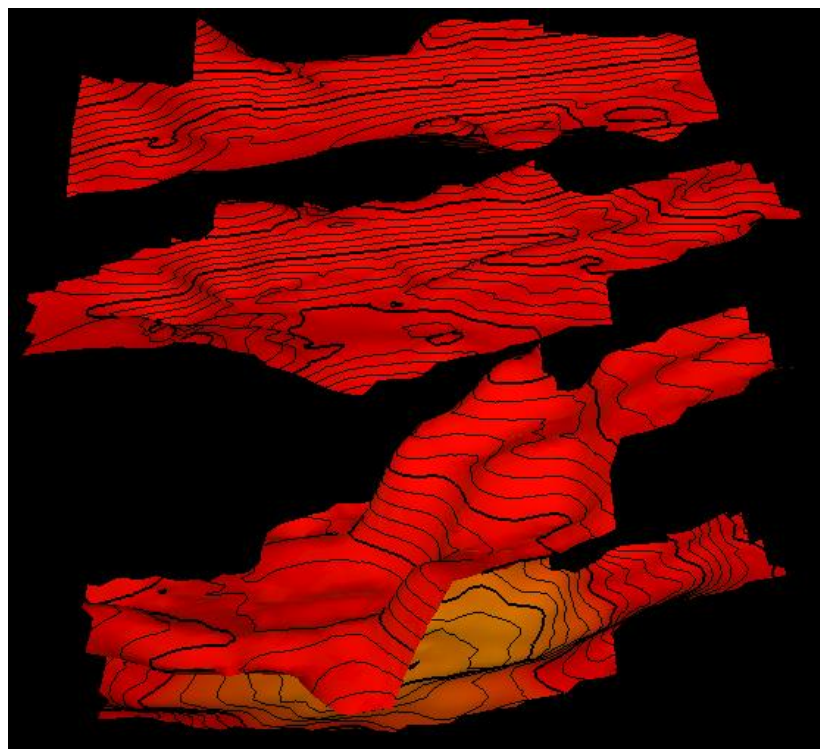


Figure 5.14 - Interpreted surfaces

Appropriate settings under the Geometry tab were chosen. If Polygons or lines are used as input, this data can be refined under the Pre Processing tab. A trend for the data could also be added here. Every 4 horizons were inserted through this process. An example of this is shown Figure 5.14.

5.3.4 Structural Modeling

After manual interpretation of seismic profiles, structural modeling was made. Structural modeling is subdivided into three processes: fault modeling, pillar gridding and making horizons. These processes are similar to the first modeling (Poprad basin) and they are described in the previous methodology. Results from structural modeling are shown in the pictures below.

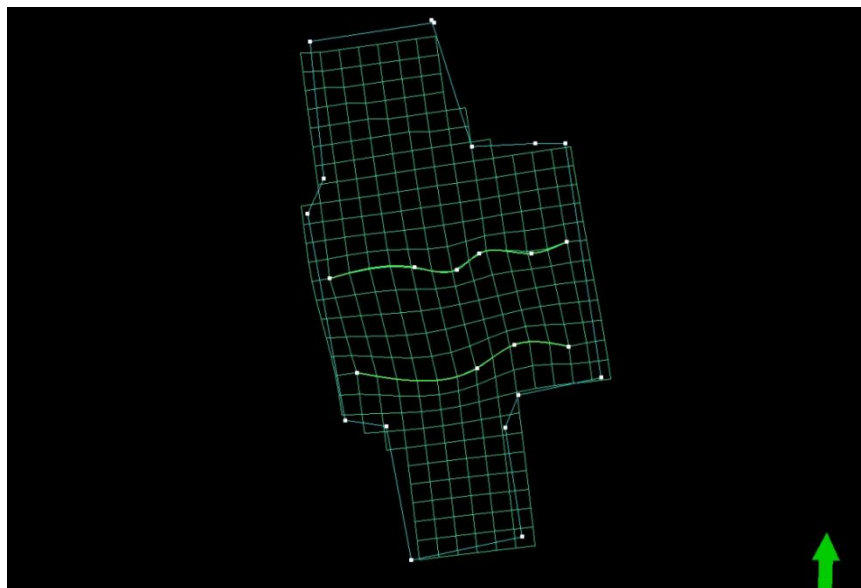


Figure 5.15 - Grid of the model showing grid boundary and faults

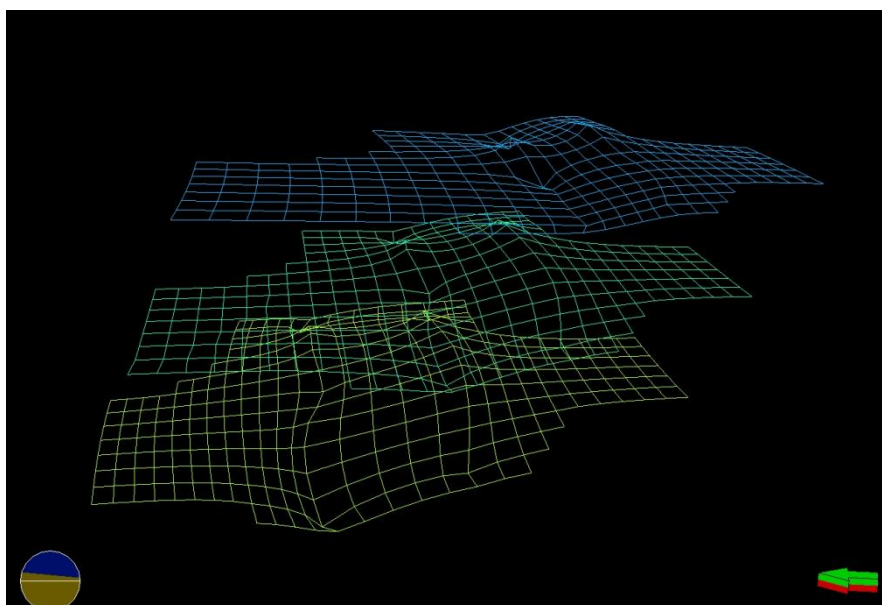


Figure 5.16 - Grid of model

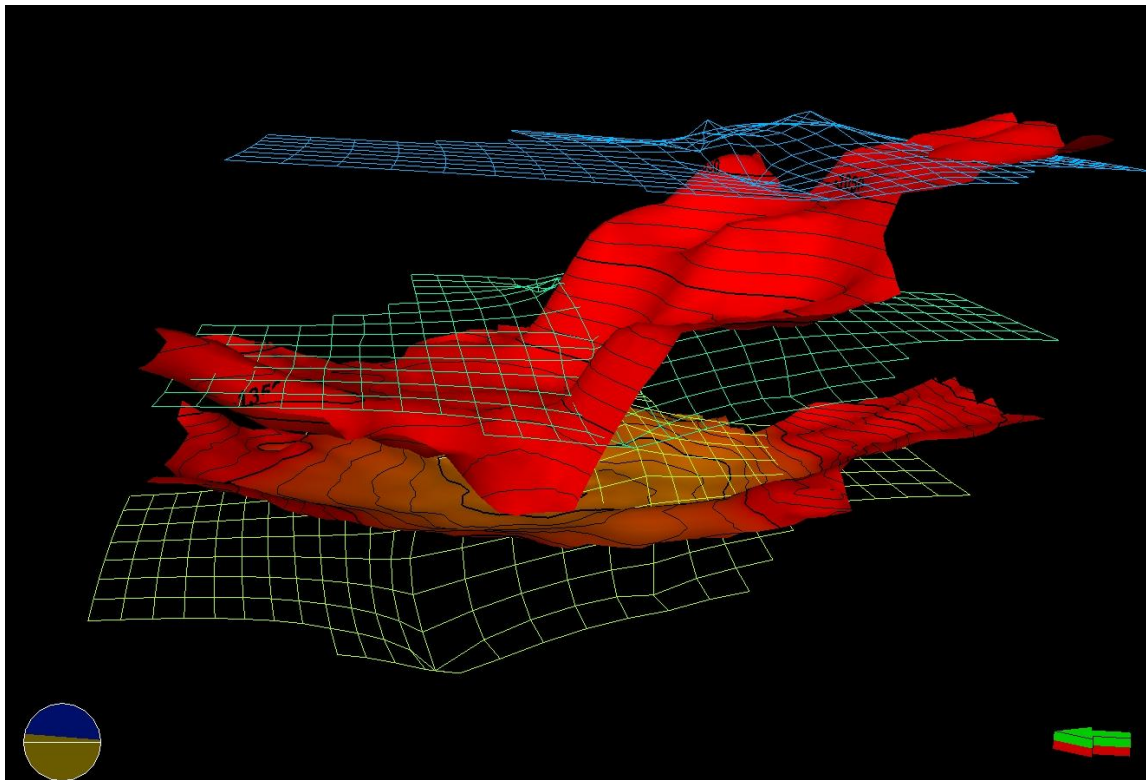


Figure 5.17 - Grid model with Choc and Krizna nappe surfaces

6 RESULTS AND DISCUSSION

6.1 Poprad basin

Based on the results from my model the following bases were characterized:

- The Paleogene base
- the base of Mesozoic Choc Nappe
- the base of Mesozoic Krizna Nappe

The tectonic structure (faults) in the studied area was also interpreted. Larger and more detailed images are found in Appendix A.

6.1.1 The Paleogene base

On the seismic profiles the Paleogene base (Figure 6.1) was possible to interpret precisely. The Paleogene part of the unit is formed by chaotic reflectors in the higher part, probably representing alternating sandstones and claystones. In the lower part the reflectors are less visible and this part is probably represented by monotonous claystones. This interpretation is also documented by the geological structure of the wider area confirmed by several wells (i.e. PP-1, FGP-1, VR -1, 2).

The Paleogene rocks in Poprad Basin area are represented by thick rocks formations. They are the isolator for geothermal water aquifers which are situated under this unit.

The thicknesses of Paleogene unit are from 400 to approx. 1400 m.

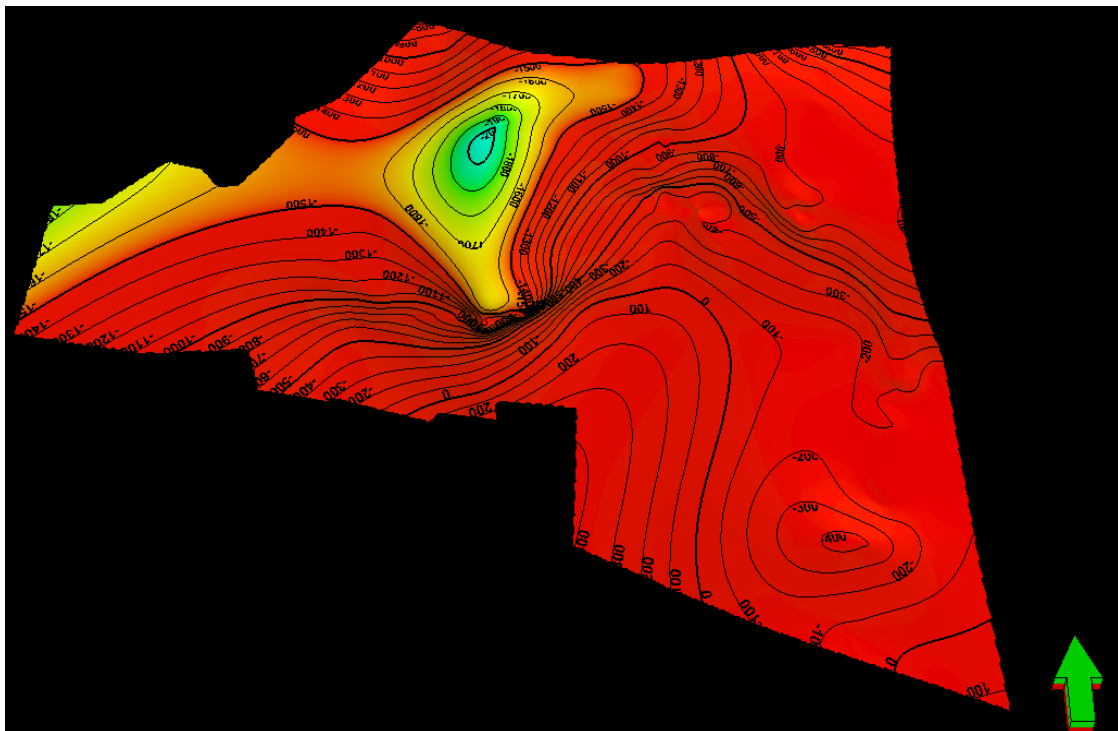


Figure 6.1 - Surface of the Paleogene base

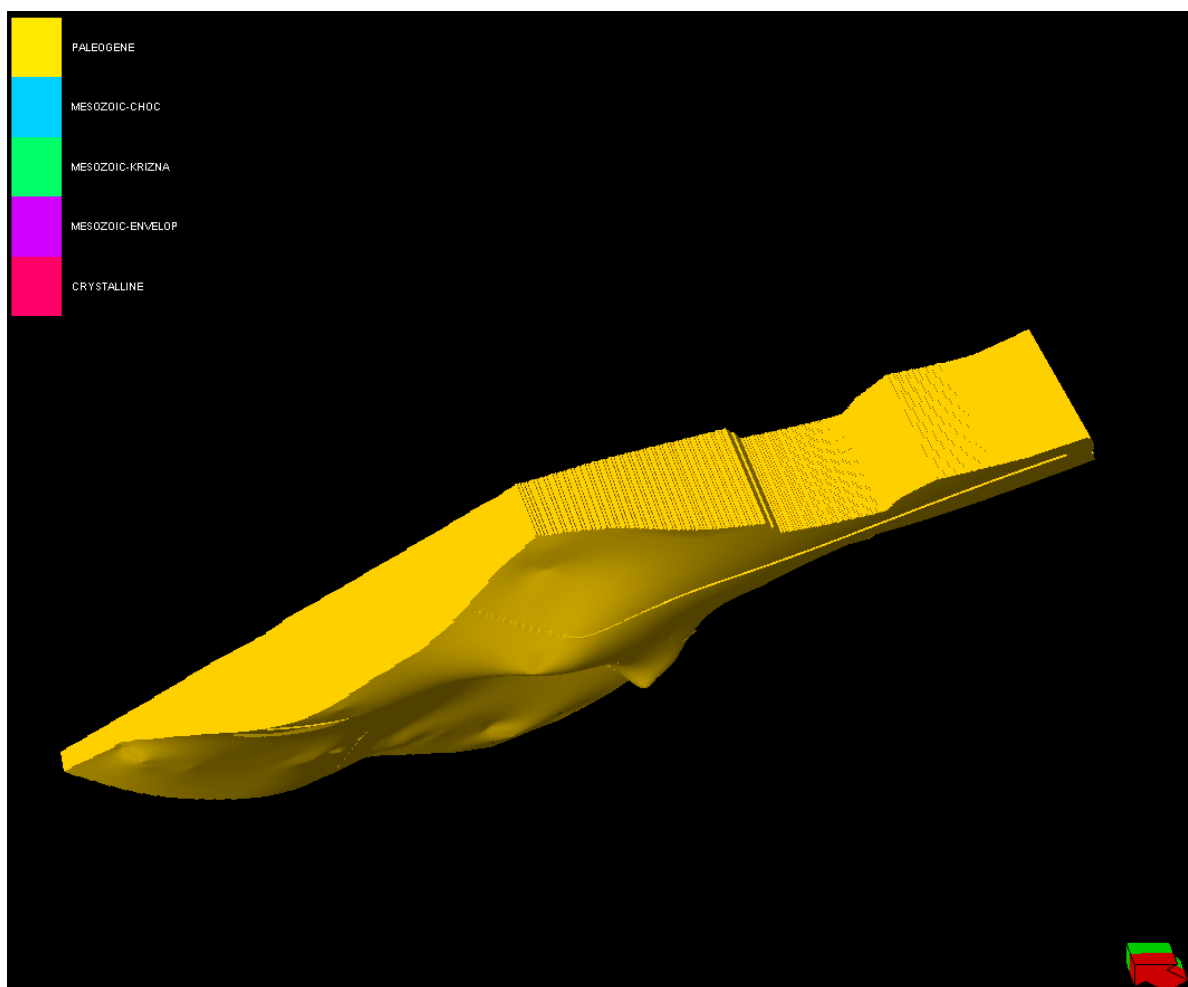


Figure 6.2 - Representation of the body of the Paleogene unit

6.1.2 Choc Nappe

Under the Paleogene unit Choc nappe underlain by Krizna Nappe was interpreted. (Figure 6.3) The lowermost complex is represented by Mesozoic envelope covering crystalline rocks.

The base of the interpreted Choc nappe is showed in Figure 6.4 as it was modeled in the PETREL software.

The rock sequences of Choc Nappe are the main geothermal water aquifers. The lithological composition of the nappe is known from the exposures cropping out in the area of Kozie chrby Mts. and from boreholes in Poprad Basin. Carbonate rocks of the nappe are found in northern part of Hornad Basin. This Mesozoic unit is represented by dolomites. Based on their properties and knowing the hydrothermal water localizations, those dolomites are a major aquifer for these waters.

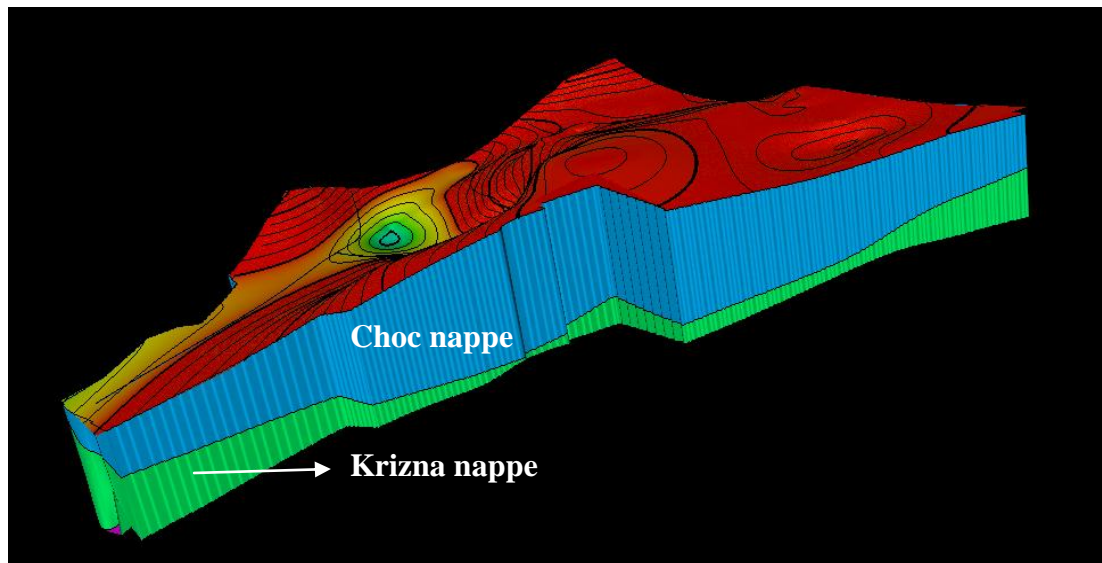


Figure 6.3 - Choc Nappe and Krizna Nappe horizons as interpreted in PETREL

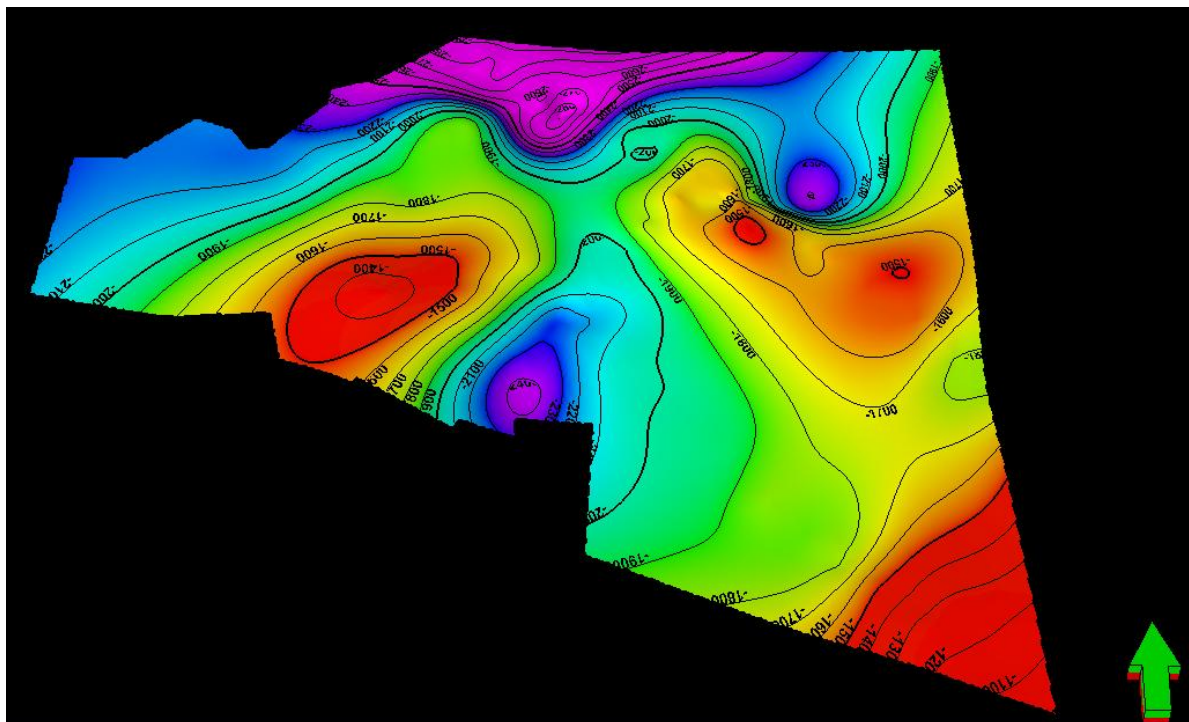


Figure 6.4 - Base of the Choc Nappe

Choc nappe thicknesses are variable in the interested area. In the central part of the basin the thickness of the nappe varies from 200 to 1100 m. The thickness increases from southwest to northeast. The highest elevation of the Choc Nappe surface occurs in the northern part of the study area where thickness varies from 700 to 1000 m. Smaller thicknesses of around 400 m are close to borehole FGP-1. Toward the south, the thicknesses are again larger-approximately 700 m and more. The bigger thicknesses in elevations and lower thicknesses in depressions in Choc Nappe showed the more advantageous places for hydrothermal water localization. (Figure 6.11)

A different situation can be seen in the southeast of Vrbov fault toward the Hornad basin. In this area the thicknesses of the Choc Nappe varies from 1200 to 2000 m. (Figure 6.5)

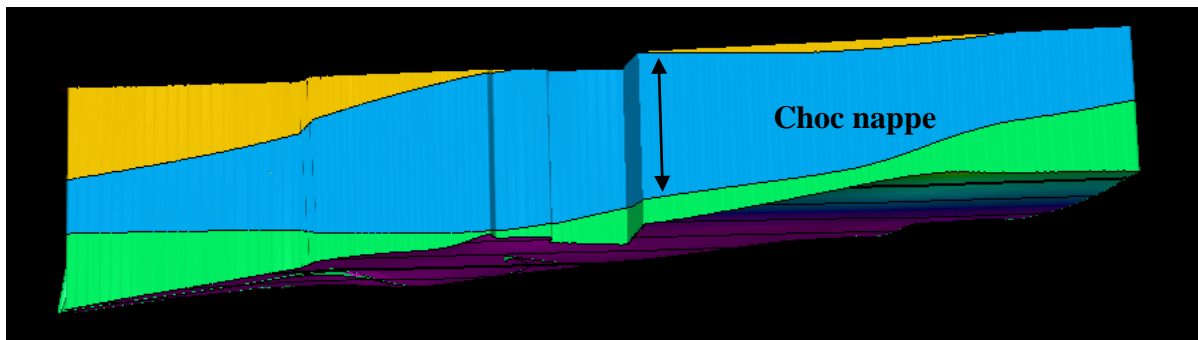


Figure 6.5 - Choc Nappe thickness in the southern part of the study area

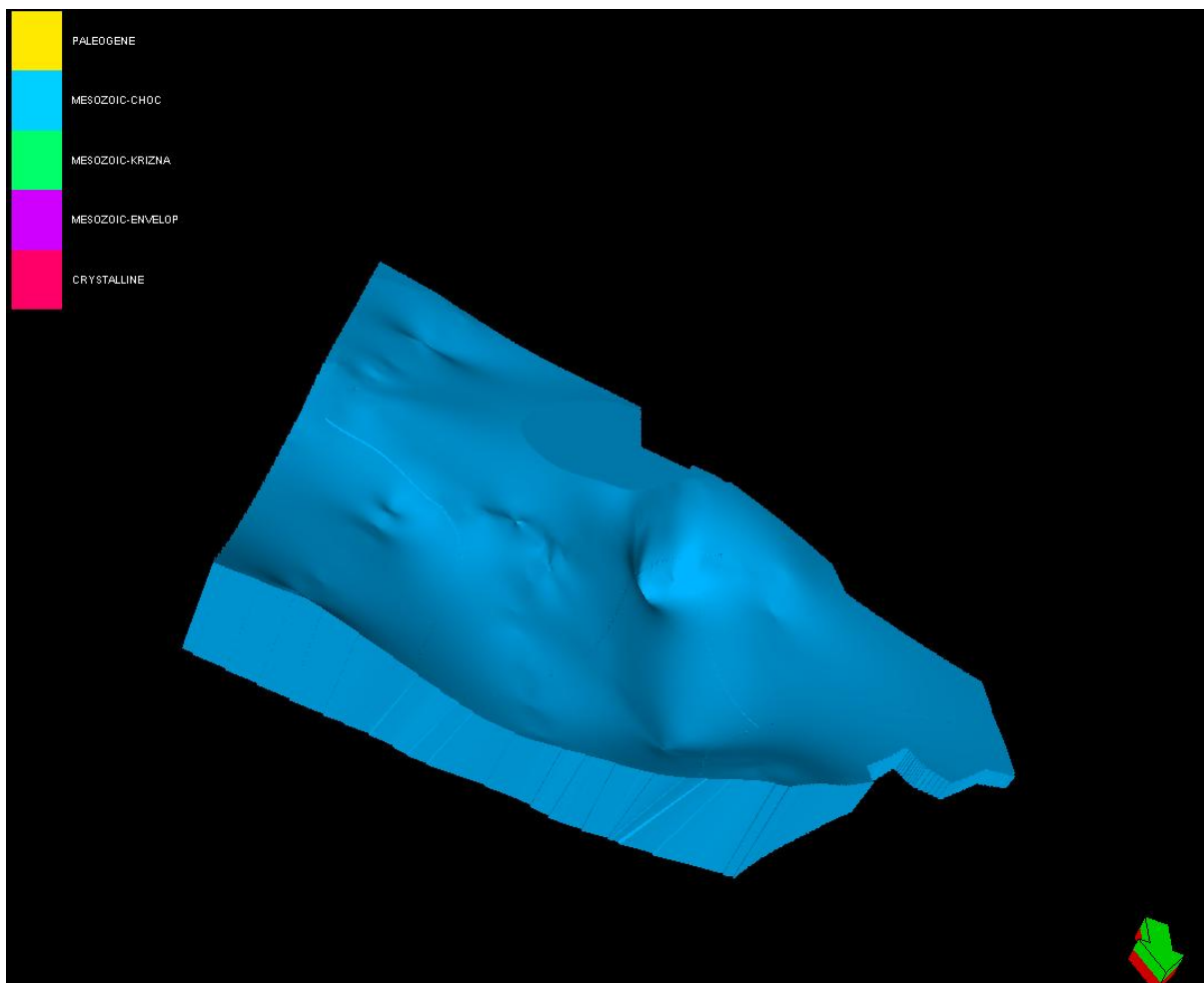


Figure 6.6 - Representation of the body of Choc nappe

6.1.3 Krizna nappe

Krizna nappe is separate from the Mesozoic envelope by tectonized surface. The base of the Krizna nappe unit was the last base to be interpreted. (Figure 6.7)

Krizna nappe rocks were documented in two wells – FGP –1 (drilled all part of Krizna nappe) and VR- 2 (finished in Krizna nappe).

The main rocks are limestones of Jurassic age, Keuperian formation and Triassic dark limestones. In the borehole FGP – 1 the documented nappe thickness is 1445 m.

Based on the rock composition of Krizna and Choc Nappes and well information we can conclude that the Krizna unit is less favorable from the viewpoint of water accumulation and circulation.

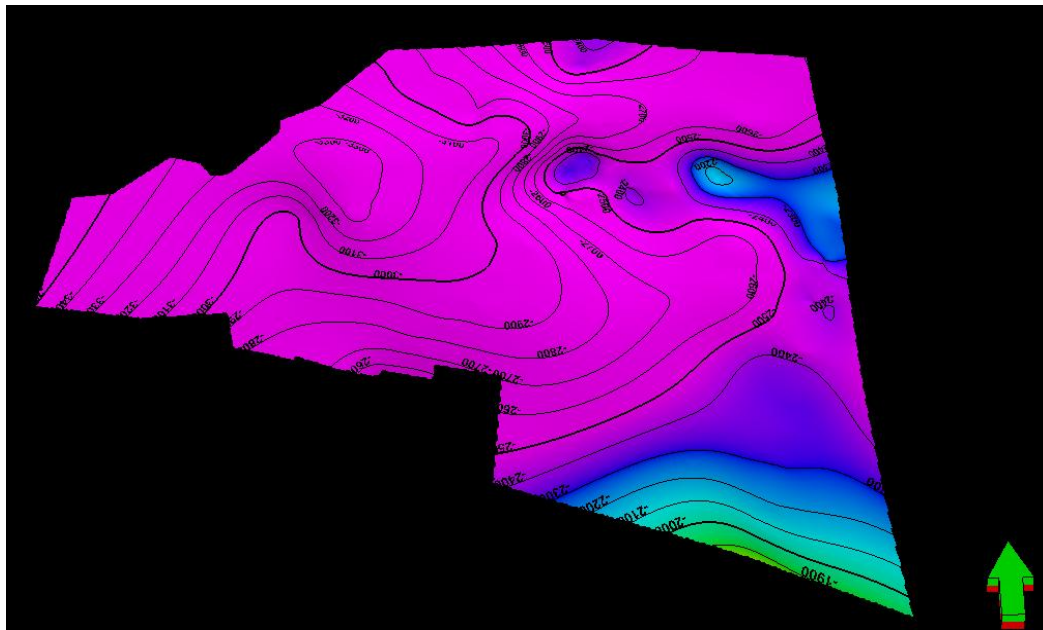


Figure 6.7 - Basal surface of Krizna Nappe

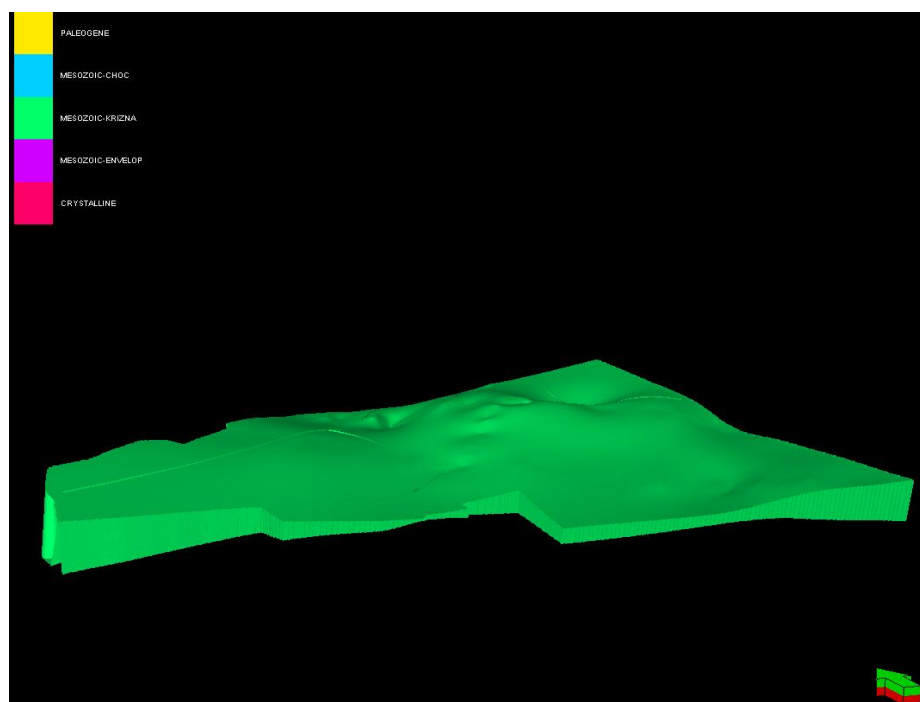


Figure 6.8 - Representation of the Krizna nappe body

6.1.4 Tectonic structure

The main faults in the Poprad Basin are the Subtatric fault and the Vrbov fault. The Subtatric fault occurs close to the north-western border of the studied area. Vrbov fault trends from south-west to north-east and is situated on the south-eastern part of Poprad Basin. In the study area, four faults have been interpreted that importantly influence the structure of the basin (Figure 6.9).

The subtatric dips toward southeast and south. Vrbov fault dips toward north-west and the amplitude of throw varies from 200 to 700 m.

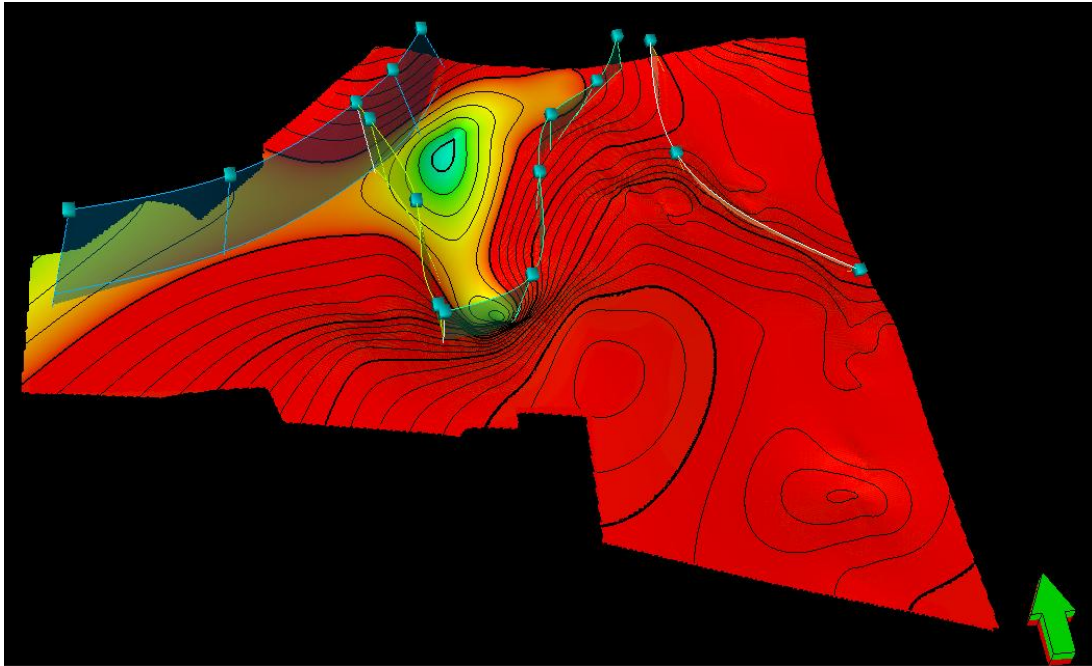


Figure 6.9 - Demonstration of interpreted faults intersecting the base of Paleogene unit

Between them a fault going from south (Vrbov fault) to north-west (Subtatric fault) was interpreted. This fault bounds the depression from the western margin (Figure 6.9). The base of the Poprad Basin gradually sinks from west to north-east between Subtatric and Vrbov faults. The deepest depression occurs close to Subtatric fault. Those faults form the basic structure of Poprad Basin.

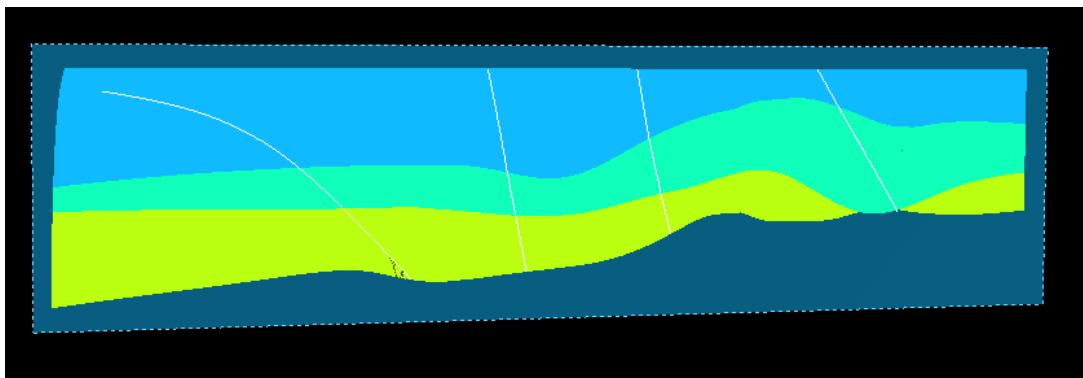


Figure 6.10 - West - East intersection of the modeled area showing all interpreted faults

Based on wells from the surrounding areas as well as on the interpretation of the seismic, dolomites of Choc Unit below the Paleogene unit were interpreted. These are underlain by carbonates of Krizna nappe. Dolomites are the main aquifers for geothermal waters. Depressions and elevations of dolomite base between the faults are the structures of synclinal and anticline with elevation differences from 200 to 800 m (Figure 6.10 and Figure 6.11). These structures are covered by thick Paleogene strata. Paleogene sediments are isolators for water transfer. Permeable dolomite structures are places for geothermal waters cumulating under impermeable top seal. There are expectations that water is getting inside to the dolomite base by faults zones. Figure 6.13 and Figure 6.14 show the faults surfaces in the different bases.

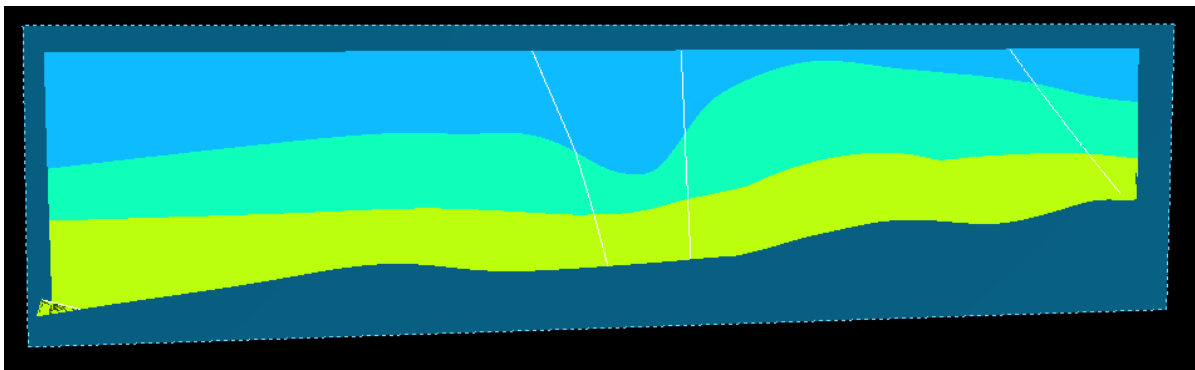


Figure 6.11 - West - East intersection of the modeled area showing the syncline and anticline structures

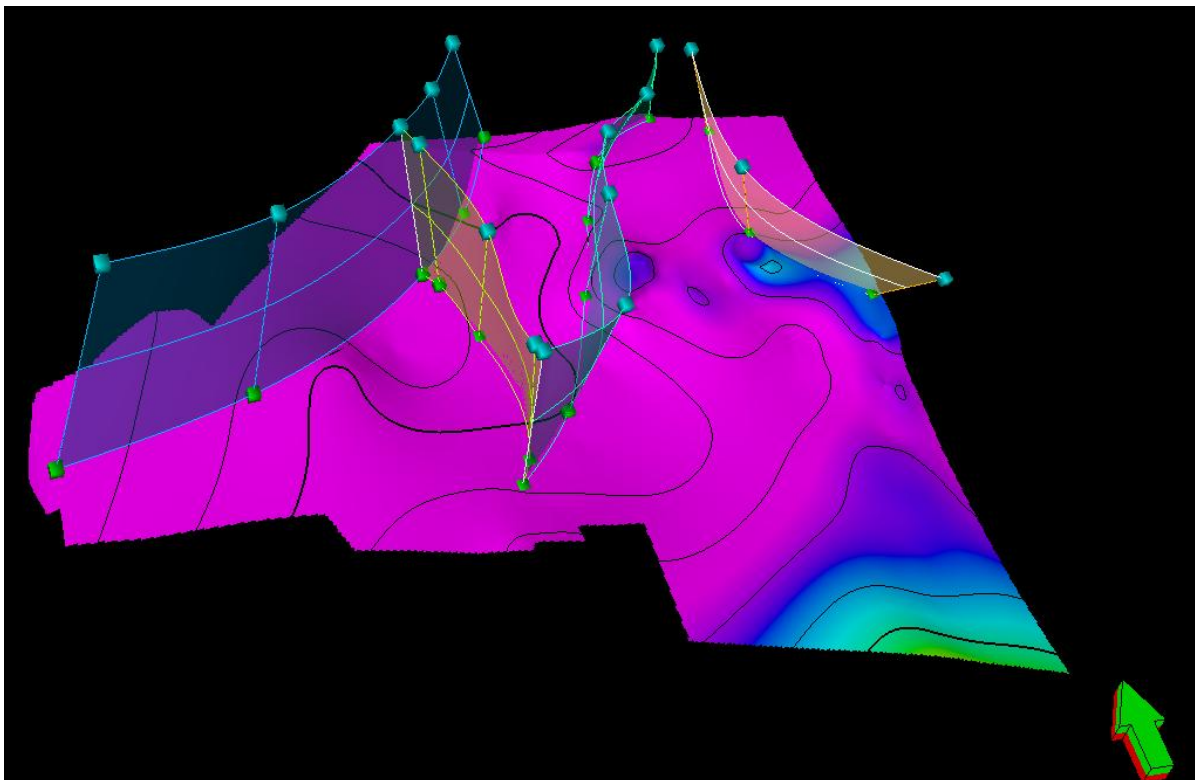


Figure 6.12 - Demonstration of interpreted faults on the base of Krizna Nappe

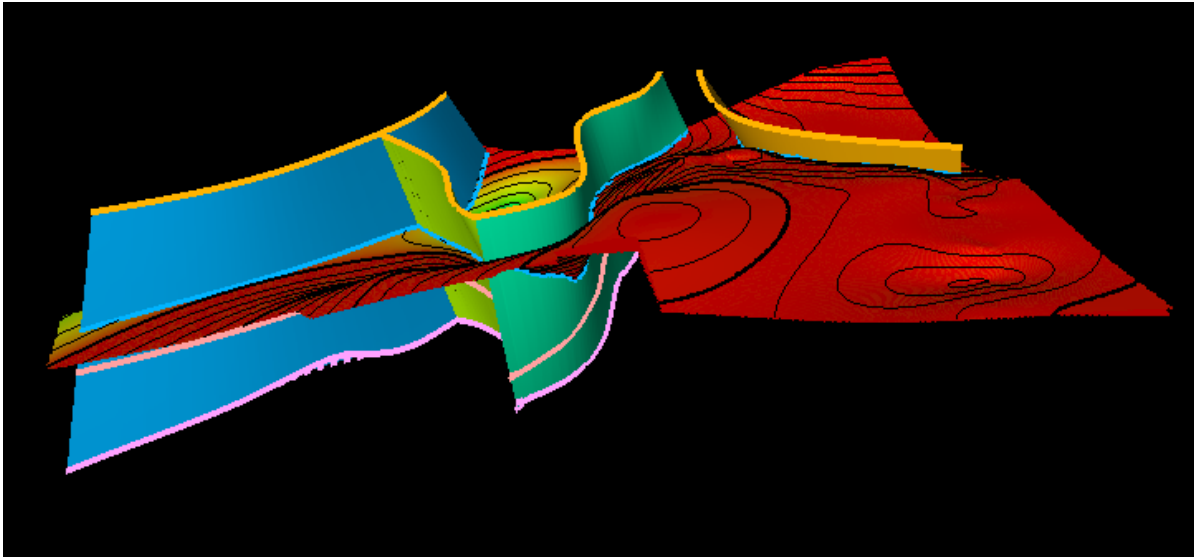


Figure 6.13 - Faults surfaces with Paleogene base

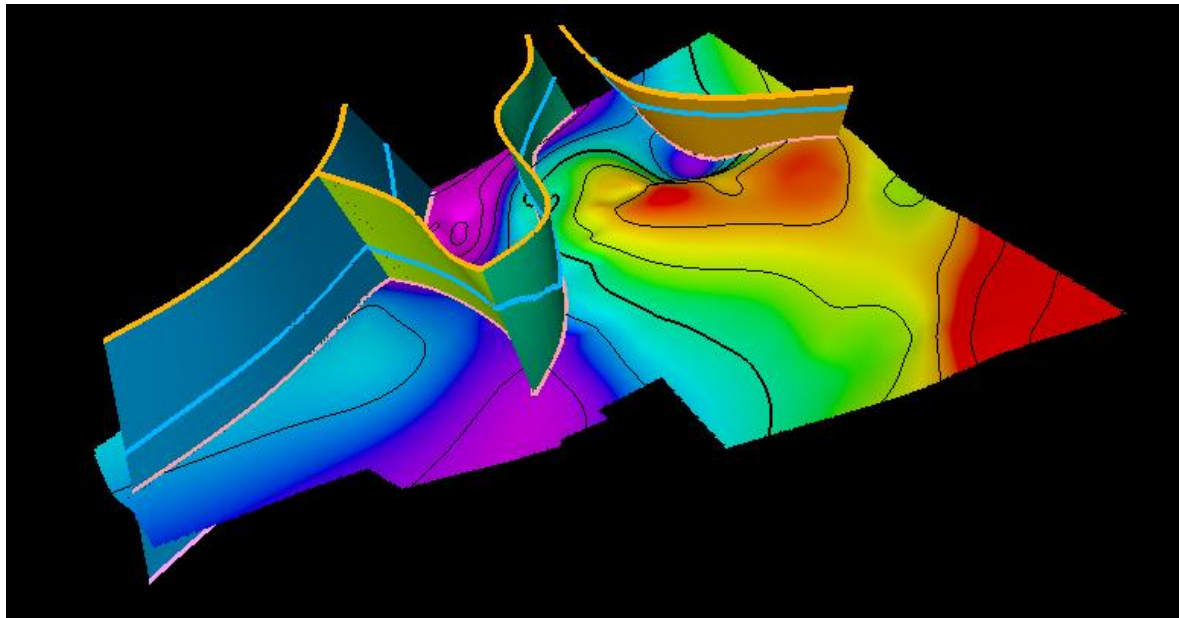


Figure 6.14 - Faults surfaces with base of Choc nappe

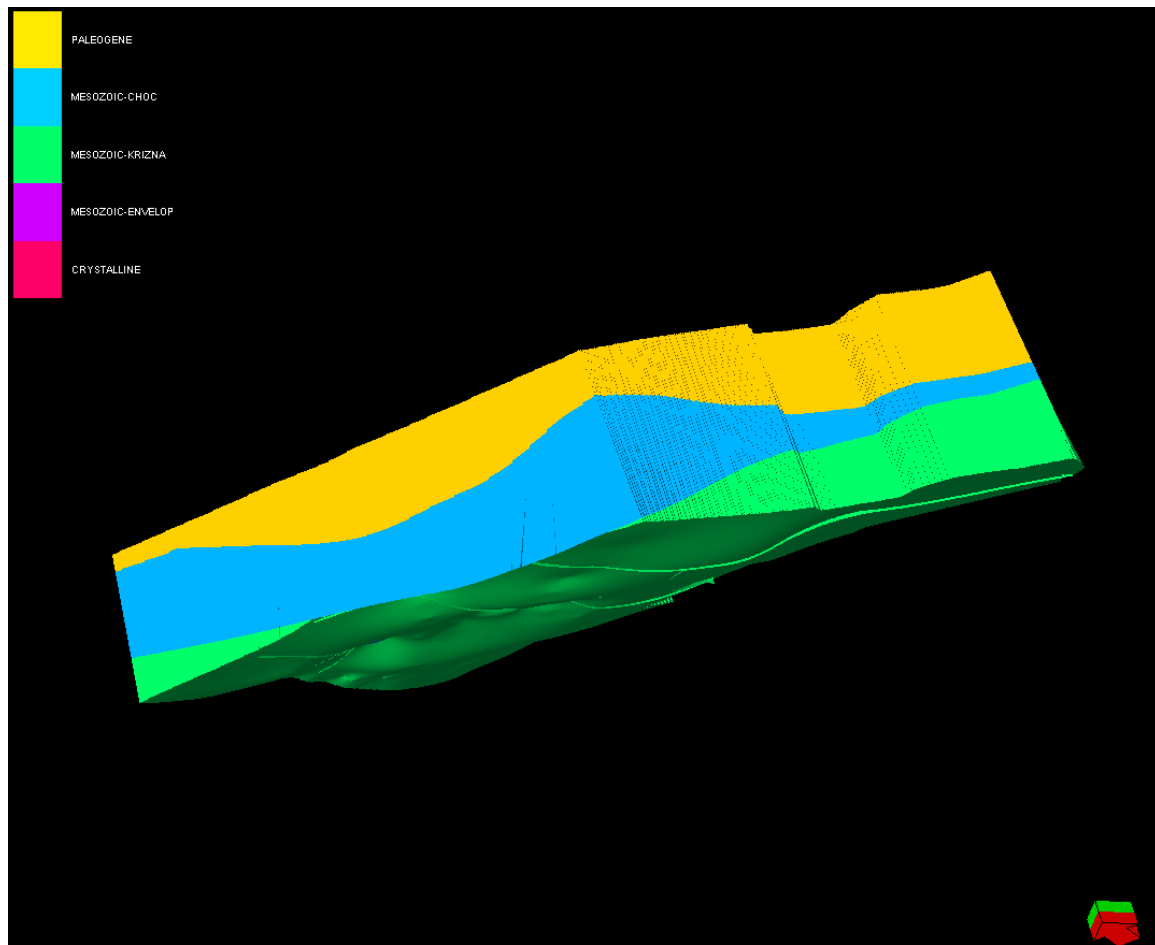


Figure 6.15 - Model of interpreted geological units

Based on the 3 D model (Figure 6.15) we can see the general geologic composition, thicknesses of Paleogene sediments, Choc and Krizna Nappe carbonates in study area. The most important tectonics structures were interpreted (Figure 6.9). As was mention before, the Choc nappe is the main reservoir for geothermal waters. After modeling that we can see the reservoir position, tectonic breach of this layer and thicknesses. This model can show us the possible places for geothermal well locations.

6.2 Gerlachov

6.2.1 Seismic profiles interpretation

The analysis of seismic profiles shows 3 distinctive seismic units (Figure 6.16). The differences depend on their different physical properties.

The first seismic unit was defined in the highest part of the profiles, and it reaches some 1300 ms depth. This group is made by transparent reflectors, which are chaotic and faint in the topmost part of the profiles. They are more visible farther down in the profiles.

The second seismic unit is made by strong reflectors, which reflect acoustic impedance changes along striking lithologic boundaries. In each profile there occur these reflexes below the first seismic unit. They start at 800 ms TWT and on the left side of profiles they reach 1300 ms. The reflectors are more organized and parallel than in first unit.

The third seismic unit is situated in the lowermost part of the profiles. Similar to the first unit it is characteristic by transparent and weakly visible reflectors. The parallel structure, suggesting the parallel bedding, is visible.

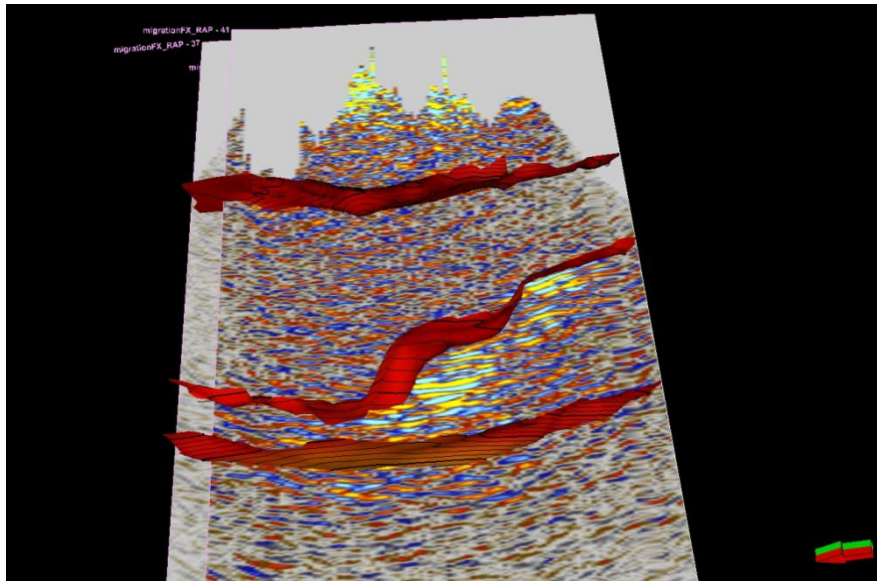


Figure 6.16 - Interpreted seismic units

6.2.2 Seismic unit I - Paleogene deposits

The first seismic unit (Figure 6.17) contains Paleogene sediments assigned to the Subtatric Group. Transparent reflexes, with chaotic structure, suggest that the whole complex is built of rocks with similar physical properties, most probably claystones. The highest part of the unit is formed by stronger reflectors, probably representing alternating sandstones and claystones. In the lower part the reflectors are less visible and this part is probably represented by monotonous claystones. This interpretation is also documented by the geological structure of the wider area confirmed by several wells (i.e. FGP-1). The upper part of the unit consists of Zuberecke Fm. (alternating sandstones and claystones) that is underlain by Huty Fm. mostly represented by claystones. The age of these formations is Late Eocene – Oligocene.

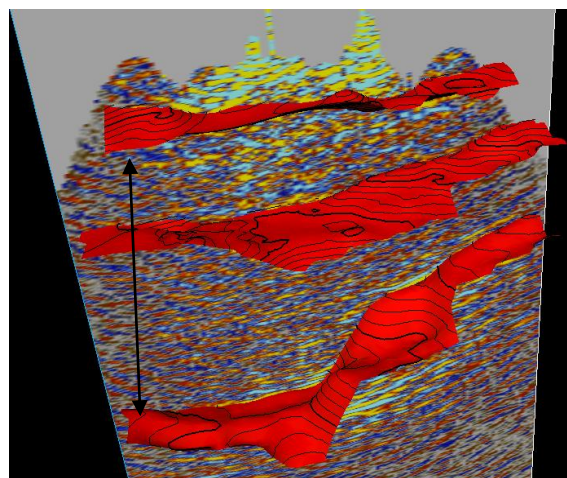


Figure 6.17 - Seismic unit I Paleogene deposit

6.2.3 Seismic unit II - Choc Nappe

The second seismic unit (Figure 6.18) is characterized by strong reflectors with relatively good internal organization showing parallel reflectors. This suggests alternating thick bedded lithology like dolomites typical for Choč Nappe. The thickness of Choc Nappe interpreted from seismic profiles 753/93 and 756/93 (mentioned in the interpretation from the Poprad Basin) varies from 400 to 600 m. Choc Nappe thickness documented in borehole FGP-1 Stara Lesna was 425 m while the thickness of the nappe based on our interpretation is max. 600 m.

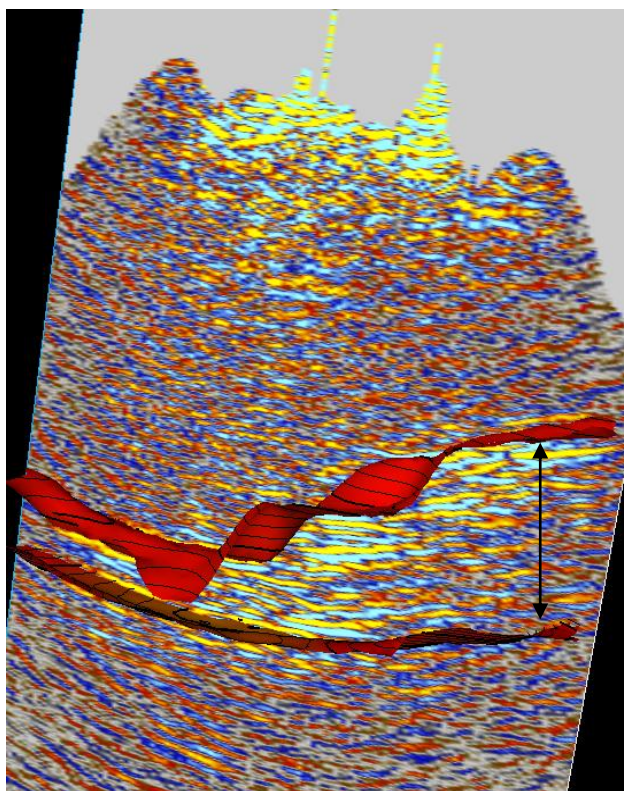


Figure 6.18 - Seismic unit II Choc Nappe

6.2.4 Seismic unit III – Krizna Nappe

The seismic unit III (Figure 6.19) is typical by high-amplitude chaotic reflectors. The change of the reflector characteristics compared to the unit II suggests a change of the lithology. Based on the geological structure revealed by deep wells (see geological profile of FGP-1, PP-1) we assume that this unit represents the rocks of Krizna Nappe. The thickness of Krizna Nappe is about 500 – 600 m. For geothermal research, the highest part of this area is interesting, especially the Choc Nappe sequence.

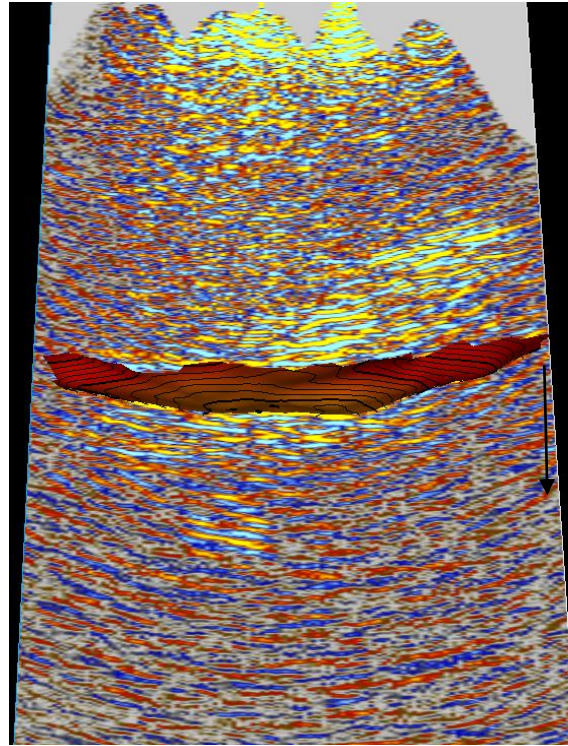


Figure 6.19 - Seismic unit III Krizna Nappe

6.2.5 Tectonic structure

Fault interpretation was made manually in the seismic interpretation–geophysics window. On every interpreted profile, faults and horizons were drawn at the same time. In the documented area we can see expressive tectonic deformation and a system of normal faults trending from south to north (Figure 6.20). Those faults determined the subsidence of the Paleogene base northward. From the interpretation we can see that in the northern part of the study area the thickness of the Paleogene unit is more than 1000 m.

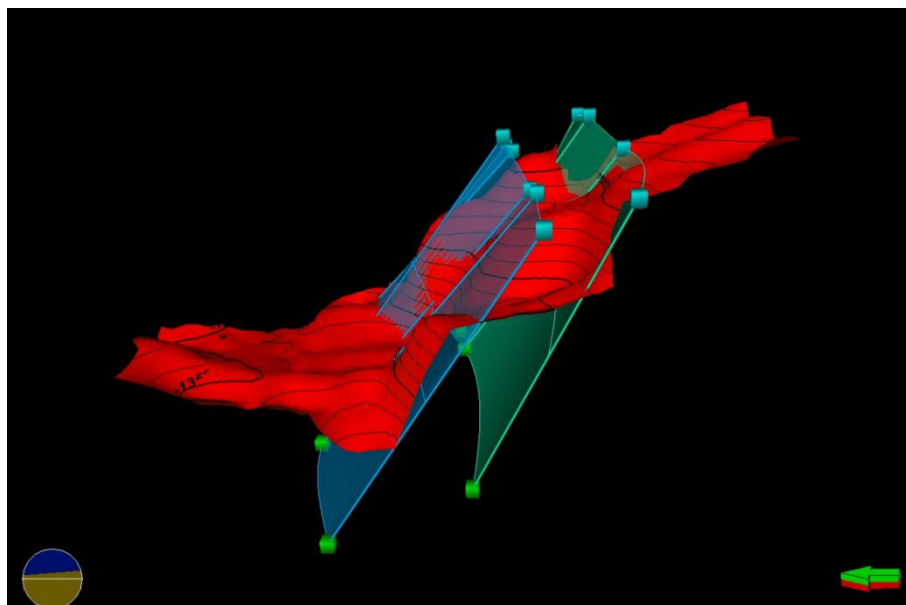


Figure 6.20 - Faulted Choc nappe

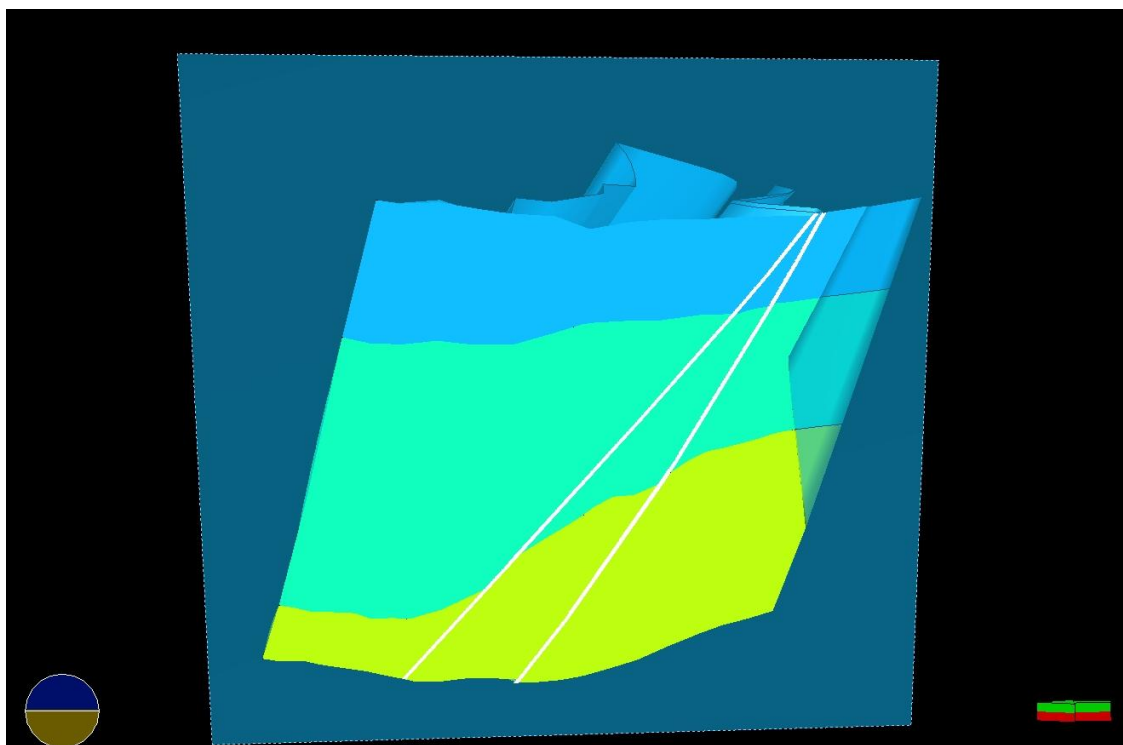


Figure 6.21 - Intersection of model showing faults intersecting Paleogene and Choc Nappes

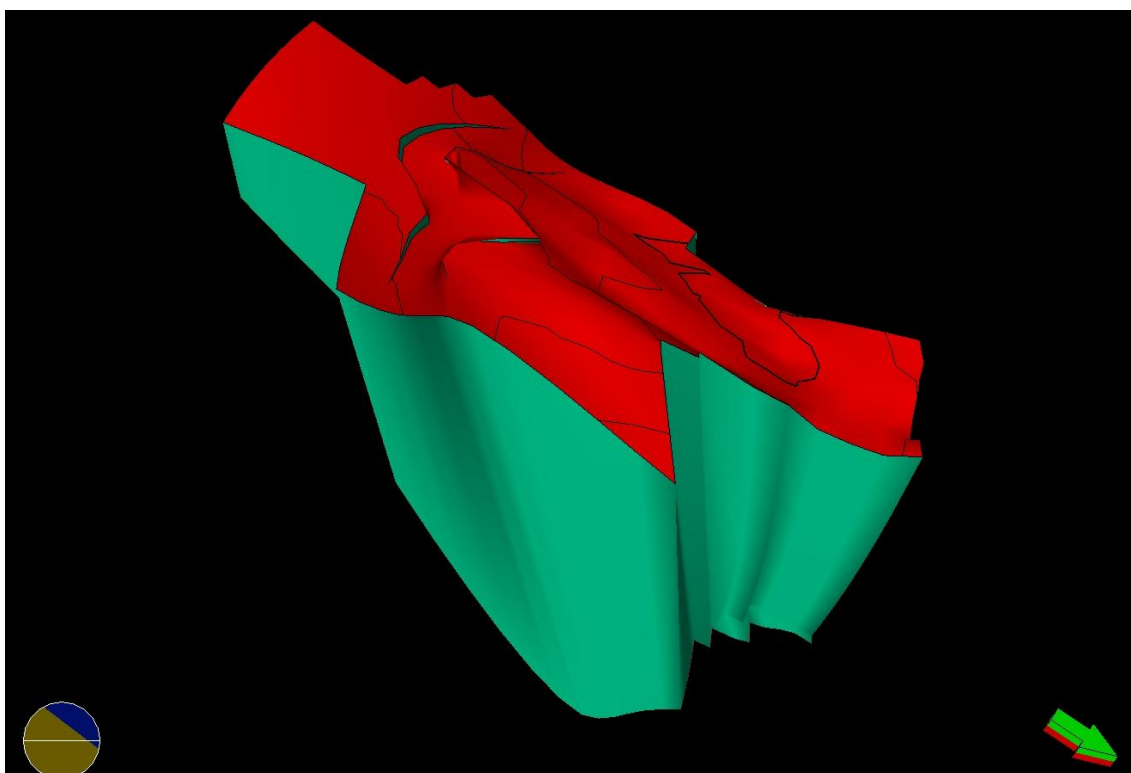


Figure 6.22 - Choc nappe segment

Interpretation of seismic profiles showed the geologic composition of the interested area close to Gerlachov village. The area in this part of the Poprad Basin is built of Subatric Group sediments from claystones of the Huty Formation and Mesozoic rocks of Choc Nappe and Krizna Nappe. Beneath this there can be expected Mesozoic envelope rocks and crystalline basement. Based on seismic profiles we can see the tectonic structure of the study area mainly represented by normal faults. The faults gradually drop down toward the north, resulting in deformation of the Paleogene base. This is an important aspect when considering geothermal drilling.

From the interpreted profiles the boundary is visible between the Paleogene and Mesozoic rocks. Besides these two seismic units it is possible to see the third unit, which is characterised by parallel reflections. This unit probably contains Mesozoic envelope rocks and the crystalline rocks forming the basement.

Based on the 3 D model we can see the general geologic composition of the studied area. The thicknesses of Paleogene sediments, tectonic deformation and the Choc Nappe position suggest possible sites for geothermal well location. In this case it is the place in the southern part of the modeled area.

7 CONCLUSION

The objective of this work was to model the geothermal reservoirs of Poprad basin, the north part of Hornad basin area and a small area in detail, which is close to the village of Gerlachov in Poprad basin. The model allowed for the visualization of the different layers and surfaces of the studied area.

The main aquifers are built by Triassic carbonates – dolomites and limestones of Choc and Krizna nappe. In the central part of Poprad basin, on the basis of seismic interpretation, Choc nappe thicknesses from 200 to 1100 m were obtained. Larger nappe thicknesses from 1200 to 1500 m were obtained on the east and southeast part of the studied area.

Based on geothermal reviewing we can say that Poprad basin and northern part of Hornad basin are active geothermal areas. The average geothermal gradient is $32,6 - 34,5^{\circ}\text{C}/\text{km}$, the average density of heat flow is $67 \text{ mW}\cdot\text{m}^{-2}$. Under Poprad basin Paleogene sediments, temperatures are between $50 - 85^{\circ}\text{C}$ and in Hornad basin temperatures are between $30 - 35^{\circ}\text{C}$. The general natural flow of water is $232,9 \text{ l}\cdot\text{s}^{-1}$, which corresponds to $34,8 \text{ MWt}$.

The existing boreholes from the interested area were described. From this, boreholes VR-1 and VR-2 are currently utilized and boreholes PP-1 and FGP-1 in Poprad basin along with HKJ-3 and HKJ-4 in Hornad basin are still not utilized.

In this work the geologic structure of Gerlachov area was also interpreted. This area also has potential for geothermal energy exploitation. Gerlachov is situated in the northwestern part of Poprad Basin. Seismic interpretation showed different geological units from a geothermal point of view: those with the most potential are Mesozoic units represented by Choč and Krížna Nappes underlying Paleogene rocks. Based on the geologic composition of Choc Nappe we can expect very good conditions for the existence of geothermal water reservoir. Krizna Nappe has less positive conditions for geothermal water exploitation. The general discharge of groundwater in Choc Nappe should be more than $22 \text{ l}\cdot\text{s}^{-1}$. Temperatures in Choc Nappe are between 35 and 45°C . By drilling to the deepest structure, Krizna Nappe, the temperature can increase 10 or 20°C . But it is the risk and possibility here that the discharge will be lower in Krizna Nappe than in Choc Nappe.

Based on interpretation and mentioned conditions we can state that the Gerlachov area is suitable for geothermal utilization.

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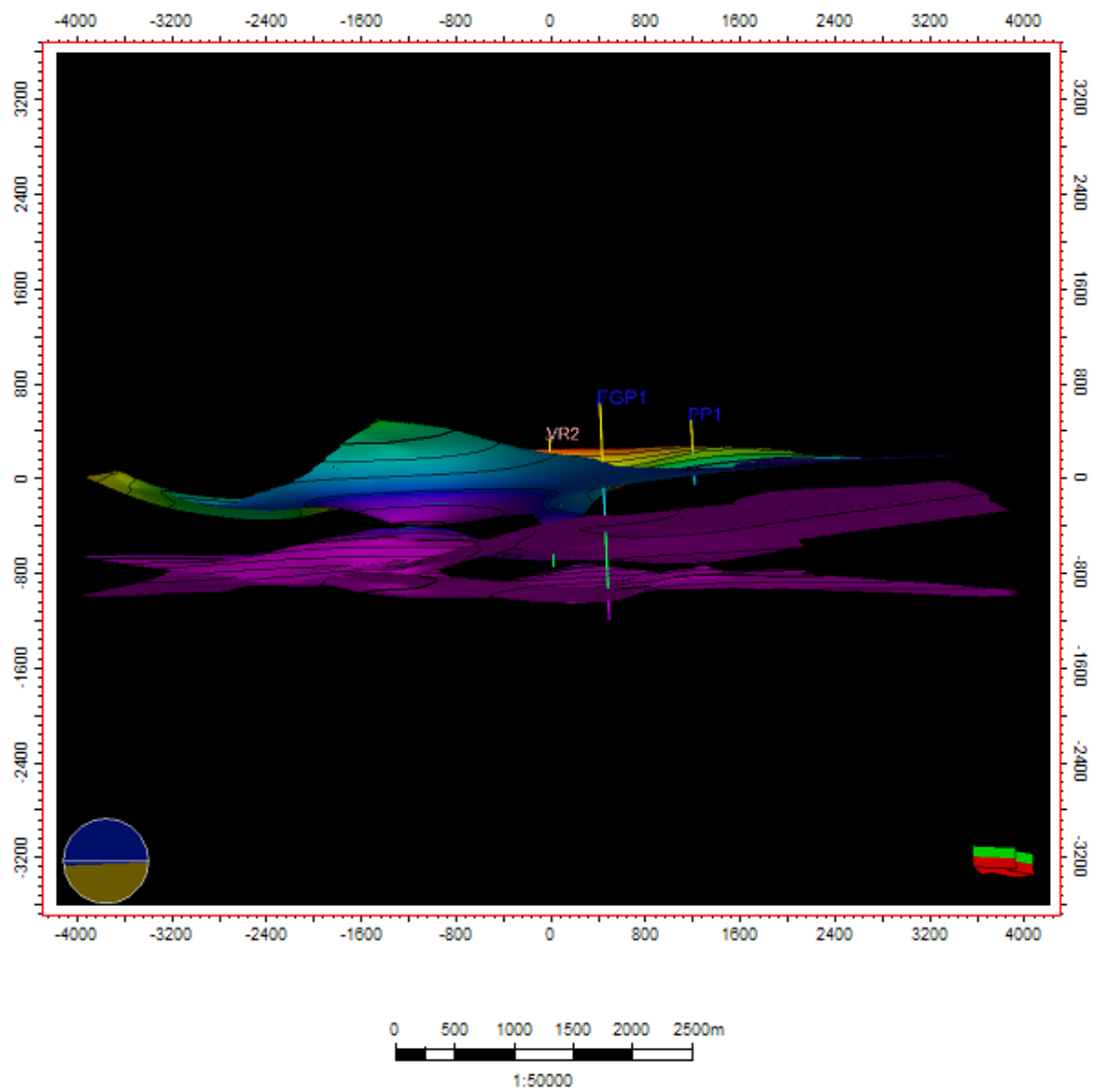
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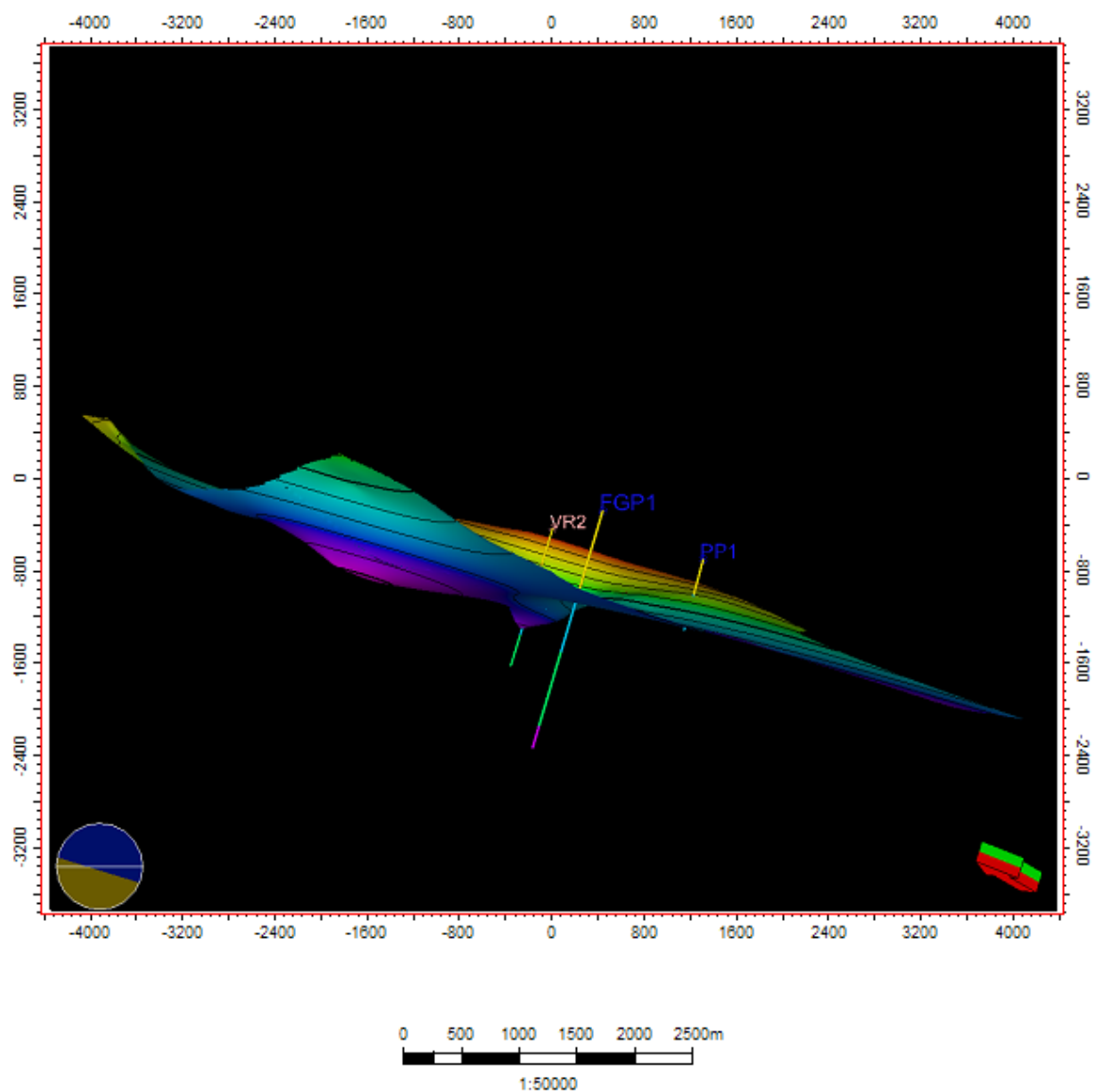
APPENDIX A

Poprad basin - 3D geothermal reservoir modelling

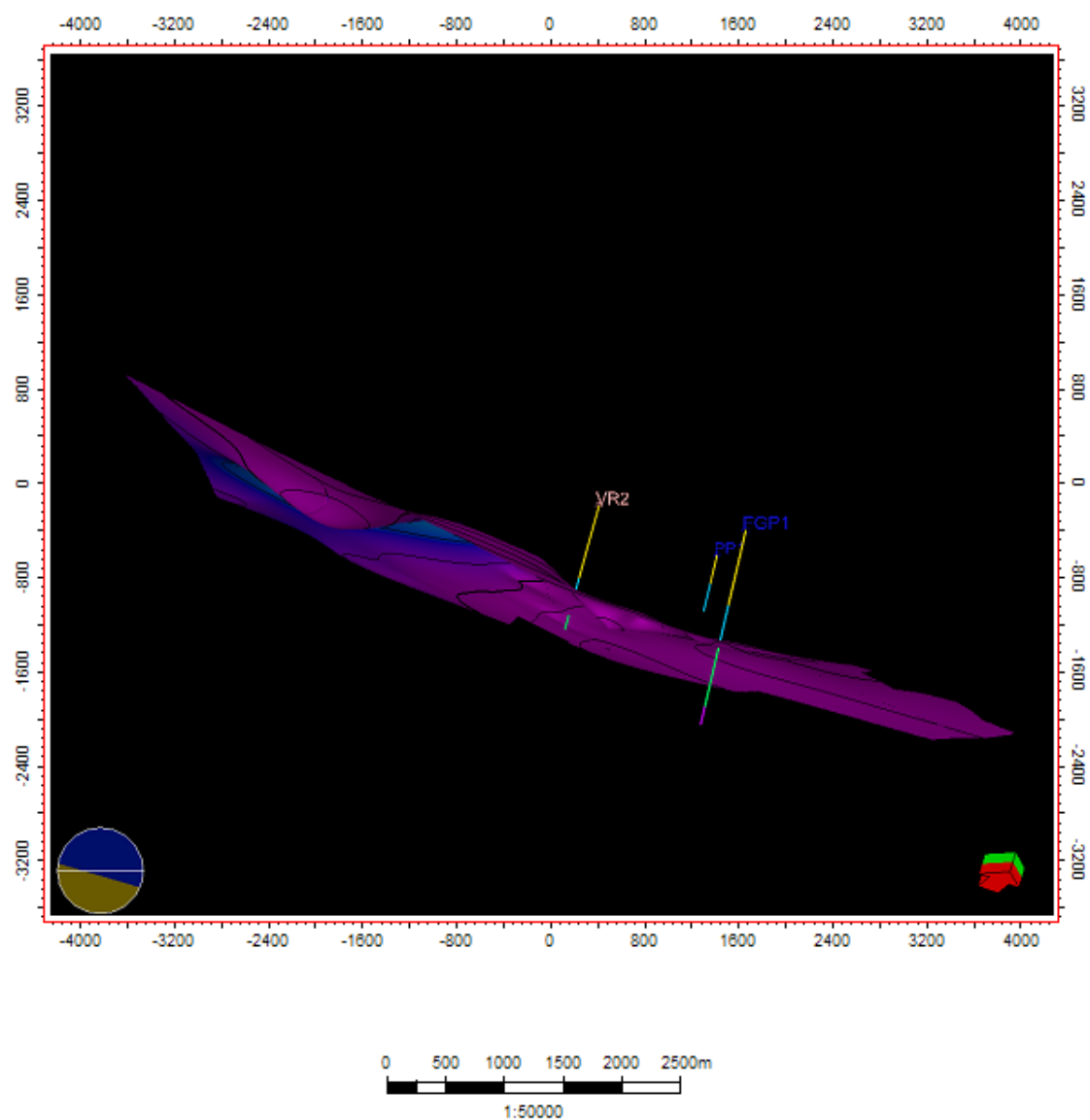
Interpreted surfaces



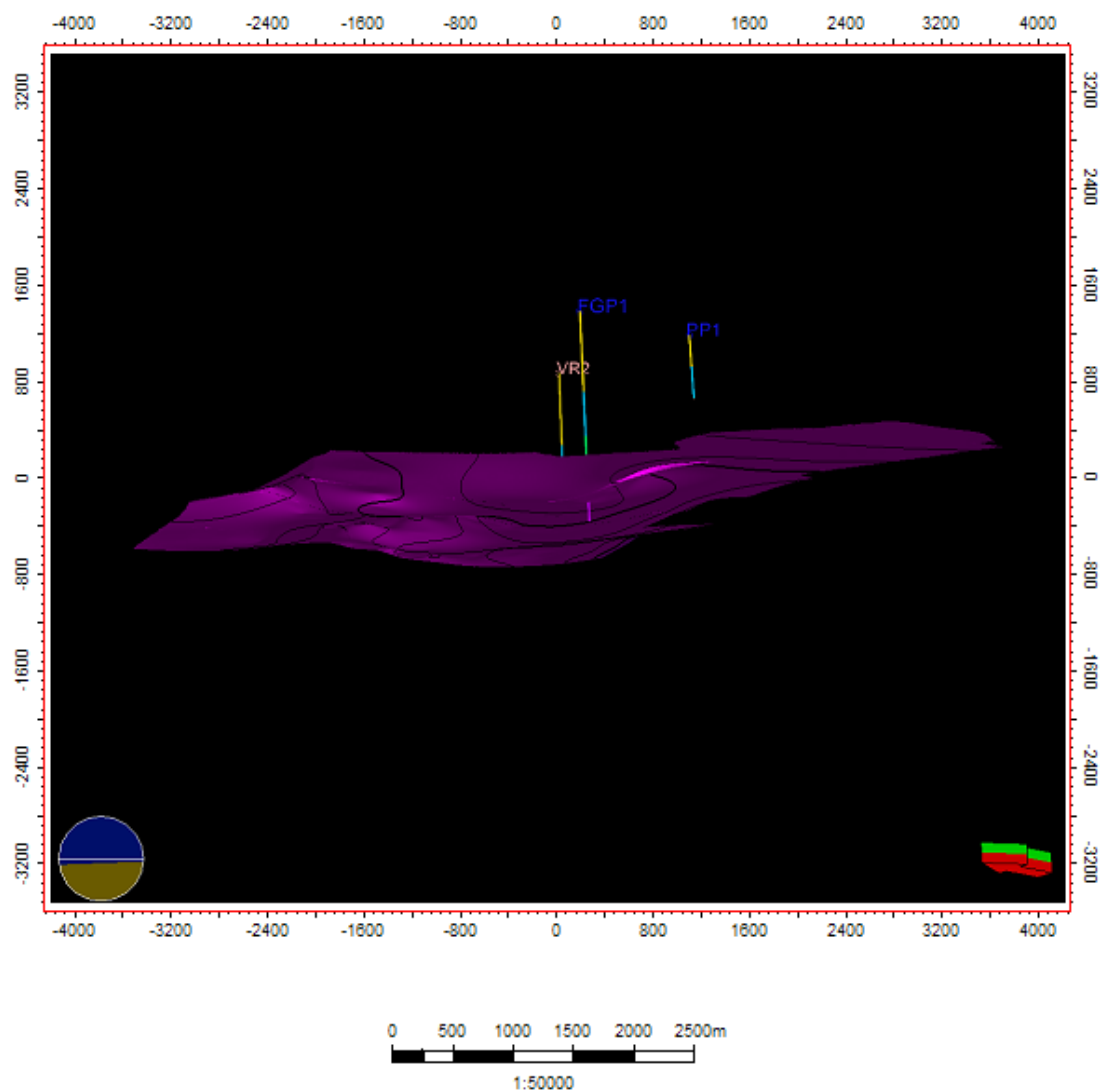
Surface of the paleogene base



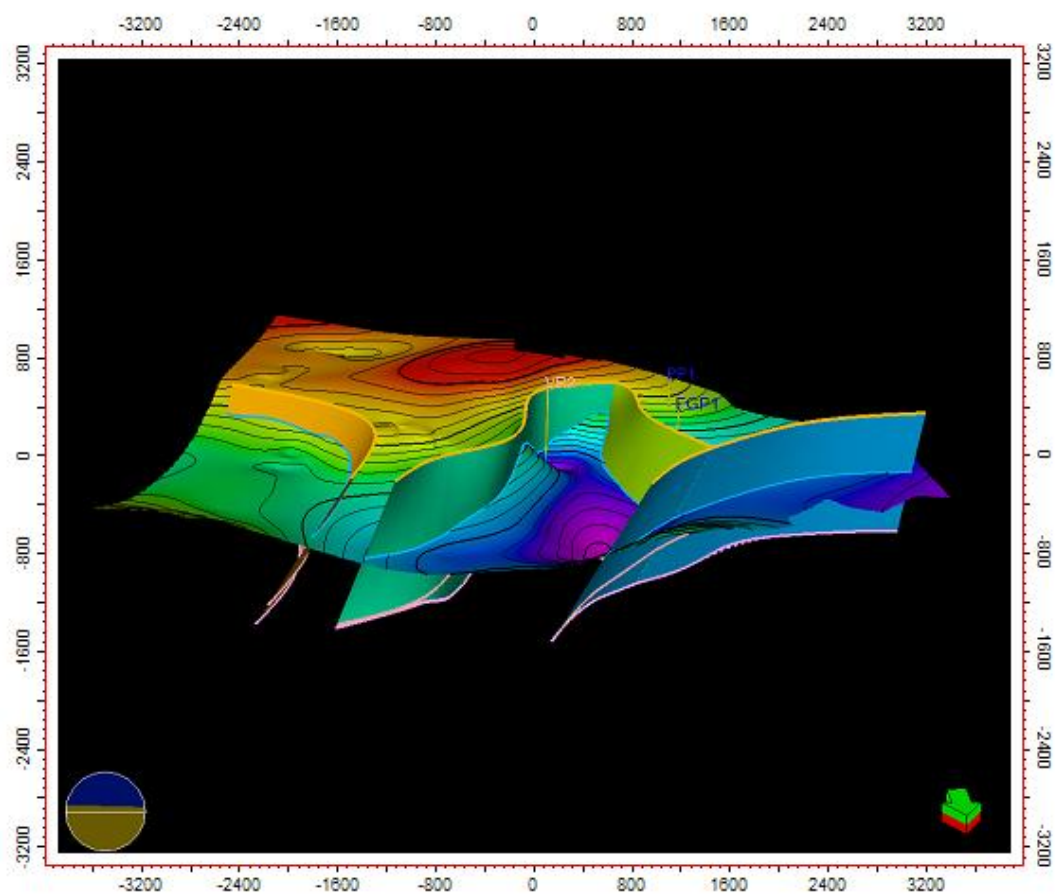
Base of the Choc Nappe



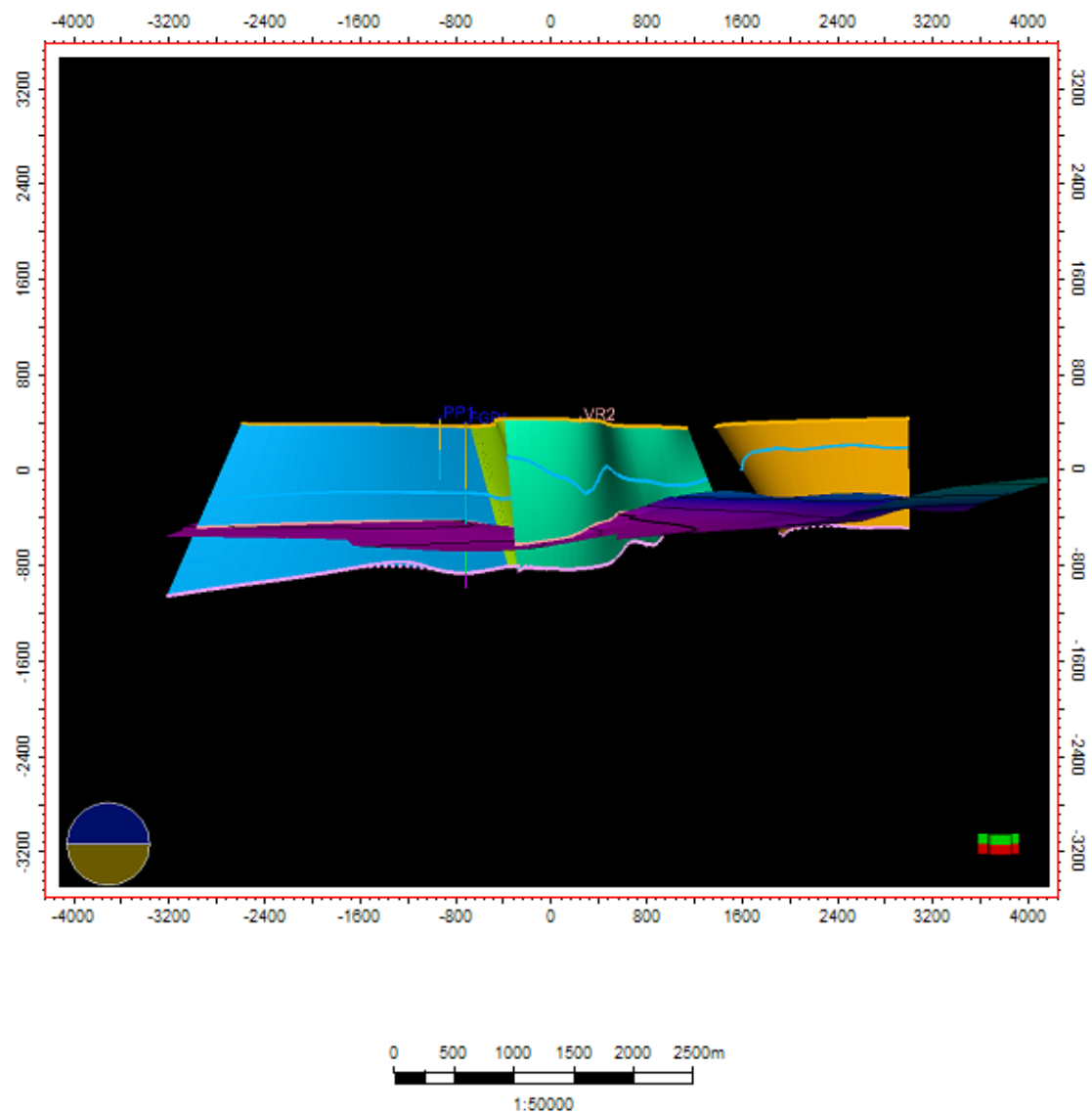
Basal surface of the Krizna Nappe



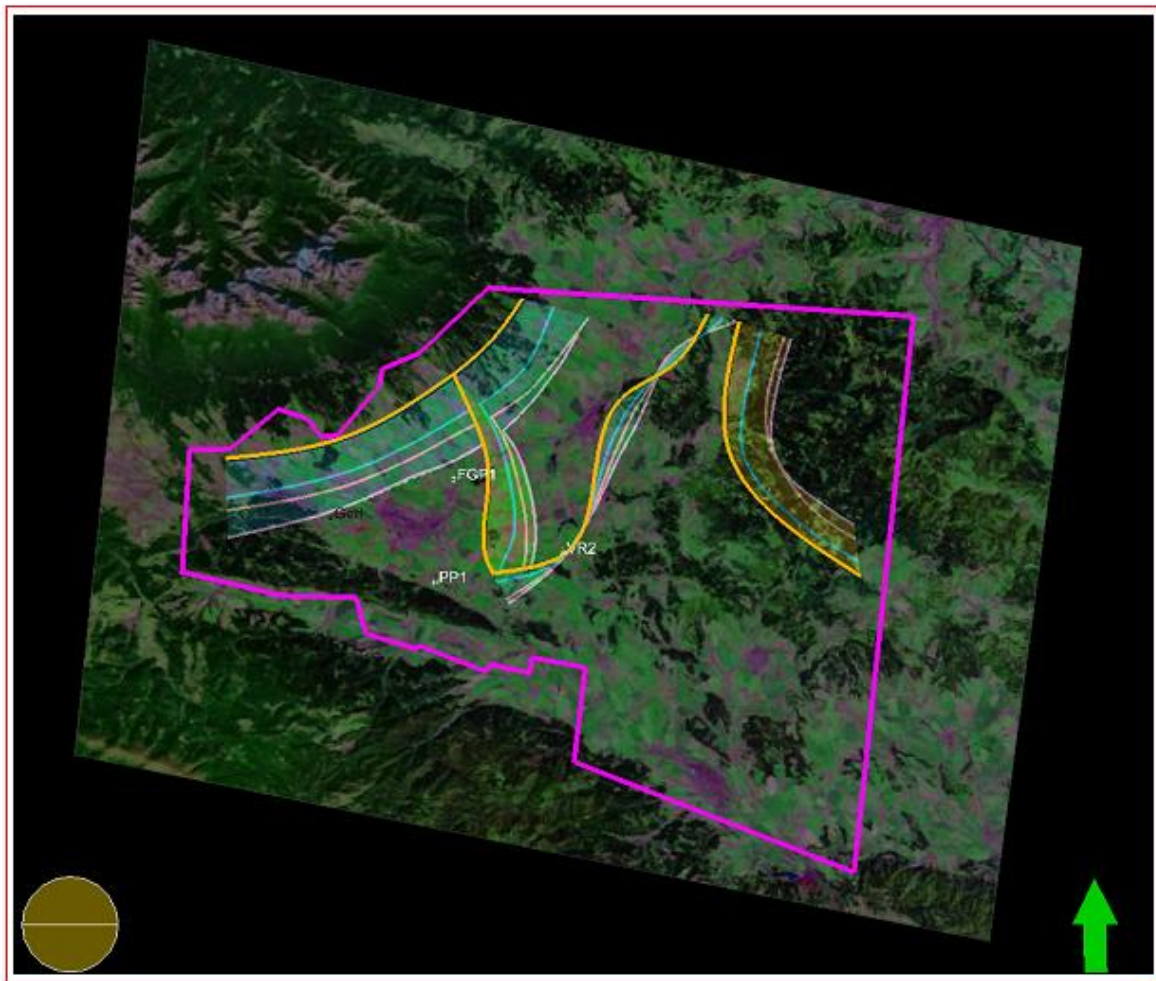
Faults surfaces with Paleogene base



Faults planes with Choc Nappe base

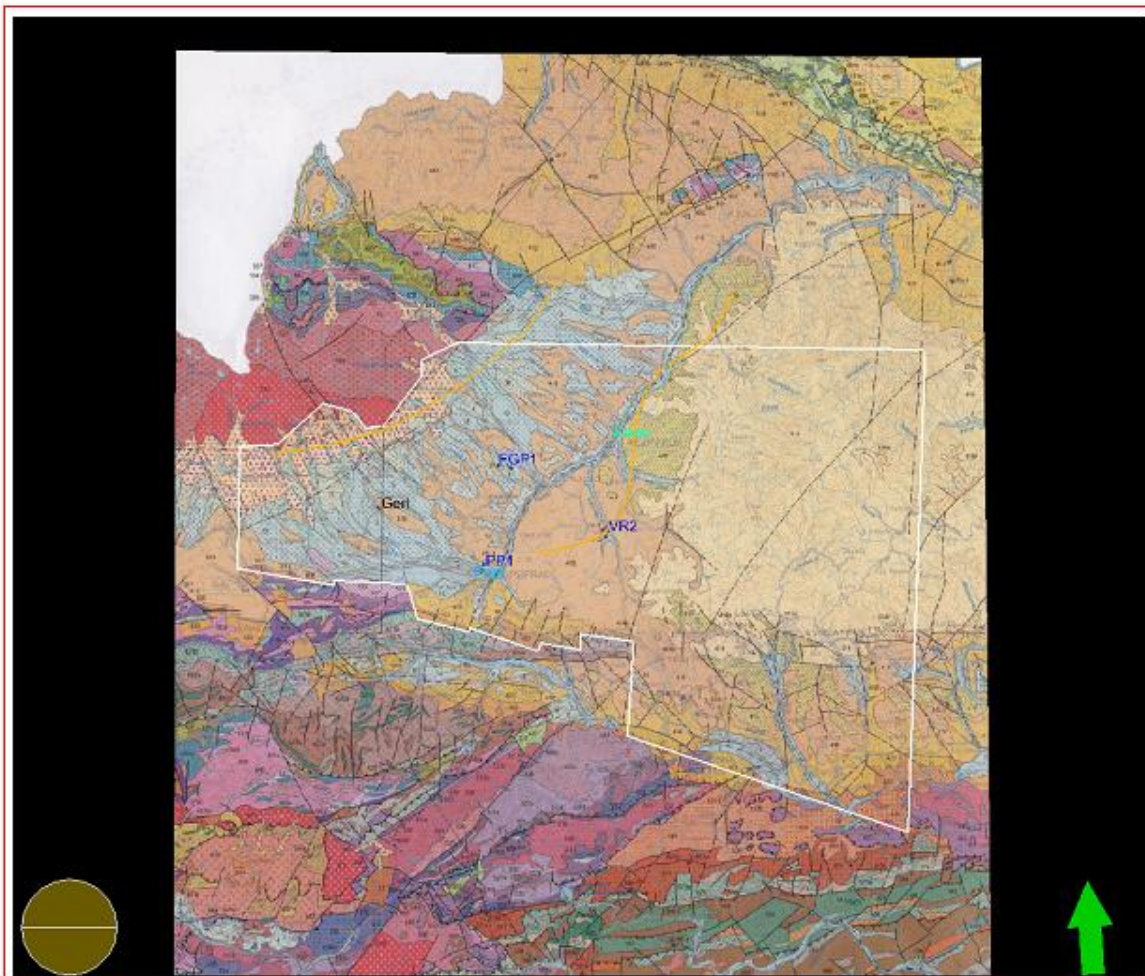


Satelite map with interpreted faults

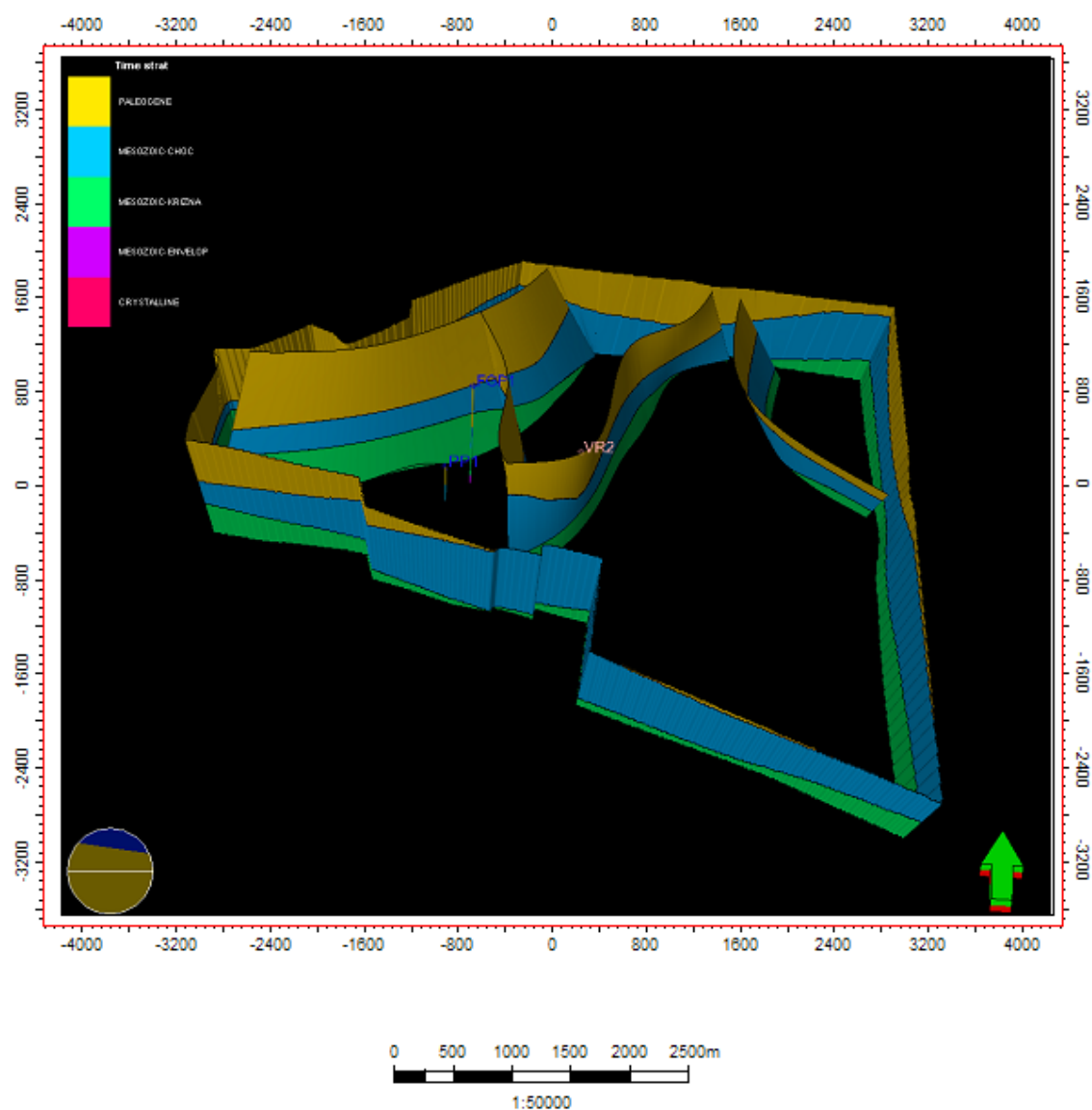


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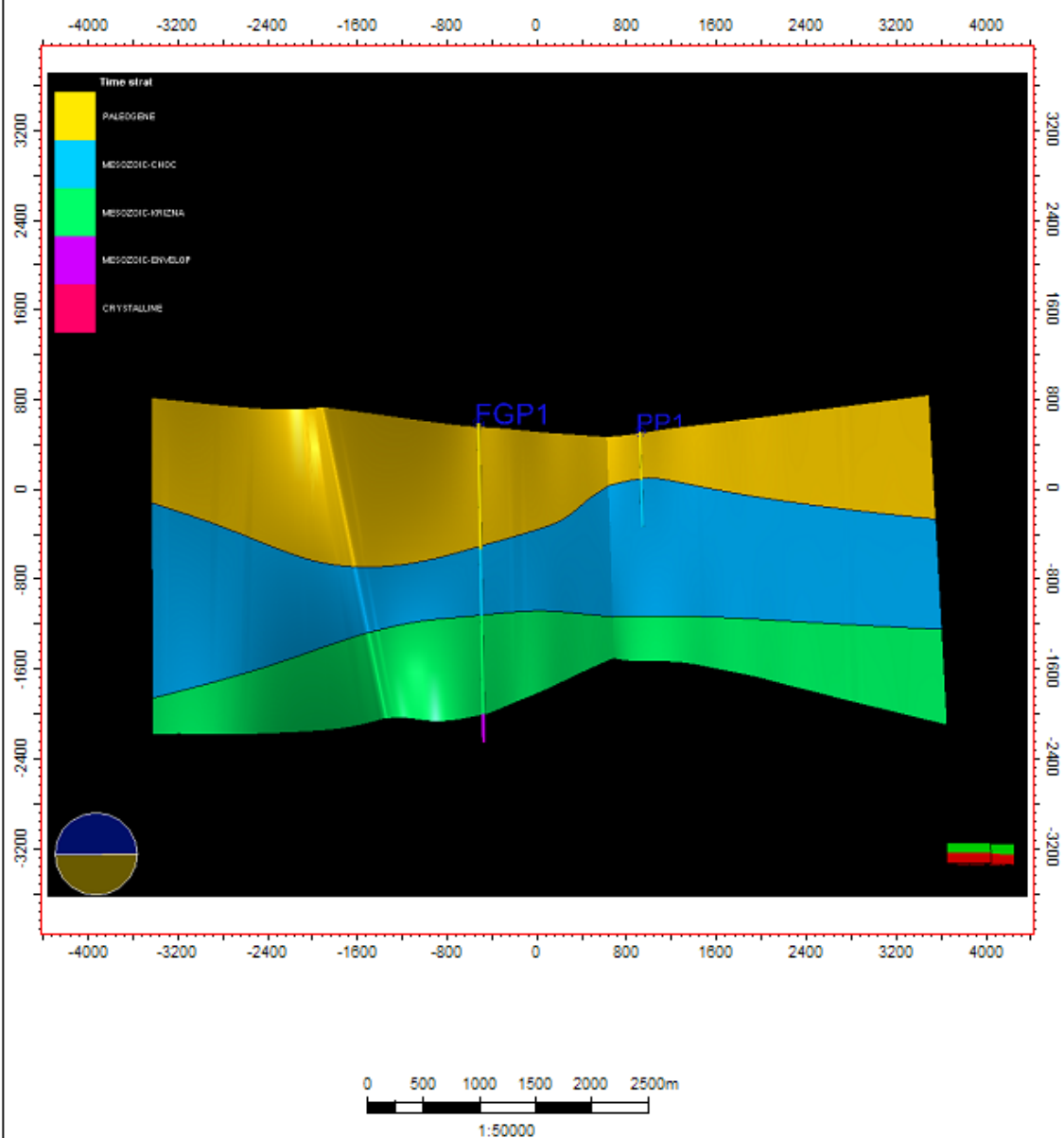
Geological map of study area with wells location



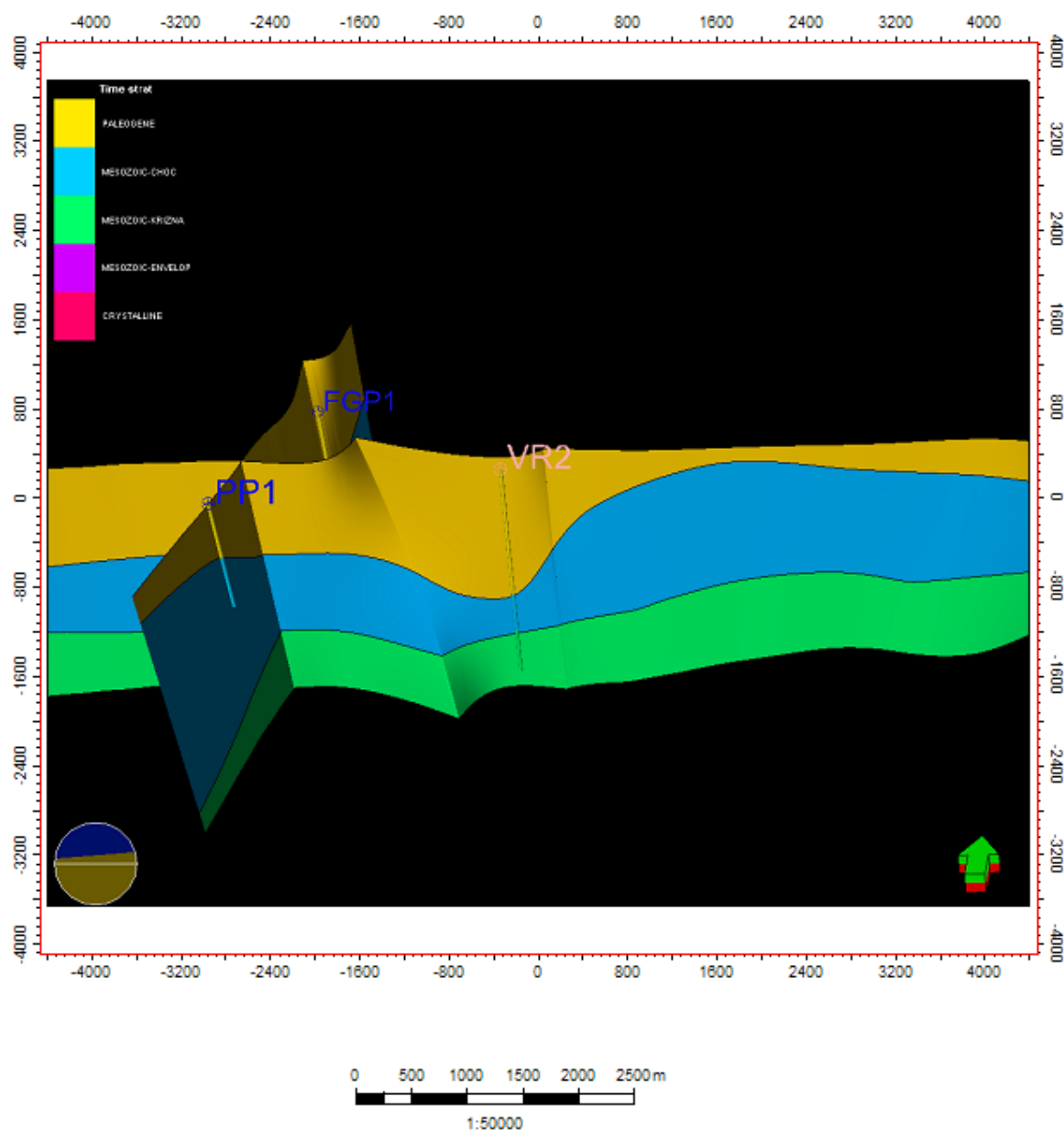
Edges of study area showing faults and interpreted units



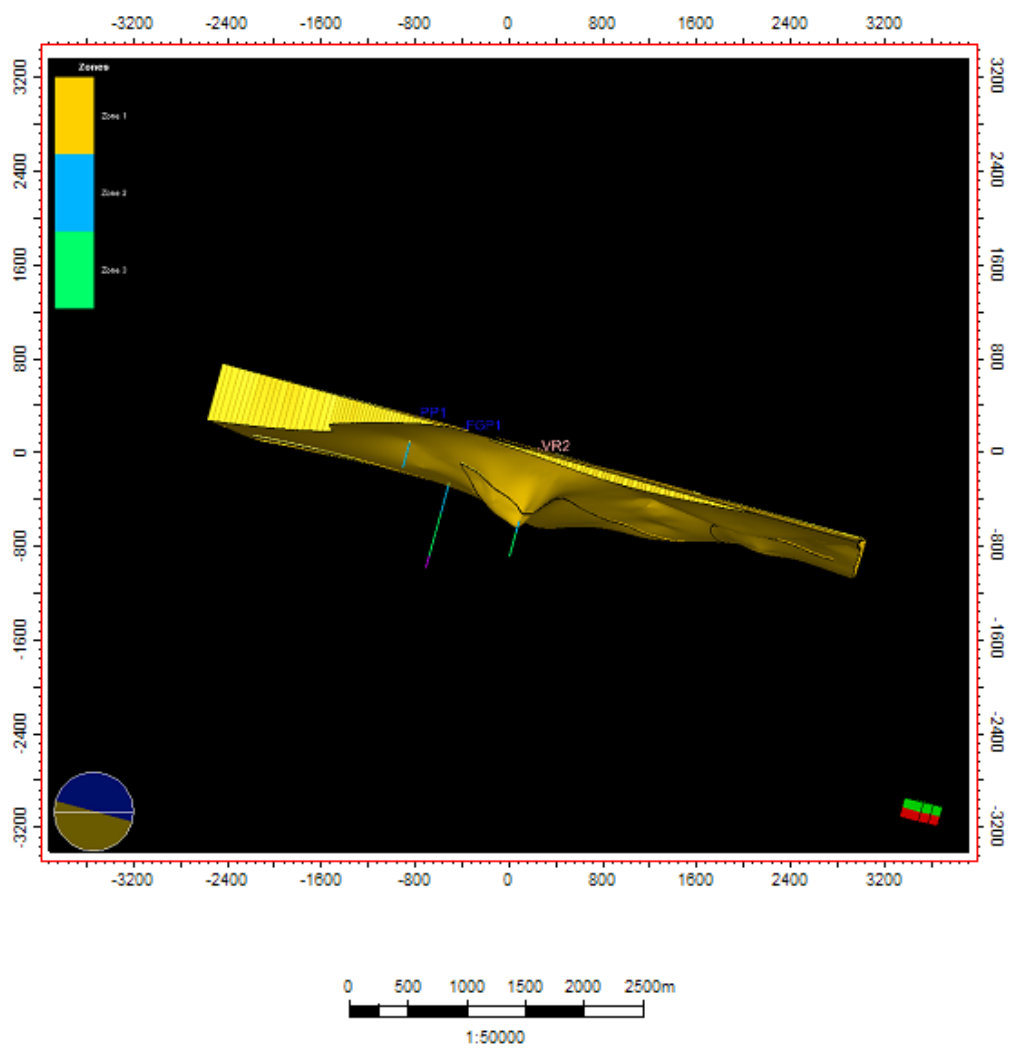
Well FGP-1 and PP-1 intersection with interpreted horizons



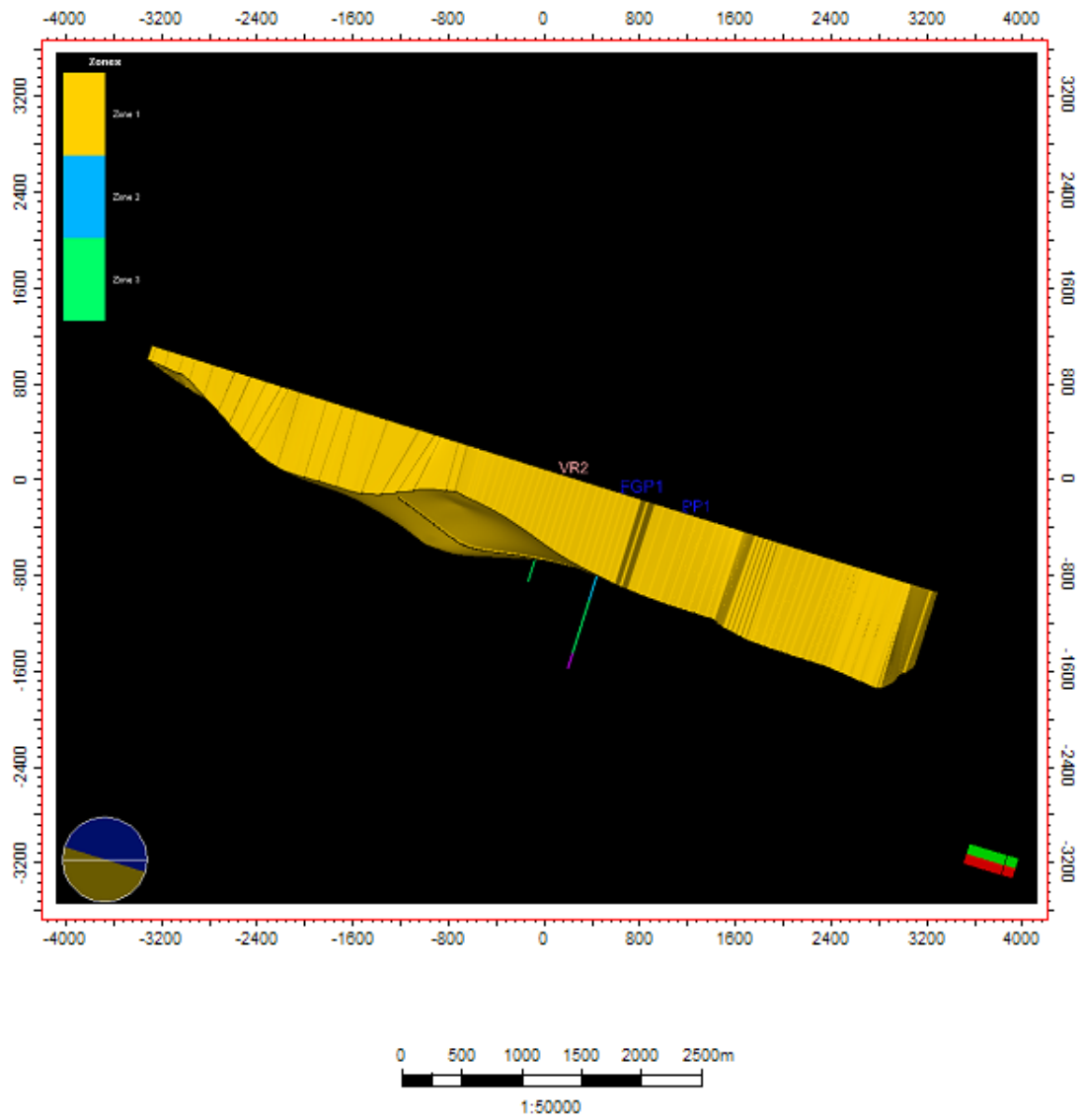
Well PP-1 and VR-2 intersection with interpreted horizons



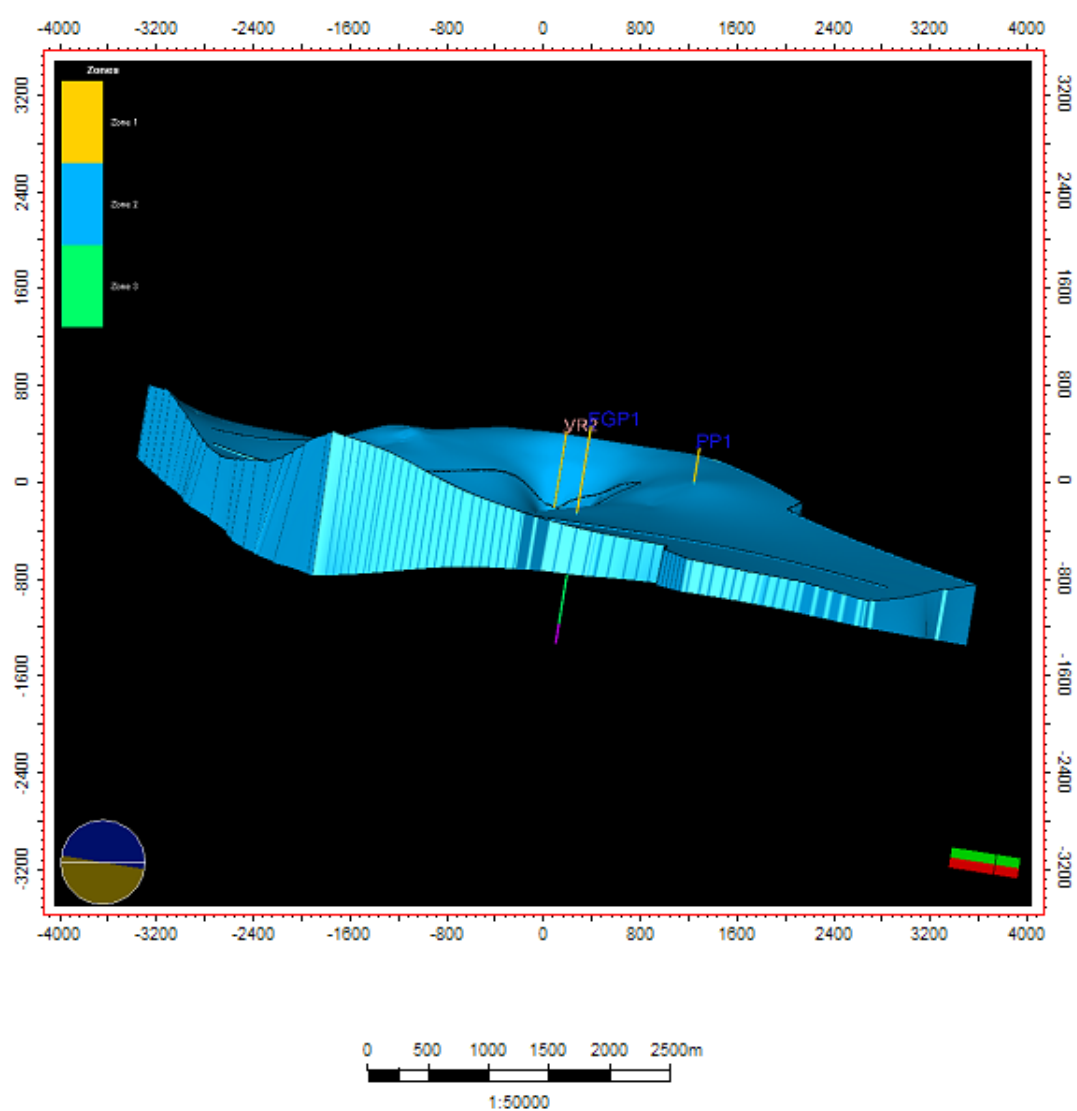
Paleogene body



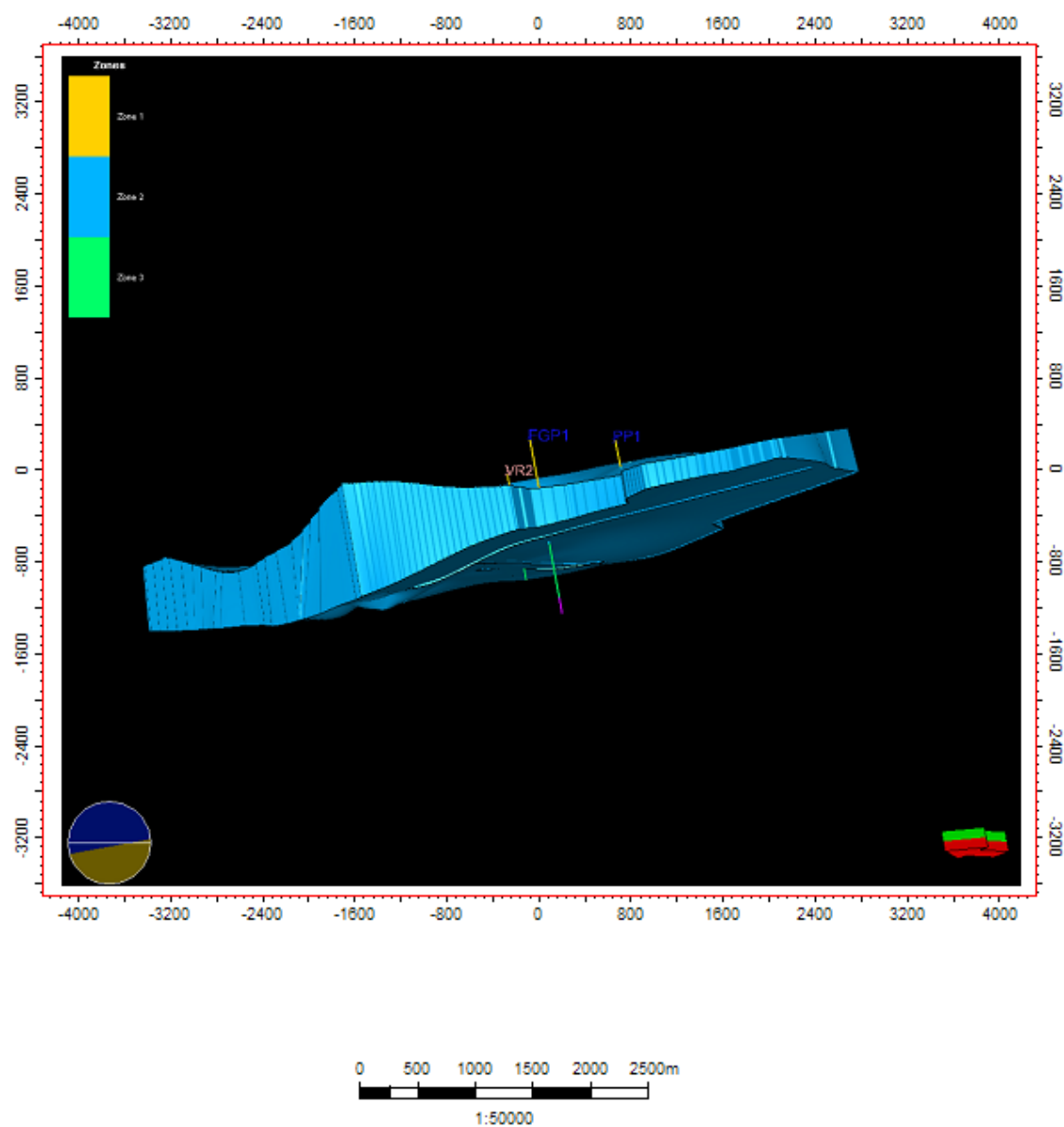
Paleogene body



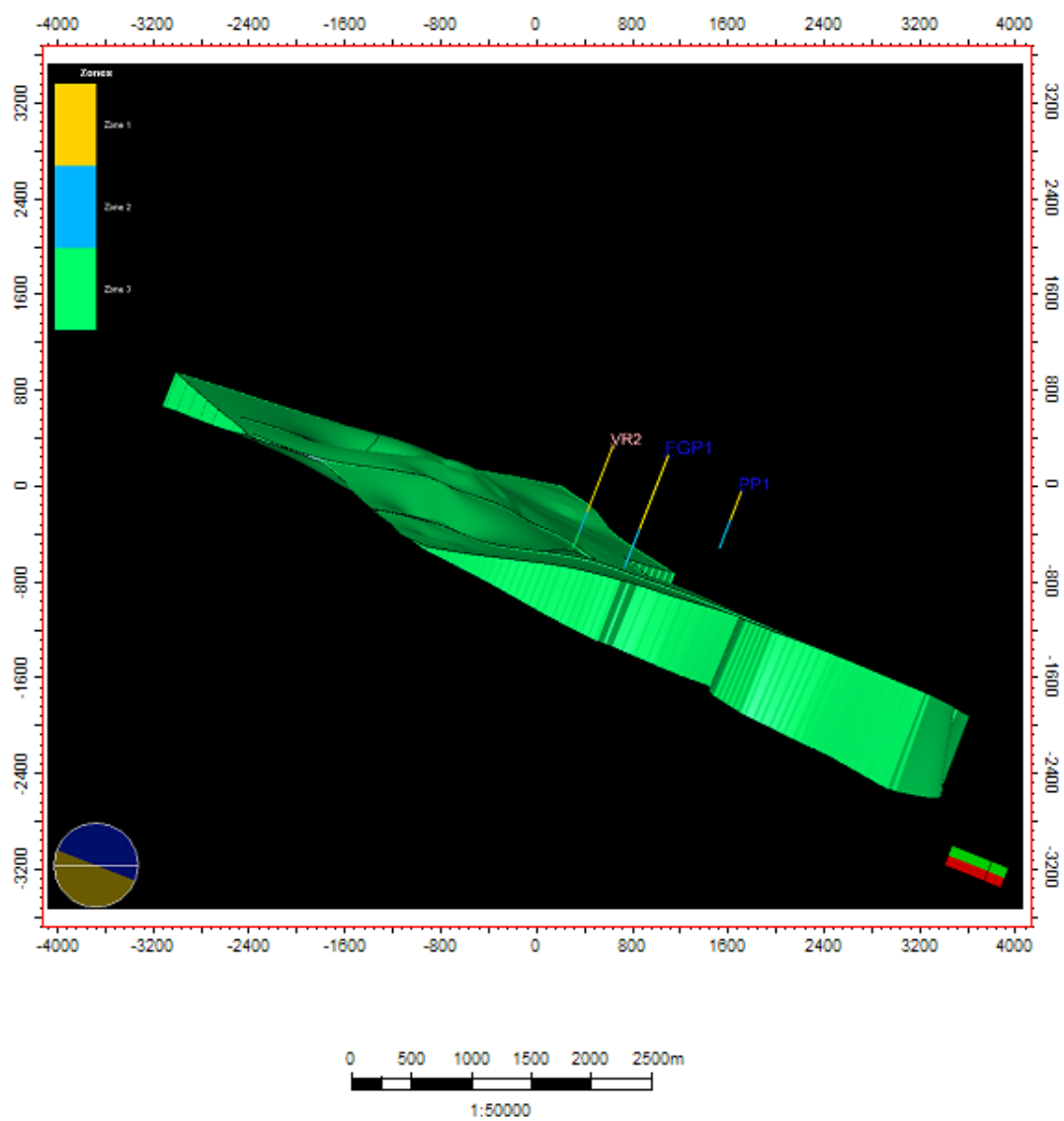
Choc Nappe body



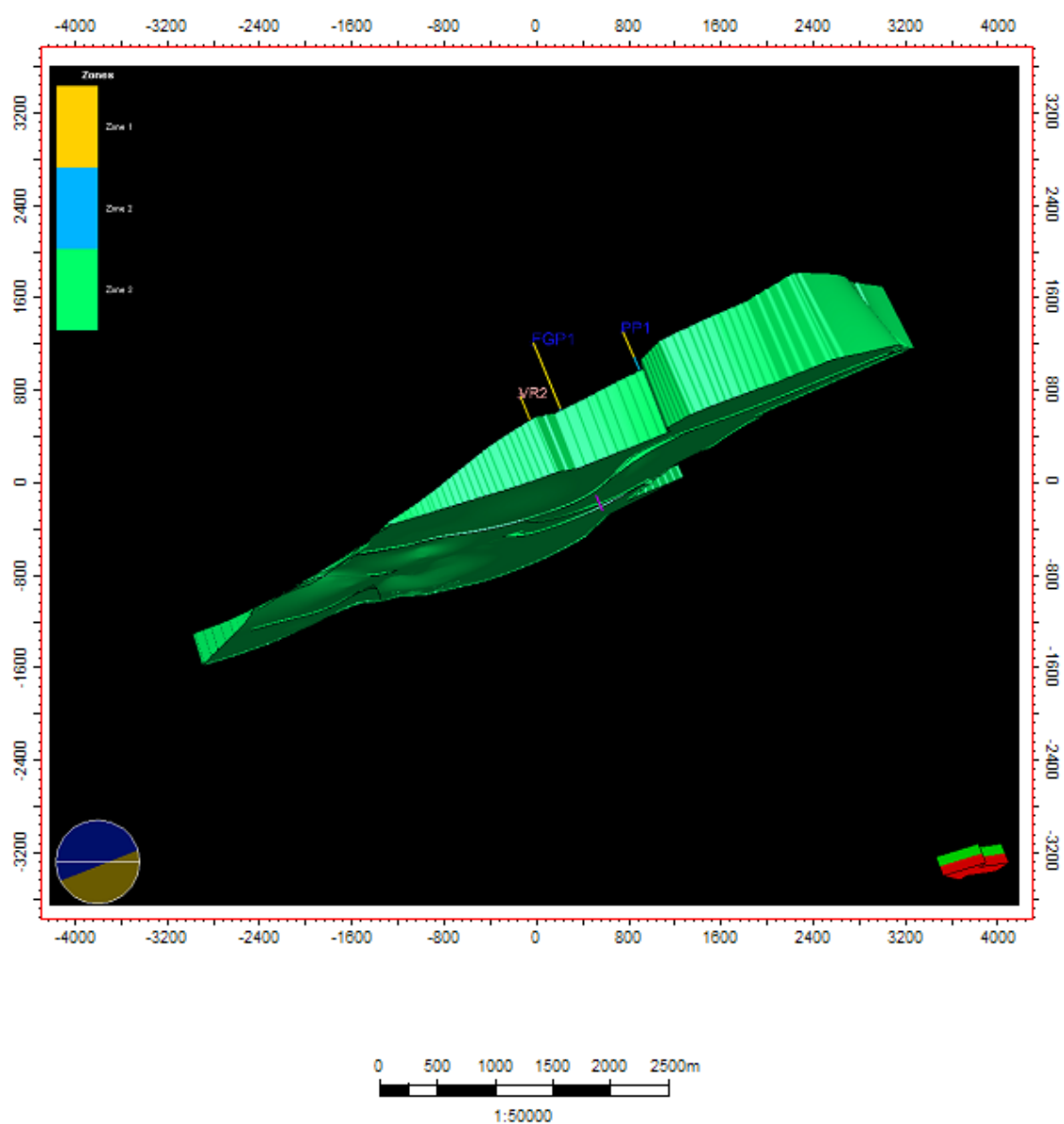
Choc Nappe body



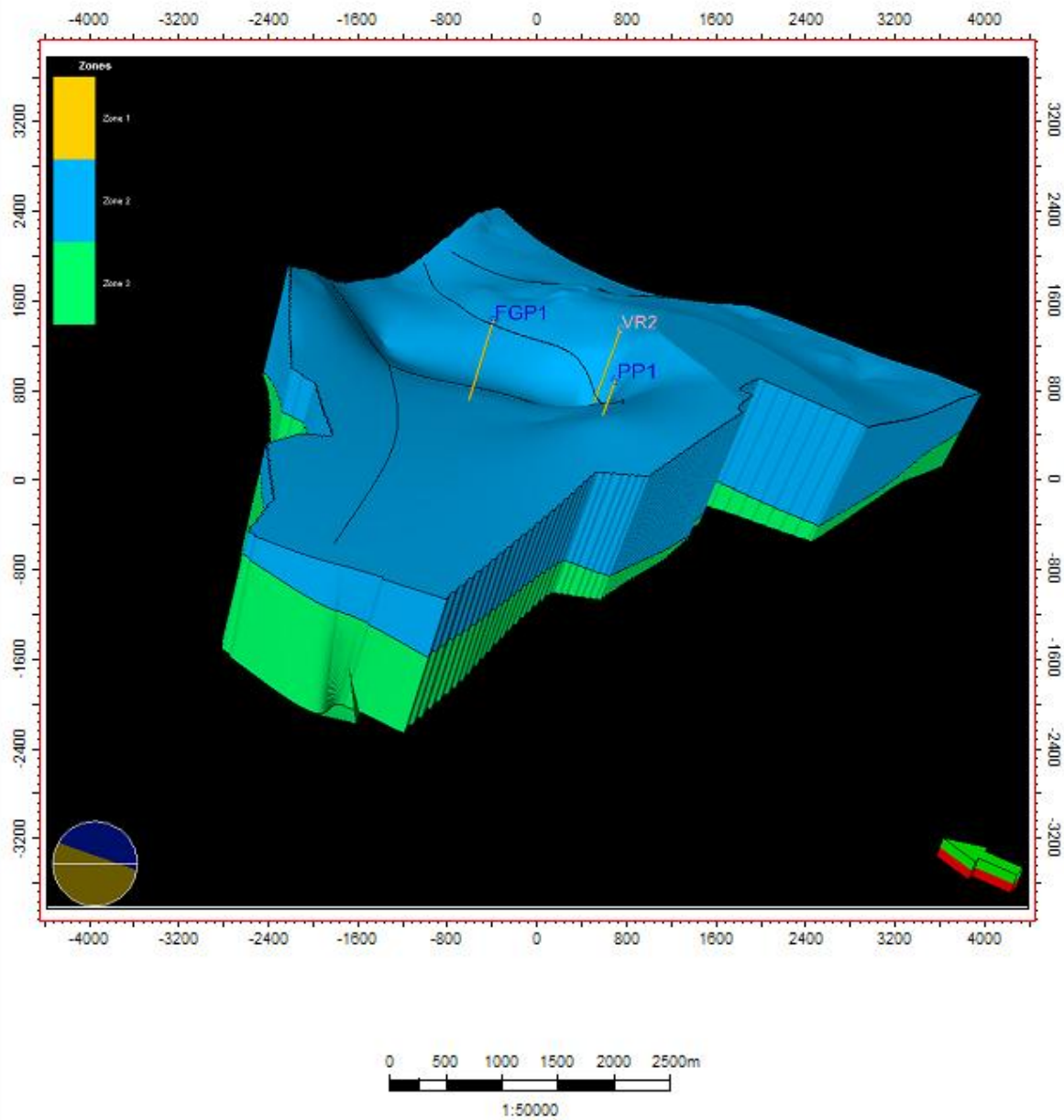
Krizna Nappe body



Krizna Nappe body



Choc and Krizna Nappe horizons





Model of interpreted geological units

