# 4. Local and regional aquifers

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While the local aquifers are known primarily from hydrocarbon deposits and are "relatively geometrically limited" regional aquifers everywhere in the world have the greatest potential for $CO_2$ storage. Unfortunately, the relevant knowledge about these structures is insufficient in contrast to the local ones. Apart from structural and non-structural hydrocarbon traps these structures are open (localized predominantly in the basins created by the pull-apart tectonic mode) and, in the case of the $CO_2$ storage they pose potential threats to neighbouring areas. Everything is subject to the knowledge of the geological situation and tectonic characteristic, which is the crucial one, because it decides about imperviousness, and leakage. Again, we have to point out, that we are dealing with aquifers, which contain saline waters. According to the general adopted criteria, the saline water (unsuitable for drinking and other commercial purposes) is the water with higher mineralization than 1,000 $ppm.l^{-1}$.

The volume of carbon dioxide that can be stored in an aquifer depends on many parameters defined in ordinary cases very poorly. They are, for example (Chadwick, et al., 2008):

- The volume of the pores in a structural or stratigraphic trap;
- Whether a trap will loose a stored gas due to leakage;
- Proportion of accessible $CO_2$ saturation in a trap;
- Cases, where only a certain percentage of the repository contains several smaller traps, and only certain number of them can be reached by wells;
- Amount of $CO_2$ which shall dissolve in saline fluids, contained in the pores;
- Amount of $CO_2$ which shall be trapped in the form of residual capture, while migrating through capillaries;
- Whether a local or regional hermetic sealing of an aquifer will limit a storage capacity due to $CO_2$ injection;
- Bulk density of $CO_2$ and any impurity contained within.

For this reason, there is a necessity in a significant amount of information, in addition to the area of a reservoir, thickness and porosity of a collector, which, however, in most cases are not available. Among the local aquifers we have included the hydrocarbon structures of the Danube Basin, in particular. In this respect, for some others from other territories of Slovakia, their character can be set up on the basis of the results of further works. We present an overview of the objects for potential storage $CO_2$ in the following text.

## 4.1 The Danube Basin

Within the Danube Basin we focused primarily on the local aquifers of small gas deposits (Fig. 4.1.2.1), located in marginal areas; however, we cannot exclude that, due to its extensive area, it will be possible to find out appropriate structures of these objects. Therefore, we devote a lot of focus to the lithology of the region.

### 4.1.1 The geological setting of the Danube Basin

The Danube Basin belongs to the intramountain depressions and extends finger-like between the Core mountain ranges of the Western Carpathians, which define individual partial depressions (Fig. 4.1.1.1).

The Core Mountain ranges of the Malé Karpaty, Považský Inovec and Tribeč are made up of mostly granitoid rocks and Mesozoic carbonatic sediments. Sedimentary fill of the Danube Basin is made up of pelitic, sandy and coarse-clastic rocks of Miocene and Pliocene age (Fig. 4.1.1.2). The area of Central Slovakia Neovolcanites is built of volcanic and volcanoclastic rocks representing the south-western parts of the Štiavnica Stratovolcano and Pohronský Inovec.

In the geological setting of the Pre-Tertiary basement a dominant part take the Veporicum rocks and their envelope, with more or less preserved outliers of Palaeozoic to Mesozoic age. In the South-Eastern part of the territory, behind the Hurbanovo fault, the Pelsö rock units are present, reaching on our territory from Hungary. With the exception of the above mentioned Core Mountains and isolated islands in the NW part of the Levice-Turová Horst near Levice, the Pre-Tertiary subsoil does not crop out within the territory of interest.

The Neogene sediments of the Danube Basin overlie transgressively and discordantly the Pre-Tertiary basement. On the interface between the Neogene sedimentary fill and the basement rocks there have been preserved a few isolated stratovolcanic centres, Early Badenian in

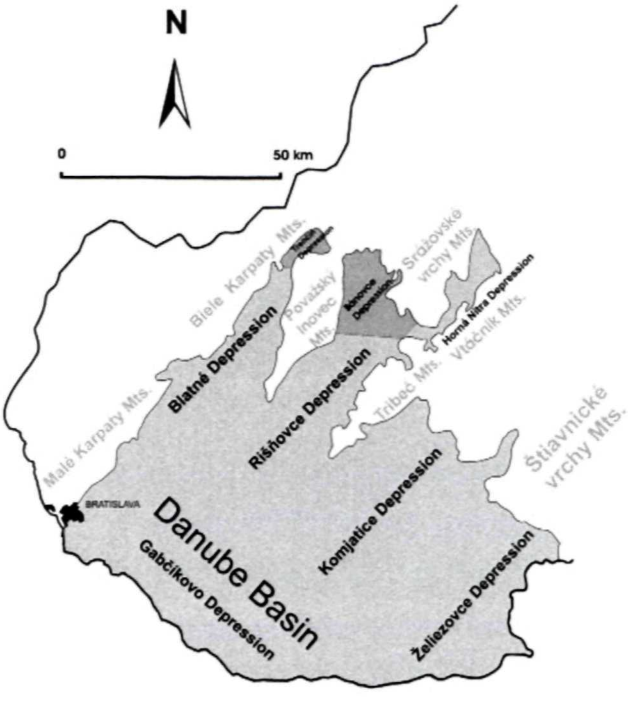


*Fig. 4.1.1.1 Regional geological division of the territory of the Danube Basin (according to Vass et al., 1988 compiled by Nagy 2011).*

age, representing the buried Šurany volcanites. Into the sedimentary fill in the southern part of the map the volcanoclastic rocks of the Börzsöny Stratovolcano, Early Badenian in age, are exposed; in the northern and eastern part of the territory the Sarmatian, Pannonian and Pliocene sediments are present.

On the entire territory the Quaternary deposits are developed, representing different genetic types from the river terrace sediments in the area of terraces; the gravelly-sandy Danube sediments near Gabčíkovo reach a thickness of approx. 500 m.

PRE-TERTIARY BASEMENT

On the basis of the work of Fusán et al. (1987), Haas et al. (2000) and own interpretation based on new knowledge of wider tectonics of the Western Carpathians, in the setting of Pre-Tertiary basement the tectonic units of the Tatricum, Veporicum, Hronicum and the Transdanubian Mountains (unit Pelsö or Pelsőnia) take part.

The Tatricum rock sequences are represented by crystalline fundament, made of predominantly granitoid crystalline rocks and schists.

The Veporicum unit is located mainly in the southeastern part of the territory. It consists of granitoid rocks, below which mica schists are present. In the area of Pozba, Podhájska and Vráble Mesozoic rocks are present; we affiliate them to the Northern Veporicum envelope. The Mesozoic sequence cropping out in the form of so-called "Levice Islands" is considered to be a part of the Hronicum tectonic unit (Nagy et al., 1998).

In the southernmost part of the territory the wells reached Palaeozoic and Mesozoic rocks belonging to the Transdanubian Mountains of the Dinarides Province (c.f. Haas et al., 2000). With the units of the Inner Western Carpathians they have a contact along significant tectonic line of Rába - Hurbanovo - Diósjenö (Hurbanovo Fault).

NEOGENE

The oldest rocks are of Middle Miocene age. They are overlain by younger Late Miocene and Pliocene sediments, and besides the Sarmatian deposits none of them have been exposed. Buried volcanic centres are located at the interface of the Pre-Tertiary basement and Neogene sedimentary fill (Figure 4.1.1.2).

According to the data from seismic sounding (Hrušecký et al., 1993, 1996, 1998) the thickness of the sedimentary rocks in the Gabčíkovo central depression is approximately 8-9,000 m.

The figure 4.1.1.2 shows horizons, which due to their lithology can serve for potential $CO_2$ storage. The problem seems to be the fact that the area is the largest reservoir of potable water in the Central Europe.

In the following text we characterise in detail only stratigraphic sequence of the rocks potentially suitable for the $CO_2$ storage.

**Eggenburgian**

The Neogene sequence starts with Eggenburgian clastics; in the Blatné Depression they are represented by Podbranč Conglomerate and in the northern part of the Rišňovce Depression by Kľačno Conglomerate. The Fm. reaches a thickness of up to approx. 50 m. Atop the basal clastics there is a pelitic member - Čausa Fm. (Figure 4.1.1.3).

**Karpatian**

Early Karpatian coarse-clastic deposits (Planina Fm.) overlay locally the Pre-Neogene surface. In the basinal environment the deposition had continued without interruption from Karpatian to Ottnangian, mostly. A number of recurring graded cycles of conglomerates (breccias)-siltstones-claystones in distal facies development reflects the dynamics of the sedimentary environment. Within the basinal environment siltstones deposited with interlayers of sandstone and claystone (**Lakšárska Nová Ves Fm.**). The maximum thickness of the formation is approximately 700 m (Figure 4.1.1.4).

**Badenian**

Early Badenian

Marine sediments of Early Badenian age are found in the Želiezovce and Komjatice depressions, where they represent **Bajtava Fm.** (Vass 1989, in Keith et al. 1989). The main mass of sediment is formed by disintegrating grey calcareous siltstones and claystones. Their thickness is about 1,400 m.

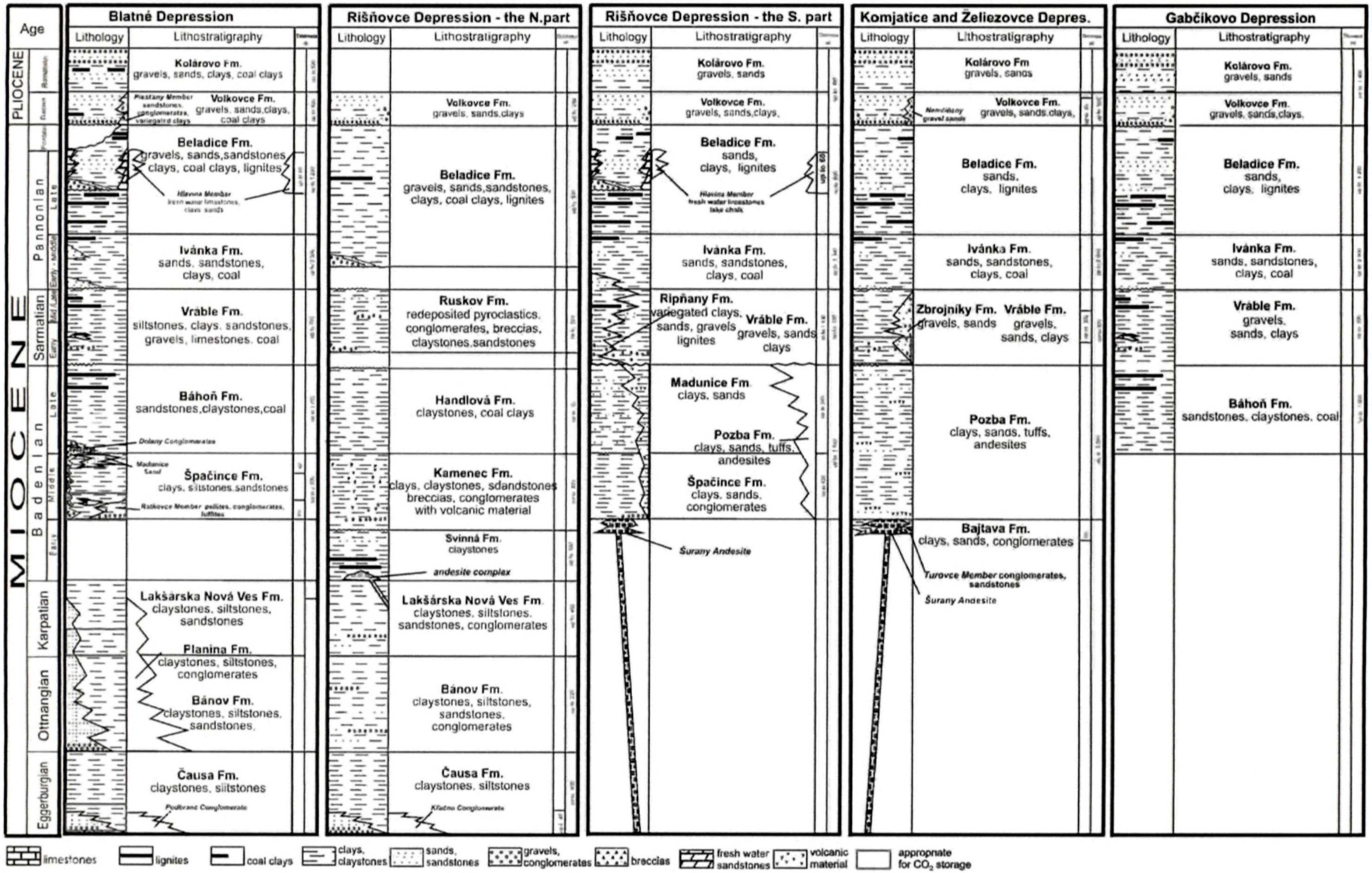


*Fig. 4.1.1.2 Lithostratigraphic column of the Neogene sedimentary fill of the Danube Basin (Nagy 2011).*

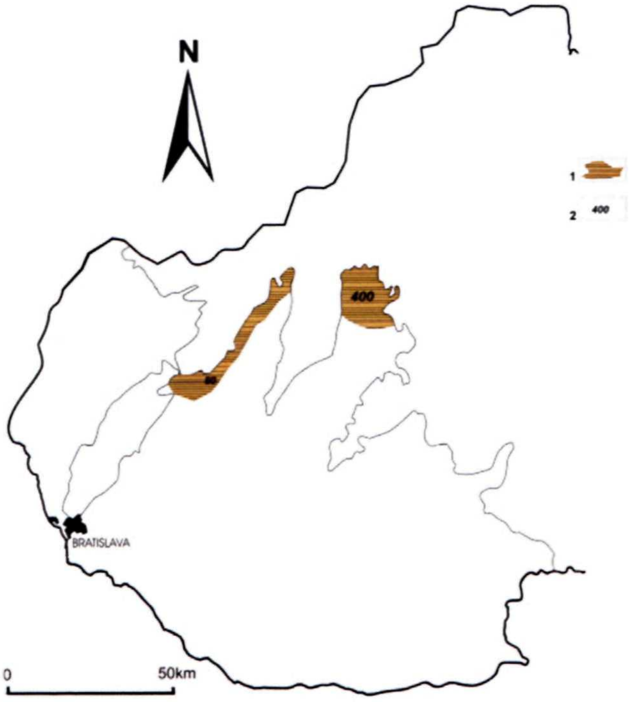


*Fig. 4.1.1.3 Distribution of Eggenburgian sediments in the Danube Basin (Nagy, 2011).*

*Explanatory notes: 1-grey calcareous sandy clays and siltstones with tiny layers of rhyodacite tuff (Čausa Formation) with marginal facies of conglomerate and sandstone (Podbranč and Kľačno Conglomerates), 2-the sediments thickness.*

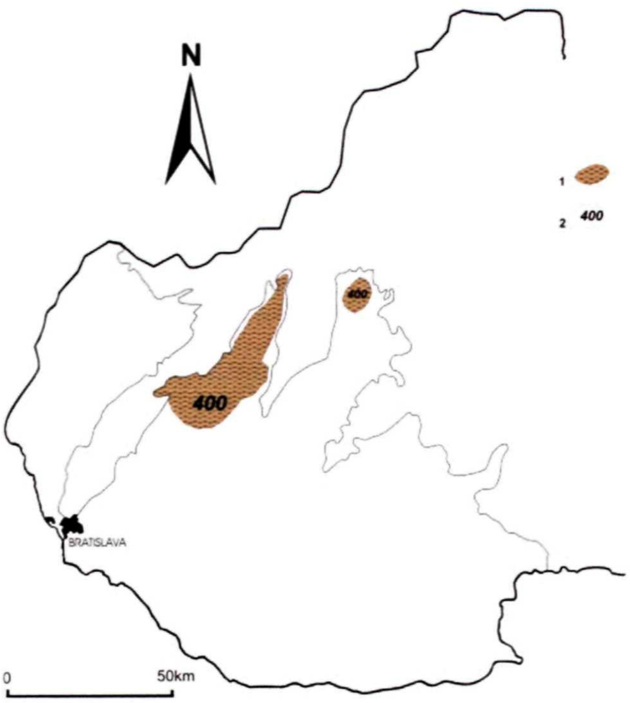


*Fig. 4.1.1.4 Distribution of Karpatian sediments in the Danube Basin (Nagy 2011).*

*Explanatory notes: 1-grey calcareous siltstones, or alternation of siltstones with sandstones of basinal facies (Lakšárska Nová Ves Formation), siltstones and claystones with tuffs (Prietrž Member), distal clastic facies (Jablonica Conglomerate), 2-thickness of the sediments.*

In the NE part of the Komjatice Depression and the E part of the Želiezovce Depression, ***Turová Member*** underlays the Bajtava Fm. (Vass in Melioris & Vass in 1982), made up of rare quartzose sands with sporadic pebbles of quartz and quartzite, conglomerates and breccias, variegated clays and silts, and andesite tuffs.

The thickness is a few tens of metres (Vass et al., 1980). They occur also in the Bátovce partial depression in the vicinity of PKŠ-1 borehole (Gondovo, Nagy et al. 1998).

In the northern part of the Rišňovce Depression the Badenian sediments are represented by Svinná Fm. made of claystones, sandstones, lignites and at the bottom part by andesite intrusions.

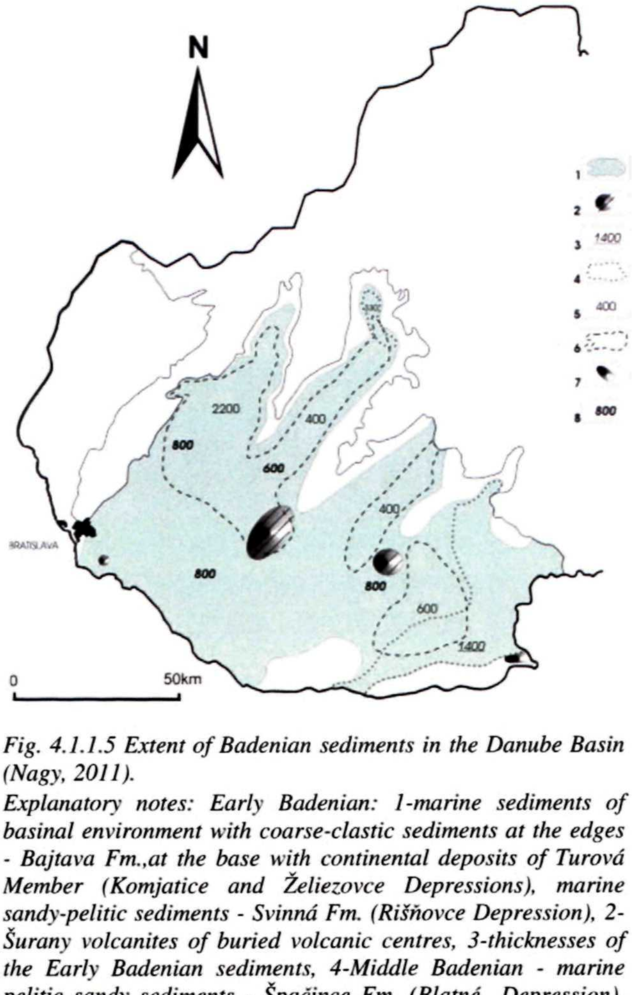


*Fig. 4.1.1.5 Extent of Badenian sediments in the Danube Basin (Nagy, 2011).*

*Explanatory notes: Early Badenian: 1-marine sediments of basinal environment with coarse-clastic sediments at the edges - Bajtava Fm.,at the base with continental deposits of Turová Member (Komjatice and Želiezovce Depressions), marine sandy-pelitic sediments - Svinná Fm. (Rišňovce Depression), 2-Šurany volcanites of buried volcanic centres, 3-thicknesses of the Early Badenian sediments, 4-Middle Badenian - marine pelitic sandy sediments - Špačince Fm. (Blatné Depression), bottom part of the Pozba Fm. (Komjatice and Želiezovce Depressions), claystone, sandstone, clays, conglomerates, breccias, with volcanic admixture - Kamenec Fm. (northern part of the Rišňovce Depression), 5-thickness of the Middle Badenian sediments, Late Badenian: 6-marine littoral sediments - Báhoň Fm. (Blatné, Rišňovce Depressions, Gabčíkovo Basin), top part of the Pozba Fm. (Komjatice and Želiezovce Depressions), 7-volcanoclastics of the Burda Fm., 8-thickness of the Late Badenian sediments*

In the Danube Basin, below the Middle Badenian sediments (Fig. 4.1.1.5) andesite volcanites of stratovolcanic structure are buried - andesite lava flows alternating with andesite volcanoclastics. They are widespread in the central part of the basin and also at the western edge of the basin and they are termed as **Šurany volcanites** (Vass 2002). According to boreholes they reach a thickness of 230 to 890 m.

Middle Badenian

In the Blatné and the southern part of the Rišňovce depressions the Middle Badenian sediments are represented by the **Špačince Fm.** basinal facies of grey calcareous clay with shaly slaking (tegel), siltstone and claystone (Jiříček in Papp et al., 1974, Vass, 1989, in Keith et al., 1989). The lower part of the formation (***Ratková Member***) and distal facies are made up of sandstones, conglomerates, rarely organogeneous sandy limestone (***Doľany Conglomerate***).

In the northern part of the Rišňovce Depression Middle Badenian is represented by **Kamenec Fm.**, consisting of clays, claystones, sandstones, conglomerates, locally breccias. They contain a volcanic admixture.

Thanks to their distinctness caused by the presence of andesite and acid volcanoclastics the sediments of the Komjatice and Želiezovce Depressions were included under the common name of **Pozba Fm**. The Formation is typical of conglomerates, sandstones and tuffs on the margins. Towards the Basin basal clastics disappear. Basinal facies represent slaking grey calcareous siltstones and claystones.

Closer to the northern edge of the Basin the Formation is dominated by calcareous, at places sandy claystones and siltstones. According to the geophysical measurements, on the flanks of the Levice Horst, which separates the Komjatice and Želiezovce Depressions, bioherms of algae limestone can be expected (Hrušecký et al., 1996). The thickness of the Formation in the territory studied amounts to approx. 600 m (Fig. 4.1.1.5).

Late Badenian

The Late Badenian sediments are preserved throughout the almost entire Danube Basin (Figure 4.1.1.5). In the Blatné Depression they are represented by the **Báhoň Fm.** (Vass, 2002). They consist of alternating layers of slaking grey calcareous siltstones and claystones with minor sandstone/sands layers (Homola 1951, fide Biela, 1978a; Homola in Homola edit., 1958). On the western edge of the Blatné Depression the upper part of the Formation is made of clays, coaly clays with coal seams 0.8-3 m thick (Vass & Gašparík et al., 1978). The maximum thickness of the Formation in the area studied is 800 m.

In the course of this period, in the northern part of the Rišňovce Depression, pelitic **Handlová Fm.** deposited reaching a thickness of about 10 m. In its southern part clays and sands of **Madunice Fm.** deposited reaching a thickness of approximately 340 m. In the Komjatice and Želiezovce Depressions the referred to above **Pozba Fm.** is present. The total thickness of the Pozba Fm. is approximately 700 m.

*Sarmatian*

In the Danube Basin the Sarmatian sediments (Figure 4.1.1.6), which were formed at the same time along with the products of contemporary volcanism described above, are represented by the Vráble Fm. (Priechodská et al., 1988).

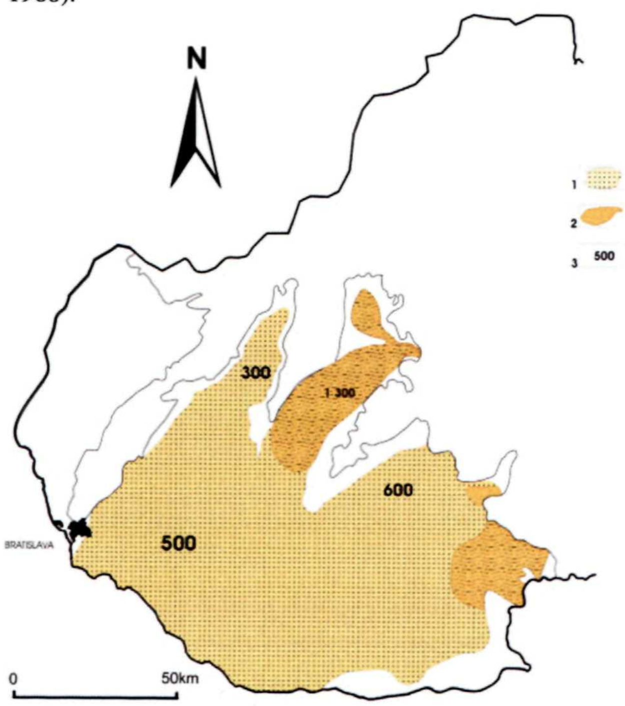


*Fig. 4.1.1.6 Distribution of Sarmatian sediments in the Danube Basin (Nagy 2010).*

*Explanatory notes: 1-calcareous green clays, siltstones and sands (Vráble Fm.), conglomerate of the distal facies (Doľany Conglomerate), 2-organodetritic limestones, sandstones, acid tuffs, clays, clays and locally coaly clays and tiny seams of coal representing deltaic sediments (Ripňany Fm.), 3-the thickness of the sediments.*

The Formation has a varied lithological composition. In the Blatné Depression and in part of the Rišňovce Depression calcareous silts and clays dominate, on the outskirts of the Depression with positions of gravel and organogeneous limestone. The upper part of the Formation consists of sands and clays, variegated clays, coaly clays with lenses and tiny seams of coal (Gaža, 1961, Gaža et al., 1985; Homola et al. (1955, fide Biela, 1978). Mainly at its basis the Vráble Fm. in the Želiezovce Depression is formed of conglomerates, sandy, oolitic and lumachella limestones, and sandstones/sands and acid biotitic tuffs. Towards the centre of the Depression a proportion of grey calcareous, locally tuffaceous clays, is growing.

The total thickness of the Vráble Fm. according to Hrušecký et al. (1996) is 300 m (Želiezovce Depression), 500 or 700 m (Blatné, Rišňovce and Komjatice Depressions).

In the central part of the Rišňovce Depression a subsidence of the Danube Basin resulted in the retreat of the sea to the South. In its northern part the redeposited pyroclastics, conglomerates, breccias, claystones and sandstones of the **Ruskov Fm.** were deposited reaching a thickness of approx 120 m.

In the course of the Sarmatian to Early Pannonian in the southern part deltaic freshwater sediments of the **Ripňany Fm.** deposited (Fordinál & Elečko, 2000). At the edge of the Basin finger-like contact with the Vráble Fm. occurs; the sequence is covered by younger sediments. The maximum thickness is 1,430 m.

The Komjatice Depression is dominated by the clays and sands, frequently the tuffaceous ones. They are exposed in the area of the Kozmálovské vŕšky Hills. In the Želiezovce Depression marginal shallow-water sediments of the Vráble Fm. (**Zbrojníky Fm.**) are represented by fine-grained tuffaceous sands and sandstones with interlayers of fine conglomerates, tuffaceous siltstones and claystones. The sediments reach approximately 300 m in thickness.

QUATERNARY

For the purpose of $CO_2$ storage the Quaternary has no practical meaning, and therefore we do not discuss it.

TECTONICS

The Danube Basin was opened as a result of heterogeneous thinning of the lithosphere. Its evolution started with initial phase of rifting, later continuing with synrift and finally postrift opening phase (Vass & Pereszlényi 1998). The initial rifting phase occurred during the Early and Middle Miocene. The main part of the synrift phase was activated during the Middle Miocene, the postrift phase filled-up the Basin in the Late Miocene and in Pliocene.

For the $CO_2$ storage **neotectonic evolution** is of particular importance, since this directly affected the integrity of already incurred traps regardless of whether they are filled with hydrocarbons, or not. The neotectonic events and processes that have taken place in the period since the end of the Pliocene, represent the youngest stage of the last tectonic-sedimentary megacycle of the Danube Basin evolution (Kováč & Baráth 1995, Kováč et al. 1997). In conformity with the megacycle beginning, at the same time changed the characteristics of the stress field, which have persisted until recent (Bada 1999).

From the above it can be seen, which fault structures can be expected in the scope of detailed works, which could lead to the potential repository.

If we summarize this fairly detailed entry, so for this purpose are suitable mainly lower members of Eggenburgian (Čausa Fm.), Karpatian (Lakšárska Nová Ves Fm.), Badenian (Špačince Fm.) and Sarmatian (Vráble gravels and sands). Most of these complexes are located in the Blatné and Rišňovce Depressions.

### 4.1.2 Hydrocarbon deposits in the Danube Basin - local aquifers

The Danube Basin is in compare to the "hydrocarbon more productive" basins (Vienna and East-Slovakian) less demonstrated in terms of production; however, especially in its peripheral parts the structure are existing, that could serve the purpose. They are located in the areas of the municipalities Krupá, Cífer, Báhoň, Trakovice, Sereď and Ivánka - Golianovo (Fig. 4.1.2.1).

They were characterised lithologically and lithostratigraphically with regard to the geological and structural setting of the site. The estimated parameters were sealing structures and the presence of natural gas in the structures or in their superincumbent. The following estimates are based on the dimensions and capacity of the collector lithology, their average or predicted porosity and permeability, taking into account the factor of solubility of carbon dioxide under given conditions. ***We have to note, that unlike the objects in the Vienna and Trans-Carpathian Basins we are dealing with capacities of the local aquifers of the deposits and not the deposits objects.***

Supplementary information provided the calculated natural gas reserves in the superincumbent or in the upper parts of the selected structures. In the case of their extraction new capacities for $CO_2$ storing would be gained.

#### 4.1.2.1 The Krupá Structure

The structure is located in the north-western part of the Blatné Depression of the Danube Basin (Fig. 4.1.2.2).

It is made up of conglomerates and sandy conglomerates, Eggenburgian in age (Dobrá Voda Conglomerate of the Čausa Fm.), and of Karpatian conglomerates (Jablonica Conglomerate of the Bánovce Fm.), separated by Eggenburgian calcareous claystone interlayer from the Čausa Fm. Both coarse-clastic horizons are water-bearing. These are mineralized aquiferous types of a collector.

On the basis of the work by Gaža (1979) and Biela (1978) the basement consists of Middle Triassic solid dolomitic brown-grey limestones of Havranica type affiliated to Hronicum Nappe. The basal Eggenburgian littoral conglomerates and sandy conglomerates - Dobrá Voda Conglomerate, form planar and thinly-lenticular layers. They reach a thickness of about 60 m and are water-bearing.

They are overlain by neritic clayey facies of the Čausa Fm. in a variable thickness, whereas they gradually wedge out towards the Northwest.

The following base of the Karpatian sediments is made of conglomerates and sandstones of anoxic lagoonal-marine origin, belonging to the upper part of the Planina Fm. (in the lithostratigraphic column of the Danube Basin they are assigned to the Jablonica Conglomerate). They reach a thickness of about 110 m and are water-bearing.

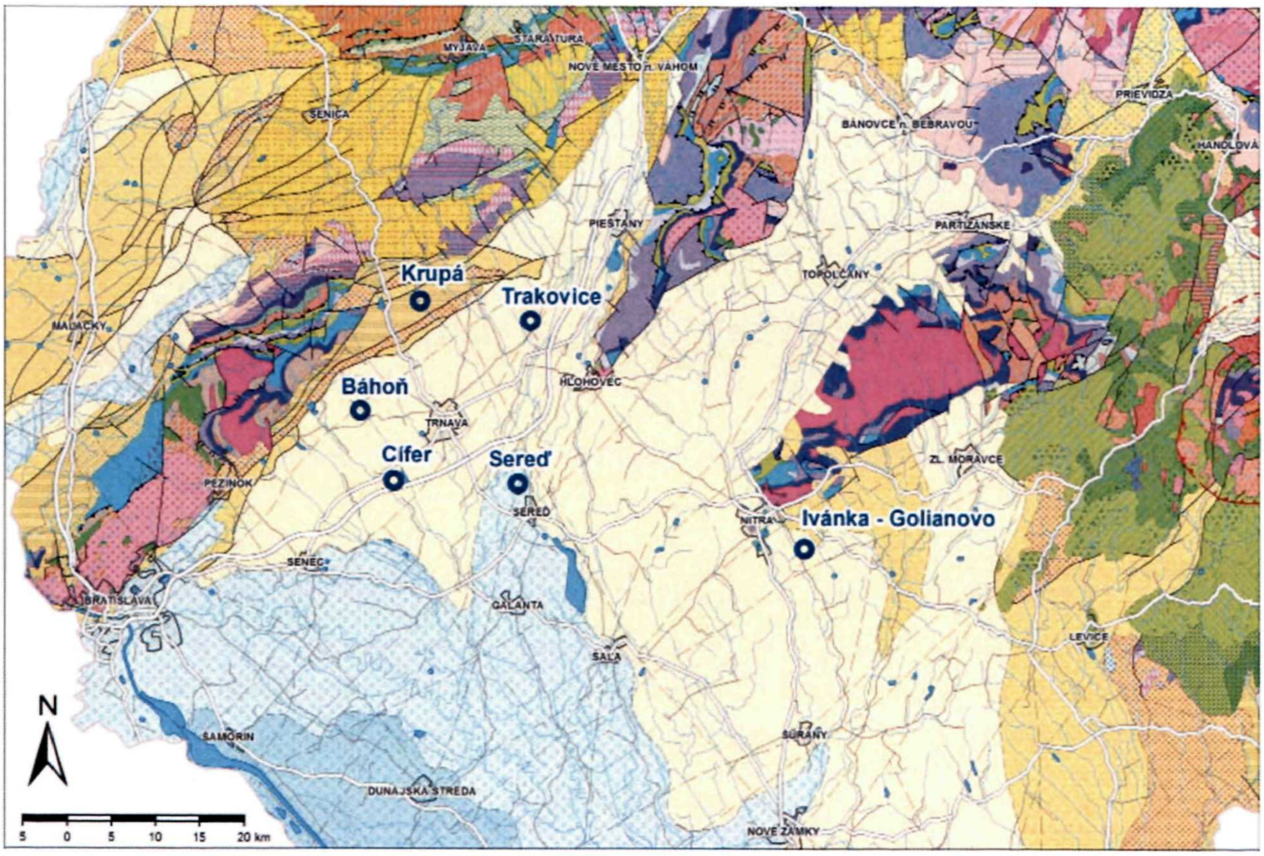


*Fig.4.1.2.1 Gas structures of interest in the Danube Basin*

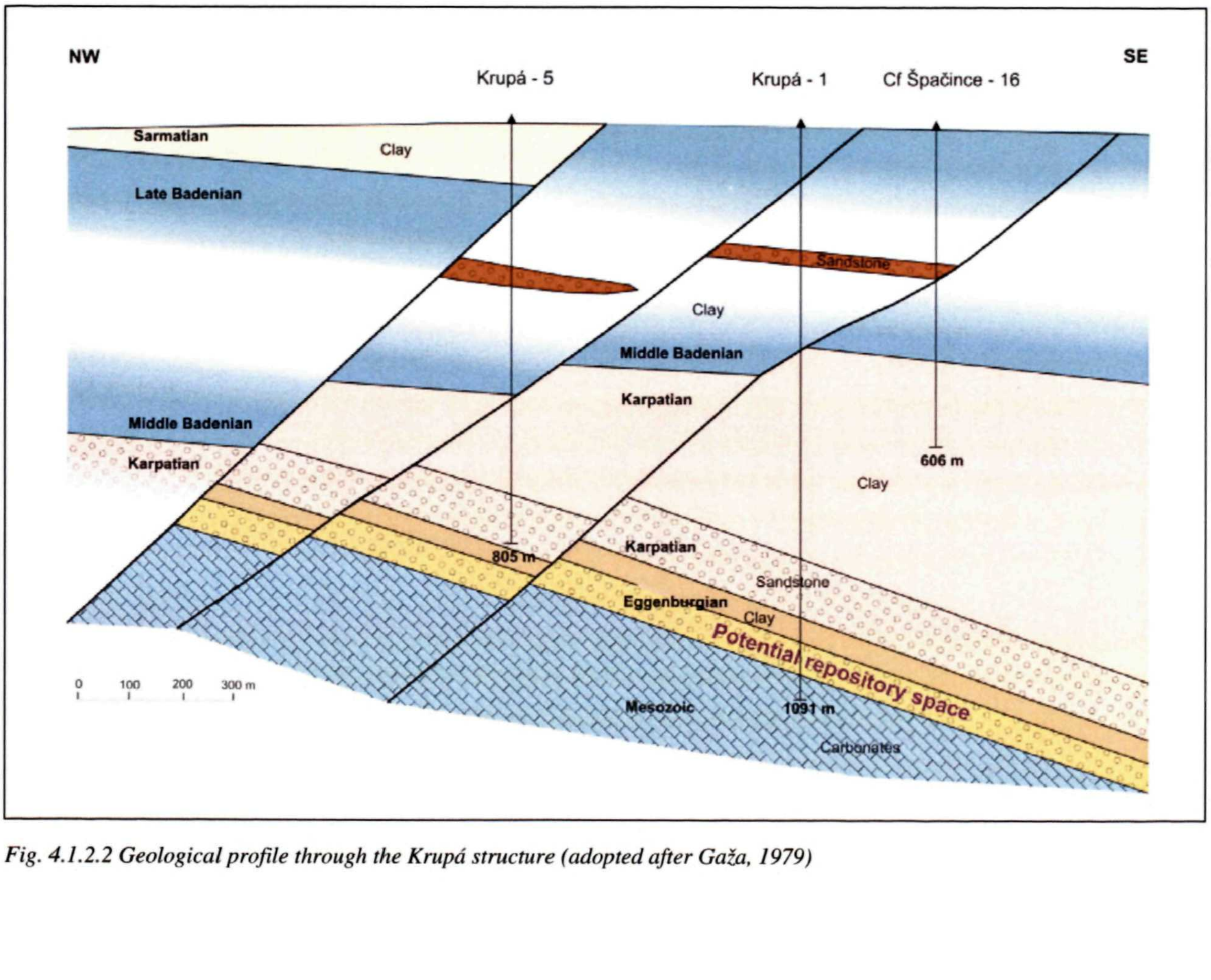


*Fig. 4.1.2.2 Geological profile through the Krupá structure (adopted after Gaža, 1979)*

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They are overlain by Karpatian neritic schlieren facies of aleuritic claystones of the top of the Bánovce Fm. Their thickness here exceeds well beyond 100 m.

Thanks to postsedimentary deformation the sediments form SE inclined slope of a brachysyncline (Pěničková, Dvořáková, 1985). In the North-West it partially restricts the Kátlovce sinistral-normal fault system of WSW-ENE strike with a NNW dip, while on the southern edge the restriction constitutes Dubovany sinistral-normal fault and on the East foot the structure is enclosed by Dechtice normal fault. On the western and northern boundaries erodible wedging out of clastics is likely involved.

The uppermost part of the collector is located at a depth of 600 m and it is inclined with an angle of 15° to the southeast, later steeply up to a depth of about 1,300 meters.

The structure of the collector is of a brachysyncline shape and its top marginal parts are limited due to erosive-transgressive colmatage of Middle Badenian pelitic sediments of the Špačince Fm.

For the sealing parameters of the collector critical are normal faults of the Kátlovce sinistral-normal fault system with a dip to N to NW, it means the direction beneath the Dechtice Block of the northern part of the Malé Karpaty Mts.

Lateral migration of fluids to the northwest through the northern Kátlovce fault, enclosing the structure from the North, is limited by normal fault closure, made of Karpatian impermeable claystones of the top of the Bánovce Fm., and overlying complex of Middle Badenian calcareous claystones of the Špačince Fm.

In the vertical direction the Kátlovce fault system crosses up to 700 m thick complex of pelitic sediments, Karpatian and Badenian in age, which are characterized by good adhesion to the fault plane surfaces.

The sealing nature of the fault zone is well documented by natural gas accumulation in a thin horizon of Badenian sands, high up in the caprock of the collector.

The Krupá structure has an area of approximately 27 800 000 $m^2$. The average porosity of coarse clastics can be up to 23%. According to different sources of information the formation $CO_2$ factor for aquiferous type of collector, can vary between 0.02 and 0.30. For the calculation we are prone to adopt the minimum capacity factor.

On the basis of the calculation the capacity of the collector can reach up to 5 294 232 t $CO_2$ in the 60 m thick Eggenburgian conglomerates and 9 706 092 t $CO_2$ in 110 m thick Karpatian conglomerates.

The total capacity of the two horizons could thus be 15 000 324 t $CO_2$.

The value, in spite of the lowest value of the formation factor, is to be understood as the maximum, with no adjustments on the variability in thicknesses, the inhomogeneity in cementation and permeability, etc.

#### 4.1.2.2 The Cífer Structure

It is the elevation structure in the central part of the Blatné Depression of the Danube Basin (Fig. 4.1.2.1). On the basis of the works of Gaža (1994a) and Biela (1978), Middle Badenian water-bearing basal sandy conglomerates overlain by pelitic facies are present here; the sequence belongs to the Špačince Fm. To the collector we can potentially assign the Karpatian Jablonica Conglomerate and sandstones of the top of the Bánovce Fm. (separated from the Badenian conglomerate by schlieren facies of the Bánovce Fm.), as well as the even deeper lying (beneath pelites) conglomerates and sandy conglomerates of undetermined, supposedly Palaeogene age. This is a mineralized aquiferous type of collector. Geological cross -section is presented in Figure 4.1.2.3.

The basement of the Danube Basin in the zone of the aquifer has not been validated by drilling survey; however, it is assumed that is formed by Tatricum crystalline complexes. Basal sandy conglomerates horizon of the Špačince Fm. of Middle Badenian is made of planar and thinly lenticular strata, representing transgressive facies of the western slopes of the Trnava elevation. They reach a thickness of about 60 m and are overlain by neritic clayey facies of the Špačince Fm. with the thickness of over 200 m.

In its basement, the potential collector is separated by a 100 m thick sequence of Karpatian marine aleuritic claystone of the top of the Bánovce Fm. and is made up of 200 m thick Karpatian conglomerate and sandstone of the Jablonica type, a complex belonging to the base of the upper part of the Bánovce Fm. The sediments are likely of alluvial-deltaic origin; upwards they transit into marine littoral facies. They represent a southern marginal base of the Neogene fill of the Danube Basin in this area.

As the next potential collector in the basement we can consider Palaeogene conglomerates and sandstones, separated from the overlying Karpatian conglomerates by a 50 m thick layer of shale. The Palaeogene conglomerates and sandstones are likely of shallow-marine origin and contain a number of thin shale interlayers. They were identified in the borehole Cífer-2, for instance. They where not completely drilled-through; there were encountered only around 130 m of this incomplete core recovery.

The Cífer structure represents a cover of the brachyanticline slope on the western slope of the Trnava elevation (Pěničková, Dvořáková, 1985). In the central area, the upper part of the structure, formed by Badenian clastics, is dipping subhorizontally with a very slight slope eastwards. This situation is due to the tilt of sunken block - in opposite to the Trnava elevation, along the main Trnava normal fault of the NNE-SSW direction, which surrounds the structure at the eastern and southern sides.

From the western side the Cífer structure collector is bounded by another North-South normal Cífer fault, sloping westwards, into the basinal depocentre. In its vicinity the stratification becomes significantly steeper with persisting westward inclination. The northern boundary of the collector is conventionally bounded to isohypse of 2100 m depth of the basin basement; northwards sinks into the larger depths. On the basis of seismic profile in

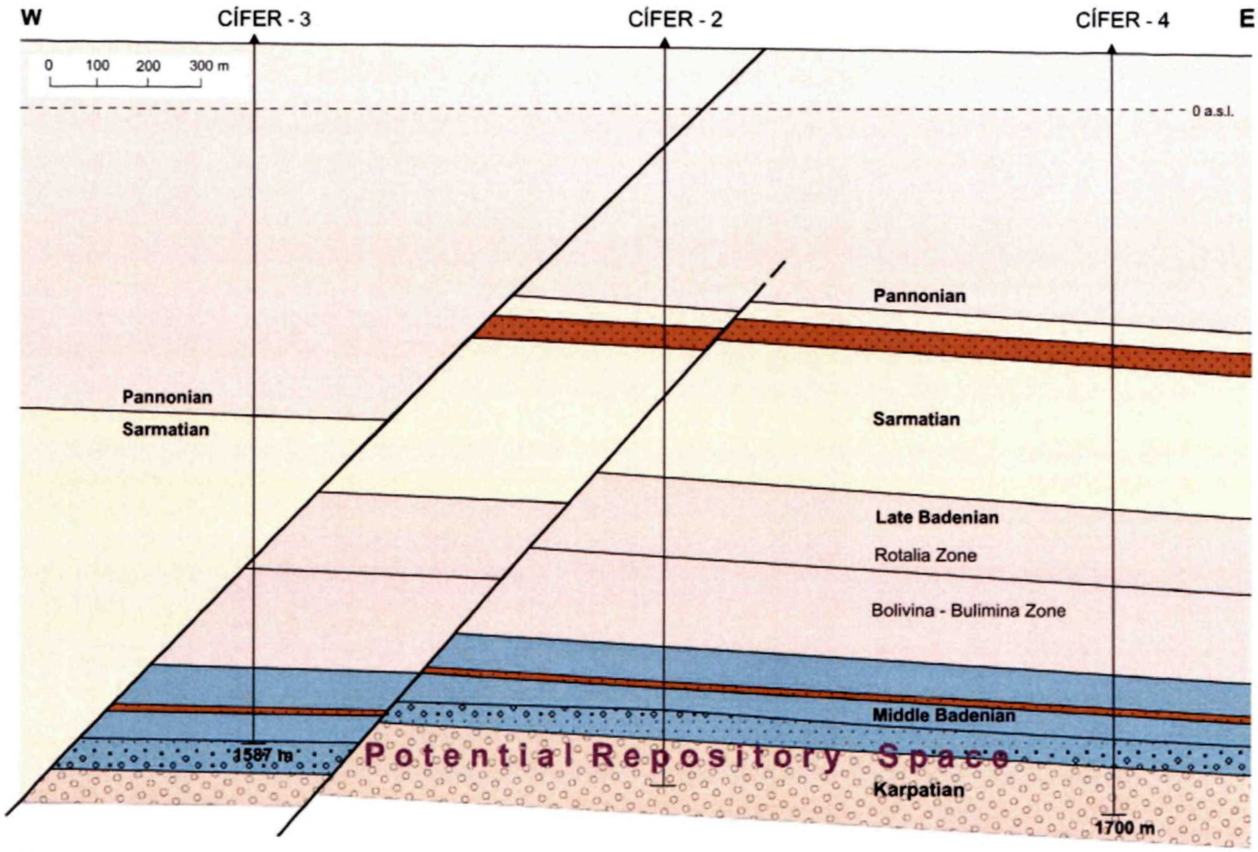


*Fig. 4.1.2.3 Geological profile of the Cífer structure (adopted after Gaža, 1994a)*

this area (554/77) there is also possible to identify the transverse transpression Cífer fault of the WSW-ENE direction, causing steep southerly arching of the Cífer structure.

The uppermost part of the collector is located at a depth of around 1500 m and drops slightly toward the East. To the West and the North the structure is declining steeply into larger depths.

For sealing parameters of the collector critical are normal faults of the Cífer fault system, restricting the top part of the structure of sunken block, with westerly inclination to the basinal depocentre. Lateral westward migration of fluids through the Cífer faults is limited by normal fault sealing made of impermeable Badenian claystones of the Špačince Fm.

In the vertical direction the Cífer fault system crosses up to a few hundred meters thick complexes of dominantly pelitic sediments, Badenian and Sarmatian in age. They are characterized by good adhesion to the fault plane surfaces.

The sealing nature of the fault zone is well documented by preserved accumulation of natural gas within Middle Badenian and Late Sarmatian thin sandy horizons in the close and more distant superincumbent of the collector proposed.

The Cífer structure has an area of approximately 14 250 000 $m^2$. Porosity of coarse clastics may be up to 20% on average.

The capacity of the collector in the ideal state of physical properties may be at the minimum formation factor for the aquiferous type of collector about 2 359 800 t $CO_2$ in the 60 m thick horizon of Middle Badenian age, or 7 866 000 t of $CO_2$ in the 200 m thick Karpatian conglomerates; finally, a potential of 5 112 900 t $CO_2$ is assigned to 130 m thick Palaeogene conglomerates.

In sealed and from the aquifer isolated superincumbent of the aquiferous body there are two horizons of porous sandstone containing gas with dominating nitrogen ($N_2$) (Gaža, 1994a).

The upper horizon is located in the sandstone horizon, Late Sarmatian in age, intercalated within sealing claystone (Vráble Fm.). The thickness of the horizon ranges between 4 and 10 metres; in the borehole Cífer 2 it was identified in a depth of 620 m. Calculated capacity of the horizon is 11.45 million $m^3$ of natural gas, of which 2.62 million $m^3$ consists of methane and dominant 8.83 million $m^3$ is the representation of nitrogen.

In the case of extraction of the balancing amount of ca. 7.6 mil. $m^3$ of natural gas, it would be theoretically possible to replace the gas in the collector by $CO_2$ injecting, but due to a small depth of the horizon, the $CO_2$ storage would not be effective.

A deeper horizon is tied to a relatively thin layer of Middle Badenian sandstone inside a sealing claystone (Špačince Fm.). It reaches a thickness of 4-10 m and in the well Cífer 2 it is identified in the depth of 1,435 m.

Gas reserves were calculated at 66.63 million $m^3$ of which 15.26 million $m^3$ involves methane, and 51.37 million $m^3$ is made up of nitrogen (Gaža 1994).

In the case of extraction of the balancing amount of ca. 44.4 million $m^3$ of natural gas, it would be theoretically possible to replace a gas capacity of the collector by $CO_2$ injecting. At the assumed bulk density of $CO_2$ at the rate of 0.7 $g.cm^{-3}$, the mass of $CO_2$ could be about 31.1 million tonnes. While applying formation factor of 0.003, the real capacity could reach 93 ths. tonnes of $CO_2$.

The calculations are approximate, but the structure is a good candidate for a model solution to the technological possibilities of $CO_2$ storage into depleted deposit space in the form of a pilot program. The question is whether the $N_2$ reserves are an interesting commodity for a potential customer.

### 4.1.2.3 The Báhoň Structure

The object is located in the western part of the Blatné Depression of the Danube Basin (Fig. 4.1.2.1). According to the borehole database (Biela, 1978) the object is made of Middle Badenian conglomerates and sandstones at the base of the Špačince Fm. overlying Pre-Neogene basement. Clastic horizons are water-bearing. This is a mineralized aquiferous type of collector. The seismic profile across the site is presented in Figure 4.1.2.4.

The basement of the collector in the southern area, as validated by drillings, is made up of crystalline rocks of the Malé Karpaty Mts. (mainly granitoids and biotitic mica schist gneisses). Middle Badenian basal conglomerates and sandstones of the Špačince Fm. in the borehole Vištuk 2 are of likely alluvial origin on their basis, and upwards they transit into littoral marine facies. The basal conglomerates here reach the thickness of up to 300 m and the sandstones in their direct superincumbent are around 200 m thick. Therefore they represent a gigantic water-bearing collector. In the borehole Báhoň 1 the sequence is not completely drilled-through and only the top part of the marine sandstone-conglomerate collector is recovered reaching a thickness of 220 m with multiple thin claystone interlayers. In their superincumbent, the claystones belonging also to the Špačince Fm. occur again along with sandy claystones of the Madunice Fm., reaching a summary thickness of more than 1000 m.

The Báhoň structure represents a Middle Badenian active segment of the subsiding pull-apart partial depression, filled-up in short period of time by enormous accumulations of coarse clastics, which have not been completely drilled-through by deep survey. In the northern part of the territory in the borehole Suchá 3 they are known in incomplete thickness of more than 500 m in significant depths. Their clastic material is derived from Tatricum units and to the North also from the nappe units of the Malé Karpaty Mts. They overlie probably a dissected Pre-Neogene basement, formed of the Malé Karpaty Mts. Tatricum. They have the nature of depression fill and its western supplying slope, which is reflected in their depositional geometry - while in the eastern part they are deposited subhorizontally. To the West their stratification is controlled by normal faulting.

According to the structural map (Pěničková, Dvořáková, 1985) in the West the Báhoň structure is restricted by the southern branch of the Boleráz fault of the SW-NE direction, of mostly normal fault nature. In the East, the border of the structure is controlled by uneven Budatín fault of strike-slip mechanism with a strong normal faulting component. Its direction is approximately NE-SW with a dip to the ESE. The western border of the structure is kept very conventionally, at very approximate isobath contours of Pre-Neogene basement of about 1,700 m.

In the borehole Báhoň 1 the clastics collector surface was encountered at a depth of 1,830 m, and in the borehole Vištuk 2 at a depth of 1,780 m (Biela, 1978).

The structure of the collector has the shape of syncline with dissected internal block structure, which is not sufficiently explored in detail. Vertical migration of the fluids in the rock environment is limited by thick clayey sediments cover of the Middle and Late Badenian.

Lateral migration of the fluids in the East is bounded by a tectonic amputation. In the West we assume a similar amputation, which is, however, necessary to verify in more detail with respect to the height of the vertical displacement of the Boleráz fault system. Due to the steep palaeoshore slope of the pull-apart basin we assume wedging out of coarse-clastic facies at the basement isobath of around 1,700 m.

In this case, we can document the nature of the normal fault sealing and preserved contents of methane and nitrogen in marine mineralized aquifer in wells in the area.

The Báhoň structure is characterized by good porosity and water-bearing just at the top of the marine horizon of the collector (ca 150 m), while the lower coarse-clastic members display a significant degree of cementation with consequent drop in their porosity and permeability.

The structure has an area of approximately 64 000 000 $m^2$. The average porosity of the coarse clastics can reach up to 14%. The capacity of the collector can attain at the minimum formation $CO_2$ factor for aquiferous collector type up to 18 547 200 t of $CO_2$ at the estimated 150 m thick sandstone and conglomerate complex.

### 4.1.2.4 The Trakovice Structure

The structure is located in the eastern part of the Blatné Depression of the Danube Basin (Fig. 4.1.2.1). It consists of sandstones and sandy conglomerates of the Early and Middle Badenian (lower part of the Špačince and Trakovice Fms.) of variable thicknesses with several clayey sandstone and claystone interlayers. The clastic horizons are water-bearing. This is a mineralized aquiferous type of collector. Geological cross-section is presented in Figure 4.1.2.5.

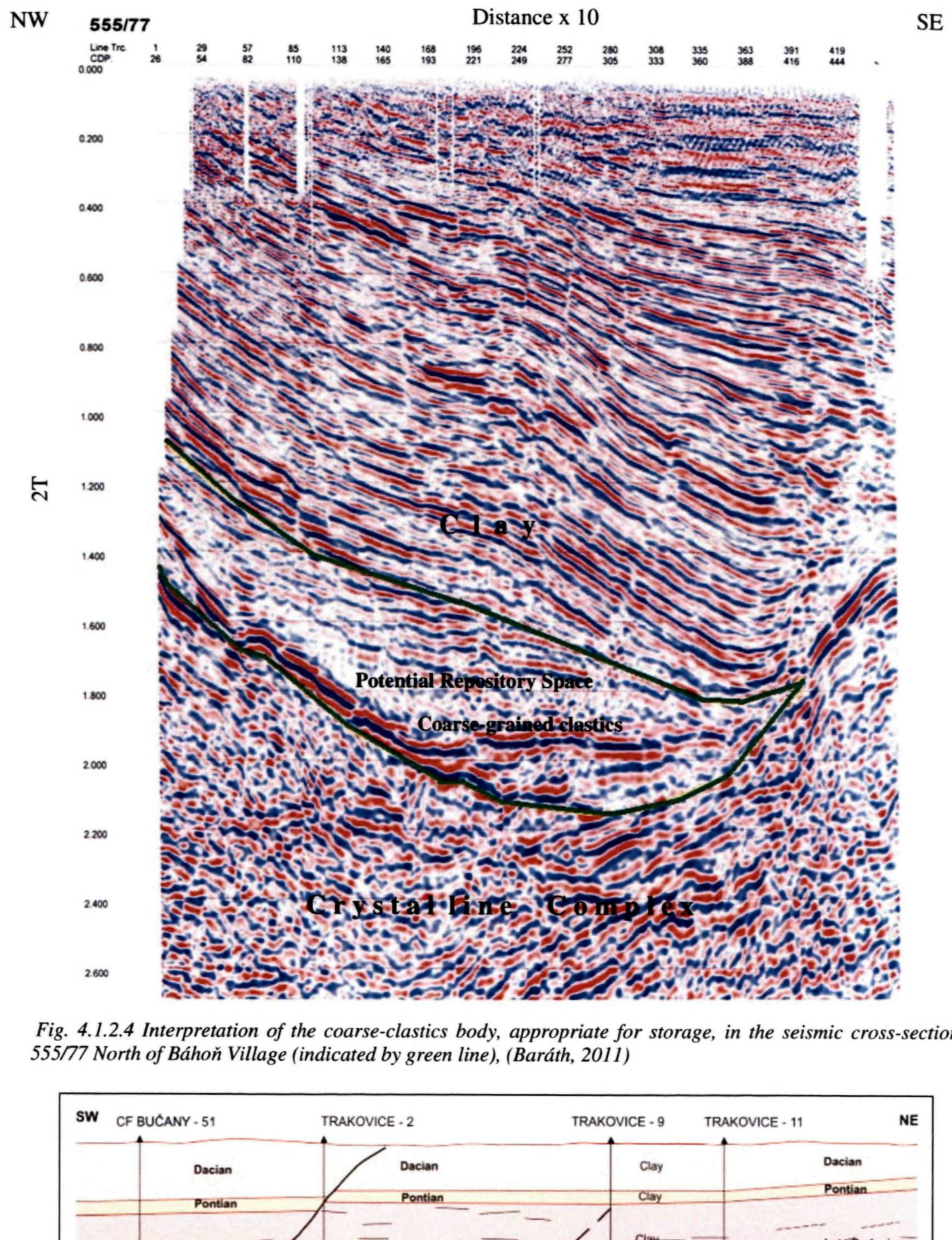


*Fig. 4.1.2.4 Interpretation of the coarse-clastics body, appropriate for storage, in the seismic cross-section 555/77 North of Báhoň Village (indicated by green line), (Baráth, 2011)*

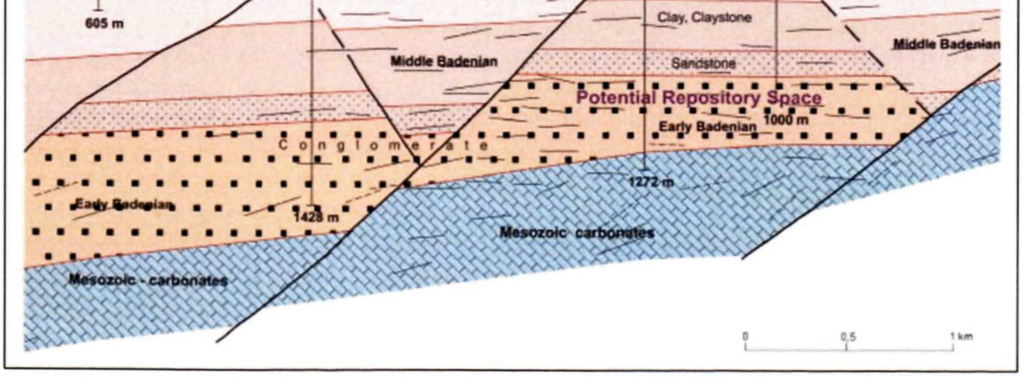


*Fig. 4.1.2.5 Geological profile through the Trakovice structure (adapted after Gaža, 1994)*

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On the basis of the work of Gaža (1994b) and Biela (1978) the basement consists of Triassic dolomites and dolomitic limestones of Krížna Nappe. Basal Early Badenian sandstones and conglomerates of the Trakovice Fm. are of likely littoral origin and have a variable thickness, depending on the dissection of their palaeorelief. In the Trakovice 3 borehole they reach a thickness of 260 m, including three significant interlayers of claystone with thicknesses of 10, 25 and 55 m, while in the upper part of the borehole Trakovice 9 only the uppermost part of the sequence deposited with a thickness of around 50 m. In their superincumbent calcareous shales are present again belonging to the Trakovice Fm., reaching a thickness of up to 100 to 120 m.

The overlying Middle Badenian sandstones of the bottom part of the Špačince Fm. show signs of deltaic deposition environment and they have frequent claystone and clayey sandstones interlayers. In the borehole Trakovice 9 they reach a thickness of around 200 m, while in the borehole Trakovice 3 the proportion of claystone interlayers is significantly increased, so the sandstone thickness reaches around 70 m in total.

They are covered by neritic claystone facies of the Špačince and Madunice Fms. of a thickness of more than 400 m.

The structure Trakovice represents a cover of the south-western slope of rugged brachyanticline of Trakovice elevation (Pěničková, Dvořáková, 1985). The oldest members of the sequence are found in the deepest parts of the south-eastern part of the structure and towards the North and North-East on the Pre-Neogene basement gradually younger sediments were transgressively deposited. Higher horizons have a subhorizontal stratification with finger-like intrusions of the basinal claystone facies from the West, as well as with the signs of wedging out of sandy horizons in the eastward direction.

To the West the Trakovice structure is restricted by the North-South Trnava normal fault system ($t_2$) with a western slope and to the East the structure is limited by the other fault of the North-South Trnava normal fault system (t3) with a dip to the West. The northern border of the structure is assumed conventionally at the depth of 1,500 m and in the South the conventional boundaries are also interpreted by a short stretch on the slopes of the transverse elevation of the NW-SE direction, probably tectonically limited.

The uppermost part of the collector in the Northeast is located at a depth of 810-830 m and in the south-western part of the territory its base reaches to the depths of up to 1,800 m.

The brachyanticlinal structure of the collector has a complex internal block construction and has not been sufficiently studied in detail. Vertical migration of the fluids in the rock environment is limited by thick clay sediments cover of the Middle and Late Badenian in the collector superincumbent.

Lateral migration of the fluids is bounded by lithologic wedging out and transition into claystone facies.

For sealing parameters of the collector critical are normal faults of the Trnava fault zone on the eastern and the western edge of the structure.

In the vertical direction the fault system crosses over 400 m thick, dominantly pelitic Badenian sediments complex, which is characterized by good adhesion to the fault planes surfaces.

The sealing nature of the fault zone is documented by preserved small accumulations of natural gas in the horizons of the highest part of the Middle Badenian sands and in the thin sandy horizons in structure's superincumbent.

The Trakovice structure has an area of approximately 18 750 000 m$^2$. The average porosity of the collector's clastics can reach up to 14%. The capacity of the collector at the minimum formation $CO_2$ factor for aquiferous collector type can attain at an average thickness 115 m of the clastics complex of Early Badenian age 4 165 875 t $CO_2$ and at an average thickness of 135 m of the Middle Badenian clastics 4 890 375 t $CO_2$.

The total capacity of the two systems could thus achieve 9 056 250 t $CO_2$.

#### 4.1.2.5 The Ivánka - Golianovo Structure

The structure is located on the western slopes of the Komjatice Depression of the Danube Basin (Fig. 4.1.2.1). It consists of Sarmatian basal sandy conglomerates and sandstones of the Vráble Fm. The sediments reach a thickness of about 60 m and are covered mostly by neritic clayey facies of the Vráble and Ivánka Fms. of a great thickness, reaching almost 1800 m (boreholes Ivánka I-2, 3, 6 and Golianovo G-1) (Biela, 1978, Šályová and Možiš, 2002). This is a mineralized aquiferous type of the collector with gas "caprock". The basement of the Danube Basin in the area of proposed collector is formed by the Palaeozoic crystalline Tatricum rocks of the Tríbeč block. Basal sandy conglomerates and sandstones form lenticular layers and represent alluvial-fan facies on the south-eastern slopes of the Tríbeč mountain range. The Ivánka - Golianovo structure is a normal fault-restricted Early-Sarmatian alluvial-deltaic body along the Mojmírovce fault of the SSW-NNE direction, accompanied by antithetic fault, crossing the structure. The layers are deposited with a slight dip toward the West-Northwest and the clastics gradually transits into marly facies laterally.

The uppermost part of the collector is located at a depth of about 1,750 m with the base at a depth of around 2,080 m. For collector's sealing parameters the Mojmírovce normal fault is of utmost importance. However, a good sealing against vertical migration of fluids is ensured by overlying clay complexes.

The sealing nature of the Mojmírovce fault zone is well documented by the preserved accumulations of natural gas in the top parts of the Early Sarmatian mineralized aquifer.

Geological cross-section is presented in Figure 4.1.2.6.

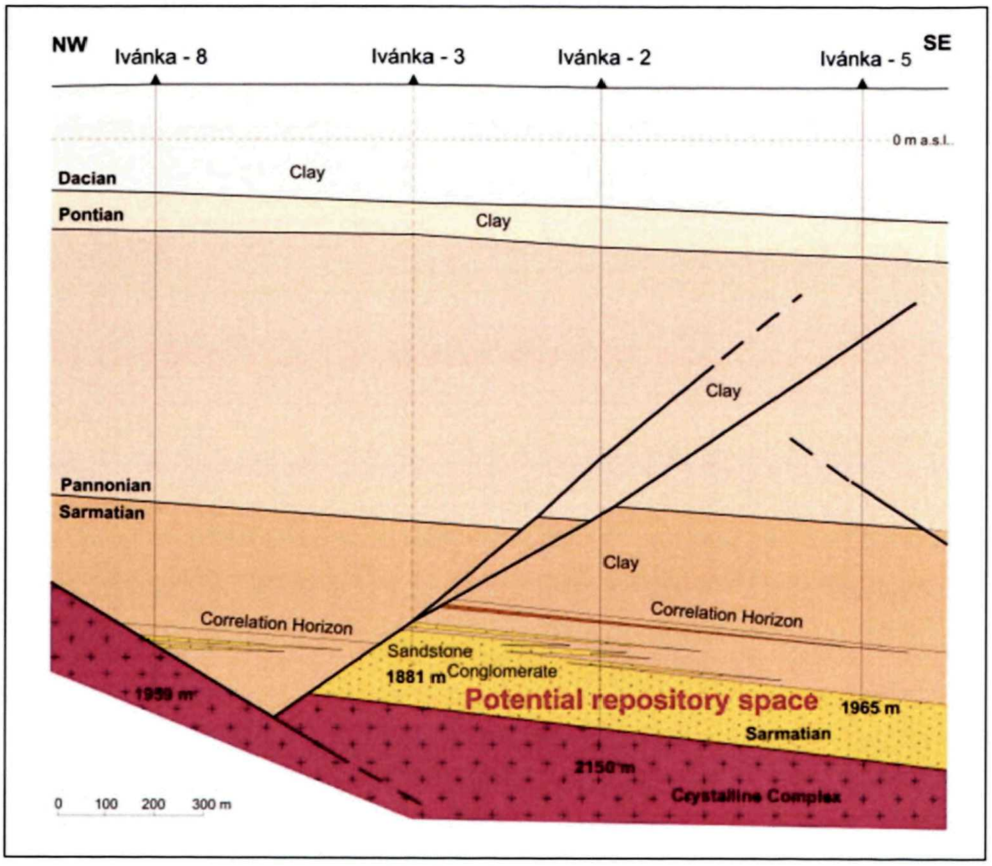


*Fig. 4.1.2.6 Geological cross-section through the structure Ivánka - Golianovo (adopted after Šályová and Mojžiš, 2002)*

The structure Ivánka - Golianovo has a minimum area of approximately 12.5 km$^2$. The average porosity of coarse clastics may be up to 12%. The measured permeability of the collector is considerably variable, reaching a maximum of 20 mDa. For an estimate of the capacity of the collector, we used the minimum value of the formation factor.

On the basis of the calculation, the collector's capacity in the ideal state of physical characteristics may be at the minimum formation $CO_2$ factor for the aquiferous type of collector up to 4,140,000 t.

At the top and the peripheral parts of the structure there have been identified a total of 5 gas-deposit horizons (borehole Golianovo 1 (1999) - operated deposit Ivánka pri Nitre, ENGAS s.r.o. Bratislava, Šályová and Mojžiš, 2002). This is a sandstone-conglomerate collector at the base of Sarmatian sediments of the Vráble Formation.

The 1$^{st}$ up to the 4$^{th}$ horizons are made up of sandstones with the thickness of 2-13 m and the 5$^{th}$ (bottom) horizon is made up of water-bearing sandstones and conglomerates with a thickness of up to 71 m. The upper part of the horizons is sealed with claystones, while in the lower part of the 5$^{th}$ horizon the water/gas boundary was detected inside the clastics at a depth 1695 m.

The total capacity of the collectors was calculated to 1,160 million m$^3$, of which 0.416 million m$^3$ consists of methane with ethane ($C_2H_6$ + $CH_4$), 0.438 million m$^3$ consists of $CO_2$ and 0.305 m. m$^3$ constitutes nitrogen $N_2$. The bulk of the reserves (91%) is tied to the bottom 5$^{th}$ horizon.

In the case of extraction of the balancing amount of ca. 733 million m$^3$ of natural gas, it would be theoretically possible to replace a gas capacity of the collector by injected $CO_2$. After calculating the bulk density the overall exchangeable mass will reach ca 513 mil. tonnes $CO_2$. After application of the formation factor 0.003 the capacity of the stored $CO_2$ is balanced to 1,539,000 tonnes.

#### 4.1.2.6 The Sereď Deposit

**(UGSF Križovany nad Dudváhom - Underground Gas Storage Facility)**

The deposit is located in the Danube Lowland, North of Sereď, where it was detected by pioneer survey on the structure of Križovany. The deposit is bound to the base of Middle Badenian in the depth of 960-1,060 m (Lorenc, 1968). Its location is depicted in Figure 4.1.2.1.

This is the semi-arch, brachyanticlinal structure, interrupted by Majcichov fault of the ENE-WSW direction. The brachyanticline structure evolved due to arching of the Pre-Neogene basement, encountered by drilling at a depth of 1,385 m. This elevation element presents a continuation of Abrahámovce elevation, which has the general N-S direction.

In terms of facies development the main collector horizon is variable in both the horizontal and vertical directions. It is made up of partly cemented weakly- to

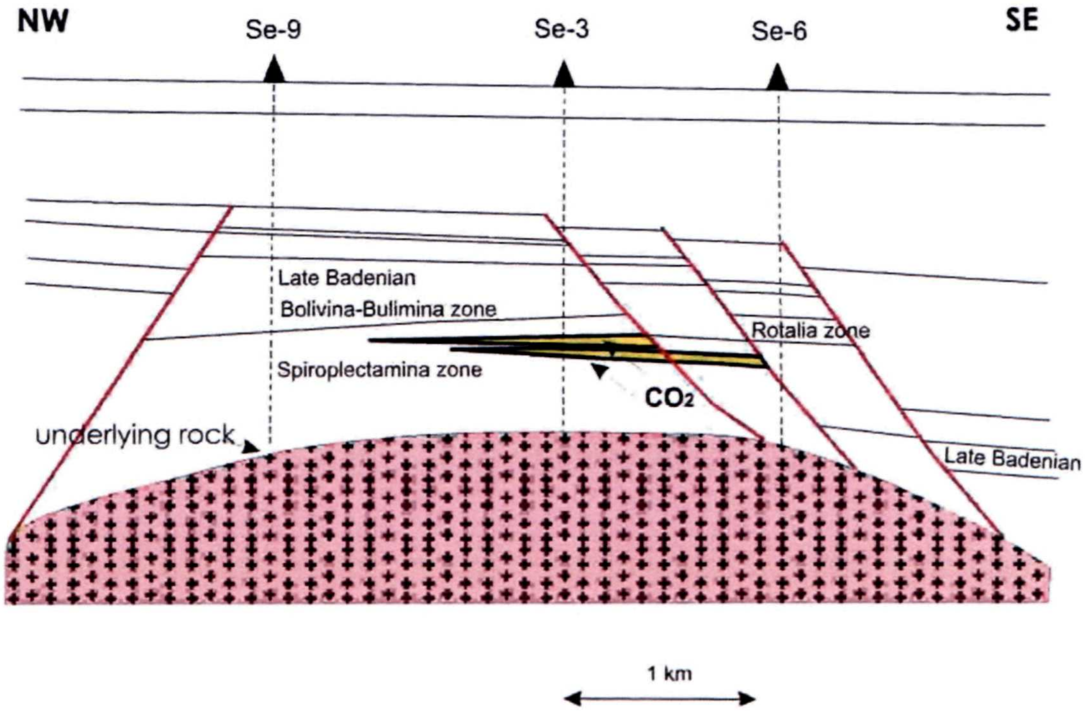


*Fig. 4.1.2.7 Geological cross-section through the deposit Sereď (in yellow) (According to Gaža, 1994)*

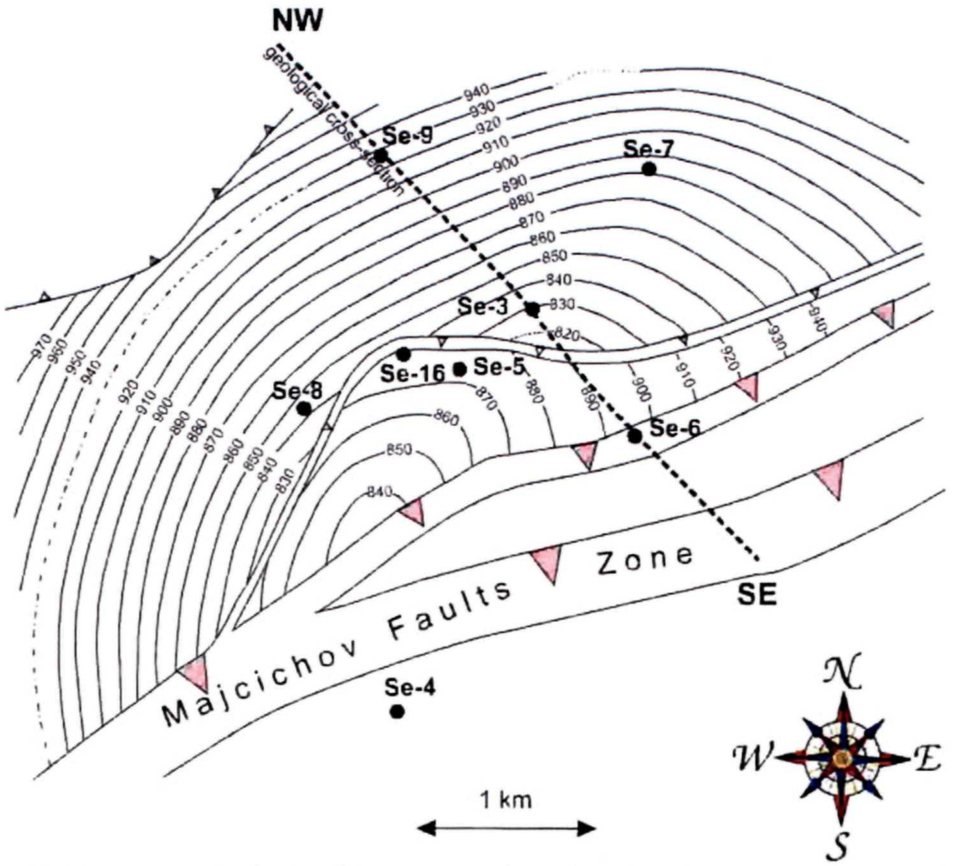


*Fig. 4.1.2.8 Structural map of the Sereď deposit with the isobaths of the deposit cap (According to Gaža, 1994)*

moderately calcareous sands, with numerous intercalations of calcareous shales, tuffites, tuffaceous sands and sandstones. According to the interpretation of sounding records it is essential, that the upper part of the collector (max. thickness 56.5 m) is permeable, the average porosity is 27%. The deposit water is strongly mineralized, of alkali-haline, sodium-bicarbonate type with summary mineralization of 28.88 $g.l^{-1}$. In the calculation of reserves its considerable extent was accounted for. The deposit water is saturated by carbon dioxide. In 1994 the original calculation was converted to a new category within the meaning of the legislation, when there were established (Gaža, 1994) reserves ($CO_2$ + $N_2$) in the volume of 4,716 billion $m^3$. The exploitability coefficient was estimated at 0.7 ratio. The gas composition is as follows: $CO_2$ = 82.7%; hydrocarbons 6.6%; nitrogen 10.7%; the deposit pressure 11,7 MPa; deposit temperature 57°C; the share of hydrocarbons 314.8 million $Nm^3$. The adverse gas composition was the reason for further exploration had halted and the NE restriction of the productive zone has not been verified.

From the above it is clear that in the deposit the volume of almost 5 billion $m^3$ of potential capacity for storage is available in theory.

The hermetic sealing of the deposit was disrupted by the eruption of gas, water and sandy material on the borehole Sereď-3 situated in the top part of the deposit in the sixties of the last century. The uncontrolled emission occurred in the course of gas-bearing horizon testing, when the attempt to stop the pumping test had failed. There was a gas evasion outside column casing rig and the drilling fluid was over-gassed. In the place of the borehole a crater evolved with subsequent collapse of the head-gear. In 1968 on the spot was a circular crater with a diameter of about 20 meters, filled with water with a table level of 1 m below the then terrain with gas gurgling slightly through the water. In the wake of this event the deposit structure has not been recommended for underground storage of gas (Lorenc, 1968).

The deposit should be exploited in order to work out the gas in the Vienna Basin (deposit Vysoká) 40 years ago. An annual production of 500 million $Nm^3$ gas was foreseen. Today, we are in a different situation, though we don't need to work out a natural carbon dioxide, as it is contained in exhaust gas emissions in a variety of industrial works, but already in the previous period there arose the intentions, which have been revived again today - to take advantage of the deposit for underground storage of natural gas. This would be probably the biggest reservoir in the territory of the Slovak Republic. The question remains - what to do with the dominant $CO_2$ in the deposit, because the share of the gas methane is almost irrelevant. The deposit can therefore serve as **a natural analogue**, simulating the $CO_2$ storage, where it would be possible to monitor all the necessary parameters affecting the safe operation of the disposal facility in terms of its hermetic sealing. The deposit meets the criterion of a great depth, providing supercritical status of the gas, along with the corresponding temperature.

At present, the hermetic sealing of the repository has been reviewed and the business plans intend to use it as an underground reservoir. An open question remains where to place the natural $CO_2$. In the last two years we have not recorded any progress in this activity.

#### 4.1.2.7 The Marcelová Structure

This undoubtedly interesting structure was found within the framework of basic research of geothermal resources of the Komárno High Elevated Block in the seventies of the last century (Remšík, et al., 1979). A follow-up search survey (Klago and Tyleček, 1988) brought the amount of knowledge that we have summarized, for the purposes of the task, in the following text.

***Pre-Tertiary basement of the Komárno Elevated Block***

Fusán et al. (1971) defined in the Pre-Tertiary basement of the Danube Basin the Komárno Elevated Block. Its boundary was later (Fusán et al., 1987) specified within the area between Komárno and Štúrovo in the South and restricted by the course of the Hurbanovo fault in the North.

***The geological and hydrogeothermal characteristics***

According to regional geological division the area of interest is situated in the SW part of the Želiezovce Depression and in the eastern part of the Gabčíkovo Depression (see Fig. 4.1). From the practical reasons we use a tectonic division, which is utilised in the exploration for oil and gas and is presented in Fig. 4.1.2.9.

The Komárno Elevated Block represents a tectonically strongly affected territory, where Mesozoic was encountered at various depths, ranging from tens of meters to 1 km below the surface. As it has been observed from deep boreholes, there were encountered the rocks in the range of Triassic sediments till the Cretaceous ones. From the Palaeogene sequences there were identified Eocene and Oligocene in the area of Modrany (NE of the site). The Neogene sediments of variable thicknesses in the wider surroundings of the site are present in the stratigraphic range from Badenian till Romanian, comprising dominant sandy and clayey sediments. In the youngest members gravel is also present. The characteristics of this important phenomenon in this regard have been displayed in the Atlas of Geothermal Energy in Slovakia (Franko, et al. 1995). The Mesozoic carbonate rocks present in the Neogene basement represent a major and important hydrogeologic structure of the thermal waters. Triassic limestones and dolomites are collectors with fissure and karst-fissure permeability. In the Komárno High Elevated Block we distinguish the High Elevated Block itself and a Marginal Elevated Block; they differ in hydrogeothermal conditions, physico-chemical properties of thermal waters, as well as the values of geothermal gradient. Borehole GTM-1 is located in the Marginal Elevated Block (see Fig. 4.1.2.10), encompassing the High Elevated Block from the West, North and East.

As the infiltration areas of the thermal waters are considered the Mesozoic carbonate complexes of the Transdanubian Mountains, exposed on the surface on the right bank of the Danube in the Vertes, Gerecse and Pilis mountains.

According to the geophysical data (Zbořil, et al., 1988) the territory is segmented into number of partial blocks, of the directions NE-SW or NW-SE, with dis-

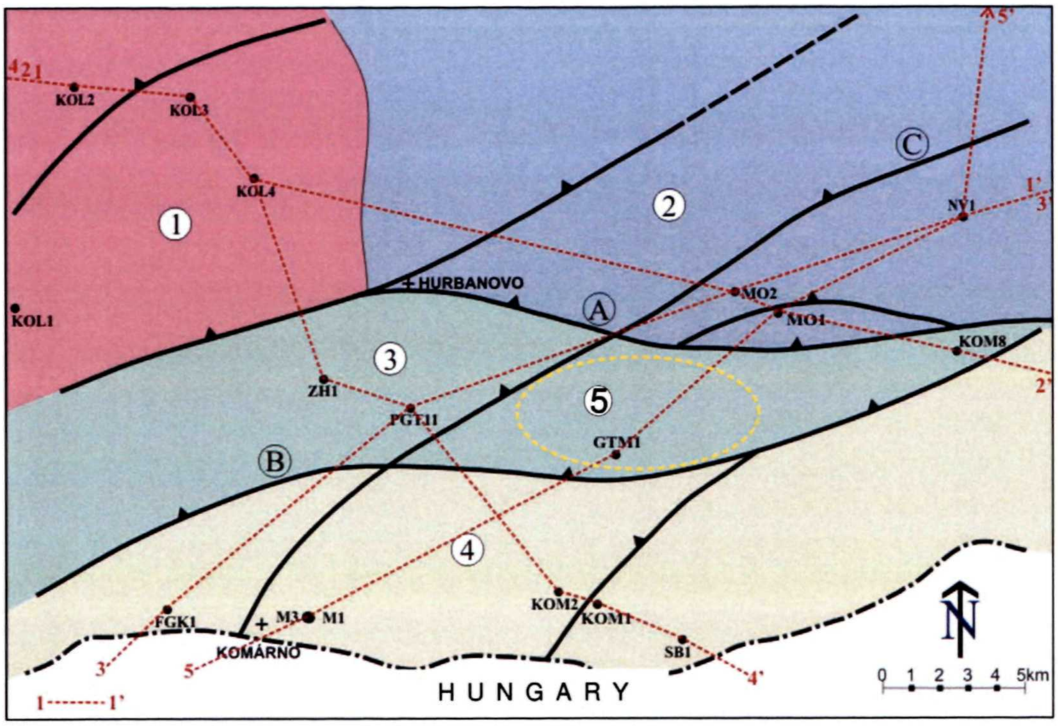


*Fig. 4.1.2.9 Tectonic classification of the south-eastern part of the Danube Basin 1-Kolárovo elevation, 2-Dubník Depression, 3-Komárno Marginal Elevated Block, 4-Komárno High Elevated Block, 5-studied area, A-Hurbanovo fault, B-Komárno fault, C-Nové Zámky fault, 1-1' geological cross-section (adopted after Franko, et al., 2011)*

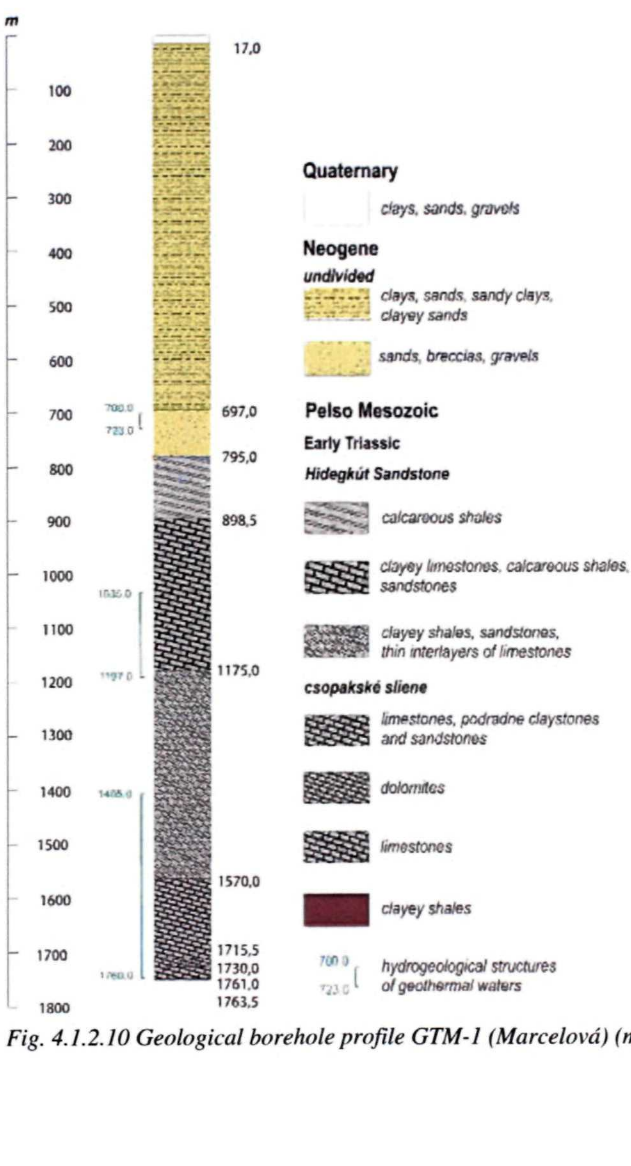


*Fig. 4.1.2.10 Geological borehole profile GTM-1 (Marcelová) (modified by Jezný, et al., 1988)*

placement amplitudes of 50-300 m. Of a number of indications for the geothermal borehole purpose the territory of internal block was chosen between the villages of Modrany and Marcelová, which is represented by Dacian sediments on the surface. The geothermal borehole GTM-1 location is evident from the Figure 4.1.2.9. The borehole was drilled in 1987 with a designed depth of 1 800 m, the actual depth was 1,763.5 m. The borehole identified two hydrogeological structures of geothermal waters in the Mesozoic complex (Klago, 1988):

First depth 1,035.0-1,197.5 m

Second depth 1,405.0-1,760.0 m.

The groundwater is highly-mineralized - 90 $g.l^{-1}$; the yield is 8.33 $l.s^{-1}$. The Na-Cl type water contains higher levels of iodine, bromine, lithium, strontium and metaborite acid. The temperature at a depth of 1,760 m was 65 °C, on the mouth of the borehole it reached 56 °C. In addition, it was also identified a shallower hydrogeologic structure at a depth of 700-723 m, with the yield of 1.66 $l.s^{-1}$ and mineralization of 0.82$g.l^{-1}$, of the type Ca-Mg-SO4-$HCO_3$, however, this is outside of our scope of interest. The drilling profile is shown in Figure. 4.1.2.11.

Klago (1988) notes, that the borehole GTM-1 has not documented the sequel of the hydrogeological structure of thermal waters from the area of Patince towards the Marcelová area. The rational use of this resource has been evaluated negatively.

In 1998, it was elaborated "Calculation of reserves of mineralized J-Br water in the hydrogeological structure Marcelová" (Januš and Kandera), where the volume of

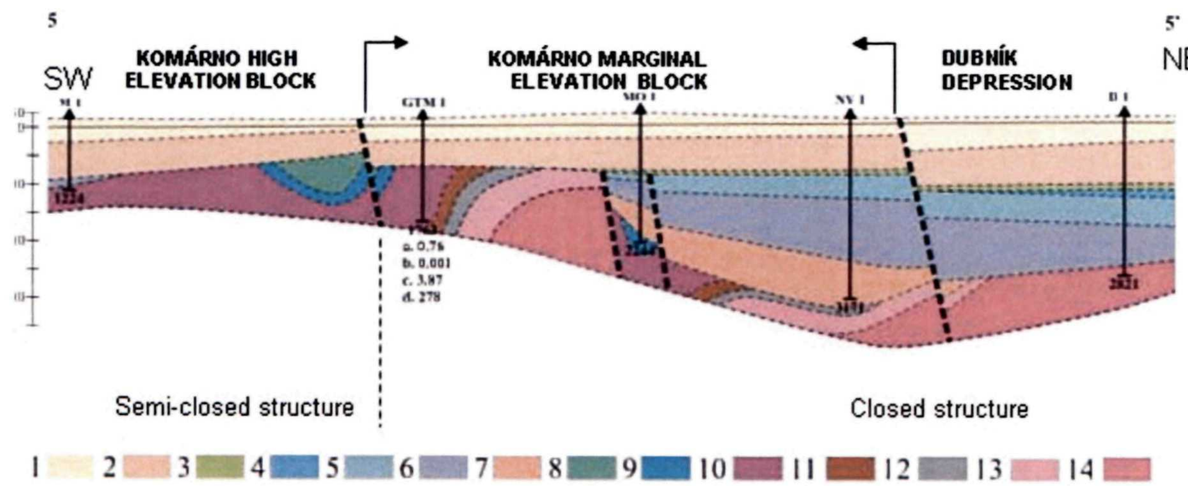


*Fig. 4.1.2.11 Geological-hydrogeochemical cross-section through the area of interest.*
*1-Pontian and Dacian, 2-Pannonian, 3-Sarmatian, 4-Late Badenian, 5-Middle Badenian, 6-Early Badenian, 7-Palaeogene, 8-Cretaceous, 9-Jurassic, 10-Triassic, 11-Permian, 12-Carboniferous, 13-Early Palaeozoic (Devonian), 14-Veporicum Crystalline, a-rNa+rK/rCl, b-rHCO$_3$/rCl, c-rNa+rK/rCa+rMg, d-Cl/Br (after Franko, et al., 2011)*

1 892 000 m$^3$ estimated reserves were quantified. According to the following calculation (Jezný and Januš, 1988) there were calculated reserves under the terms of the exclusive deposit exploitability, it means according to the reserves economic suitability classified as balance reserves of mineralized waters with the contents of the iodine and bromine salts in the volume of 3 658 176 000 litres, which in 90 g.l$^{-1}$ mineralization represents 329,236 tonnes of raw mineral material. After the calculation, according to the results of physico-chemical analysis it is possible to determine the amount to 84.14 tonnes of iodides and 724.32 tonnes of bromides. In the permanent extraction of 5.88 l.s$^{-1}$ of water from the borehole the reserves of mineralized waters are sufficient for a period of 20 years.

The water samples from Mesozoic rocks of the borehole GTM-1 within the meaning of hydrochemical field chart belong to the Na-Cl type, which corresponds to the **closed structure**, in which no endogenous $CO_2$ evolves and it stores **fossil water**. The cross-section through the structure is depicted in Fig. 4.1.2.11.

### *The knowledge for the $CO_2$ storage*

From the above established facts and knowledge the following conclusions and proposals of the $CO_2$ storage can be formulated:

***a) facts***

– Highly-mineralized water is located in the tectonic internal block Marcelová, on the border of the Western Carpathians and the Pelső unit - encountered by the borehole GTM in the Early Triassic of this unit in depths of 1,037.5-1,045.5 m and 1,739.5-1,761 m. The total thickness of the water-bearing layer is 29.5 m.

– High mineralization from 90 g.l$^{-1}$ due to Na-Cl water with higher levels of iodine (11 mg.l$^{-1}$) and bromine (190 mg.l$^{-1}$), pH 6.1-7.2, satisfies the conditions of the reserves exploitability for the exclusive deposit Marcelová, which is classified as economic deposit (free) with calculated iodides reserves in the amount of 84.14 tonnes and 724.32 tonnes of bromides (Jezný & Januš, 1998).

– Within the meaning of the chart of hydrogeochemical field the waters correspond to closed structure, in which no endogenous $CO_2$ evolves - these are fossil waters. Such waters represent I, Br rim of oil terrains, in which the parent hydrocarbon volatilized and the brines are residual fluids.

– The structure is closed, despite the carbonate surroundings - see high mineralization and the borehole GTM-1 did not affect the hydrodynamic regime of boreholes in southerly-situated Patince - the distance of about 5-6 km. This finding is very unique in this kind of geologic environment.

– The reserves of mineralized water have been calculated in the category Z3 in volume 3 658 176 m$^3$. The reserves are classified as the economic ones, free.

***b) output into the $CO_2$ storage issue***

– The depths of both horizons are sufficient for achieving the supercritical state of $CO_2$ (7.38 MPa, 31.1°C), because both of them are at a depth of over 1,000 m. This is evidenced by the measured temperatures of 65°C and pressures at the end of the drill: the pressure at a depth of 1,300 m was above 12 MPa.

– The structure's tightness is an **excellent** argument for the potential repository, because a high level of reliability is assured in terms of leaks. Under keeping the criteria for the pressure of the injection mode the only possible escape routes from the structure are the boreholes, either the injection or the monitoring ones. Permanent decrease in the yield or static pressure values in time also points out to the fact that it is closed hydrogeologic structure (Jezný, et al., 1988).

– Despite the fact that the object is located in a seismically very active zone in Slovakia, this aspect has so far had no impact on its integrity, because they have not been observed any escapes from the reservoir.

– Taking into account the density of the carbon dioxide and formation factor the calculated volume of groundwater reserves for a particular depth at applied volumetric approach in the calculation of the storage capacity allows us to assume the storage of about 70 M tonnes of $CO_2$, which is the amount sufficient even for the industrially used repository.

– Geochemical modelling of $CO_2$ suggests that there will occur a solubility trapping. In brine there will be dissolved 0.39 $mol.kg^{-1}$ of $CO_2$. The water will become aggressive and will dissolve mainly the carbonate mineral phases, with consequent change in saturation indices and likely mineral phases will become under-saturated. This will increase the effective porosity, and thus the increase in the storage capacity, in theory, - the effect of residual trapping and, later, mineral carbonatization, due to the extension of the storage space. (See Chapter 5.1 Geochemical aspects of the storage).

– The above points are very positive in terms of the safety of the repository, because due to foreseen trapping it would not occur an increase in the $CO_2$ pressure in the reservoir, but the $CO_2$ will sink to the bottom of the aquifer due to its heavier bulk density.

– The added economic value to $CO_2$ storage are increased concentrations of iodine and bromine - calculated iodides reserves 84.14 t and bromides 724.32 tonnes (Jezný, et al., 1988). If we compare this with the current prices on the world market (June 2011) the approximate value ranges between 3.5 to 4 million USD. The next value added is the water temperature, which reaches from 63 to 65.5 °C within the intervals of interest and can therefore be used for agricultural or curative purposes, because the waters of this type are scarce (spa Číž as the only region with this type water suffers the lack of replenishment). The assumption of the life of the structure is 20 years, under the operational withdrawal of 5.88 $l.s^{-1}$.

– In practice, this would mean that by the progressive extraction of brine the space for the stored $CO_2$ would be gradually emptied.

– This aspect would undoubtedly economically benefit the costly storage of $CO_2$.

– In theory, as a source of $CO_2$ injection the emissions of the big producers of $CO_2$ in the optimum distance from the structure, for example, Duslo Šaľa (approx. 50 km) with an annual production of 500,000 t/year, which produces $CO_2$ emissions with high purity (99%) are of interest and the only necessary technological adaptation is its compression for the purposes of transport.

## Conclusion

The structure has a number of positive features, and not only from the point of view of the projected level of safety of the geological repository, but also provides an economic opportunity to use aquiferous water as a commodity, which is currently scarce on the market. The only Slovak spas - Číž with this type of mineralized water have significant problems with the insufficient capacity of the source.

The deposit is classified among the exclusive deposits "Marcelová - mineralized I-Br waters"; however, its production is not foreseen in the near future. If we assume that the storage capacity which is derived from the calculation of the reserves is overly optimistic, even at the 50% reduction of the structure parameters the potential repository should satisfy industrial $CO_2$ storage. In any case, it is referred to as a serious candidate for a potential pilot project structure, which in the case of positive findings could be extended to industrial scale.

*Note: Further results with focusing in the hydrogeochemic aspects are presented in the Chapter 5.1 Geochemical aspects of* $CO_2$ *storage.*

## 4.2 Zlatá baňa - Slanské vrchy Mts.

The original intent of a search of the appropriate structures for underground $CO_2$ storage has been focused primarily in the sedimentary complexes of Neogene, Palaeogene, or Flysch, or where there is a presumption of "relatively more favourable" rocks with the required lithologic-tectonic and reservoir characteristics. A summary study of porosity we focused in the rock complex, which from the first point of view is perhaps a bit "odd", but the found parameters, as well as consultations with the responsible staff involved in research work in the area of base metal deposit of Zlatá Baňa in the Slanské vrchy Mts. caused, that we have carried out a more detailed analysis of this site for the purpose of the project.

A Zlatá Baňa andesite Stratovolcano is the most extensive volcanic formation in the northern part of the Slanské vrchy mountain range. It represents a typical conical structure with a diameter of 10 km. The Volcano was named after the village of Zlatá Baňa and is made up of the homonymous formation. In its structure it is possible to allocate the central, transitional and distal volcanic zones. The Zlatá Baňa Stratovolcano represents a range of petrographically differentiated rocks. From the stratigraphical point of view it is assigned to the Early Sarmatian to Early Pannonian periods. The Zlatá Baňa Stratovolcano volcanism products overlie Palaeogene deposits of the Inner Carpathian Palaeogene basin and Karpatian-Badenian sediments of the East-Slovakian Basin (Kaličiak, et al., 1991).

The Pre-Neogene complexes are not exposed in the territory of interest. According to data from deep oil-boreholes Prešov-1, Kecerovské Pekľany-1, Hanušovce-1 and Vranov-1, where these complexes were encountered, the presence of Hronicum is assumed (Grecula, et al., 1980, Tözsér, 1983). According to Pospíšil and Kaličiak, (1978) in the basement of the volcanic complex interferes Humenné Mesozoic.

The deposit of base metal ores Zlatá Baňa (Pb-Zn-Cu + antimonite and cinnabar) evolved in the form of short, steeply-inclined veins and stockworks, accompanied by the impregnations within the hydrothermally-altered

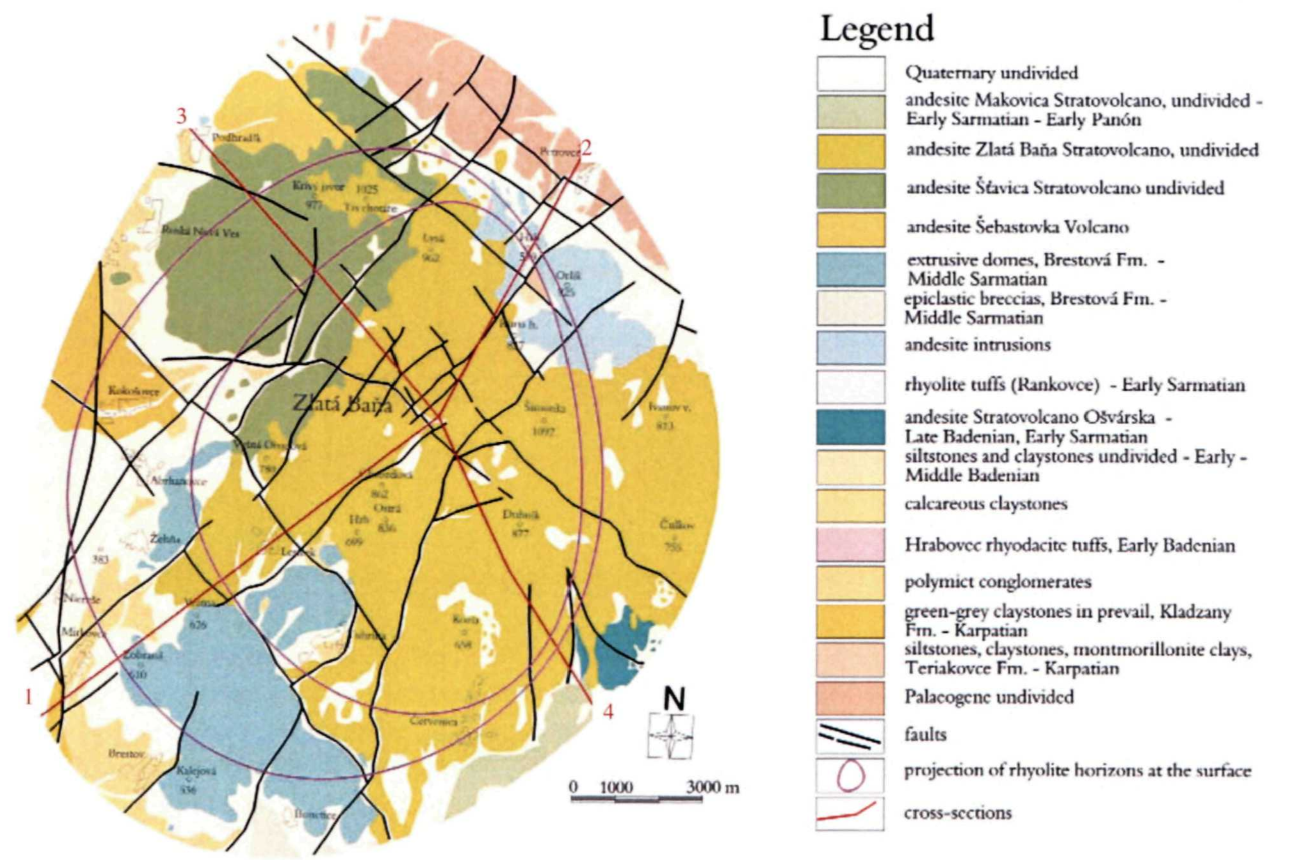


*Fig. 4.2.1 Geological situation of the Zlatá Baňa area (adopted after Kaličiak et al., 1991)*

breccias and is located in the central zone of the Zlatá Baňa Stratovolcano. The deposit has been the subject of intense exploration in the second half of the 20th century (Divinec, et al., 1985, 1989). We would like to avoid repeat the data, we will focus only on the characteristics which are interesting for the objectives of the solved task. Geological map of the site is presented on the modified figure. 4.2.1

In the study of porosity of the volcanic complex rocks we have note quite high values of rhyolites and andesites. In the context of the presented geological setting in geological cross-sections (Kaličiak, et al., 1991) the idea of a potentially possible imposition of carbon dioxide in this space has gradually begun to develop. The following input factors have led us to this concept:

– The volcanic activity in this space started with the eruptions of rhyolite volcanism, when the prevailing rocks were different types of rhyolite volcanoclastics. This activity is dated to the Karpatian period and its products were deposited upon the sedimentary members of the Prešov Fm. - siltstones and sandstones belonging to Eggenburgian (Figs. 4.2.2, 4.2.3). In the superincumbent of the volcanic complex, which is considerable thick - around 500 m - and off the Central volcanic zone it gradually wedges out, once again a sedimentary member - green-grey siltstones and claystones, are developed with horizons of montmorillonite clays that are assigned to the Teriakovce Fm. Above them there are again products of the rhyolite volcanism, although in comparison with the aforementioned horizon, their thickness and spatial extension are obviously smaller - their maximum thickness does not exceed 300 m. From the morphological point of view both horizons create in fact anticlinal structure. The spatial expansion of both rhyolite horizons is documented in figures 4.2.2 and 4.2.3. In the superincumbent of the higher lying horizon there is again a sedimentary complex of the Kladzany Fm. - green-grey aleuritic shales in prevail over sandstones. Both rhyolite horizons, as well as Kladzany Fm., are dated to Karpatian.

– Atop the volcano-sedimentary complex there is developed a horizon of rhyolite volcanism products - mostly rhyolite pumice tuffs (Badenian). Its dimensions as well as the thickness are the smallest of the all rhyolite horizons. It is sealed by cover of calcareous claystones and siltstones of Badenian age. This sequence is overlain by andesite volcanism products, Sarmatian in age.

– The concentric structure of the Stratovolcano is intruded by younger necks and dikes of diorite porphyrite and andesite intrusions. The Central volcanic zone forms a distinct depression in the wider surroundings of the Zlatá Baňa Village. It is made of a complex of hydrothermally altered andesite rocks. Intense hydrothermally altered are lava flows, intrusions and breccias, in which intruded the diorite porphyrites in the form of necks and dikes. The intrusive bodies have variable forms and dimensions, ranging from isometric stocks (necks) through platy N-S and NW-SE oriented dike bodies. The Central volcanic zone is formed by the extrusions of hypersthene-

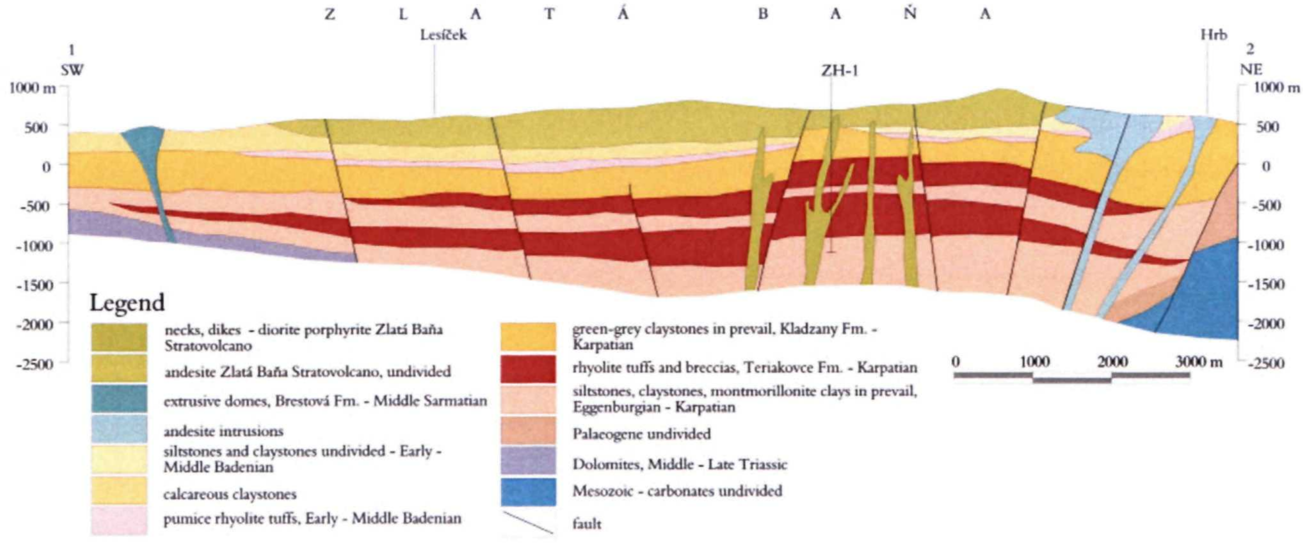


*Fig. 4.2.2 Geological cross-section 1-2 Zlatá baňa (modified after Kaličiak et al., 1991)*

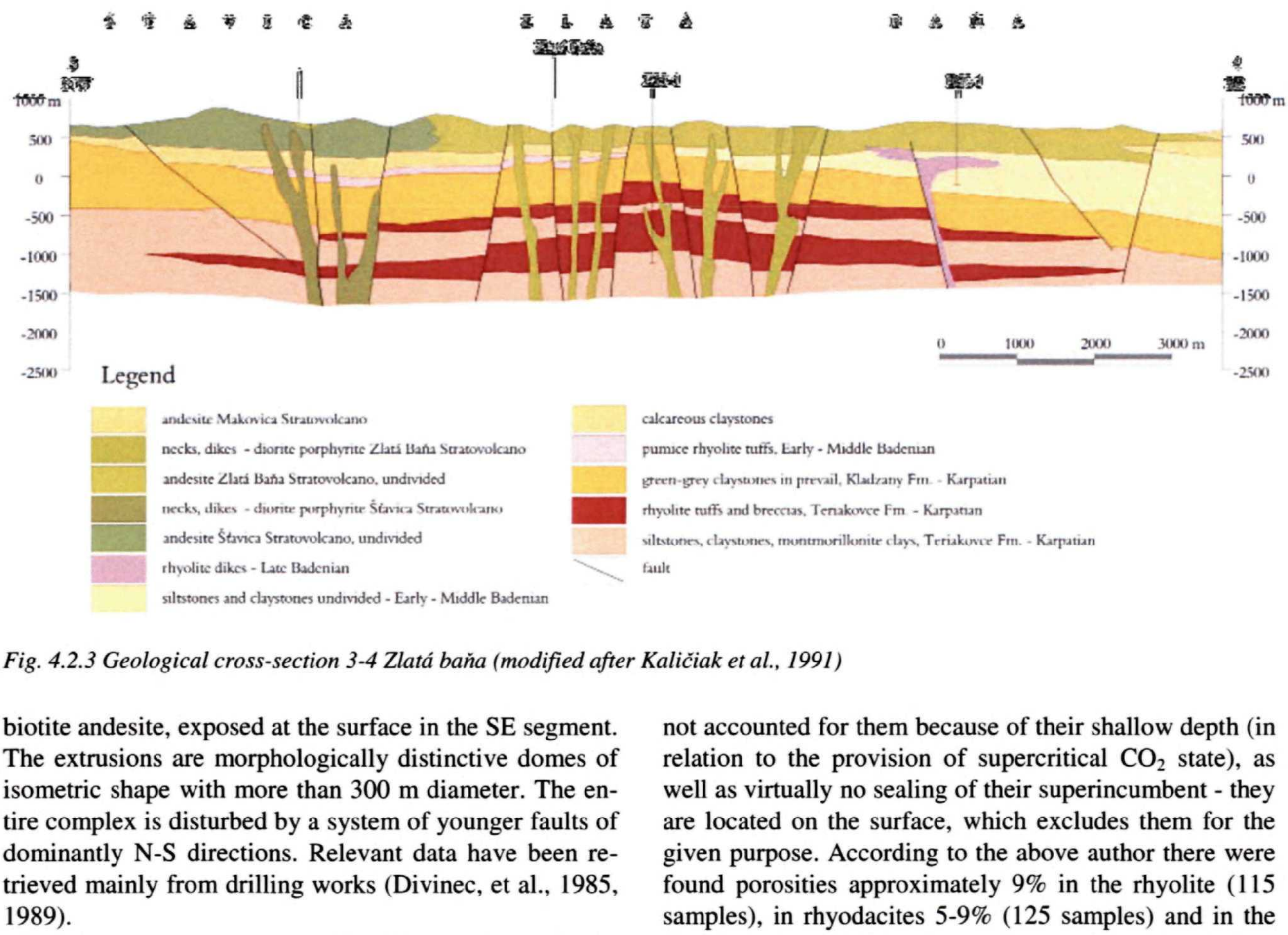


*Fig. 4.2.3 Geological cross-section 3-4 Zlatá baňa (modified after Kaličiak et al., 1991)*

biotite andesite, exposed at the surface in the SE segment. The extrusions are morphologically distinctive domes of isometric shape with more than 300 m diameter. The entire complex is disturbed by a system of younger faults of dominantly N-S directions. Relevant data have been retrieved mainly from drilling works (Divinec, et al., 1985, 1989).

– For the purposes of a potential of carbon dioxide storage we consider the following factors:

– The initial stimulus gave relatively high porosity values in volcanic complex in general; both in andesite and in rhyolite products. We have retrieved the porosity values from the data identified by Husák (1986) and Husák et al., (1992). As a rule, the porosity was determined from the boreholes recovery at the site. We have to note that even if the products of andesite volcanism have a higher porosity, for the purposes of this project we have not accounted for them because of their shallow depth (in relation to the provision of supercritical $CO_2$ state), as well as virtually no sealing of their superincumbent - they are located on the surface, which excludes them for the given purpose. According to the above author there were found porosities approximately 9% in the rhyolite (115 samples), in rhyodacites 5-9% (125 samples) and in the rhyolite volcanoclastics they were at an interval of 3.93 – 19.7%. In comparison, the clay sediments, forming a seal between the horizons, do not exceed 0.75% porosity value.

– Two older (deeper seated) rhyolite horizons (Karpatian) we have chosen as a suitable environment for potential $CO_2$ storage (collectors or reservoir rocks with increased porosity parameters). In their favour proves sufficient depth of approximately 750-2,000 m beneath the surface, which provides conditions for the supercritical $CO_2$ status as well as the anticipated good sealing caused by lithological filling of the Lower stratovolcanic structure. The geometric factors interpreted in 3-D views suggest a sufficient volume of both bodies (Figure 4.2.4, 4.2.5), which is an essential criterion for the estimation of storage capacity. If we transformed the morphology of the reservoir horizons into hydrocarbon prospection, so we get to a mixed type of trap - tectonic structure, with a gradual "non-structural" wedging out in the distal zone of the Stratovolcano.

The youngest horizon of the rhyolite volcanoclastics - Badenian and Sarmatian rhyolite tuffs and pyroclastics (which has also sufficient geometric parameters), deposited in the predominantly clay environment, is not located in the sufficient depth in order to reach the supercritical $CO_2$ state and therefore it has not to been considered for the purpose.

In the calculation of the theoretical capacity we have made a conservative estimation. The average porosity was established on 5%, despite the fact that they were not

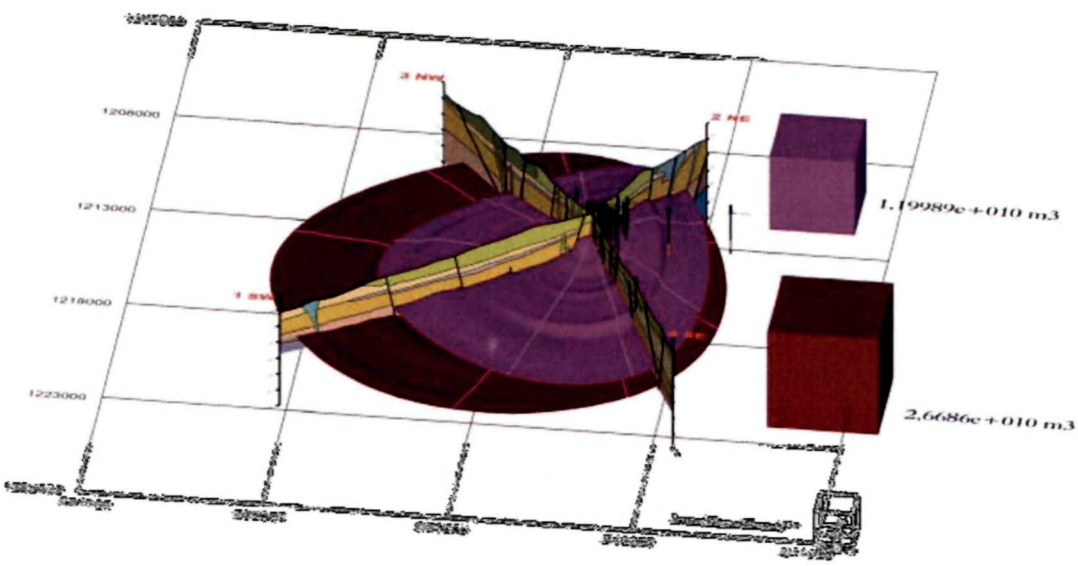


*Fig. 4.2.4 Spatial interpretation of rhyolite bodies, view from the South. The cubes indicate the total cubature (Šesták, 2011)*

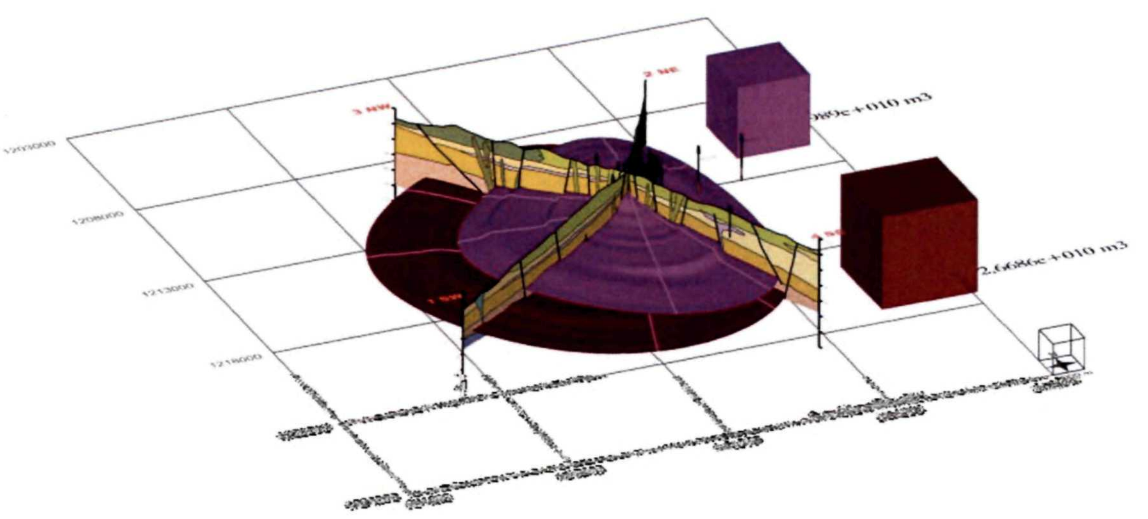

*Fig. 4.2.5 Spatial interpretation of rhyolite bodies, SW view. The cubes indicate the total cubature (Šesták, 2011)*

rare the porosity values close to 20% either in the rhyolites, or in their volcanoclastics. However, we have kept in mind that the data on the permeability of these rocks are missing, and the high porosity does not secure high permeability. Also for this reason, we have set a minimum value of the sweep coefficient to 2%. When applying the adopted formula we have reached for the top horizon a storage capacity in the volume of 7.8 Mt $CO_2$ and for the bottom one the storage capacity of 17.3 Mt of $CO_2$. In summary, this represents approximately 25 Mt, which corresponds to, or it could be close to the parameter for the industrially used deposit. To illustrate the spatial extension of the situation we present a variety of previews on the site in the 3-D view in Figures 4.2.6 and 4.2.7.

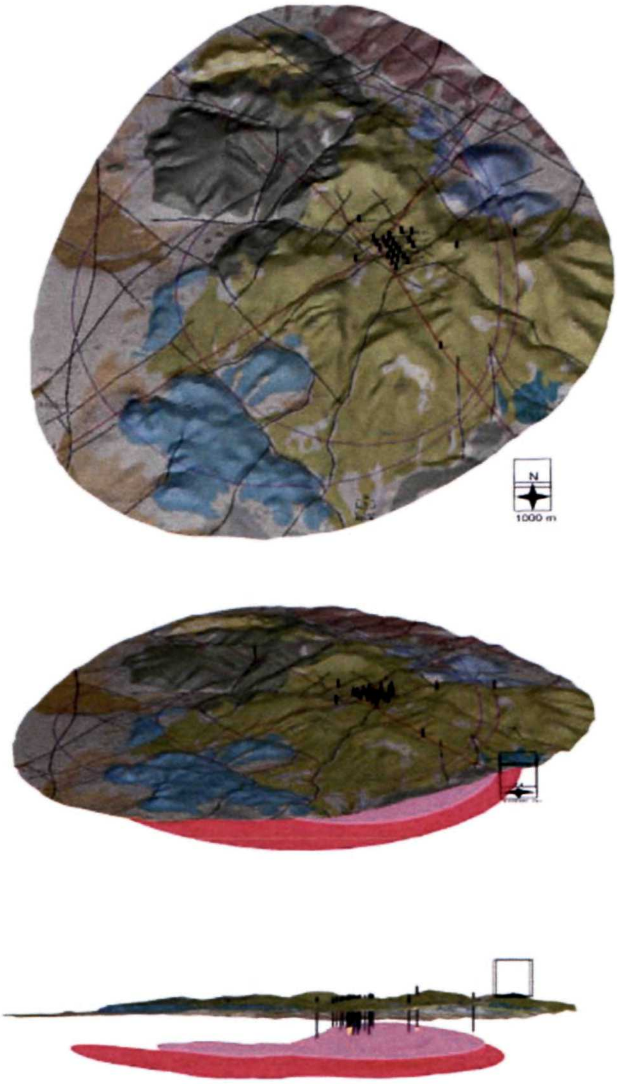

*Fig. 4.2.6 3-D view of the rhyolite horizons at different angles (northern orientation (Šesták, 2011)*

As a source for the $CO_2$ storage could be used $CO_2$ produced by thermal power plant Veľké Kapušany, with an annual production of around 3.5 Mt. The plant is the second largest producer of this gas on the territory of Slovakia. Its distance from the site is about 50-60 km, which is in the context of viable economic criteria, which are currently accepted. On the other hand the calculated storage volumes are likely to be inadequate for effective deposition, because commonly a lifetime of storage is a period of 20-30 years. But it is illusory to think of such a quantity of the injection currently (full year capacity) because usually one injection borehole represents the amount of 1 million tonnes per year. This would then ask for a number of injection wells, or for storage of only a part of the produced gas. But these ideas have already reached too far into the future scenarios that will eventually direct the development of the negative consequences of global warming, the economic situation in the energy market, the overall political climate as well as socio-economic factors.

***Problematic (to be discussed) points:***

– Although at the site there were drilled 26 deep boreholes (with a depth of 1 km) these are very unevenly distributed for a given task. The construction of the relief of the rhyolite bodies was based on the existing cross-sections (Kaličiak, et al., 1991) and the auxiliary cross-sections (the tossing ones); they served for interpolation using a Microstation code. It is obvious that the shape of the body is definitely "idealized", but basically comes from the general premise of the Stratovolcano setting - a concentric structure.

– Unfortunately, the physical properties of rocks were not studied in detail, so it is not sufficiently verified which horizon has the best porosity parameters. The rhyolite rocks were evaluated in summary, without allocation into lithostratigraphic sequence. In this case, we had to introduce an "expert-assessed" average value.

– There are no sufficient data to determine a justified permeability of the collector horizons.

– The capacity calculation is basically an estimate because it is necessary to introduce a number of coefficients, whereas the aspect of variability, inhomogeneity and anisotropy is virtually impossible to simulate numerically in order to get a plausible result.

– In terms of the security of the potential repository first of all the attention should be paid to the technical condition of the old wells (passable and impassable), which encountered the horizon, and can potentially serve as an escape route from the repository.

– Another potential risk pose young meridional faults, which disturb the structure of the Stratovolcano, especially in the near-surface parts. Their function is not known in terms of tightness, while theoretically the more opened upper sections (unroofing effect) might not represent the factual state in the rhyolite superincumbent, it means in the depths interesting for the project.

– The similar risk may pose numerous dikes and necks of rhyolites and andesites, if these feeders are not completely filled-up with volcanic products. We have in mind the mechanical condition of the walls of the tectonic structures, along which these rocks penetrate through older volcano-sedimentary complex. In most cases they will be reinforced by the thermal fringe, but this assumption must not be valid along the whole length of the feeders.

The site presents a peculiarity in the usual assessments so far for the rock complexes suitable for $CO_2$ storage. In general, the volcanic products do not represent "appropriate" environment for the carbon dioxide storage. From the point of view of capacity, we are in a very "conservative estimate" for the summary value for both horizons in the volume of approximately 25 Mt.

We summarized the aspects, although only indicatively, which have led us to include this object among the appropriate structures. On the other hand, the attention has to be paid to the outstanding storage issues or the

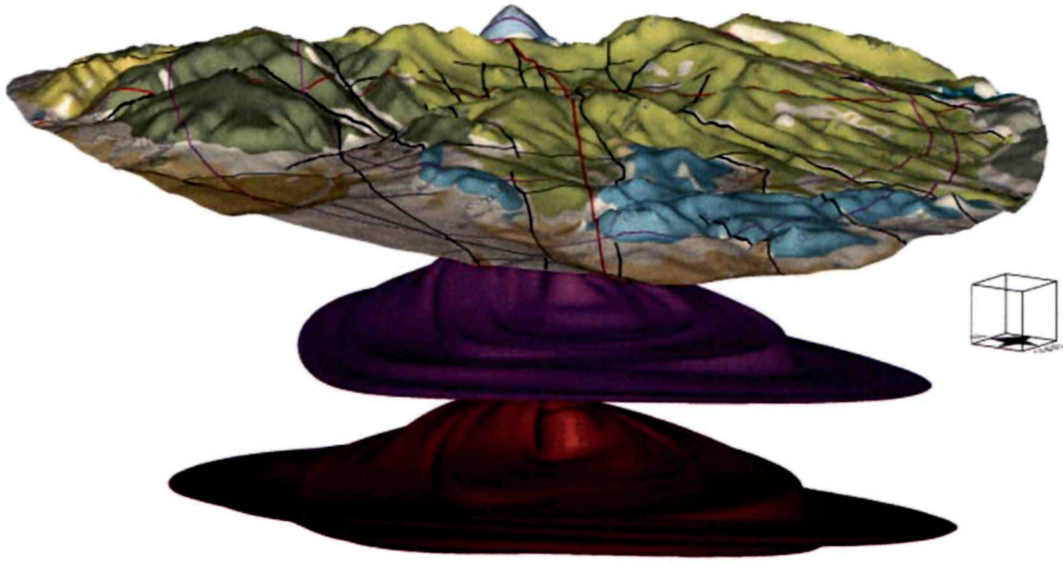

*Fig. 4.2.7 Exaggerated 3-D model of the relief and rhyolite bodies (Šesták, 2011)*

geological conditions of the site, which will be necessary to verify, because they could affect potential repository. We are still only at the level of theoretical considerations and, therefore, if the current situation should arise to tackle the issue of storage, in the first place is the necessity to verify the practical storage options as soon as possible through a pilot project, the results of which will be crucial for the consideration of the potential repository on an industrial scale.

## 4.3 Levočské vrchy Mts. and Šarišská vrchovina Upland

In terms of the geomorphological division (Mazúr and Lukniš, 1978) occupies the territory of interest Poprad and Hornád basins, Levočské vrchy Mts., and Šarišská vrchovina Upland and Spišsko-šarišské medzihorie Intermountains. In terms of regional geological division (Vass, et al., 1988) it forms the Popradská and Hornádska kotlina Depressions, Levočské vrchy Mts. and Šariš Palaeogene. The Late Eocene sediments transgraded upon various members of the Fatricum, Hronicum, or Gemericum units. The whole territory was dissected by the younger stages of Alpine Orogene in the series of blocks (normal faults, overthrusts), while in the North and northeastern part the more plastic complexes were folded (Gross et al., 1999). Some faults are morphologically distinctive, and accompanied by springs of ordinary and mineral waters with the formation of foam-stones and travertines. The area was explored for hydrocarbons and geothermal energy resources, with the corresponding great amount of geological works. Their results were verified by deep drilling. Whereas the considerable part of the territory is utilised for balneologic and recreational purposes, our interest was focused mainly in the "classic" Hromoš-Šambron anticlinal zone as the continuation of Lipany elevation structure, which was the main target in the search for hydrocarbons in the previous century. Therefore, at this stage, we're looking at two sites that could be potentially considered as storage of $CO_2$: Lipany and Plavnica.

### 4.3.1 The Lipany Structure

***To-date knowledge***

The Lipany structure was the subject of prospection for hydrocarbons in the 80ties of the last century, with numerous seismic works, which interpreted in this territory the elevation structure of the basement, which was parallel to the direction of the Klippen Belt. The structure is located in its immediate vicinity (1-4 km).

On the basis of the results of these works (Leško et al., 1974) a deep borehole - Lipany-1 (depth 4,000 m) was drilled in the scope of the project "Research into the deep structures of the Western Carpathians, with regard to the occurrence of oil and gas" (Leško et al., 1983). The borehole was situated relatively close to the Klippen Belt - about 1-1.5 km from its southern edge (Fig. 4.3.1.1). The borehole, inter alia, drilled through a small occurrence of hydrocarbons in the vicinity of the Palaeogene basement; this led to implementation of another 5 deep boreholes (depths of about 3,000 m), in order to determine and verify the hydrocarbon perspective of the site. However, despite these small signs of oil presence, the effort did not produce encouraging results from this point of view.

The Lipany elevation structure is genetically tied to the Mesozoic basement elevation, parallel to the course of the Klippen Belt. In the NW-SE direction it is split by Červeník fault dipping towards SE. In the transverse direction the structure is dislocated by numerous normal faults (Rudinec, et al., 1988). According to the hydrocarbon evaluation the natural gas is found in several hori-

Tab. 4.3.1.1 Overview of the basic parameters of the Lipany boreholes

| Well No. | Thickness of Palaeogene (m) | Thickness/depth of horizon (m)/ hydrocarbon indicia | Well depth (m) | The deepest body | Note |
|---|---|---|---|---|---|
| Lipany 1 | 2,790 | 40/2,360-2,400/yes | 4,000 | Carbonates T2-3 | Productive horizon of gas |
| Lipany 2 | 2,870 | 225/2,455-2,680/yes | 3,500 | T3 | |
| Lipany 3 | 3,030 | 410/2,560-2,970/yes | 3,100 | T3 dolomite | 3x productive hydrocarbon horizons 150 m intercalations included |
| Lipany 4 | ? | 2,250-2,400 | 3,000 | Shales, sandstones Pg | |
| Lipany 5 | 2,957 | 2,134-2,865 | 3,003 | T 2-3 dolomites | |
| Lipany 6 | ? | 2,290-2,400 | 2,850 | Sandstones, siltstones Pg | |

zons, mainly in (or near) 1,800-2,000 m depths, at the Palaeogene base. In addition, there was a light presence of paraffinic oil. The methane is either with low nitrogen content - up to 1%, or with its share of nearly 50%. The collectors are fine-grained, at places coarse-grained calcareous sandstones, intensely cemented, which show great facies variability. Some collectors are saturated with $CO_2$ up to 85.3%. The trial tests have shown, that the calcareous component is a favourable factor, because after acidizing (30% HCL) the capacity increased from 10,559 $m^3$ to 70,000 $m^3$/24 hours. From the borehole Lipany-4 for the first time in the Eastern Slovakia oil was exploited from the depth of 2,239-2,303 m in a quantity of 20-30 $m^3$/24 h. The paradox here is that no water-bearing aquifer has been identified within the Palaeogene horizons.

The surges of natural gas have been found in all of the Lipany wells. The main component was methane, an average of 80-90%. According to the operative reserves calculation, the borehole Lipany-1 was quantified as economic reserves in the volume of 25 148 000 $m^3$ (Rudinec, 1988), in what was then the category C2. Other reserves are considered to be non-economic. The quantity of the horizon in the borehole Lipany-1, after converting the density parameters and application of formation factor, constitutes approximately 600,000 tonnes of carbon dioxide. The calculated amount in terms of the practical use of CCS would be only the volume suitable for a pilot project. In the framework of the project, we conducted a review of the horizon intraformation breccias, which are considered to be an aquifer. The original interpretation by Rudinec (1988), interpreted them as the product of slumps within the submarine channels of the Palaeogene sequence. These horizons, however, have considerably large thickness and extension. On the other hand, the presence of the troughs in such a frequency and thickness in such a small space seems unlikely. We, therefore, on the basis of considerations, as well as on the basis of the data from the other areas of the Inner Carpathian Palaeogene (Plavnica), reinterpreted this factor as a continuous, variably changing layer (Fig. 4.3.1.2). This way we have achieved significant space of water-bearing rocks, potentially suitable for the $CO_2$ storage. The question of the eventual use of such a small quantity of gas to supply the vicinity of the site, which could be exploited as a by-product of the $CO_2$ injection (Enhanced Gas Recovery), remains open, because it could substantially improve the economic parameters of the storage.

In terms of potential $CO_2$ storage the collector's overburden is made of Šambron Member, represented by alternating layers of calcareous sandstone and sandy limestone with horizons of non-calcareous claystone. The primary porosity of the calcareous sandstones and sandy limestones is reduced thanks to processes of diagenesis and cementation; the porosity value is less than 2%. These rocks are only slightly jointed, the porosity ranges just in tenths of a percent, and therefore has no practical significance. The permeability of the rock matrix is zero, the permeability of a few cracks is low to moderate - up to 20 $nm^2.10^3$, the joints'width is in the range 0.02-0.04 mm. The collector properties of rocks are rated as inappropriate (Jandová, 1986). In the sections where the coarser facies are developed, the situation is similar - the cementation has filled up the intergranular pores and low permeability have the crevices of very small effective widths. Therefore, this aspect of the Šambron Member confirms its suitability as sealing horizon.

In terms of potential $CO_2$ storage, the intraformation marly breccias appear to be suitable collector, located close to the Palaeogene complex base; the microfossils content confirmed their Cretaceous and Jurassic age (Řehánek, 1985). These rocks are considered to have more favourable hydrogeological characteristics (Jetel, in Gross, et al. 1999). The author admits that in some parts of the carbonatic breccias it is possible to assume increased permeability of the parameters. Due to the fact that the complex is somewhere very thick - e.g. in the borehole Lipany-5 almost 750 m, the assumption is realistic that certain horizons in terms of the needs of the pilot project would be promising. In particular, the top part of the intraformation breccias at a depth of 2,134-2,157 m could be suitable, where the yield of 11,100 $m^3$/24 hrs of $CO_2$ was observed (Rudinec and Řeřicha, 1985), because the quantity equals to approx. 7-9 kt. However, the borehole was liquidated as negative in economic terms (search for hydrocarbons).

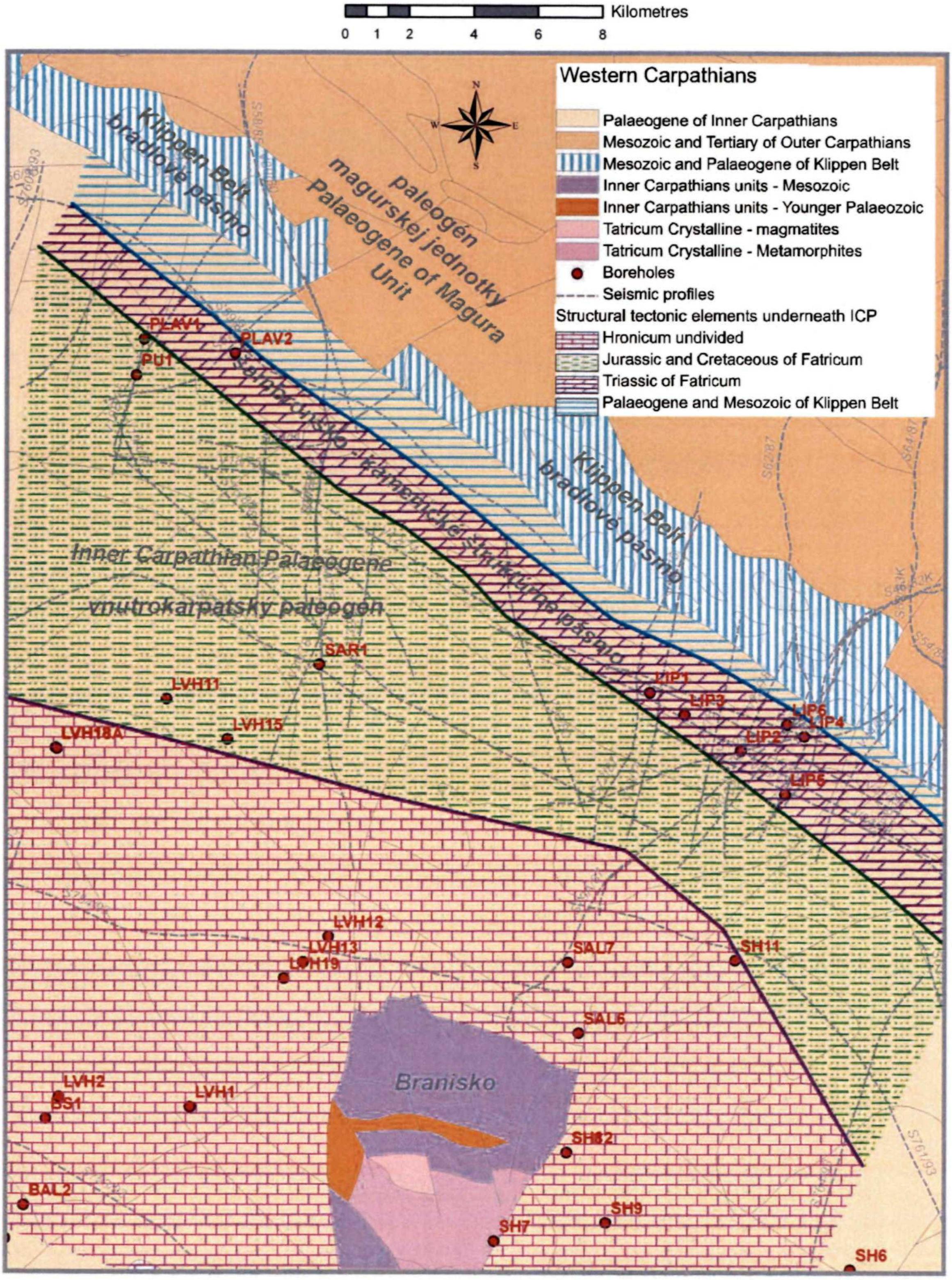


*Fig. 4.3.1.1 Structural-tectonic units in the Pre-Tertiary basement of wider vicinity of Lipany (according to Kráľ, et al. 2009)*

The complex, which is considered as collector - brecciated limestones and dolomites, lying stratigraphically close to the Palaeogene base, has a relatively good collector properties. The rock is rated as a good collector, with joint porosity from 3 to 5%. Although in this case in the pores reduction cementation played the role, some crevasses remained loose with calcites crystals on cavities' walls. The fissures are fairly abundant, often branched, mutually intersecting, with a width from 0.02 to 0.06 mm which is a space suitable for transition of gaseous and liquid fluids. Total primary porosity, along with the joints one, is around 3%, in areas with small cavities it is

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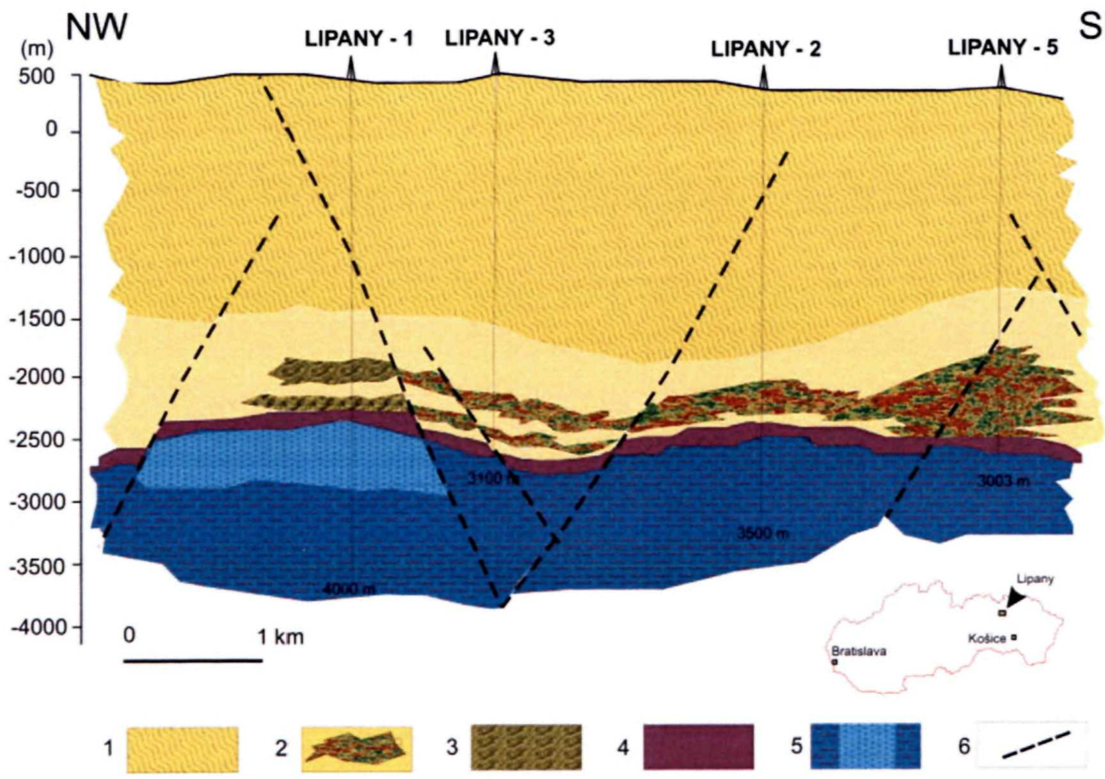


*Fig. 4.3.1.2 Geological cross-section through the Lipany elevation axis (modified after Rudinec, et al, 1983)*
*Explanatory notes: 1-siltstones and claystone in prevail, 2-horizon of intraformation breccias in claystone collector horizon, 3-gas deposit, 4-variegated shales-Keuper, 5-carbonates, collector of geothermal water, 6-faults*

around 5%. They are often developed by stylolith sutures. The stylolithisation process, however, does not have a significant impact on the improvement of the collector properties of the rocks. The permeability of the brecciated carbonates is evaluated as good and reaches values of 50-100 $nm^2$. $10^3$.

In the collector's bedrock there is developed an impermeable horizon of Carpathian Keuper - variegated brecciated claystones.

### *Potential utilisation of the site*

The city of Lipany plans to take advantage of the deep thermal borehole Lipany-1 as a source of geothermal water for construction of a water park with associated infrastructure. For this purpose, the project "Lipany - geothermal energy" (Kráľ et al., 2009) was solved. Intake of geothermal water is expected from Pre-Tertiary basement, which was encountered in the exploratory borehole Lipany-1. The objective of the geological project was to verify the source of geothermal water with a temperature of approximately 100 °C, a yield of free overflow up to 10 $l.s^{-1}$ and the total mineralization at the level of 5 $g.l^{-1}$. These data are based on the results of the tester tests carried out during the borehole Lipany-1 drilling.

This objective has been achieved, because the borehole has been made passable and the reserves were calculated, as well as the regime of geothermal waters withdrawal (Kráľ et al., 2009). To ensure this objective there was designed complete technical reconstruction of the borehole Lipany-1, implementation of sounding measurements in order to allocate water-bearing horizons, intensifying and perforation works, and realisation of a long-term hydrodynamic test for the purpose of determining the exploitable amount of geothermal water from the source, including its liquidation after its utilisation for thermal purposes. Further works consisted of assessment of pressure and temperature in the hydrogeothermal structure in the vicinity of the drill, the calculation of the hydraulic parameters of the geothermal water collector, determination of the gas evasion point, chemical, isotopic, and radiological analyses of geothermal water samples and the accompanying gas, and the determination of the age of the geothermal water.

The problem is the high content of carbon dioxide in the water of the collector horizons of Fatricum, because after trespassing the evasion point there occur a considerable creation of incrustation of carbonates in the inlet tubes and therefore the use of inhibitor is an unconditional necessity. In order to get more instructive idea of the situation we depicted 3-D models of relevant geological structures, displayed in the figures 4.3.1.3 a, b.

In addition to this objective, which is the most realistic and in terms of the acceptance by the population perceived as the most convenient, the following factors underpin the meaning and wider use of the structure.

In view of the high levels of $CO_2$ in the geothermal water and the existence of a small natural gas deposit within the Palaeogene superincumbent of the Fatricum carbonate reservoir it opens up the possibility of $CO_2$

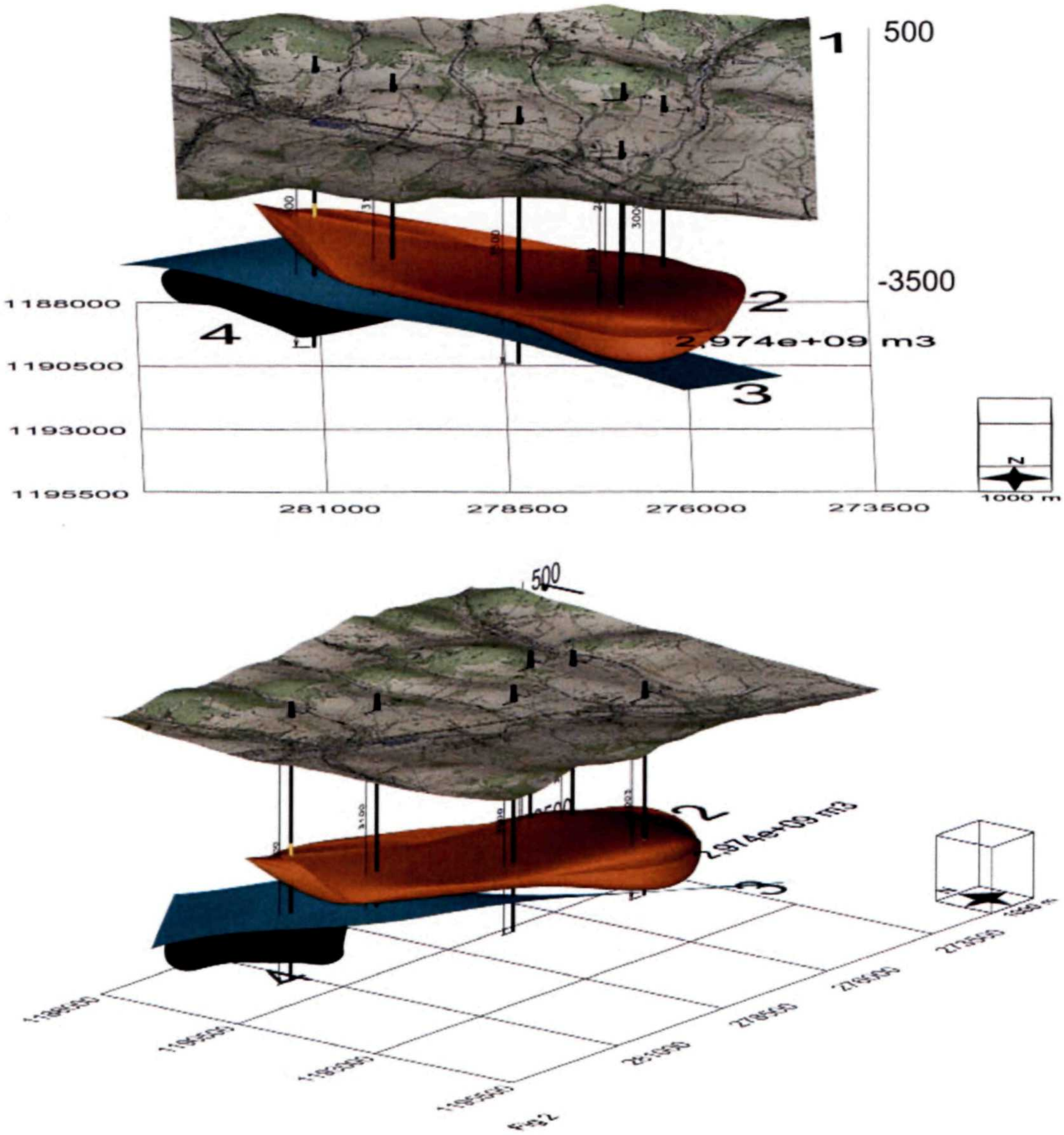


*Fig. 4.3.1.3 a (top), b (bottom) 3-D view of Lipany elevation with the essential exploitable geological objects (Šesták, Kucharič & Bodiš, 2011)*

*Explanatory notes: 1- relief of the surface of the ground, 2-collector horizon - intraformation breccias, 3-Pre-Neogene basement, 4-collector horizon of geothermal water*

injecting into the gas deposit, which would alleviate its exploitability and gas thus obtained could be used for the energy needs of the planned water park (ca 1.5 mil. t/ year). It is understandable that such activity would require additional costs (additional borehole with associated infrastructure), but on the other hand, it would be possible to store $CO_2$, which deflation into the atmosphere would have to be subject to the emission limits. According to preliminary estimated capacity, the volume of methane would satisfy the pilot phase of $CO_2$ storage. Of course, the population attitude to such a solution would have been significant.

After filling up in the volume of the gas deposit and its extraction it would be possible to proceed to the $CO_2$ storage within the intraformation breccias, which we have reinterpreted. Thus we have got the volume of the 10 Mt in our capacity estimates, what is already sufficient to build an industrial-scale $CO_2$ storage capacity. However, similarly as in the previous case, we would have to count with a strong resistance from the public.

Of course the last two steps, although to-date they look unlikely, they remain as a potential backup for the issue of $CO_2$ storing. The actual use of such sites will depend on the overall geopolitical situation in the medium term and the development in energy prices, the situation in the field of climate change, as well as in the level of prices of the $CO_2$ discharge permits. Of course, we can't forget about the attitude of the public, which is in the vast majority of these cases fundamentally negative.

### 4.3.2 The Plavnica Structure

The structure of Plavnica is located in the "Subtatric Group" of the Inner Carpathian Palaeogene at the southern

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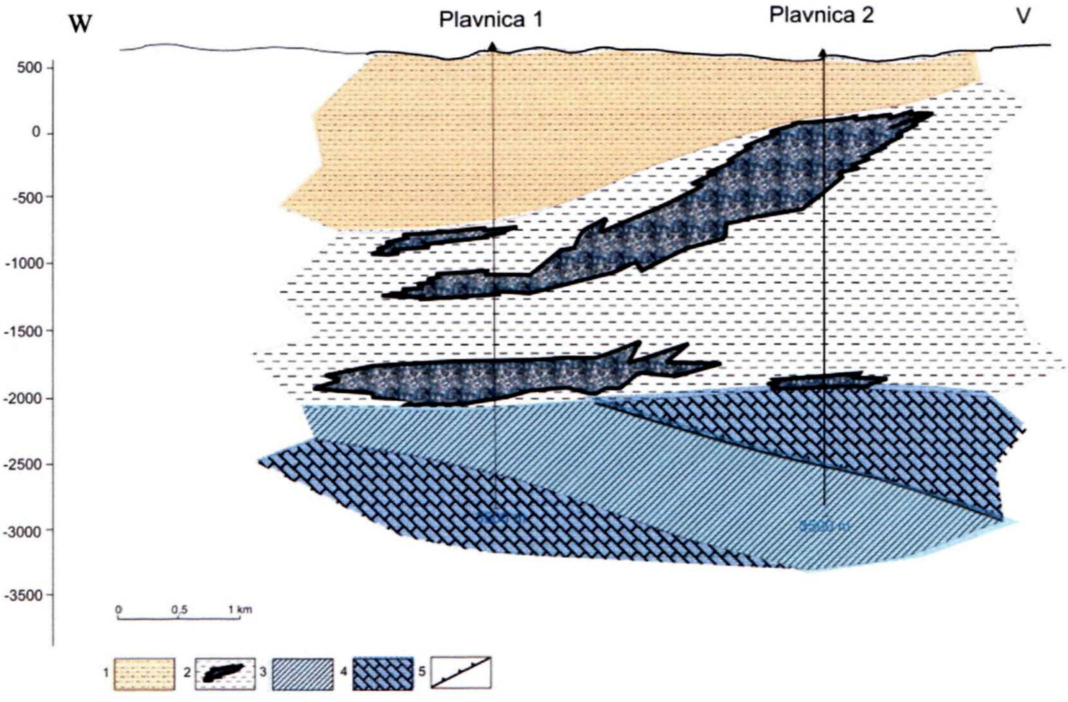


*Fig. 4.3.2.1 Geological cross-section through the boreholes Plavnica 1 and Plavnica 2 (modified after Rudinec, et al., 1983)*
*1-clay, siltstone, sandstone (Flysch sequence); 2-limestone, dolomite, sandstone, strongly brecciated, intraformation breccia located in clayey environment* - ***considered as potential storage space;*** *3-calcareous-dolomitic clay (Jurassic?); 4-mostly carbonatic complex (Triassic); 5-assumed overthrust plane*

foot of the Klippen Belt. Geographically, it belongs to the north-western part of the Šarišské medzihorie in Ľubotínska pahorkatina Upland (Mazúr and Lukniš, 1980). The structure is situated between the villages of Šambron-Plavnica and Hromoš. In this area the elevation structure was detected by reflective seismic investigation; the structure is assigned to the Hromoš–Šambron elevation zone. In essence, it is a continuation of the Lipany elevation structure of the basement, protruding here from south-east. However, it is very difficult to interpret the seismic image in the internal structure of the Palaeogene and the interface Palaeogene/Fatricum is quite problematic, because of the records are not of sufficient quality.

In the top part of the structure there was implemented Plavnica 1 borehole with a depth of 3,500 m. Another borehole Plavnica 2 was located in the easterly direction in the same structure with the same depth reached. Both wells have drilled-through the Subtatric group and encountered Fatricum. Oil and gas indications in Palaeogene and Fatricum proved to be uneconomic, even though the contents of hydrocarbon gases from the borehole Plavnica 1 from Mesozoic were surprisingly high. The main economic result was a detection of the thermal medium mineralized water (approx. 10 $g.l^{-1}$) with the temperature at the borehole collar of 45-50 °C and yield of max. 3.9-4.6 $l.s^{-1}$.

In terms of $CO_2$ storage distinctive feature of the lower part of the Palaeogene formation may be interesting - the incidence of a number of horizons of the intraformation conglomerates and breccias. In the borehole Plavnica 1 they are more prominent and more numerous from the depth of 1,350 m, in the borehole Plavnica 2 they are less pronounced in an interval of 1,700-2,500 m (Rudinec, et al., 1989). Dominant material of conglomerate are pebbles of carbonates (limestone and dolomites). There occur also pebbles of shales, siltstones and quartzose sandstones. The cement has the character of non-assorted polymictic psamite (Řehánek, 1988).

The most distinct intraformation body is in the borehole Plavnica 1 at a depth of 2,306-2,657 m. It is made of medium- to coarse-granular dolomites, which are disrupted by omni-directional crevasses of varying intensity. A significant number of cracks is open. This horizon caused a reflex of seismic rays which was regarded as an elevation structure. Both drillings encountered the Mesozoic carbonates, which are classified as good collector, with the inflows of the mineralized saline thermal water, and carbon dioxide, but with a small amount of hydrocarbon indications.

The horizon in the borehole Plavnica 1 has the original porous space cemented with calcite crystals, so the intergranular porosity porous amounts to only 2%. At a later period the rock was disrupted by crevasses of 0.02-0.06 mm width, enabling a propagation of both gaseous and liquid fluid (Jandová, et al., 1986). The permeability is rated as good - 200 $nm^2.10^3$. The authors assess the rocks of the Palaeogene base as pore-joint type of collector with a low total porosity, but a **good joint permeability**. The Mesozoic carbonates are rated at the same level, with the difference that the permeability is **moderate**, rarely **good**. Almost similar characteristics are valid for the rocks encountered in the borehole Plavnica 2 (Jandová et al. 1988).

Similar to the site of Lipany, the intraformation bodies were interpreted as a few hundred meters thick lenses, as the product of sedimentation from the submarine channels. For the reasons discussed at the aforementioned Lipany site we reinterpreted their course in similar way, we have got a bulky body, which could serve as a $CO_2$ repository. Such an idea is documented by geological cross-section (Fig. 4.3.2.1). Total capacity is estimated at approximately 5,000 kt.

The site might be a good place for the implementation of the pilot project. However, the problem may be the technical condition of the two boreholes.

## 4.4 The Zboj Structure

In the framework of the project Magnetic Map of the Slovak Republic (Kubeš, et al., 2008) a ground-based magnetic method (total vector of the Earth's magnetic field) was applied for measuring the eastern section of the Outer Flysch space. Although the Flysch complexes are typical of magnetic materials absence (Ondra and Hanák, 1989), however in the north easternmost tip of Slovakia, on the border with Poland and Ukraine (fig. 4.4.1), a relatively significant negative anomaly of almost rhomboidal shape was detected with a diameter of about 5 km and amplitude to 100 nT. The anomaly is situated in the area between the municipalities Zboj and Nová Sedlica. In the northwest direction it continues to the village Runina. The territory belongs to the region of Bukovské vrchy Mts. The main ridge of the mountains is of the N-S direction and actually creates the western boundaries of the anomaly. From the morphological point of view, a significant part of the anomaly is located within depression formed by a sudden change in direction of valleys (almost 90$^o$), conditioned probably by fault structures (see Figure 4.4.2). From the geological point of view the territory belongs to the Dukla geological unit. At the surface, there were not detected rocks that could cause this anomaly. Whereas the Flysch sequences are without magnetic rocks, it is obvious that we have captured the effect of a magnetic object, "coming" from the basement of the Flysch complex which had penetrated the Flysch sequence,. Therefore, it had to be younger in age, and its roof did not reach the level of the existing topography, apparently depleted of its kinetic energy (Fig. 4.4.4).

It is an interesting fact that the borehole Zboj-1 (Ďurkovič, et al., 1982), which was situated in the eastern zone in this part of the territory of the Flysch Dukla unit, was set about 6 km to the SW of the anomaly, in the valley of the Zboj Brook, North of the village of Uličské Krivé. Of course, at that time the discussed magnetic anomaly was not detected, because this part of the Slovak territory had not been investigated by the magnetic measurements. In the light of the interpretation of the seismic measurements - two profiles end close to the anomaly - this part of the territory was considered to be an elevation, the Pre-Tertiary bedrock was interpreted in depths of around 2,500 m (Mořkovský, 1992). The borehole drilled-through four complexes (Ďurkovič, 1982), which are presented in the Tab. 4.4.1.

From the hydrogeological point of view the Submenilite Member is rated as an insulator layer, Cisna Member as semi-aquiclude or semi-aquifer, Łupkow Member as aquiclude and Zboj Member as an aquifer. In the borehole there were detected gases surges - methane 92.1-96.3%, particularly in the Łupkow Member in the depths of 2,900-3,663 m. In the Zboj Member in the depths 3,694-3,992.5 and 4,690-4,724 $CO_2$ surges as well as the saline water inflows were detected.

From the oil-deposit point of view the most perspective was the upper part of the Zboj Member, which was tectonically disintegrated, even with the presence of cavities. Pumping tests were done only in these Zboj strata and according to the chemical composition these waters are classified as highly-mineralized up to brines with the mineralization of 43.95-56.14 g.l$^{-1}$. According to the carbonate coefficient these waters are of deep circulation, without being affected by shallow groundwaters (Žakovič in Ďurkovič, et al., 1982).

According to the results of a sounding in the borehole Zboj-1 positive effect of secondary jointing is obvious, because on the basis of these measurements the porosity was calculated at an interval of 2,000-3,000 m at the rate of 8.4%, at an interval of 3,000-3,500 at the rate of 4.6% and at an interval of 3,500-4,000 at the rate of 6.6%. In the last km - up to 5,000 m, the porosity reached only 4% (Rudinec, 1989). Here it is clearly seen of what relevance is the younger tectonics to the density parameters. In the majority of the rocks of the Dukla unit in which the well is located, the primary porosity was less than 2%. This fact indicates that the site was tectonically exposed, which has an effect on its further evaluation.

Significant influence on the hydraulic communication within the Palaeogene and Flysch rocks attributed Jetel (2000) to fissured zones, where he defined them as subvertical zones of intense disintegration, with close genetic and spatial relation to the course of the tectonic discontinuities that often predispose the morphological depressions. They run over stratification and dip of the beds independently to greater distances and represent privileged communications of hydraulic movement of groundwater in larger depths to greater distances.

But it may be noted that at the bottom of the Łupkow Member there has been verified a gas-bearing horizon at the depth interval of 2,900-3,663 m with less intensive, but yet six surge spots of flammable gas (methane) at the test capacity of 900 m$^3$/24 hrs, using 2 mm nozzle (Rudinec in Ďurkovič, et al., 1982).

### Interpretation

After analysis of the magnetic field in the area of interest and possible geological variants we come to the conclusion, that the anomalous body is likely neck-shape object tilted to the Northeast. On the basis of the overall concept of the geological structure of the territory and the necessary physical characteristics to achieve maximum compliance between measured and calculated curves in a magnetic modelling, we came to the conclusion that the anomalous element should be the product of the Neogene andesite volcanism. Such a notion we applied in 2-D modelling of the magnetic field, and we have achieved a very good compliance between the measured and calculated curves of its total vector. As a possible source we assume Neogene diorite porphyry which generally has fairly strong magnetic properties.

Tab. 4.4.1 Simplified geological profile of the borehole Zboj-1 (according to Ďurkovič et al., 1982)

| Depth (m) | Rock complex |
|---|---|
| 0-300 | **SUB-MENILITE MEMBER** represented by sandy grey and green-grey non-calcareous or weak calcareous claystones alternating with mica silts (Palaeocene) |
| 300-800 | **CISNA MEMBER** in the development of typical Flysch. The share of sandstones is from 30-80%, the beds are slightly tectonically disturbed. (Palaeocene). |
| 800-3,800 | **ŁUPKOW MEMBER** - claystones - sandstone Flysch. The ratio claystones/sandstones is 4:1. The colour of claystones is dark-grey; calcareous share in sandstones is very variable 1.4-35.7%. (Cretaceous-Palaeogene) |
| 3,800-5,002 | **ZBOJ MEMBER** has the main lithotype the massive sandstones with homogenous texture (the content of $SiO_2$ is 53-89%). The top of the beds is tectonically disintegrated (Late Eocene-to Early Oligocene?) |

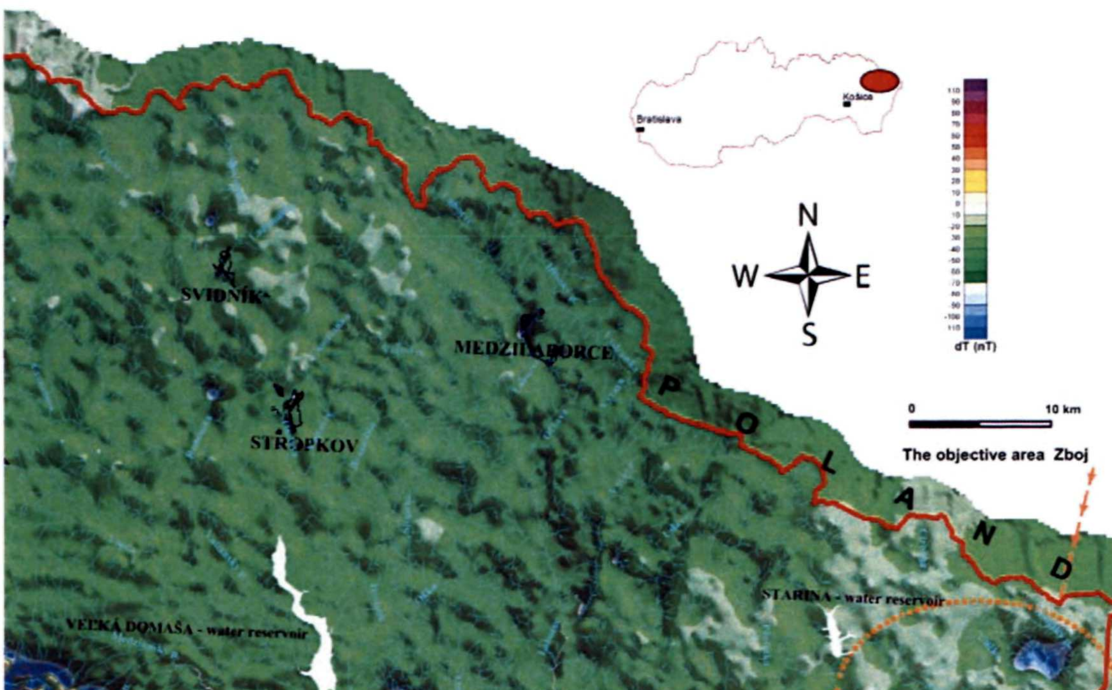


*Fig. 4.4.1 Magnetic map of the NE part of Slovakia - Flysch Belt (after Kubeš et al., 2008)*

The modelled body along with the geological interpretation is displayed in Figs. 4.4.3 and 4.4.4. The reasons for which we assigned the magnetic anomaly among Neogene volcanism products, we discussed in detail in the work of Kucharič et al. (2013).

### *Output into $CO_2$ storage issue*

For the carbon dioxide storing the premise is important, that in the course of Flysch complex penetration the body of such dimensions affected the sedimentary environment not only thermally but also tectonic deformations occurred in the form of secondary porosity, according to Rudinec (1989) even in the great depths as confirmed by the borehole Zboj-1, which is out of the detected object. Primary porosity is generally very low. We assume that within the exo-contact parts of the interpreted body it should be created an aureole of crushed rocks, surrounding the andesite body, which could be a suitable environment for the storage of carbon dioxide.

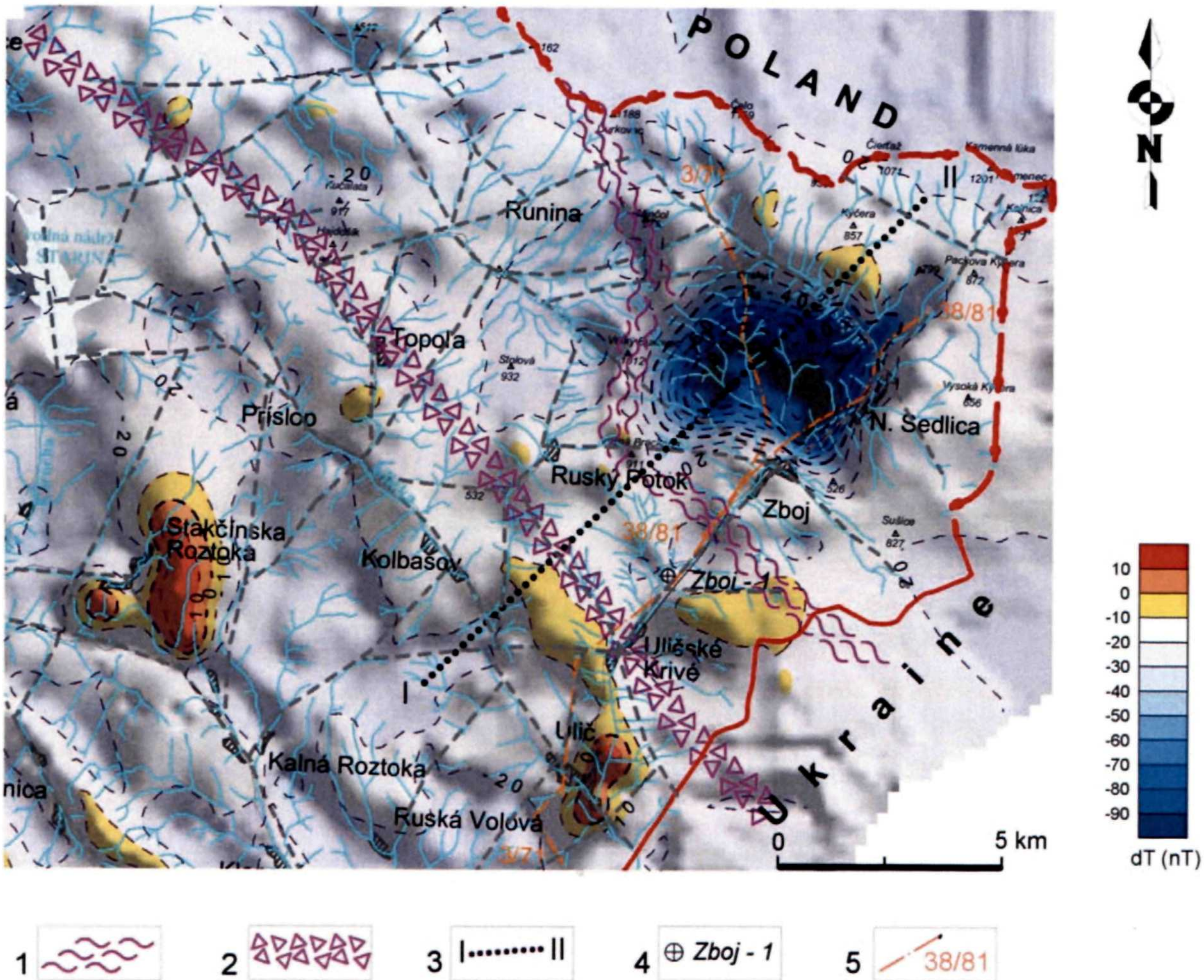


*Fig. 4.4.2 Magnetic map of the area showing major Carpathian physical anomalies (gravity low and conductivity anomalies)(after Kucharič et al., 2013). Explanatory notes: 1-the southern boundary of the Carpathian gravity low, 2-Carpathian conductivity anomaly, 3-interpretative profile, 4-location of the borehole, 5-seismic profiles*

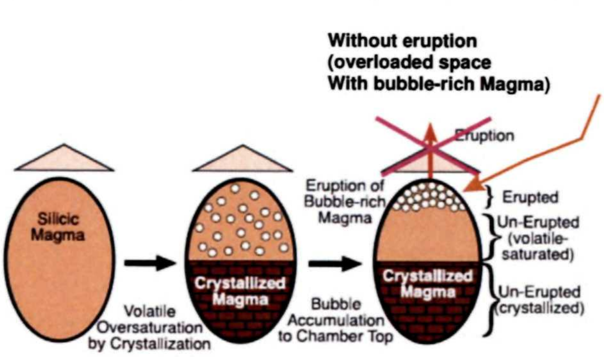


*Fig. 4.4.3 Schematic diagrams of bubble accumulation processes in a magma chamber (adopted after Shinohara, 2008)*

The effect of secondary porosity we have already mentioned in the previous text.

If we assume subvolcanic body, its lift should be accompanied by the emission of gas, as a result of the separation of magmatic gases from the magma. According to Shinohara (2008) degassing of non-eruptive magma occupies a considerably large space around magmatic body. The expansion of the volcanic gas phase is the main driving force of the magma ascent. In volcanic gases the most common components are water, $CO_2$ and $SO_2$. It is therefore possible that due to the dimensions of the body the gases saturation was limited, the kinetic energy during the saturation was consumed in the course of the ascent, and therefore did not reached the stage of eruptive magma. At the final stop of the magma ascent on the estimated geological border, saturation by the volatile components occurs, which without a doubt increases the porosity of the top of magmatic body. However, we did not include this effect in the calculation of capacity, but with great certainty it represents an added value to the capacity of the storage space. The estimated limit, where the ascent had stopped will be likely a relatively clear cut interface between the sandstones and claystones in the Łupkow Member. Plastic properties of claystone apparently diminish residual kinetic energy, and their almost horizontal roof can represent this interface. This aspect was also modelled in the laboratory conditions, when it was found that each volcanic rock solidifying in a subvolcanic environment creates a three-dimensional network of bubbles during the drop in pressure, generated by volatile components such as water, carbon dioxide and methane (Berg, et al. 2011). A similar conclusion presents also Sparks (2003), who found out that in more viscous magmas, such as the andesite, or rhyolite ones, the

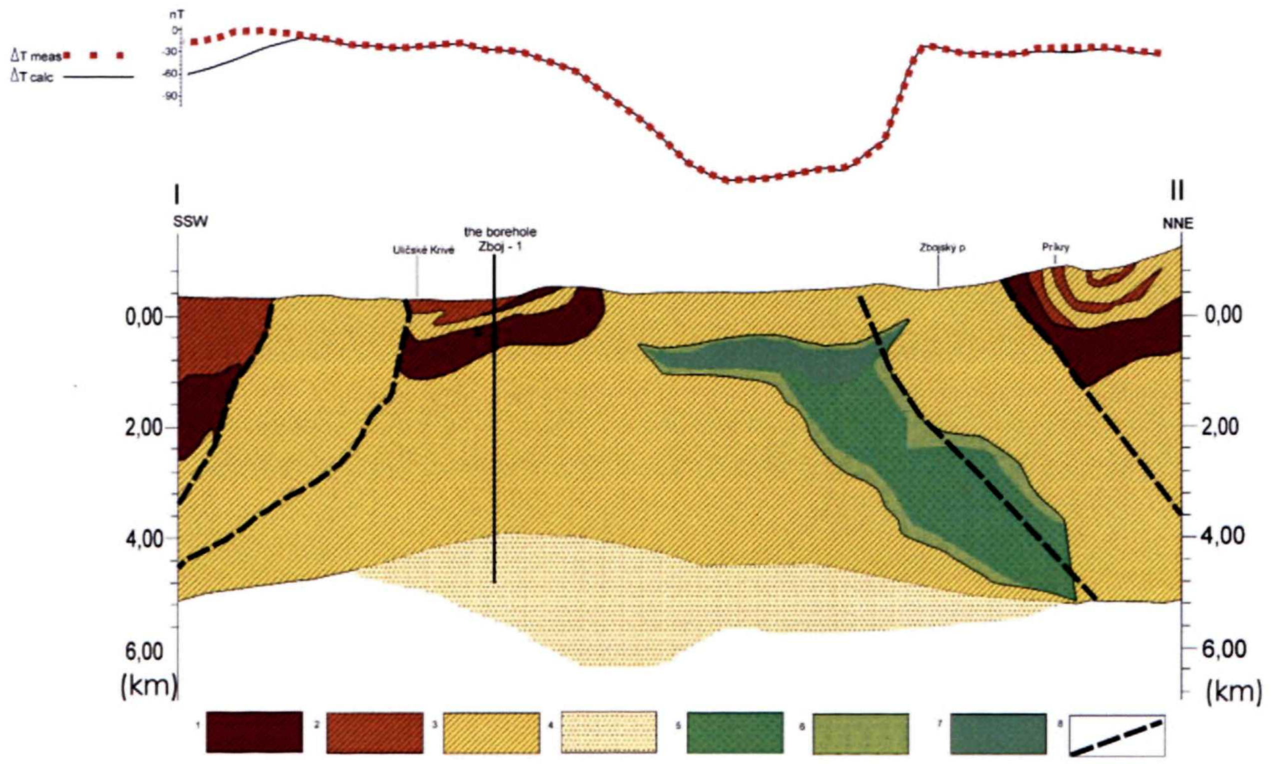


*Fig. 4.4.4 The geological interpretation of 2D magnetic modeling (after Kucharič et al., 2013)*
*1-Sub-Menilite Member, 2-Cisna Member, 3-Łupkow Member, 4-Zboj Member, 5-subvolcanic body, 6-contact zone, 7-oversaturated zone with volatile components, 8-inferred faults*

bubbles of gas rise through a body independently and can create a "magmatic foam" at the top, which becomes so pervious, that the main escape routes do not lead through the contact rock, but along the fault lines.

When calculating storage capacity we were based upon the commonly sed formula for regional aquifers which we modified for a given environment. We approximate the modelled body with the shape of the inclined cylinder. If we assume a crushed aureole around the body, caused by the ascent into the Flysch sequence in the shape of a cylinder with a wider diameter, so for a storage volume we assumed this aureole space, or in other words, the volume of the annulus between the body itself and the intact rocks. The calculation was carried out for different thicknesses of the crushed zone and different depth of carbon dioxide injection, taking into account its supercritical state, thus the depth greater than 800 m below the surface.

We retain a constant carbon dioxide density, porosity, and the coefficient of efficiency. In porosity we were based on data from the borehole Zboj-1 sounding records, albeit with a certain risk that the data may not correspond to the place where the body is located and for the coefficient of efficiency, we used the "pessimistic approach". The result is shown in the database.

### *Output into the issues of hydrocarbons prospection*

Evidence found in the deep borehole Zboj-1 indicates that the site has some of the features of the hydrocarbons potential. The detected and interpreted magnetic anomaly enhances the overall picture of this part of the eastern section of the Flysch Zone. According to the existing information, the occurrence of hydrocarbons in the vicinity of the volcanic rocks is known almost from the hundreds of sites in the world. The volcanic rocks can create hydrocarbon traps because of their good porosity in greater depths. The traps can be created as well between volcanic structures and their sedimentary surroundings. Occurrences of the volcanic rocks turn from these "forgotten areas" to "target ones" in terms of the occurrence of hydrocarbons, as they are the subject of the hydrocarbon prospection. In doing so, hydrocarbons in volcanic rock reservoirs are of biogenic as well as abiogenic origin. The volcanism can effectively increase the maturity, the rate of the generated hydrocarbons, can provide the abiogenic hydrocarbon formation and open their migratory routes (Wang, et al., 2010). Volcanic liquids and gases positively affect the migration of hydrocarbons. On the other hand, although volcanic rocks generally occupy less than a quarter of the volume in the basin fills, the hydrocarbons reserves represent only 1% of the world's proven hydrocarbon stocks. Nevertheless, as a result of the rising consumption of hydrocarbons in the energy sector the volcanic regions are becoming increasingly more interesting objects in the prospection (Liu et al., 2010). In the present case, once again we draw the attention to the previous hydrocarbons presence forecast in the area evaluated (Rudinec, 1989).

***Output into metallogenetic issues***

Our assumption that the magnetic anomaly is probably caused by the Miocene volcanic andesite body (Trua, et al. 2002), there may be expected in its contact zone mineralization stages, similar to what has been committed in Pieniny andesites in which in the 18th century Au, Ag and Pb were mined (Birkenmajer, et al., 2004):

1st stage - the highest temperature with poikilitic texture of biotite phenocrysts with inclusions of quartz, chlorine apatite and feldspar

2nd stage - lower temperature with the creation of pyrrhotite, pyrite, chalcopyrite, rarely electrum and epidote. This corresponds to the propylitisation phase.

3rd stage - andesite carbonatization, caused by cooling-down of water enriched with $CO_2$.

4th stage - in which under lower pH and temperature conditions the primary sulphides were replaced by their alteration products, such as: chalcopyrite-covelline, and pyrrhotite- marcasite.

Note: 1st and 2nd stages are accompanied by silicification and argillitisation.

***Conclusions***

The site is proof that in spite of a generally negative assessment of the Flysch for the purpose, due to the absence of appropriate collector horizons, there may be found in different parts of the Flysch Zone appropriate sites for $CO_2$ storage, in theory.

In addition, there is a benefit to the fact that, when examining a suitable environment for $CO_2$ storing, it is often possible to find other interesting facts, encompassing wider geological structures and the practical sphere of use, thereby stimulating a groundswell for the emergence of other potential projects of geological works (Kucharič et al., 2012).