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# 3. Depleted hydrocarbon deposits

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## 3.1 Depleted hydrocarbon hydrocarbon deposits in Vienna and East Slovakian Basins

The capacity of the reservoirs of oil and gas for this review are defined as underground volumes that had been carriers of natural oil or natural gas, which, in the future - can be used to store carbon dioxide. In these cases it is not necessary to inspect the sealing of the original structures (the spill points), because the sealing of these structures and hydrocarbon reserves (determined either by the volumetric method, or the method of decrease in pressure) has been confirmed by extracted volume. In the calculation of carbon dioxide storage capacity we disposed exclusively with the original lithological conditions, that is, in the case of not exceeding the value of the original deposit pressure pressure values of each object, which is the main justification for the retention of stored $CO_2$, and in the careful progress of security minimising the risk of deposit capacity of spill through the cap.

The existence of the hydrocarbon accumulation is also a testament to the original system had not been suitable as potable water source and therefore there is no secondary threat to the sources of drinking water.

The hydrocarbon production demonstrated that porous space is communicative, i.e. if we are talking about its volume, it is the volume of the effective porosity and its permeabilities are conducive for the flow of media and the deposit circumstances might be favorable even in the reverse deposit operation, i.e. during the injection and storage of carbon dioxide in these depleted spaces. In many cases, the deposit pressure after extracting the original hydrocarbon reserves is substantially lower than the value of the original pressure and this pressure difference can be understood as a value representing a potential volume, which could be replaced by a stored carbon dioxide. The methodology for calculating the storage volume for deposits of oil and/or natural gas have been simplified in order to provide the broadest possible applicable basis (the source of the U.S. Department of Energy, 2006).

The calculation was based on the quantification of the $CO_2$ volume, where both the hydrocarbons volume and the $CO_2$ volume are calculated according to the original terms and conditions, in which the accumulation of hydrocarbons had existed in the original deposit. Two basic methods are used for the evaluation: (a) the volumetric calculation of the stored $CO_2$ capacity and (i) the calculation of original production of hydrocarbons in order to determine the capacity of the stored $CO_2$. Key data used such a value that better suits the existing data (if there was a production of deposit/deposit object/part of deposit object, the (ii) methodology was used. In both methodologies the efficiency of the use of the original pore volume is reflected.

**(i) Volumetric calculation of geological objects storage capacity for $CO_2$ storing** using the standard methods for calculating the initial volume of geological oil reserves (OOIP) and the original volume of the geological reserves of natural gas (OGIP) - it is determined by the "coefficient of effective use of original volume" – "E" (as a fraction of the original total capacity of pore space):

$$G_{CO_2} = V.\phi.(1-S_w).B_i.\rho.E ,$$

For the calculation of the formation factor $B_{gi}$ we used the Standing`s formula:

$$B_{gi} = \frac{P_s \times T_f}{P_{fi} \times T_s} \times Z_{fi}$$

$P_s$, $P_{fi}$ - standard pressure, the initial deposit pressure (MPa)

$T_s$, $T_f$ - standard temperature, temperature of a deposit (K)

$Z_{fi}$ - compressibility coefficient of gas under the conditions of the $T_f$ and $P_{fi}$

The value of standard pressure is 0.1013 MPa

The value of standard temperature is 293.2 K (20 °C)

Basic data entering into the calculation are listed in the individual sheet forms of the deposit objects.

**(ii) Calculation of geological objects storage capacity for $CO_2$ storing based on the original production** makes use of the standard methods for calculating the initial volume of geological reserves of oil (OOIP) and the original volume of geological reserves of natural gas (OGIP), taking into account the fact that the volume of the produced hydrocarbons is known.

The volume of produced hydrocarbons corresponds to (a) the effective volume of rocks, (b) the value of the effective porosity of the rock – through their multiplication we shall get effective pore space, (c) saturation with hydrocarbons – effective pore space filled with hydrocarbons, and (d) the coefficient of factual mining exploitability $R_f$ is determined by the ratio of the achieved extraction vs the original volume of geological reserves of hydrocarbons (in the case of non-extracted deposit the coefficient is determined from the reserves calculation). In this way, we get the value of the extracted volume of hydrocarbons registered at the surface:

$$Q_{CH} = \frac{V.\phi.(1-S_w)}{R_f}$$

Then to calculate the storage capacity for the given storage conditions we use a relationship, in which we convert the volume of extracted hydrocarbons measured at the surface by means of formation factor $B_i$ to the volume in the original geological conditions and for this volume we determine the $CO_2$ storage capacity by using the value of the density of $CO_2$ storage in such conditions, which are known for the given object:

$$G_{CO2} = Q_{CH}.B_i.\rho\,.$$

This method is applicable in the circumstances, that there are reliable records of the course of mineral extraction. The extracted deposit water volumes and volumes of the accompanying raw materials (especially gasoline when extracting natural gas and dissolved gas in oil) are not taken into account in the calculations in ordinary cases. As well, in this calculation the volumes of injected water are not comprised, although these data ought to be included into the detailed analysis for the specification of the given projects.

In the application of this methodology, it is important to use the appropriate formation factor, in order to implement properly the conversion of hydrocarbons volume registered at the surface in relation to the volume which the original raw material occupied in deposit conditions.

### *The conversion of geological reserves of oil and gas*

For the calculation of the capacity of the deposit objects that have been previously saturated with oil, the values of the oil density have been used according to laboratory analyses of local samples.

### *Assessment of the suitability of the objects and their evaluation*

Another part of the handling the set of the data describing basic geological, deposit, security, capacity and relational links between the sources of emissions and their disposal sites, represent the analysis, suitability assessment and evaluation of each documented object. This procedure is designed in such a sequence and the structure of the record, which allows to compare relative usefulness of objects included in the outline.

Evaluation of objects is designed in groups of data, which are both subject to verbal description of the facts and at the same time, a classification scale is proposed for various arguments.

The assessment covers the categories of:

1. Suitability of assessed deposit structure
2. Reliability of the verification and the description of the geological circumstances of the deposit structure
3. The conflicts of interests with other mining activities
4. Threats, which may pose in the long term the use of the deposit structure.

Each item is subjected to the "weights" assessment in the next step, being declared by percentages. These weights are determined empirically and represent the weightiness of the particular item in a given category of assessment. The value of the weight of each item varies in the range from 0 to 100%.

For the purposes of the structure assessment a sheet form was developed, where there were recorded all relevant parameters known from the structure. An example of the form is documented in Table 3.1.1.

In the initial evaluation essential volume values are summarized namely **the storage capacity** expressed in $m^3$ (Table 3.1.2). This value is the sorting feature, which is based on the value of the original geological reserves of natural gas or crude oil, according to approved reserves calculation. This value can be modified in the event that the actual volume of extracted hydrocarbons exceeded the value of the real achievable exploitability. In such cases, the data referred to in the text of the original hydrocarbons reserves were reviewed on the basis of the calculation of the reserves according to the drop of pressure in the deposit.

**The $CO_2$ storage capacity** represents the amount of carbon dioxide that can be potentially stored in the structure.

In the case of qualitative parameters describing the "**Appropriateness**", which assessment can reflect multiple variables, we have chosen a range of **1-5**, in which the lowest value expresses the highest quality (Table 3.1.3). We have assessed the six items - appropriatness criteria, which deal with the description and assessment of the hydraulic properties of the reservoir, the primary and secondary sealing, chemical reactivity of the environment, the existing infrastructure of the deposit and the technical tightness of probes.

In the event that **no data are available** for the assessment, **value 6** is used for such classification. This reflects the value of the maximum risk and the fact that it is necessary to begin to acquire such data for the assessment.

Similarly, we have approached the "**Reliability**" assessment, in which the selection reflects the existing status of geological and deposit situation by means of available technical tools, reference and evaluation of the facts, whether it's a two- or three-dimensional versions of the models and seismic measurements. The range is set to **1-3** and the maximum value represents absence of the selected item (Table 3.1.4).

In the case of logical opinions - category "**Conflicts of Interests**" this range is **0 to 1**, where **1** confirms the

Tab. 3.1.1 Table presenting the parameters for the object assessment

| **Field** | **Reservoir** |
|---|---|

**General Data**

| | |
|---|---|
| Location | |
| Structure | Single / Multilayer, comprising reservoirs |
| Mining Licence | |
| Exploration Area | |

**Field Location**

| | | | | |
|---|---|---|---|---|
| Emission Sources Type | | | Existing | Planned |
| Emission Volumes | [tonnes] | | Existing | Planned |
| Emission Rates | [tonnes/day] | | Existing | Planned |
| Pipeline Routes to Sources | [DN, PN] | | Existing | Planned |
| Distance to Sources | [km] | | Existing | Planned |

**Exploration/Production History**

| | |
|---|---|
| Discovery Date | |
| Start of Production | |
| End of Production (anticipated - if operated) | |

**Primary Reservoir Conditions**

| | | |
|---|---|---|
| Initial Reservoir Pressure | [MPa] | |
| Initial Pressure Gradient | [kPa.m$^{-1}$] | |
| Reservoir Temperature | [°C] | |

**Reserves & Production as of 01/01/2009 (@ 15 °C, φ=0)**

| | | | |
|---|---|---|---|
| IGIP, OGIP | [$10^6$ m$^3$], [$10^3$ tonnes] | | |
| Cumulative Production | [$10^6$ m$^3$], [$10^3$ tonnes] | | |
| Remaining GIP | [$10^6$ m$^3$], [$10^3$ tonnes] | | |

**Actual Reservoir Conditions as of 01/01/2009**

| | | |
|---|---|---|
| Reservoir Pressure | [MPa] | |
| Reservoir Temperature | [°C] | |
| | | |

**Geological & Reservoir Data of Target Horizon**

| | | |
|---|---|---|
| Reservoir Rocks | | |
| Geological Age | | |
| Type of Trap | | |
| Productive Interval Min - Max | [m] | |
| Productive Area | [km$^2$] | |
| Type of Border | | |
| Net Pay Min - Max | [m] | |
| Porosity Min - Max | [%] | |
| Permeability Min - Max | [mD] | |
| Effective porous volumes available for CCS | | |

**Geological & Reservoir Data of Overburden**

| | | |
|---|---|---|
| Reservoir Rocks | | |
| Net Pay Min - Max | [m] | |
| Productive Area | [km$^2$] | |
| Integrity of caprock | | |
| Capillary Threshold Pressure Measurements | | |
| Fracturing Pressure Measurements | | |

**Existing Reservoirs above the Caprock (in case of leakage)**

| | | |
|---|---|---|
| Reservoir Rocks | | |
| Interval Min - Max | [m] | |
| Productive Area | [km$^2$] | |

**Chemical Properties of Gas**

| | | | |
|---|---|---|---|
| Methane | [%] | | |
| Inpurities | [%] | | |

**Geological & Reservoir Data of Surroundings**

| | | |
|---|---|---|
| Reservoir Rocks | | |
| Interval Min - Max | [m] | |
| Distance to the Target Reservoir | [km] | |

**Chemical Properties of Reservoir Water**

| | | | |
|---|---|---|---|
| pH | | | |
| Mineralization | [kg.m$^{-3}$] | | |
| | | | |

**Chemical Properties of Crude Oil**

| | | | |
|---|---|---|---|
| Gravity | [g.cm$^{-3}$, °API] | | |
| Special Components | | | |

**Well Inventory**

| | Number | |
|---|---|---|
| Drilled Wells in Total | | |
| Existing Wells | | |
| Safe P & A Wells | | |
| Wells to be Additionaly Tightened | | |
| Wells Available for CCS | | |
| Wells to be Reopened for CCS | | |

**CCS Operation**

| | | | |
|---|---|---|---|
| $CO_2$ storage volume | [m$^3$] | | |
| $CO_2$ injectivity per well | [m$^3$] | | |
| $CO_2$ - injectivity per reservoir | [m$^3$] | | |
| Wells Required for CCS | | | |
| Maximal Pressure Gradient | [kPa.m$^{-1}$] | | |
| | | | |
| | | | |

existence of a conflict of interests, which either complicates or temporarily restricts the use of the site/deposit/part of a deposit for CCS projects (this proposal is supported by the idea that, in the case of a decision on logical opinion the "absence" of competing projects represents the favourable assessment = **0**, see Table 3.1.5).

In this process the conflicts of interests are assessed as competitive mining operations, which represent the upcoming projects, works in progress, or other methods of rock structures utilisation than the $CO_2$ storage, and under these circumstances, they reduce, or fully eliminate the potential possibility of applying such a structure in the CCS project. See the attached Table.

We evaluate the "**Threats**" in the range of **1-3** (see Table 3.1.6) in order to categorize quite strictly the types of threat that may arise from the $CO_2$ storage. Because storage safety is a priority, the negative ratings in this area are considered to be a serious obstacle to take advantage of the potential of the structures. We assume that the increasing emphasis on economically sustainable solutions must not lead to a reduction of environmental liability treshhold and we do not consider any interim solution to be adequate the time and means invested in the storage. Therefore, the solution with the least impact on existing or developing infrastructure has a value of **1**, while the worst one has got a value of **3**.

In the event that the item has not been detected in any category, it has assigned value on 1 greater than the highest (within the meaning of the worst) value of the item in the category.

For a summary evaluation of different categories, we have introduced the classification of each category, based on the value of the weighted average of the all items in the category (Table 3.1.7). Subsequently, each weighted average value there was assigned a textual assessment (classification). All the textual assessments (textual classifications) are contained in the Table of classifications.

Tab. 3.1.2 Storage capacity of the object

| **Chances and Risks (description and evaluation)** | | | **1-5** |
|---|---|---|---|
| **$CO_2$ - storage volume** | | | Volume |
| $m^3$ | IGIP (initial gas in place) | | |
| according to drop in pressure | | | |
| $CO_2$ - storage capacity | | | Capacity |
| kT | calculation | according to actual extraction | |

Tab. 3.1.3 Appropriatness of the object

| | 1-5 | |
|---|---|---|
| **$CO_2$ - injectivity for the wells/reservoirs** | 100% | Suitability |
| **Geological tightness of the reservoirs for long-term conditions** | 100% | |
| **Chemical Reactivity of Reservoir, Caprock and Fluids** | 100% | |
| **Operation wells required for the long-term $CO_2$ – injection** | 100% | |
| **Technical tightness of wells in the field** | 100% | |
| **Distance of the storage locations to existing/planned power stations** | 100% | |

Tab. 3.1.4 Reliability assessment

| | 1-3 | |
|---|---|---|
| **Seismic survey (missing, 2D, 3D)** | 100% | Reliability |
| **Geological Model (missing, 2D, 3D)** | 100% | |
| **3D Dynamic Model (missing, short term,long term simulation)** | 100% | |

Tab. 3.1.5 Conflict of interest

| | 0-1 | |
|---|---|---|
| **Existing Production of Gas/Oil** | 100% | **Conflict of Interests** |
| | **0-1** | |
| **Existing Plans for Production of Gas/Oil** | 100% | |
| | **0-1** | |
| **Existing Plans for Gas Storage** | 100% | |
| | **0-1** | |
| **Depleted and Abandoned Field/Reservoir** | 100% | |

Tab. 3.1.6 Assessment of Threats

| | 1-5 | |
|---|---|---|
| **Distance to Municipalities** | 100% | **Threats** |
| | **1-3** | |
| **Existence of Potable Water** | 100% | |
| | **1-3** | |
| **Effects Assessment** | 100% | |
| | **1-3** | |
| **Risk Characterisation (safety and integrity, uncertainties,...)** | 100% | |

Tab. 3.1.7 Summary assessment

| **Category** | **Average classification** | **Classification range** | **Overall classification** |
|---|---|---|---|
| Suitability | | | |
| Reliability | | | |
| Conflict of interests | | | |
| Threats | | | |

Tab. 3.1.8 Table of classifications

| Appropriatness | | | Reliability | | | Conflicts of interests | | | Threats | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Classification ( 1-5 ) | Range of weighted mean | | Classification ( 1-3 ) | Range of weighted mean | | Classification ( 0-1 ) | Range of weighted mean | | Classification ( 1-3 ) | Range of weighted mean |
| 1 | Very high | 1.000-1.4999 | 1 | High | 1.000-1.499 | 0 | Negligible | 0.000-0.099 | | | |
| 2 | High | 1.500-2.499 | 2 | Moderate | 1.500-2.499 | 1 | Very low | 0.100-0.299 | 1 | Low | 1.000 - 1.499 |
| 3 | Moderate | 2.500-3.499 | 3 | Low | 2.500-3.500 | 2 | Low | 0.300-0.499 | 2 | Moder. relevant | 1.500- 2.499 |
| 4 | Low | 3.500-4.499 | 4 | Insufficient | >3.500 | 3 | Relevant | 0.500-0.699 | 3 | Very relevant | 2.500- 3.500 |
| 5 | Very low | 4.500-5.500 | | | | 4 | Very relevant | 0.700-0.899 | 4 | Excessive | <3.500 |
| 6 | Not applicable | >5.500 | | | | 5 | Threathening | 0.900-1.099 | | | |
| | | | | | | 6 | Inconvenient | >1.100 | | | |

The weighted mean (classification) is calculated according to the relationship:

$$Klas = \sum_i^N \frac{Vi \times Ki}{\sum_i^N Vi}, \quad \text{where}$$

Klas - the resulting value of classification category

N - number of items in a category

$V_i$ - the weight of the i-th item category (0-100%)

$K_i$ - the value of the i-th item categories ("mark")

For the purpose of $CO_2$ storing there have been processed 5 deposits (30 deposit objects) of natural gas and oil in the East-Slovakian Basin and 10 (20 deposit objects) within the Vienna Basin.

In the **East-Slovakian Basin** there was calculated the total amount of $CO_2$ storage capacity of **7.07 Mt** in 30 deposit objects and in the **Vienna Basin** approximately **12.2 Mt** in 20 deposit objects. The affiliation of deposit objects into a lithostratigraphic sequence in the Vienna Basin is presented in the Figure 3.1.1., the distribution of individual deposits studied is in the Fig. 3.1.2.

Similarly, in the East-Slovakian Basin the affiliation of deposit objects in the lithostratigraphic sequence is presented in the Fig.3.1.3 and the location of the deposits is documented in the Fig. 3.1.4.

The most appropriate object from the perspective of the magnitude of the storage capacity in the East-Slovakian Basin is the deposit **Ptrukša 4. Sarmatian Block IX b** with the storage capacity of 571.7 kt, which has been classified in terms of the magnitude of storage capacity among the inconvenient ones. The suitability and reliability of this object is in the midst of the classification. This implies that the object is from the point of view of capacity suitable only for the pilot project.

From the perspective of the magnitude of the storage capacity in the Vienna Basin is the most appropriate is deposit **Láb, Láb Horizon – the Early Badenian West and the East** with the storage capacity of up to 2,475.7 kt which has been classified in terms of the magnitude of the storage capacity among the small ones. The suitability and reliability of this object is low, the capacity is not sufficient for industrial range of storage.

As we can see from the above capacities, despite the fact that all the proposed objects (including regional aquifers) are the most thoroughly characterised by relevant and verifiable data, in terms of industrial scale they are barely sufficient. In the summary assessment we reach the cummulative storage volume exceeding million tonnes only from both basins (average injection annual capacity ranging from 500-2,000 kT). This would mean that the objects could serve only for pilot (100 kt <) or demonstration (> 100 kT) phases. Another disadvantage is the fact that the horizons worth of interest have been often split into several partial horizons, what would brought complications of a technico-economic nature for the potential $CO_2$ injecting. We do not want to diminish the importance of those rated deposits, because both of these stages represent a fundamental step towards storage of industrial scale, which can be applied to other objects, suitable for the $CO_2$ storage. We point out that in the calculation the volume of the underlying local aquifers has not been accounted for.

The largest volume of the original geological reserves has been found in the deposit Zwerndorf-Vysoká and its deposit object the **Main Horizon at the base of Middle Badenian** and its immediate superincumbent - the **"E Horizon" of Late Badenian**. Despite the above fact (the original reserves may reach approximately 28 billion $m^3$), these objects have not been included in the submitted list, because the processing of any application for their use must be preceded by an interstate agreement, which would be elaborated within the meaning of the law modifying the regime.

Despite the fact that this deposit has not been assessed according to the above criteria, we have to emphasize some of its parameters, suitable for the objectives of the task. Althogh the current situation is not convenient, in a term of 10 to 20 years a view for this object can vastly change, and it can find its use in many ways, depending on the developments in the energy field. Theoretically, it can be expected the unification of the two countries views to its further use. For this reason, we have tried to summarize all available data on its possible use and design. Due to the size and importance of the structure we have evaluated this deposit in the following section separately.

## 3.2 Vysoká Zwerndorf

This deposit is processed separately, because it is a unique structure, with very high theoretical potential for the benefit of $CO_2$ storing.

The deposit is located in the southern part of the Záhorská nížina Lowland, in the cadastral territory of municipalities Vysoká and Láb. The deposit is the largest accumulation of hydrocarbons found in the former Czechoslovakia. The main gas-bearing object - basal Middle Badenian horizon and its superincumbent Late Badenian designated as the "E Horizon" are developed both in the Slovak and Austrian territory. The bulk of the deposit is developed in the Republic of Austria, which bears the name Zwerndorf – the ratio between the Slovak and Austrian sections is approximately 1:2. According to unverified data of April 1, 1960, in the Austrian part of the deposit there were calculated 16 billion $m^3$ of gas. It was evident that the uncontrolled mining shall influence the use of reserves in the two states. For this reason, since April 1, 1960 the agreement has been in force between the Government of Czechoslovakia and the Republic of Austria on the extraction of common oil and gas deposits. At the Slovak territory the deposit was verified by an irregular network of boreholes with spacings of about 500 m, reaching depths in the range of 1,030 m (borehole V-7) to 3,085 m (borehole V-4) - see Fig 3.2.1.

### *Geological situation and past deposit- mining data*

The deposit is a southern continuation of the Láb-Lakšárska Nová Ves stripe, whose peak antiform is located in the Austrian territory in the area of Zwerndorf-Baumgarten. From the northern Láb deposit structure it is separated by a transverse depression.

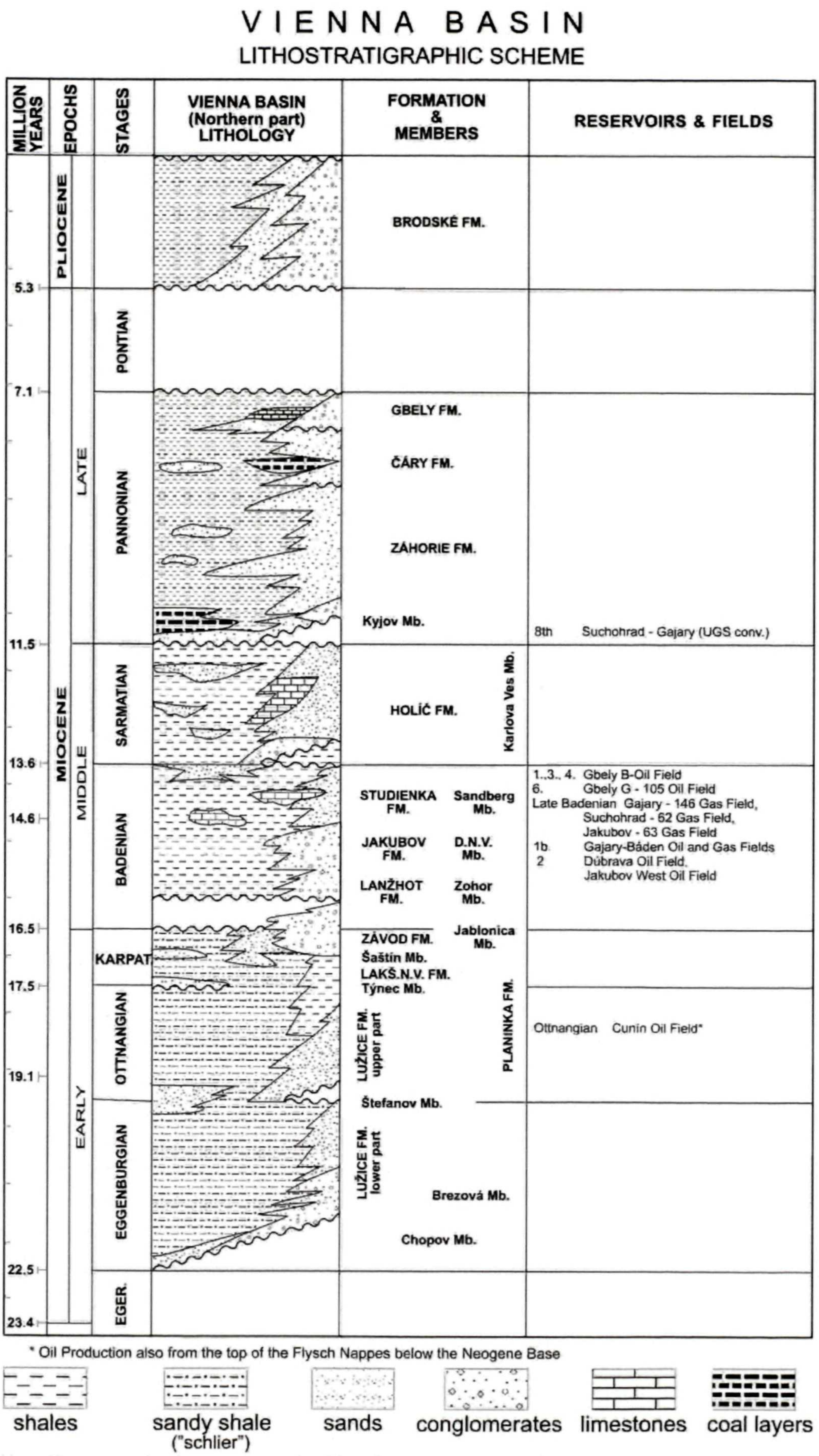



Fig. 3.1.1 The affiliation of hydrocarbon deposits in the lithostratigraphic sequence in the Vienna Basin

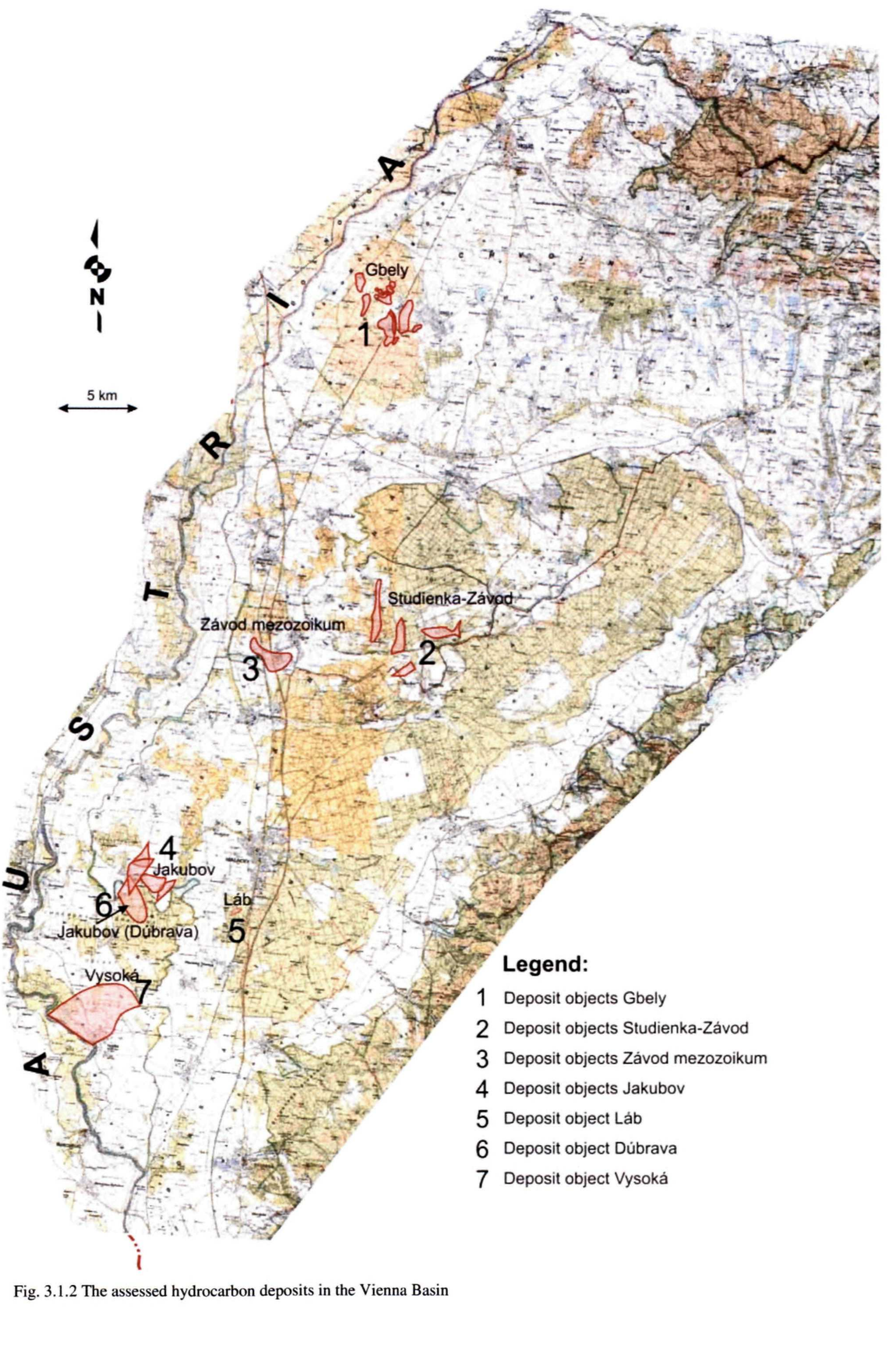



Fig. 3.1.2 The assessed hydrocarbon deposits in the Vienna Basin

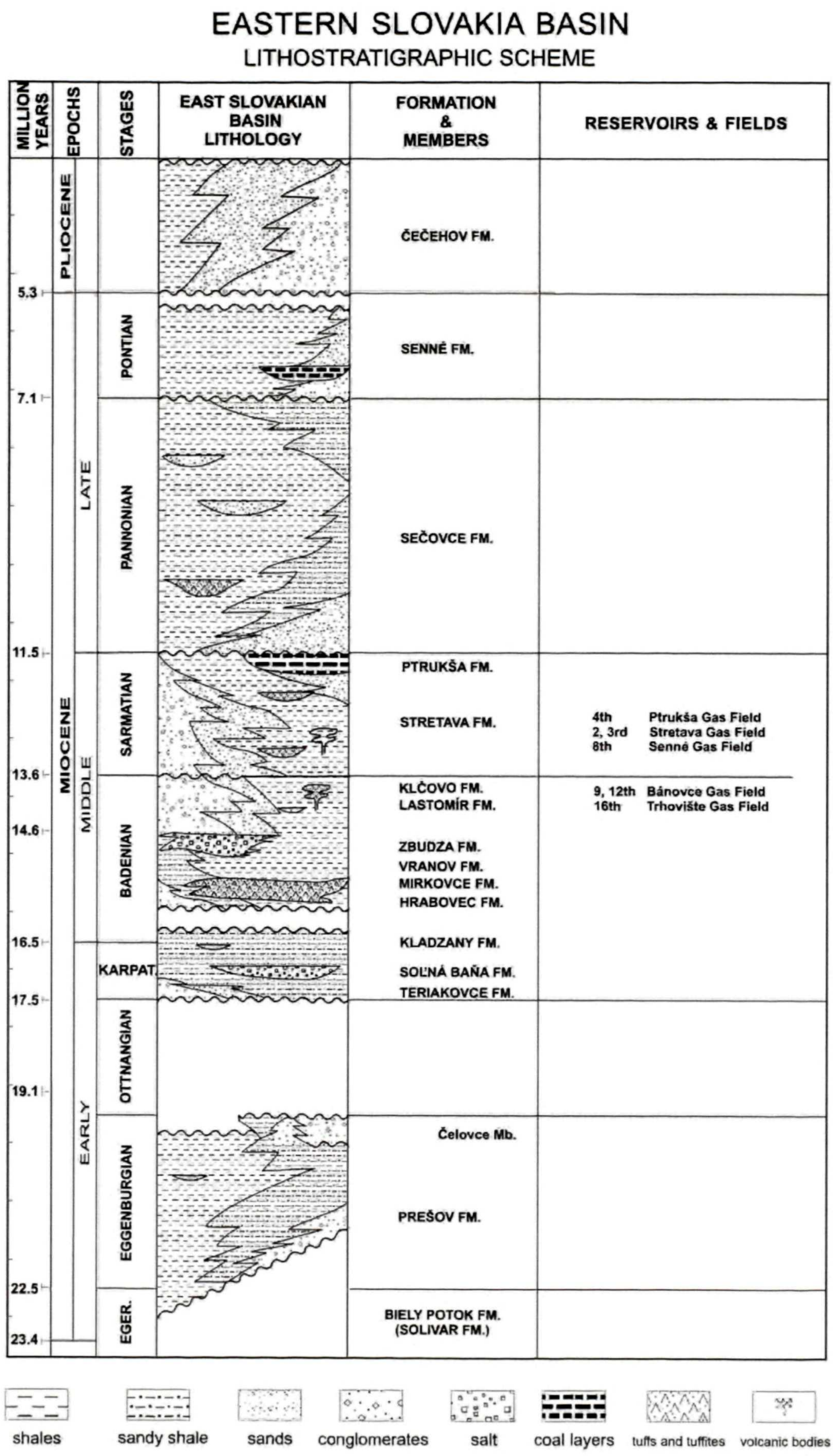
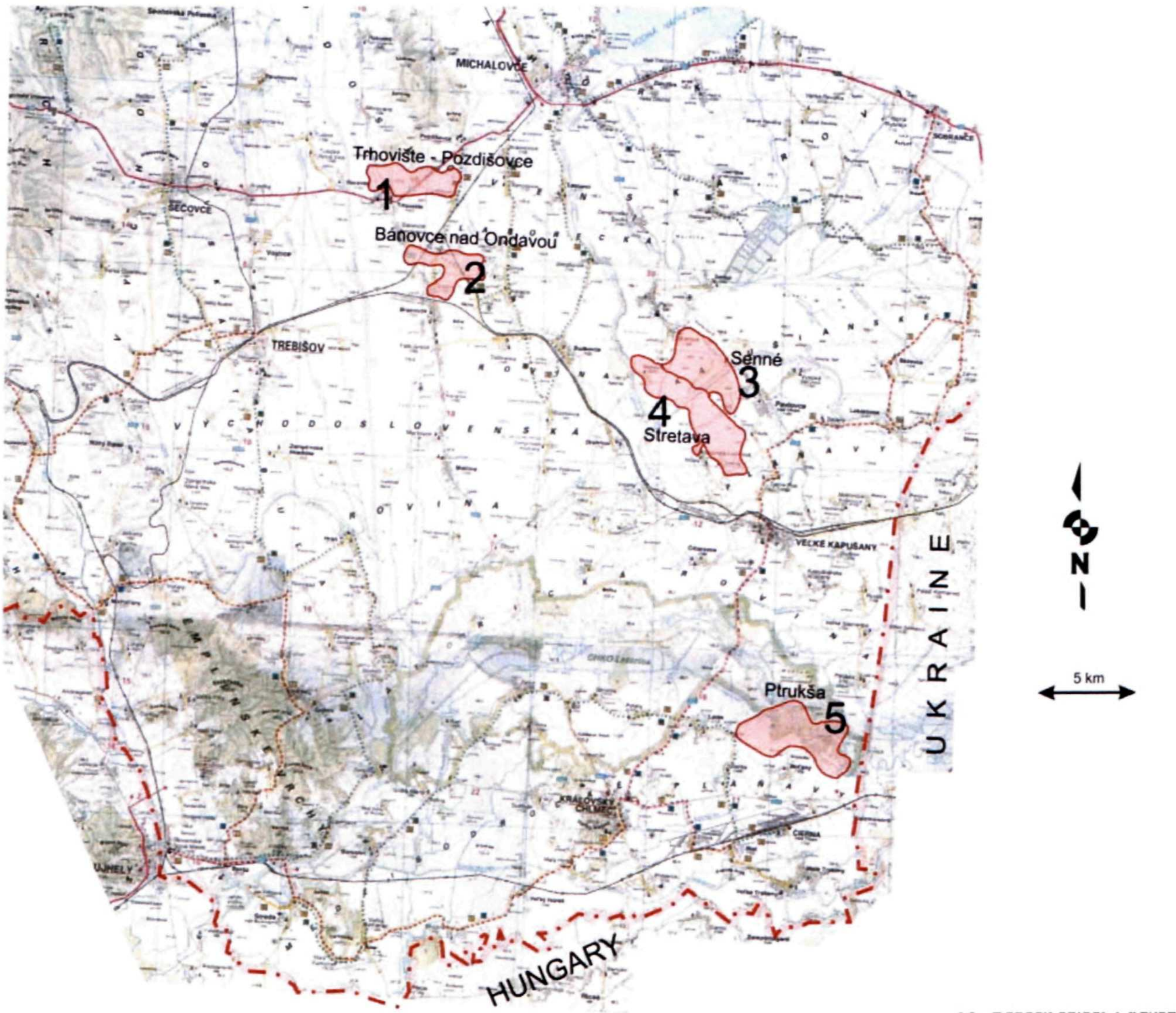



Fig. 3.1.3 The affiliation of hydrocarbon deposits in the lithostratigraphic sequence in the East-Slovakian Basin




**Legend:** 1 Deposit object Trhovište – Pozdišovce
2 Deposit object Bánovce nad Ondavou
3 Deposit object Senné
4 Deposit object Stratava
5 Deposit object Ptrukša

*Fig. 3.1.4 Assessed hydrocarbon deposits in the East-Slovakian Basin*

According to the result of the borehole Vysoká 4, in the Neogene basement the Hronicum dolomites are present what is the proof that the deposit elevation belongs to the longitudinal Láb- Lakšárska Nová Ves stripe of the NE direction. The Hronicum carbonates basement was met at a depth of 2,800 m.

The deposit is located at the stratigraphic range between Badenian – Pannonian and consists of twelve partial horizons. Mainly sandy strata are present with an average thickness of 5-10 m, some of them are lithologically divided into several hydrodynamic units. The exception is the main gas-bearing object – the base the Middle Badenian with a thickness of deltaic sedimentation products around 500 m. Its gas-saturated part reaches a thickness of nearly 60 m. The reservoir (collector) rock is cemented by fine-grained calcareous-clayey sand with intercalations of calcareous clays (Fig. 3.2.1).

In the course of mining an expansion regime prevailed with more or less limited influence of the water component activity (Hlavatý, 1994). This finding is at odds with the data from the Austrian side, where, by contrast, the aquifer was active, participating significantly in the deposit regime (Lorenc, 1968). By contrast, in the main Late Badenian horizon (E horizon) due to large cubage of the underlying water its activity was significant. Nevertheless, the rational management of mining achieved coefficient of exploitability against the planned one 0.7 up to 0.77. More than 97% of gas content was $CH_4$. The Badenian waters belong to alkali-haline, calcium-chloride type. Of the same character are also upperlying Sarmatian waters.

The calculation of the reserves from the 1960s (unauthorized) featured for basal Late Badenian horizon the reserves in the amount of 10 billion $m^3$ (not approved by

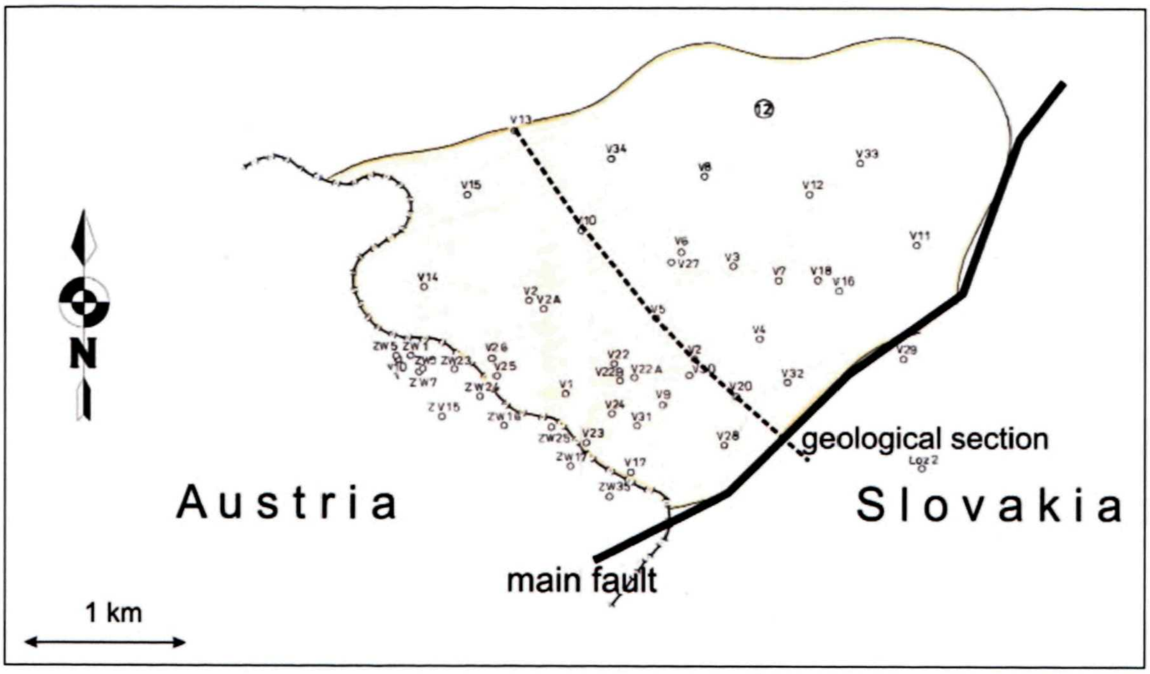



*Fig. 3.2.1 Vysoká, horizontal extension of "g"sand of Middle Badenian (base)*

CRC – Commission for Reserves Classification). Later on, the conversion of reserves in terms of the Decree No. 6/1992 Coll., was implemented, with the status of January 1, 1994 (Hlavatý, 1994). The reserves, which were originally presented in categories A, C1 and C2 have been downgraded to category Z-1, on the grounds that they were verified and depleted reserves and the geological setting of the deposit and its shape had already been solved. The deposit is currently depleted and water-saturated, from the Slovak balance of reserves remains 36 821 000 m$^3$ (36.8 million cubic meters) of gas in the main horizon of Middle Badenian. This gas is located in the highest positions of the deposit in the area of Zwerndorf Baumgarten on the Austrian territory and in the case of reservoir building it will find its use as "cushion gas". The amount of depleted reserves within the Slovak section is 3 billion m$^3$.

The main part of the deposit – basal horizon of Middle Badenian is a broad brachyanticline, of the southwest– northeast direction, which is almost not tectonically disrupted (Figure 3.2.2). The exception is the tectonic boundary to the southeast. This is a Láb fault system where a vertical throw in Sarmatian is 150-200 m with a slope of 45° to the southeast. There is also a tectonic restriction in the area of the state boundaries (drillings Vysoká 17, 23 and Zwerndorf 23), the vertical throw, however, is greater than the effective thickness of the gas-saturated layer. The elevation peak was detected by the boreholes Vysoká 1, 4, 20, 21, 22 and 25. Towards the East and the North the elevation is declining at an angle of 2°. The average depth of the contact gas/water was determined at 1,348.1 m. Since the launch of mining there has been observed a drop in the deposit pressure in the main part of the deposit. Accounting for this it has been deduced on the existence of gas (expansion) regime. According to Hlavatý (1994) the deposit consists currently of 12 blocks with non-balance reserves in the category of Z-1 - in total 3 008 billion m$^3$, of which the main horizon No. 12, of Middle Badenian base stores 2874681 million m$^3$ of gas, which represents virtually 95% of the entire deposit. (To this number there must be added the 37 million m$^3$ of balance reserves in the category Z-1 for the cushion gas in the block No. 12, which, in the case of the transformation into storage space, would be replaced by carbon dioxide). The annual consumption of gas in Slovakia is at the level of almost 6 billion m$^3$. This brings us to the conclusion that in the case of the transformation of the deposit into the $CO_2$ storage, we would be "theoretically" able to get the volume of gas through gradual $CO_2$ storage in the Main Middle Badenian horizon covering nearly 50% of the annual gas consumption of Slovakia.

The uppermost horizons 6$^{th}$ Pannonian and 8$^{th}$ Pannonian or 2$^{nd}$ and 4$^{th}$ Sarmatian are shallow-lying for the purposes of the carbon dioxide storage and therefore excluded from consideration due the impossibility of achieving its supercritical status.

The mean value of permeability in the deposit (the average from the laboratory measurements and sounding) was established at 108 mD. The value of the absolute permeability in such amount corresponds to the saturation of the residual water at the rate of 25%. The gas saturation coefficient can then be considered to be 75%, while maintaining the same deposit pressure. The porosity is set to a value of 26%.

The deposit pressures were calculated on the basis of static pressure measured at the mouths of boreholes. At the average depth of the basal horizon Middle Badenian of 1 455 m the average pressure was calculated at 12.3 MPa.

The deposit temperature was determined in accordance with the Austrian side to 64 °C.

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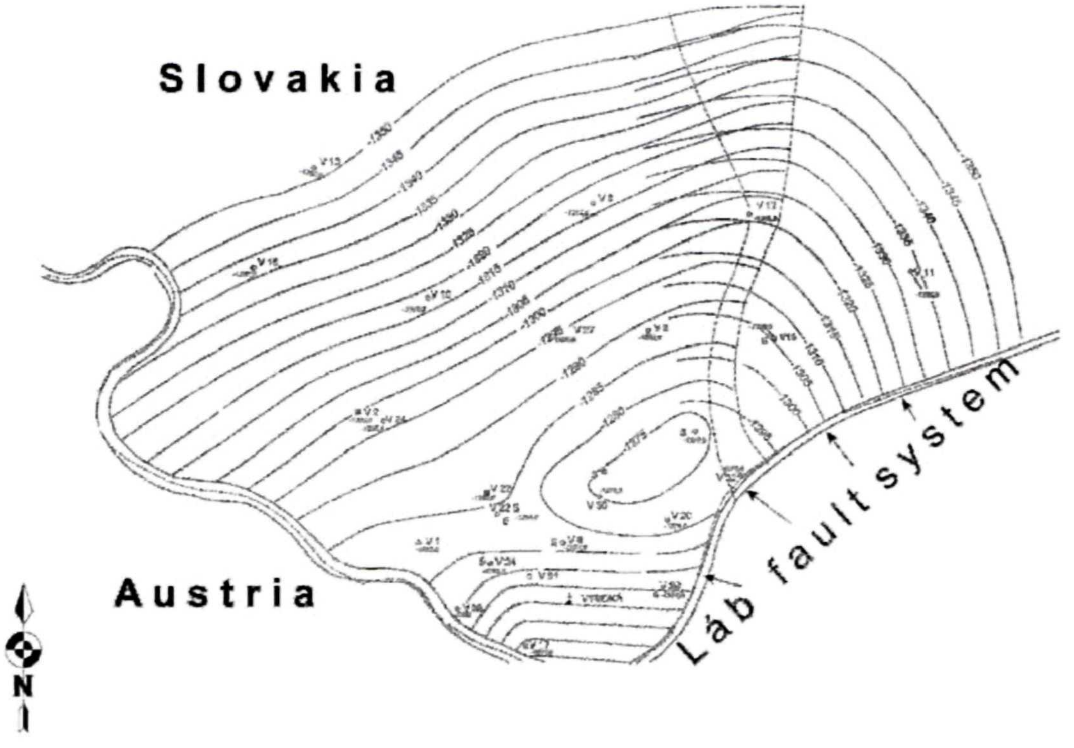


*Fig. 3.2.2 Dephts of the main productive horizon*

### *The issue of $CO_2$ storing in the deposit*

From the above it is evident that the deposit (under this term we mean the main deposit horizon - Middle Badenian base) fully meets the P and T criteria, in order to achieve the supercritical state (7.2 MPa, 31.1 °C) that are required for a structure suitable for the $CO_2$ storage. The safety in terms of the risk of leaks, according to the geological survey, is at the appropriate level, as well. (There were no leaks for a few million years until the deposit discovery).

In theory, in the cases of such hydrocarbon deposits, the premise is accepted that all extracted pore spaces containing gas and emptied due to mining will be replaced by carbon dioxide. This assumption is generally valid, if the reservoir is not in contact with the aquifers, or it is not flooded with water during the secondary or tertiary gas recovery. Another assumption is that the integrity of the roof sealing will be preserved, therefore the pressure of the $CO_2$ injected will not exceed the original deposit pressure. This estimate is conservative, because the pressure can exceed the capacity of the original pressure in such a long time on a temporary basis, which ensure that it does not exceed the limit of tensile cracks generation, or reactivation of existing faults (according to Bachu and Shaw, 2005). In this case, the storage capacity increases as a result of $CO_2$ compression and the possibility of obtaining more pores space. *Effective storage capacity* depends upon the *internal* reservoir characteristics, taking into account the the water invasion, extrusion, gravitation force, heterogeneity of a collector and the effects of water-saturation. *Practical storage capacity* is dependent on *external factors*, such as technological limitations, storage security, distance of the $CO_2$ producers, infrastructure, economic regime given by the legislation ... (Bachu and Shaw, 2005). From this point of view, we have to perceive the following "estimates" as indicative, because the number of factors is not possible to anticipate although modeling of a particular activity on the basis of reservoir engineering should be an integral part of the work. In any case, the calculated $CO_2$ storage capacity in this deposit can be regarded as the *effective storage capacity*.

The issue of aquifer in this case is one of the decisive factors. According to the data from the mining (Hlavatý, 1994) the aquifer influence in the main gas-bearing horizon at the base of Middle Badenian was not significant. However, the deposit has been flooded now (since 1972), so it will be necessary to count at any experiments with the opposite aspect. In such cases, for the ousting of all water and the achievement of the original aquifer reservoir volume, the $CO_2$ pressure will be significantly above the initial deposit pressure, what constitutes a risk factor. According to the above authors on the basis of statistics based on a study of thousands of gas horizons from the province of Alberta in Canada, in the case of "strong aquifers" – the ratio of the volume of water/gas $\geq 10$ is responsible for the reduction in the calculated capacity by an average of 30% in a deposit (range 0-48%). In the case of "weak aquifers" the ratio of water/gas $< 10$, the storage capacity reduction is virtually negligible; on average, about 3% (according to Bachu et al., 2004).

Among favourable factors we can certainly include the petrographic characteristics of the collector horizon. Its share of the calcareous component may in the case of storage activities in the optimal injection mode positively affect the increases of the effective storage capacity, especially in the longer term – application of the mineral sequestration and trapping, thus reducing the $CO_2$ pressure in the elevation part of the structure.

In the introduction of this chapter we have stated that 36.8 million $m^3$ of methane remains as a Slovak proportion at the Austrian side, which would in the case of the transformation of the deposit into the gas reservoir serve as cushion gas. It offers the opportunity to extract this gas here and its replacement by $CO_2$, which would act as a cushion, even if the deposit served as a reservoir of methane. The reservoir simulation of such methodology suggests that when using $CO_2$ as a cushion gas it is possible to increase the capacity of the methane up to 30%! (Oldenburg, 2003), provide the storage reservoir is in supercritical depths – as consequence of density changes. A critical element is a so-called mix zone between the methane and $CO_2$. Higher density and viscosity of carbon dioxide to methane should minimize this problem (Oldenburg, et al., 2001). Similar considerations appeared already in the territory of Slovakia, when was deliberated using of natural $CO_2$ gas deposits Sereď as cushion gas for deposits Veľké Kostoľany and Ivánka pri Nitre in the Podunajská nížina Lowland (Hrúziková, et al., 2006).

If we add to these considerations the capacity issue, so according to the above authors we have in the Slovak part a space from which it was extracted 3 billion $m^3$ of gas, and where it remains the same amount, that is 3 billion cubic meters of gas still not extracted in the underground (just to illustrate in the year 2010 in the District Mining Authority Bratislava area 65.746 million $m^3$ gas were extracted). The total volume of 6 billion $m^3$ of gas (volume at the surface) transformed through the density and the formation factor corresponds to the imposition of 11.7 million tonnes of $CO_2$. In doing so, we are still remaining in the area, which was, or is occupied by the gas. Logically, the original deposit space must be increased on the volume of the water aquifer, because the maximum thickness of the reservoir horizon is 500 m, the gas-bearing has or had been about 60 m prior to the start of the mining operation. It is obvious that the maximum values cannot be accounted for; it is possible to calculate the exact volume of aquifer according to drillings – but to the resulting storage capacity, which is not theoretical, but in the sense of the pyramid effective. We can add almost the same amount of storage in the aquifer that is several times thicker than the gas-bearing zone. In this approach, it is fair to count with a capacity of 25 million tonnes of $CO_2$, which satisfies the attributes of the repository of industrial character.

It should be stressed that even the water of the aquifer is interesting on the basis of analyses of pumping tests conducted by ČND Hodonín. The following considerations can be deduced from them:

The chemical composition of the water is quite monotonous, the water corresponds to the natrium-chloride type. S1 component (Cl) in the Badenian collectors environment ranges in the interval of 94.0-95.0 mval %. The second most abundant component is $Na\text{-}HCO_3$ (natrium-hydrogen-carbonate), which takes the value of 3.2-4.6 mval %, indicating the minimum impact of infiltration degradation in the geological past, as well as the presence from the hydrogeochemical point of view. This factor is also a very important *positive* contribution to the security characteristics of the repository from the perspective of potential losses, suggesting that the structure is likely to be well sealed.

From the genesis point of view the water is of marine origin, in other words, the original marine waters of the Badenian transgression, which were metamorphosed to a minimum in the water-rock system. This is indicated also by the value of total mineralization, which is moving in the range of 25-35 $g.l^{-1}$ and essentially correspondd to the Badenian palaeosalinity. The hydrogeochemical closeness of the structure testify the values of the coefficient of $HCO_3/Cl$, ranging from 0.008 to 0.018. The waters show significantly increased content of iodine and bromine, so they can be considered as iodine – bromine waters with healing effects on the human body. At present, in Slovakia natural healing water of this kind are very rare, it is exploited only in Číž Spa (source of Hygiea has a very small yield) and there are plans to use waters of similar composition in Oravská Polhora.

The content of iodine in groundwater in the structure Vysoká has a values range of 10-26 of $mg.l^{-1}$ (both in the main deposit, as well as the overlying Sarmatian horizons) which far exceeds the minimum concentration of 1 $mg.l^{-1}$ iodine ion, required by Decree No. 100/2006. For balneological use of these water bodies it is also very convenient, that they can be applied to the drinking treatments, because they do not contain substances of so-called petroleum origin, which give the water unpleasant sensory properties. An open question remains quantities of water and yield of wells in this structure, since information is missing. From this point of view, it would be necessary to carry out the calculation of these quantities and to determine iodine and bromine contents, because in addition to the balneological purposes they could serve as raw material in the pharmaceutical industry and for the protection of the environment, as a catalyst and a disinfectant (Io). The yield should be determined by the intensity of $CO_2$ injection. It follows that potentially it could be assessed besides the economic considerations of reserves calculation also with the value added of this requested raw material.

Another positive is the fact that this could be the repository with the EGR application (Enhanced Gas Recovery), thus a higher contribution to the energy base of Slovakia and an undeniable economic benefit for the company, which would implement this activity. Assuming the imposition of around 1 million t/year of $CO_2$, in the calculated capacity assumes a minimum lifetime of storage of about 25 years. Currently the world's largest volume is being stored in the deposit Weiburn, Canada – about 2.5 million t/a, which is associated with EOR - Enhanced Oil Recovery. In other cases, an average of 0.7-1 million tonnes of $CO_2$ is stored.

However, it should be noted that this activity requires negotiating with the Austrian partner. To illustrate, that only reserves in the Austrian part of the deposit (16 bil-

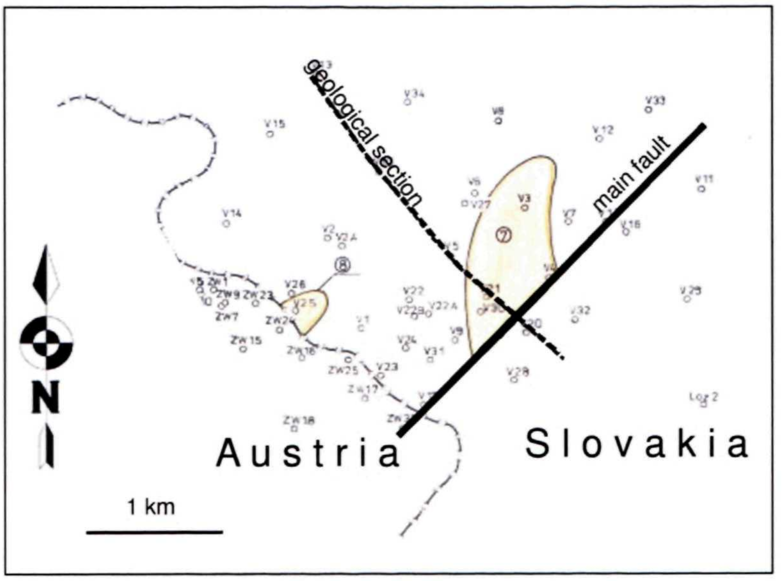


Fig. 3.2.3 Vysoká, extent of Sarmatian 7

lion m$^3$) is this space suitable for the storage of approximately 30 million tonnes of $CO_2$ (not accounting for thevolumes in aquifer). Through simple sum up, we get to the efficient capacities of the entire deposit (Austrian and Slovak parts) excessing 50 million tonnes – and this does not need further comment.

### *Alternative interim proposal for a pilot project*

The issue of additional extraction of hydrocarbon deposits utilizing pressurized carbon dioxide emerged due to purely economic reasons in the 50ties in USA, where the greenhouse gas issue was discussed limited to scientific milieu. This issue was also solved in that time ČSSR, when it was suggested to utilise $CO_2$ from its natural deposit Sereď in order to carry out additional extraction of the deposits in the Vienna Basin (Juránek, et al. 1968).

According to the survey work only the main gas horizon – base of the Late Badenian (Higher Upper Badenian) and "e horizon" extend to the territory of the Republic of Austria. For the purposes of the pilot project could suit block No 7, marked as 7$^{th}$ Sarmatian horizon that is detected only in the territory of Slovakia (isolated lens) by boreholes V-3, 4, 31 and 30. Boreholes V-5, 7, 9 reached the horizon, but they were negative due to the transition into marls. As this horizon does not extend to the territory of the neighboring state, in theory it could serve for the purpose. Although the horizon is quite inhomogeneous from the viewpoint of the facies, nevertheless such a horizon could be representative of the typical "Western Carpathian" collector horizon (Figure 3.2.3).

The gas-bearing interval is at depths 831 – 869 m below the surface, the effective thickness of the collector layer is 3.8 m. Porosity coefficient should be around 20% (on the basis of data from the 6$^{th}$ Láb horizon), the average pressure is 8.4 MPa, temperature is not stated, but according to an extrapolation from the Main horizon, as well as according to the Atlas of geothermal energy (Franko, et al., 1995), at a depth of 1,000 m below the surface temperature should be over 45 °C.

The above parameters ensure supercritical status of $CO_2$ requested for appropriate storage.

Estimated productive area is 635,000 m$^2$, cubature 2,413,000 m$^3$. On the basis of reclassification in the block are calculated nonbalance reserves in the category Z1 attaining the volume of 6,030,000 m$^3$ of gas (Hlavatý, 1994) that represents a "coarse value" of approximately 1.8 million €. If we apply the volumetric principle of calculating the capacity of $CO_2$ storage, which is the coefficient of volume, gas density and formation factor, so we get the storage capacity in the range of 3,000 to 30,000 t of $CO_2$. Such amount would be sufficient for the pilot project, moreover, useful information could be obtained for Enhanced Gas Recovery. According to the formula for the aquifers we got negligibly higher value – almost 34 000 tons. It is necessary to consider the effect of aquifer on the above numbers. Gas reserves totaled in the 7$^{th}$ Sarmatian term horizon are not great, but for a small recipient in the vicinity of kind of interest, since the gas contains more than 97% methane. In such a case it would mean the EGR (Enhanced Gas Recovery), so it is realistic to expect a higher yield than calculated reserves. This would be in addition to the undeniably necessary knowledge about the study site, relevant for decision-making criteria (state, the company concerned) in the context of the "political development" in the field of combating the adverse effects of climate change, as well as achieving a certain "economic benefit" in the form of a reduction in the cost of the project.

A very valuable factor from the geological and economic point of view is the fact that the deposit offers unique opportunity to test the pilot stage of carbon dioxide injection into the depths very favourable from both of the above considerations. In the case of a positive result of the pilot stage, it would be possible without moving the infrastructure, only through its extension, to continue in the same place by developing activities to industrial scale, provided an agreement with the Austrian party will be settled. On the Austrian side in the vicinity are also big producers of $CO_2$ – ÖMV Vienna, industrial companies and Vienna Heating, on the Slovak side Slovnaft, Bratislava, Paroplynový cyklus Bratislava, Calmit Rohožník (Figure 3.2.5).

In addition, here plays a very important role the safety factor of the potential repository. The Láb fault system, or one of its faults, that in the present situation seems to be in theory as a risk factor of potential losses, is common to both Sarmatian and the Badenian horizons, so it is possible in the pilot stage to test, in particular, potential vulnerabilities, valid for the industrial plan, which is very valuable. Both reservoir horizons are amputated by the fault; continuation of the gas-bearing positions towards the Southeast was not detected (Figure 3.2.4). Sponta-

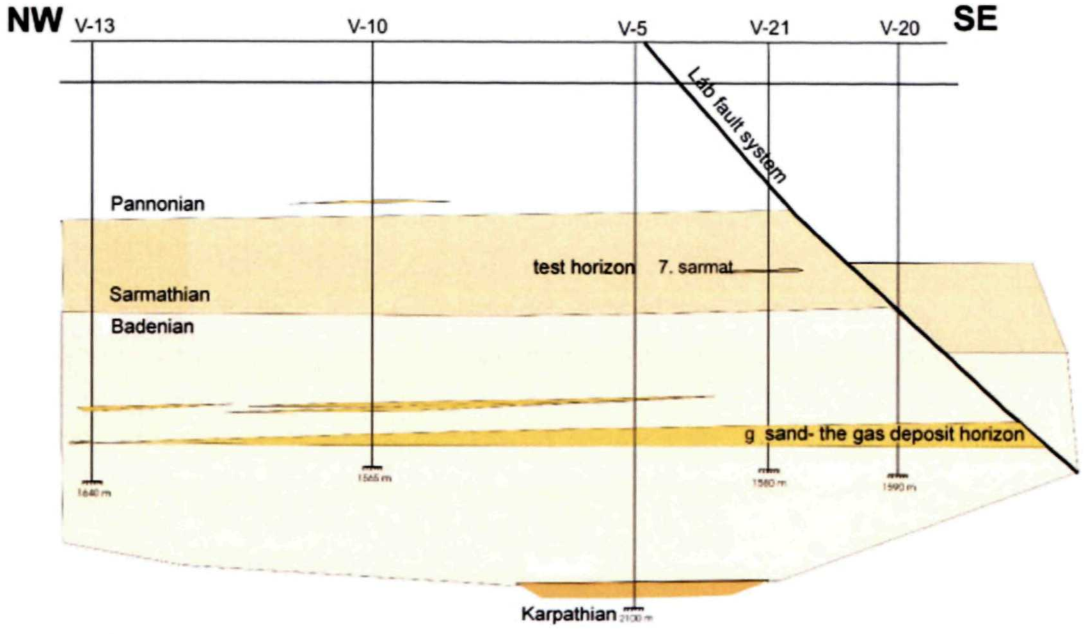


*Fig. 3.2.4 Vysoká, geological cross-section through productive horizons*


*Fig. 3.2.5 The situation of the large deposit Vysoká- gas reserves volume and complexity in terms of share between two states the deposit Vysoká-Zwerndorf, despite the gradual retreat of mining offers numerous alternatives for its economic and ecological use in the next few years.*

neous leaks of natural gas that is enclosed in natural trap were not confirmed for few million years ago. Therefore, by substantiated pressurising of collector horizons (the injection pressures shall not exceed significantly the original deposit pressures) it is possible to ensure the hermetic sealing of the reservoir space. In support of this conclusion is that the nature of the faults concluding the structural trap in Middle Badenian has usually good sealing factor, as it is for example, at the deposits in the Podunajská nížina Lowland - Sereď (Majcichov fault) and Cífer (Cífer fault), Cífer (Gaža, 1994, 1994a).

***Summary***

It is natural and understandable, that any intent, especially one that is oriented into new, non-routine methodologies has its strengths and weaknesses. In the present stage of knowledge, we can present the following:

***Problems:***

Agreement with ÕMV; the Austrian party would have to agree with the above activities – the need for a study of the Treaty, in particular in terms of cooperation and a time limitation. The Treaty applies only to the Main Middle Badenian horizon and "E" horizon. The above structural blocks are irrelevant regarding methane reserves.

The state of the old boreholes as a purpose built for the injection and monitoring, as well as the potential risk of possible escape routes. It is possible that after 50 years the technical state of the boreholes will not allow to utilise them, on the other hand they can be dangerous as a potential escape route from the $CO_2$ repository.

The attitude of the public in the case of consideration of the industrial $CO_2$ repository. Reservoirs of methane are not such a thorn in the flesh of non-governmental organisations and the public, because they belong to the normal civilisation "background".

If positive results of the pilot stage and move into the industrial variant will be reached it would have to be carried out a set of diffuse injection wells, in order to achieve the maximum yield of the gas, which would increase the costs of the project.

Low price of permits area about 4 €/t $CO_2$.

***Benefits:***

The pilot-stage 7$^{th}$ Sarmatian horizon does not apply to Interstate Treaty – it is present only in Slovakia.

Similarly, the new act on underground $CO_2$ storage does not apply to the pilot stage.

In the case of the pilot stage – 7$^{th}$ Sarmatian horizon the collector is 830-870 m deep below the surface, which already guarantees supercritical state of gas and at the same time it reduces economic demands on drilling depths (theoretical depth to achieve supercritical state is 800 m). In the first pilot stage one injection and two monitoring wells would be sufficient.

In the case of the implementation of the pilot project opens up the possibility of additional extraction of residual reserves in this block, which creates "certain" financial counterweight to the projected cost.

Not a very large depth of the boreholes of the main deposit horizon "**g sand**" (up to 1,500 m) in the case where it is not possible to use - recover old drillings.

The appropriate petrographic composition of the collector - increased proportion of carbonate components, which represents the application of the residual trapping, dissolution trapping, as well as mineral sequestration, which is suitable for the long term safety of the repository, as the pressure upon uperlying complexes is reduced – $CO_2$ sinks to the bottom of a reservoir, or it binds to the carbonates.

Favourable chemical composition of aquifer water of natrium-chloride type with high contents of iodides. These are **scarce and sought after** for balneologic use. After the calculation of the reserves it could be considered iodine and bromine exploitation from the aquifer, as exclusive mineral resources.

Due to the fact that the deposit has been **well geologically sealed** in its roof; tectonic faults are found only on the SE limitation (Láb system, which has a sealing effect), the risk of natural leakage from the reservoir is reduced, provided the **original deposit pressure would not be significantly exceeded**.

Close source of $CO_2$ (large point sources - Slovnaft 2.5 million t/year, Rohožník – Calmit 1 million t/year, Paroplynový cyklus 0.7 million t/year), all within a radius of 20-40 km. This is in addition raised by railway Zohor – Záhorská Ves passing through the territory of the deposit and offers convenient means of transport for the pilot stage (the parameters of the line speed 60km/h, max. train length 290 m – about 20 standard tanks, 1 suite).

Provided the pilot project will be tested successfully, the possibility of a continuous transition to the deeper main deposit horizon (**g sand**), without replacing the kits and the infrastructure to another location, which is **economically beneficial**.

In this case, the application of geological-deposit-technical knowledge in the pilot project, implemented at the same site to the industrial stage, greatly affects the reliability of the solutions from the professional point of view.

In the event of a decision not to proceed after the pilot phase to the industrial phase, lessons learned from this deposit will be applied to other places in the Vienna and the Danube basins, as well as in the Transcarpathian Basin, eventually.

Global trends in gas prices increase, which after the termination of the pilot stage (5-6 years) may be at a much higher level in comparison with the present, which is related to the deposit reserves extraction with conjoint $CO_2$ storage.

When engaging the Austrian side in addressing a potential increase in storage capacity, as well as to create better opportunities for the financing of the project from trans-national funds.

The **transformation** of the dominant part of the deposit - Middle Badenian base 12$^{th}$ block – **to gas repository UGSF** – the deposit contains methane reserves (3 billion cubic meters) serving as cushion gas. About the same amount had been already extracted. This would be probably the biggest gas reservoir on our territory. The alternative would be the Late Badenian "E" horizon, where, however, the capacity is many times less ($12^{th}$ block - g sand -represents 95% of the total reserves). However, considerable economically usable capacity of the gas would remain tied up in the deposit. Of course, we are considering only at the theoretical level, since there are already plans for the UGSF in the Danube Basin (Križovany nad Dudváhom and Cífer).

**To extract remaining reserves of methane (cushion) in the main deposit and replace it by $CO_2$**, which would serve as cushion instead of methane. In addition, the amount of $CO_2$ injection would serve as a medium for pushing out the residual reserves, which could lead to higher capitalization of the deposit. There should be made the decision, how much gas we want to extract; this determines the volume of $CO_2$ injected. In this case, we are moving in the range of: UGSF (methane) with dynamic exchange system according to designed capacity – static $CO_2$ storage, provided the theoretical amount (3 billion $m^3$) of all reserves of natural gas extracted, which are classified as the non-balance ones. Practical use of EGR technology (Enhanced Gas Recovery) has not been sufficiently tested, yet.

**To use the $7^{th}$ Sarmatian horizon as the study one on the basis of the development of the deposit as a pilot project** (in terms of time due to possible sources of funding to date.) The gas-bearing interval is at depths 831-869 m below the surface, the effective thickness of the collector is 3.8 m. In the course of the carbon dioxide injecting, in addition to the study of the behaviour of the deposit – technical parameters, the residual reserves of natural gas would be exploited at the same time (approximately 6 million cubic meters), which would shift the pilot project to economically more favourable relations and it would be a positive impulse for a project proposal. This would actually test out the EGS methodology (Enhanced Gas Recovery) for the first time on the territory of Slovakia and clarify behavior of all relevant parameters, ensuring a secure and permanent $CO_2$ storage.

Provided the *positive results* are obtained, the pilot phase could be transformed without excessive costs and time intensive transfers to another site, into the industrial phase of deepening and increasing the number of injection and monitoring wells, and with a maximum advantage of specific, targeted knowledge gained at this stage. In the case of *rejection* of the implementation of the industrial repository at this site, the lessons learned can be applied to other, mostly Neogene structures (Vienna, Danube and Transcarpathian Basins) selected for this purpose, because the issue of $CO_2$ storage is one of the main directions of EU policy in the fight against the adverse effects of climate change.

From the above findings the extraction of aquifer waters is realistic, which have significantly increased concentrations of iodine and bromine in the horizons. The waters of this type are in demand in balneology; the chemical elements can be applied in the pharmaceutical, chemical and energy industries. This fact certainly enhances the economic attractiveness of the proposed activities. For this purpose it is necessary to carry out the calculation of the aquifer reserves and the calculation of the amounts of iodine and bromine, respectively.