ENOS D6.7 | March 2020

D6.7 Report: Towards a strategic development plan for CO_2-EOR in the Vienna Basin

Date 27.03.2020

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Number of pages	93
Number of appendices	0
Project name	ENOS
Project website	http://www.enos-project.eu
Project number	Grant Agreement No 653718

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653718

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Executive Summary

Within the framework of the H2020 ENOS project an assessment of the CO_2 enhanced oil recovery (EOR) potential of the oil fields of the Vienna Basin was conducted. Earlier studies have been completed on the use of various techniques to maximize the production of individual mature oil fields in the Vienna Basin, spread across Austria, the Czech Republic, and Slovakia. Data on oil field properties, collected from both national geological surveys and oil companies, were analysed using a bespoke model in order to derive potential incremental recovery rates based on CO_2 injection. The potential additional recoverable amounts are monetized in order to provide insights on the economic feasibility of the activity. Furthermore, in order to approximate the environmental benefits of the activity, the total amount of CO_2 that could be stored in the activity is also provided.

In order to provide the foundations for a strategic development plan for the region, this study provides the first overview of the relevant geological, operational, economic and organizational aspects of CO_2-EOR and CO_2 storage in the Vienna Basin. In addition to the analysis of the incremental recovery rates due to CO_2-EOR in the oil fields of the Vienna Basin, an inventory is made of industrial CO_2 sources within 70 km of the oil field clusters, and pipeline routes connecting selected sources with sinks are proposed. This process has resulted in the development of two case studies, one in Austria and one in the Czech Republic. Furthermore, a stakeholder analysis and detailed regulatory assessment of CO_2-EOR and CCS in the three countries of the Vienna Basin are made.

All the three countries of the Vienna Basin have potential for both CO_2-EOR and CO_2 storage. By far the greatest potential for both EOR and CO_2 storage can be found in the Austrian part of the Vienna Basin, in the large Matzen cluster. For the entire basin, the theoretical incremental recovery of additional oil due to CO_2 injection has been calculated as of 21 million Sm^3 (130 million barrels), which, using the current (February, 2020) oil price of 40 USD per barrel of oil represents (if produced) a gross value of 5,200 million USD. The amount of CO_2 that would be needed to perform the related CO_2-EOR operations and thereafter stored in the depleted fields is estimated to nearly 140 million tonnes. Therefore, from this initial analysis, at least from a theoretical perspective, the potential for CO_2-EOR combined with CO_2 storage warrants further investigation.

Despite this theoretical potential, there are a number of technical, regulatory and economic aspects that need to be highlighted. Some of these challenges are specific to the region, others are applicable to all CCS and CO_2-EOR projects. Regarding EOR, there are some technical questions regarding the ability to achieve fully miscible CO_2 flooding conditions in the fields of the Vienna Basin, which is considered most favourable for maximum enhanced oil recovery. The presence of many legacy wells across many of the fields can lead to risk management issues that have to be dealt with during permitting. Regarding CO_2 capture, there are few sources of potentially ‘low-cost’ CO_2 in the region. The bulk of the emissions are either from oil refineries or cements plants, which are generally considered to have high CO_2 capture costs.

From a regulatory point of view, although CO_2-EOR as an industrial activity, and in combination with CO_2 storage, is fully legal within EU legislations, there are a few country-specific challenges. A key showstopper is the current prohibition of CO_2 storage in Austria. Furthermore, there is little experience in regulating the combined activities of CO_2-EOR and CO_2 storage under the EU CCS Directive.

In order to take the concept of CO_2-EOR and CO_2 storage in the Vienna Basin further, it is recommended to raise awareness amongst public and private stakeholders regarding the economic and environmental benefits of this concept. By advancing the two case studies developed within this analysis, using site-specific data, a better understanding of the technical and financial aspects of potential projects can be developed. Finally it is recommended to evaluate the suitability of European policy support mechanisms to bridge the current financing gap between the cost of CCS and the incentives given by the EU Emission Trading Scheme.

1 Introduction

Leading from the exploratory work completed for the Czech LBr-1 CO_2-EOR pilot site, this deliverable conducts an assessment of the CO_2-EOR potential of the oil fields of the Vienna Basin. Earlier studies have been completed on the use of various techniques to maximize the production of individual mature oil fields in the Vienna Basin, spread across Austria, the Czech Republic, and Slovakia. Information has been published within European projects (Šliaupa 2013, EU GeoCapacity 2008), and by commercial parties (Potsch 2004). From this information it is clear that potential exists for enhancing oil recovery in the region through CO_2 injection, however commercial projects have yet to take place. A strategic, regional dialogue involving both emitters, potential storage operators and governing bodies on the potential for CO_2-EOR and storage synergies can have considerable value for understanding the barriers and drivers for moving this concept forward.

1.1 Objective

The objective of this study is to explore the potential drivers and barriers to the development of CO_2-EOR in the Vienna Basin region of Austria, the Czech Republic, and Slovakia. Data on oil field properties, collected from both national geological surveys and oil companies, is analysed using a bespoke model in order to derive potential incremental recovery rates based on CO_2 injection. The potential additional recoverable amounts are monetized in order to provide insights on the economic feasibility of the activity. Furthermore, in order to approximate the environmental benefits of the activity, the total amount of CO_2 that could be stored in the activity is also provided. To provide a picture of the economic feasibility, the cost of capturing CO_2 from existing point sources, and the costs of building CO_2 pipelines are reviewed.

1.2 Approach

In order to provide the foundations for a strategic development plan for the region, this deliverable provides the first overview of the relevant geological, operational, economic and organizational aspects related to the realization of a strategic development plan. This approach includes a number of steps:, which are treated in Chapters 2 to 7 of this report, respectively:

1. **Collection of background information on the geology of the Vienna Basin and its suitability for CO_2-EOR**

   This section uses existing literature to provide a background on the geology of the area, including an overview of existing oil production activities and trends in production rates. Information has been gathered from the project partners – the national Geological Surveys of Austria (GBA), the Czech Republic (CGS) and Slovakia (SGIDS).

2. **Stakeholder mapping and assessment of regional industries and organizations that can play a role in the strategic development plan**

   An important part of the regional plan will be to provide recommendations to relevant stakeholders in the region. These stakeholders will be primarily investors, such as oil companies, gas transport companies and CO_2 emitters, but also governments and regional development organisations who may have an interest in the economic and environmental benefits that CO_2-EOR could provide.

3 Screening of oil fields for CO_2-EOR potential using a conceptual numerical simulation model

Using data collected in step 1, a conceptual numerical simulation model, developed by NORCE was used to screen a large number of oil fields in the Vienna Basin region in order to identify sites which are particularly suitable for CO_2-EOR. Key parameters including field depth, permeability, pressure depletion, original oil in place and the oil zone thickness were used to estimate the potential additional recovery factors.

4 Quick-scan of CO_2 point sources in the region of potential EOR sites

In order to be able to construct possible regional CO_2-EOR projects, potential CO_2 sources are identified and examined. Data from national emissions inventories were gathered, and the sources were assessed for their suitability for CO_2 capture. Here the type of energy production/industrial process, the amount of CO_2 emitted and inclusion in the EU Emissions Trading Scheme were important aspects.

5 Completing a regional source-sink matching exercise to identify possible business-cases

Data gathered from steps 3 and 4 were incorporated into GIS mapping software in order to facilitate regional source-sink matching, as the basis for potential business-case identification. The CO_2 sources, potential EOR-sites and transport routes are described. Suggestions for potential business cases are highlighted.

6 Identification of regulatory, technical and conflicting interest challenges to be addressed in a strategic development plan for EOR in the Vienna Basin

This section provides the key findings of this exercise, and where appropriate, provides recommendations to address challenges for CO_2-EOR but also CO_2 storage activities in the region.

2 Geology and hydrocarbon fields of the Vienna Basin

2.1 General geological description and evolution of the Vienna Basin

2.1.1 Introduction

The Vienna Basin (VB) is a NW promontory of the Pannonian Basin System (PB). It has several features, which make it a very unique basin described in the textbooks by well-known scientists. The VB is situated in Austria, Czech Republic and Slovakia and has a rich petroleum exploration and production history starting in the early 20th century. The VB is a SW-NE oriented rhomboid shaped body, ca. 200 km long and 55 to 60 km broad (Figure 1) in the contact zone of the Bohemian Massif, the Eastern Alps and the West Carpathians. The evolution is closely associated with the final phase of Alpine-Carpathian thrusting during the Miocene.

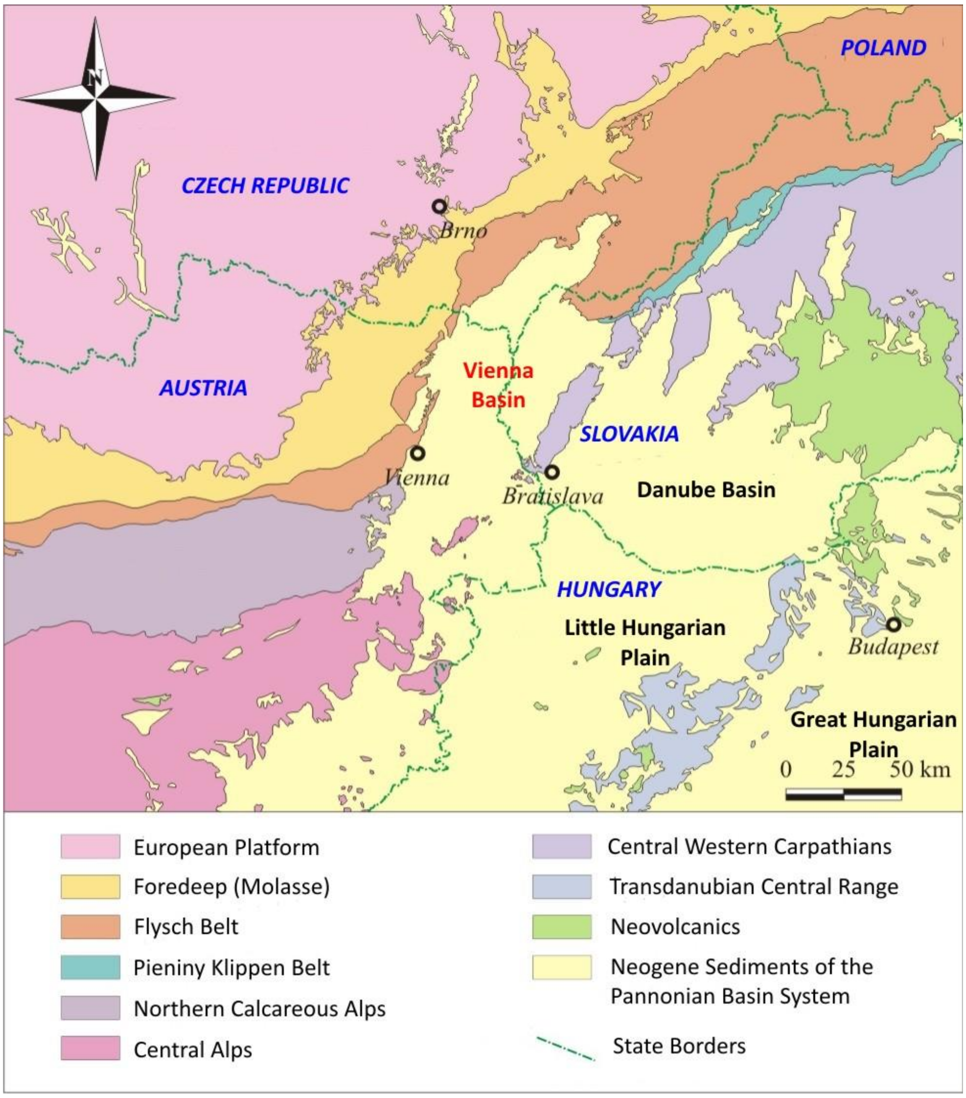

Figure 1. Location of the Vienna Basin within the Alpine-Carpathian thrust belt (Prochác et al. 2012).

The remaining hydrocarbon potential of the VB is rather low due to the long production history based on high level exploration in all three countries. Yet, there are still unexplored hydrocarbon reserves in lithological traps in Lower Miocene and in pre-Neogene units. Most of the known oil and gas fields are either exploited and abandoned, or in the final phase of production. A number of fields with sufficient capacity and good petrophysical properties, such as porosity and permeability, have been converted to underground gas storages. The high number of abandoned oil-and-gas fields provides an opportunity for application of enhanced oil recovery techniques using CO_2 followed by CO_2 storage.

2.1.2 Basin formation and evolution stages

The Vienna Basin formed during the late phase of Alpine-Carpathian thrusting and collision with the North-European platform associated with growth of an accretion prism in the orogenic front built by the nappe units of the Outer and Inner West Carpathians and Eastern Alps (Figure 2). During the past 60 years, geologists working in the area of the VB collected a large piece of information on the detailed internal structure and developed geodynamic concepts describing the basin evolution (for review see Buday & Cícha 1967; Jiricek & Seifert 1990; Wessely 1993; Arzmüller et al. 2006).

Royden et al. (1983) and Royden (1985) introduced a new concept of two phases of geodynamic evolution of the VB. During the first phase the “piggyback” basin was carried on thrust sheets approaching the Bohemian Massif. The Vienna Basin Alpine “Molasse Zone” and the Carpathian Foredeep formed a continuous depositional space by that time. At the end of the Karpatian age (ca. 16.5 Ma), the Alpine and Carpathian nappes collided with the Bohemian Massif and a new stress field formed associated with uplift in the North and subsidence in the South and generation of angle discordance of Karpatian/Badenian strata boundary (Figure 3). The obvious rhombohedral shape of the Vienna Basin, the left-stepping pattern of en-echelon faults within the basin, and the southward migration of basin extension through time strongly suggest that this basin is a pull-apart feature formed during middle Miocene left slip along a northeast-trending fault system. The papers by Royden were revolutionary and serve as a model for interpretation of numerous sedimentary basins world-wide. Geologists in Austria, the Czech Republic and Slovakia further developed the understanding of basin evolution, for review see Kováč et al. (1993), Lankreijer et al. (1995) and Arzmüller et al. (2006).

Reflection seismic lines show that the autochthonous European-plate basement continues beneath the allochthonous Carpathian nappes and beneath the Vienna Basin, and that in general the European plate is not significantly disrupted by the normal faults that bound the basin. Thus both the normal faults and the associated strike-slip faults appear to merge into a gently southeast-dipping detachment at depth. In this way, extension of the Vienna Basin appears to have been restricted mainly to shallow crustal levels above that detachment (that is, restricted mainly to the allochthonous nappes of the Carpathians). Detailed analyses of subsidence and heat-flow data indicate that little or no heating of the lithosphere occurred during extension of the Vienna Basin, and support the interpretation that extension was confined to shallow crustal levels. This interpretation explains why hydrocarbons mature at much greater depths in the Vienna Basin (>5 km) than in the neighbouring Pannonian Basin (Ladwein 1986; Franců et al. 1996).

There are several phenomena which make the VB different from typical “pull-apart” basins:

- the “thin-skinned” VB subsidence was controlled by relatively shallow faults;
- low heat flow density appears in most of the VB;
- there are no volcanic centres in the VB;
- in the pre-Neogene basin substratum there are no exotic units, only those known from the outcrops next to the VB (Vass 2002).

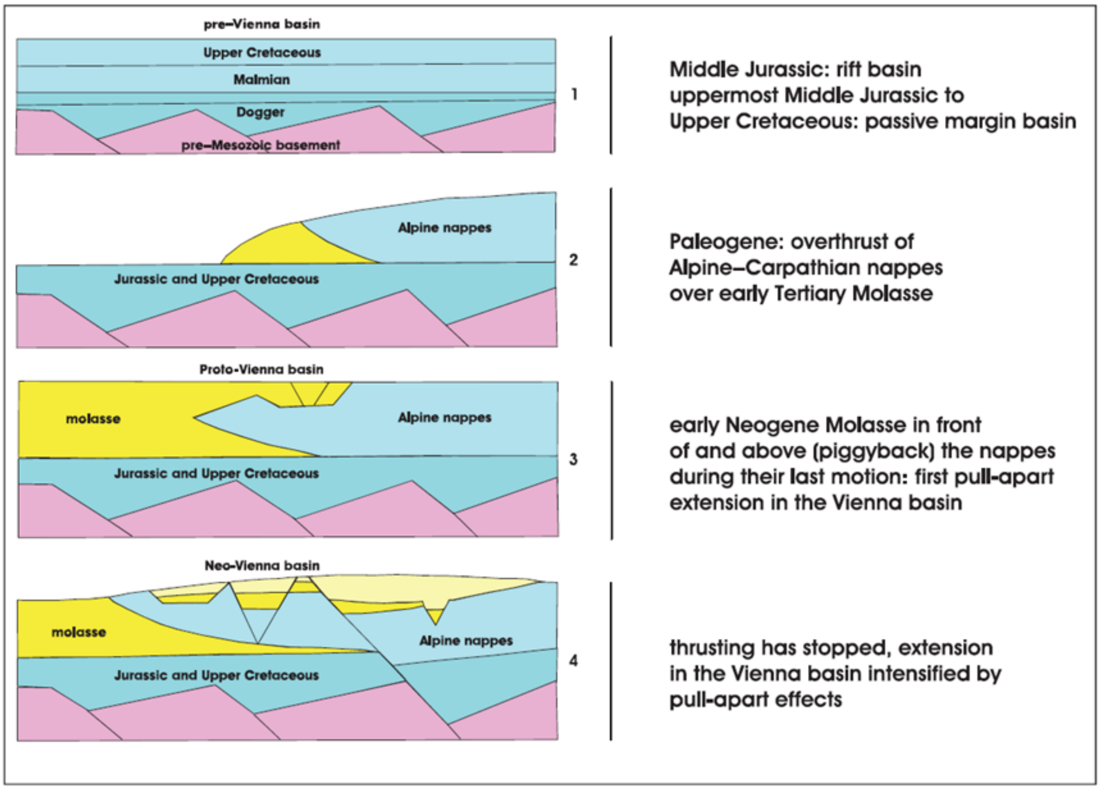

Figure 2. Stages of the Vienna Basin evolution (Arzmüller et al. 2006)

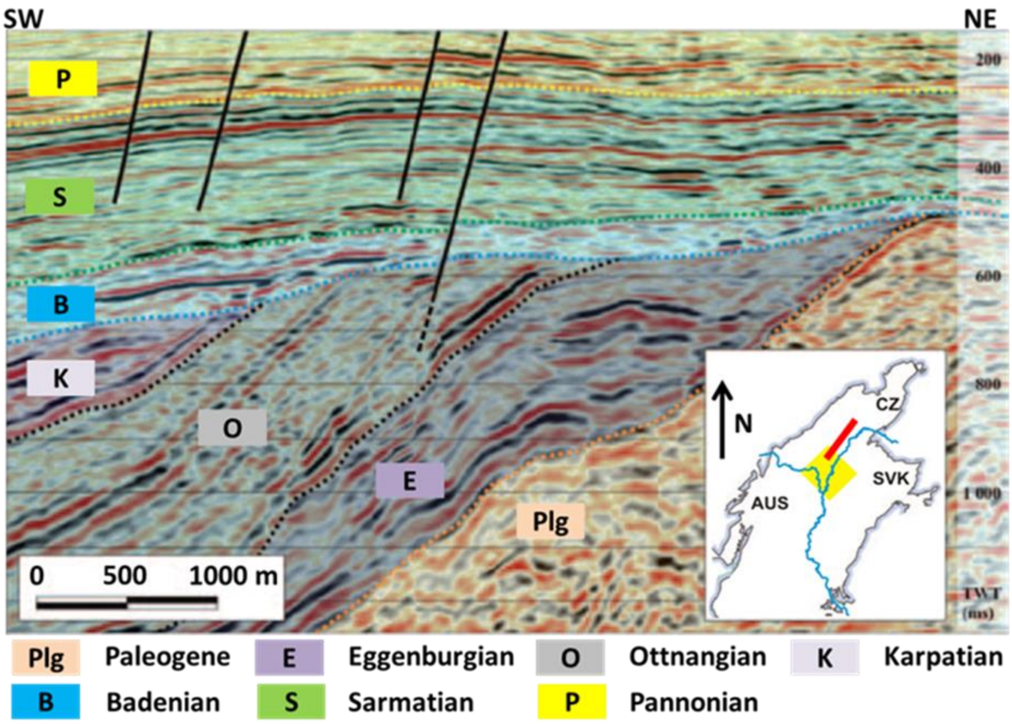

Figure 3. Example of an unconformity in the sedimentary fill of the Vienna Basin between the Lower and Middle Miocene on the Hodonín - Gbely Horst in the Northern part of the VB - Czech Republic (Prochác et al. 2012).

The given phenomena support the “thin-skinned” tectonics that does not involve extension of the entire lithosphere.

2.1.3 Pre-Neogene floor

The pre-Neogene floor of the VB was a part of an uplifted and eroded crystalline complex of the Bohemian Massif. Subsidence occurred during Devonian, Carboniferous and Jurassic, when the extensional passive margin formed of the Tethys Ocean in the South. In the Cretaceous and mainly in the Paleogene, a compressional regime developed due to Alpine and Carpathian thrusting. Jiricek (1979), Arzmüller et al (2006) and references therein identified three structural levels (Figure 2, 3, 4 and 5):

1. Lower autochthonous level is built by crystalline of the North-European platform, SE margin of the Bohemian Massif covered by Palaeozoic, Mesozoic and Tertiary sediments.
2. Middle allochthonous level is built by the direct pre-Neogene floor which consists of the nappe units of the Eastern Alps and Central West Carpathians:
   - Waschberg-Ždánice unit of Jurassic to Lower Miocene age, Flysch zone with Rača, Greifenstein, Kahlberg and Laab units (Lower Cretaceous to Eocene), built by rhythmically alternating sandstones, shales, partly conglomerates and carbonates;
   - narrow Klippenberg unit of Jurassic-Cretaceous age built by limestones, marls, shales with sandstone, conglomerate and limestone horizons;
   - nappe complex of Mesozoic to Upper Paleozoic sediments (Figure 4) of the Eastern Alps (Bajuvaricum, Tirolicum, Juvavicum) and Central West Carpathians with tectonic fragments of Cretaceous and Paleogene sediments of the Gossau unit, built by limestones, dolomites (dominant lithologies), shales, sandstones, marls, conglomerates and anhydrite layers;
   - Crystalline, partly Upper Paleozoic and Mesozoic sediments of Tatric and Grauwacken zone.
3. The upper level consists of Neogene sediments, such as shales, sandstones, a few conglomerates and organodetritic Lithotamnium limestones. The basin geometry is controlled by a trans-tensional system of faults.

2.1.4 Vienna Basin sedimentary fill

Neogene sediments in the VB reach a thickness of over 5 km in the basin centre (Figure 5) and represent an almost complete set of strata with a few hiatuses, e.g. Eger or Roman (Figure 6, Figure 7). Lower Miocene was deposited on the eroded surface of the moving tectonic units of the Alps and Carpathians (“piggy-back basin”). *Eggenburgian* succession was deposited in a marine environment in the North and in a brackish and lacustrine-deltaic environment in the central basin. The southern part of the VB area was dry land by that time. Sedimentary profile of the Eggenburgian starts with basal conglomerates and sandstones followed by “schlier”-type laminated calcareous shales and silts. The Ottnangian consists of basal sandstones overlain by typical “schlier”.

The *Karpatian* is developed in two cycles, each of them starts in the North with thick sandstones, which pinch-out towards South and change laterally and vertically to “schlier”. During the Lower Miocene, the northern part of VB was more marine and the southern part was emerged. In contrast, by the end of Karpatian and during Badenian, the most striking tectonic event, associated with sea bottom topography inversion, occurred in the area of the VB due to the late phase of Alpine and Carpathian plate collision with the Bohemian Massif. The Carpathian nappes north of the VB were uplifted while the central part of the VB subsided (Royden 1985, Jiříček 1988).

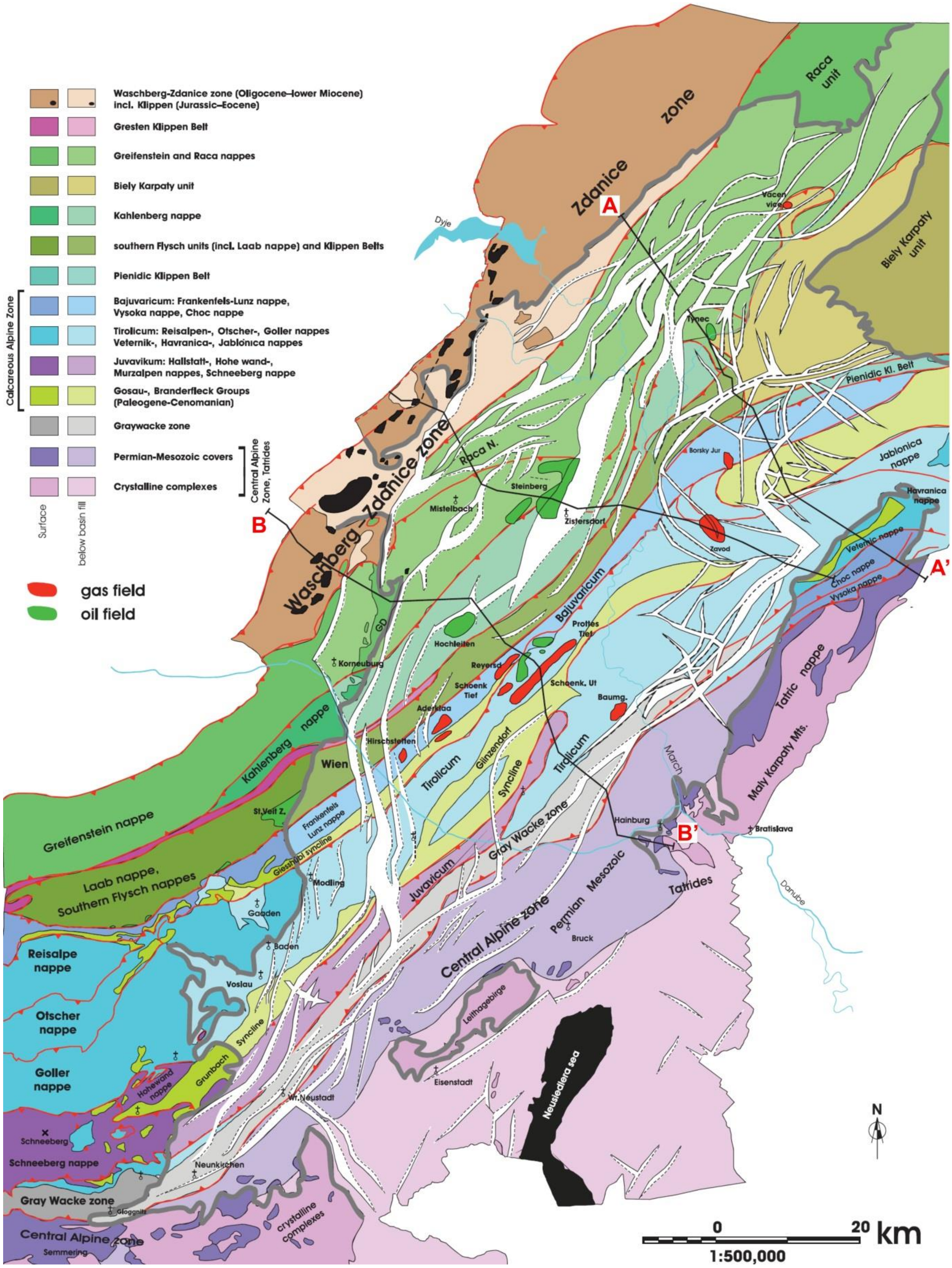

Figure 4. Geological Sketch Map – pre-Neogene Alpine-Carpathian connection in the Vienna Basin (Arzmüller et al. 2006).

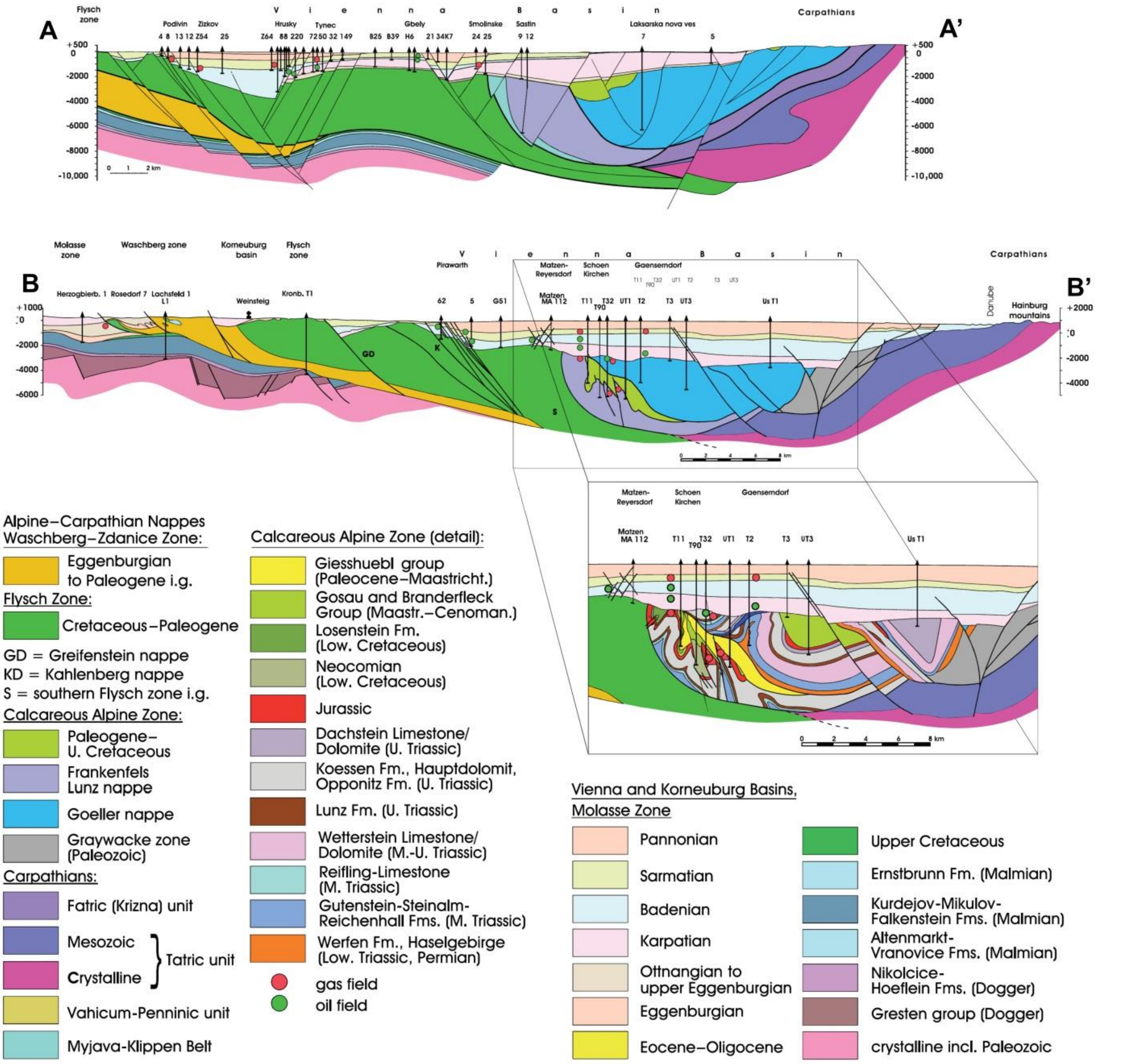

Figure 5. Geological sections through the Vienna Basin and its pre-Neogene floor (Arzmüller et al. 2006). Location of the sections is shown in Figure 4.

During the Middle and Upper Miocene, a large river delta brought significant amount of material from the West into the rapidly subsiding central VB. Two other deltas developed in the southern and northern parts. The *Lower Badenian* is built by two facial types of lithology: (1) thick sandstones of the palaeodelta in the western and central VB and (2) basal sandstones followed by overlying “Tegl” shales in the rest of the VB.

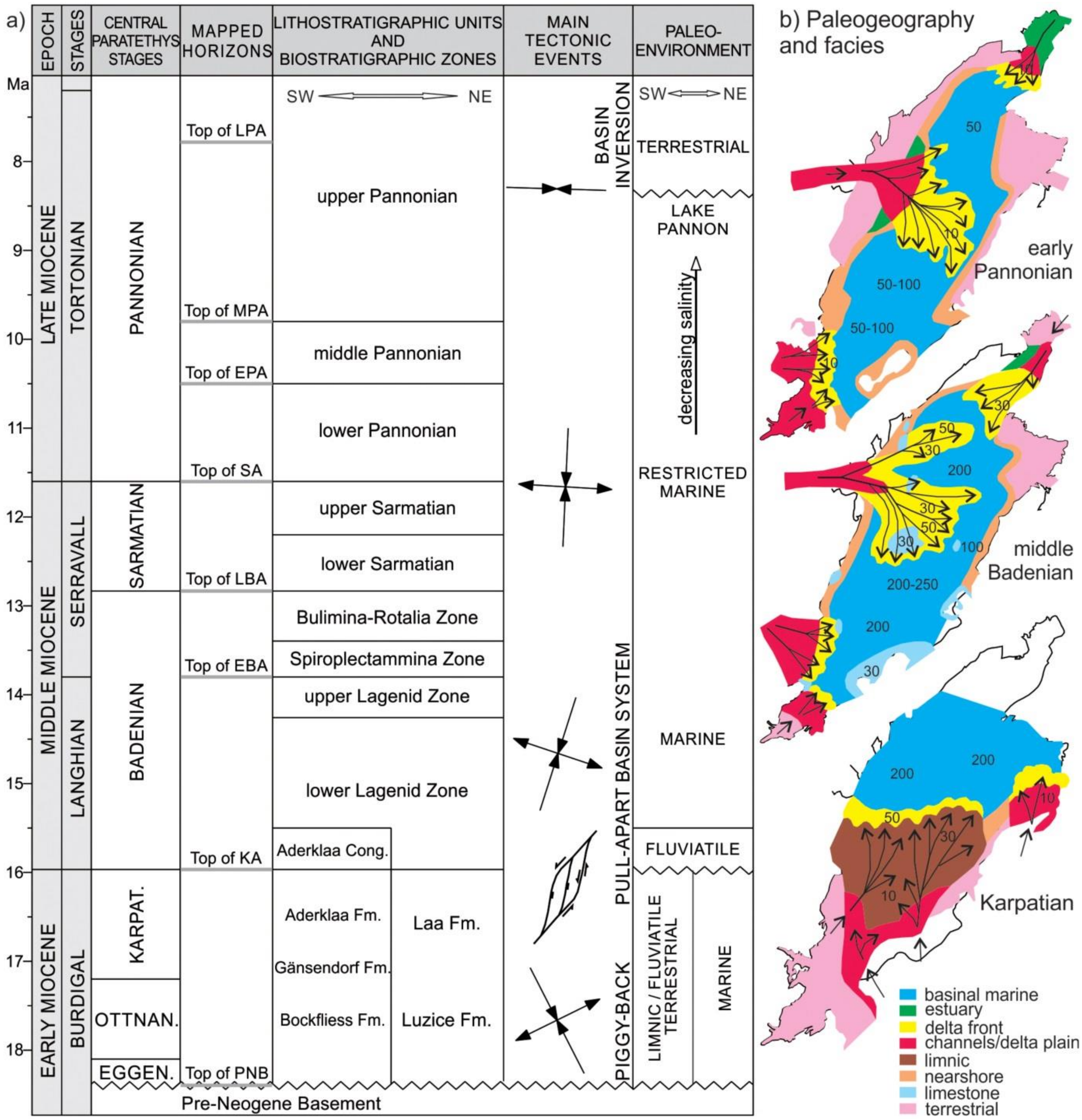

Figure 6. Stratigraphy and evolution of the Vienna Basin in the Miocene (Lee and Wagreich 2018)

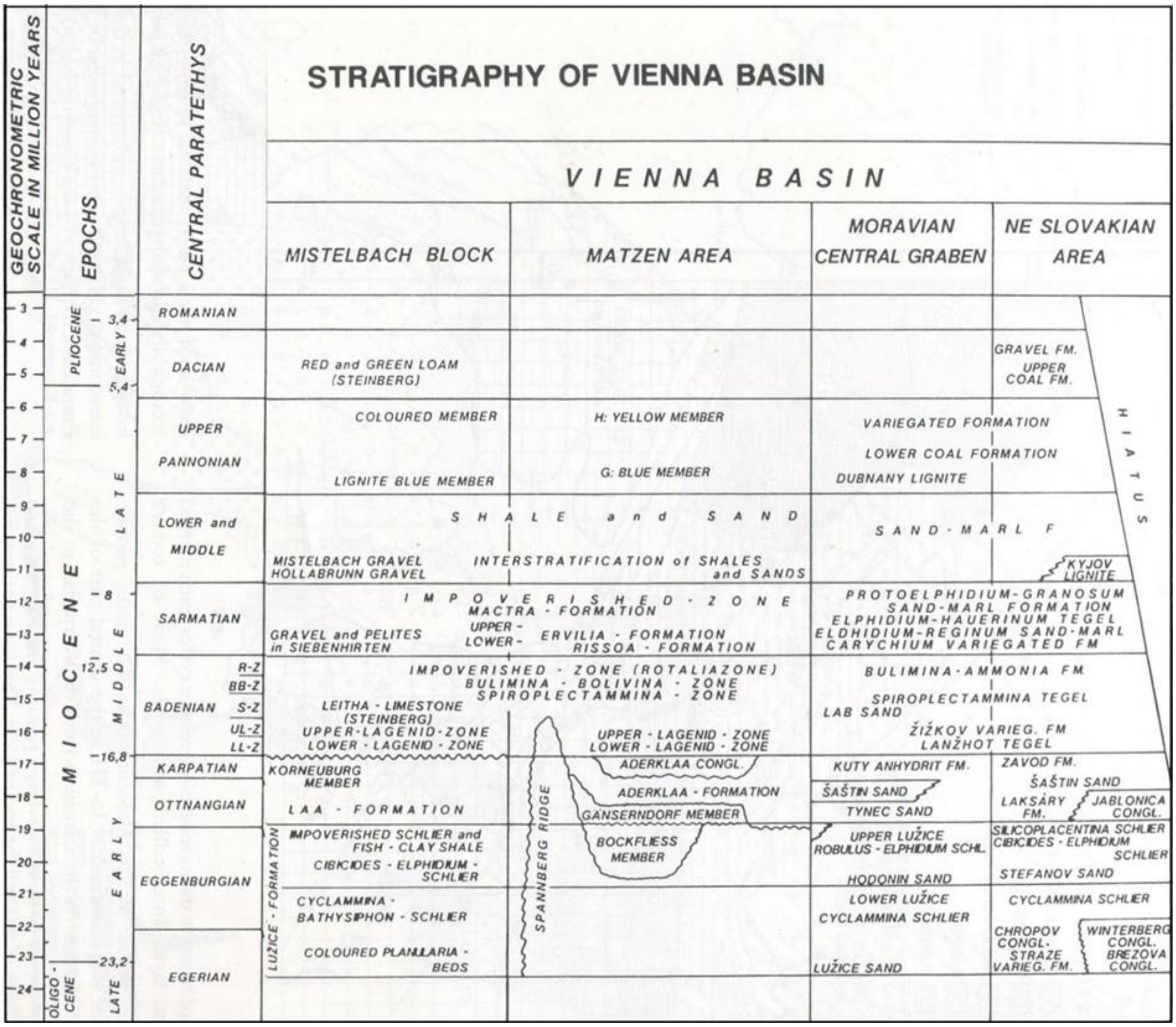

Figure 7. Stratigraphy of the Vienna Basin in the Neogene (Jiricek and Seifert 1990)

The *Middle Badenian* is built by shales and sandstone bodies, blanket sandstones and terminal shale known for its significant seal properties for hydrocarbon accumulations. The Upper Badenian is characteristic by interfingered sandstones and shales.

The *Lower Sarmatian* deposits consist of marine with grey sandy shales, siltstones and sandstones while the *Middle and Upper Sarmatian* sequence comprises brackish with greenish-grey calcareous shales, sandstones and sandy limestones. Brackish depositional conditions prevailed during the *Pannonian* with deposition of a sandy delta body in the central VB surrounded by marls and shales overlain by alternating sandstones and shales. In the Lower Pontian, coal seams were deposited with sandstones, dark calcareous shales in lacustrine environment. During the *Dacian*, the lake environment gradually changed to a fluvial environment.

2.1.5 Main tectonic elements of the Vienna Basin

During the early phase of evolution, the VB formed on moving thrusts, which have the typical Alpine tectonic structure. That is why all the pre-Neogene floor of the VB is tectonically deformed, expressed in a stacked set of many thrust sheets. All the units are uplifted and partially eroded (Figure 8).

Due to the collision of the Alpine thrust sheets with Bohemian Massif, Lower Miocene sediments were deformed and partly eroded by the end of Karpatian, especially in the northern part of the VB. Normal faults are typical for the early phase of the VB evolution. An angular unconformity developed between the sediments of the Lower and Middle Miocene.

The seismic sections show Middle Miocene and Pliocene strata in subhorizontal position (Figure 3) with little or no deformation. During the second phase of tectonic evolution, synsedimentary flexural faults formed and divided the basin into elevated horst structures and subsided deeper blocks with similar stratigraphy. Some faults terminate at the Badenian-Sarmatian boundary while others reach up to the Pliocene.

Based on the identified fault geometry, the VB is subdivided into a number of structural blocks (Figure 8), such as elevations (horsts) and depressions oriented in the longitudinal direction, e.g. Moravian Central Depression, Gbely-Hodonín Horst, Zistersdorf depression, or transverse direction, e.g. Kúty Trough, Matzen Elevation, Suchohrad Depression and Lakšáry elevation.

The leading fault systems comprise the Steinberg, Bisamberg, Leopoldsdorf, Lanžhot-Hrušky, Farské, Lakšáry, Little Carpathian, etc., where the vertical throw at the base of the Badenian is up to several thousand meters. The smaller associated fault systems show throw of several hundred meters (Figure 8 and Figure 9). Syntectonic deposition during post-Lower Miocene time produced considerable differences in sediment thickness on the footwall and hanging wall blocks. In this way, several thousand meters thick layer in the subsided block corresponds to a few hundred m thick condensed strata of the same age on the footwall block. Facial patterns follow the same areal diversification, e.g. Lithothamnium Limestones of the Middle Badenian on the elevated blocks correlate in age with clay-silt layers in the depressions.

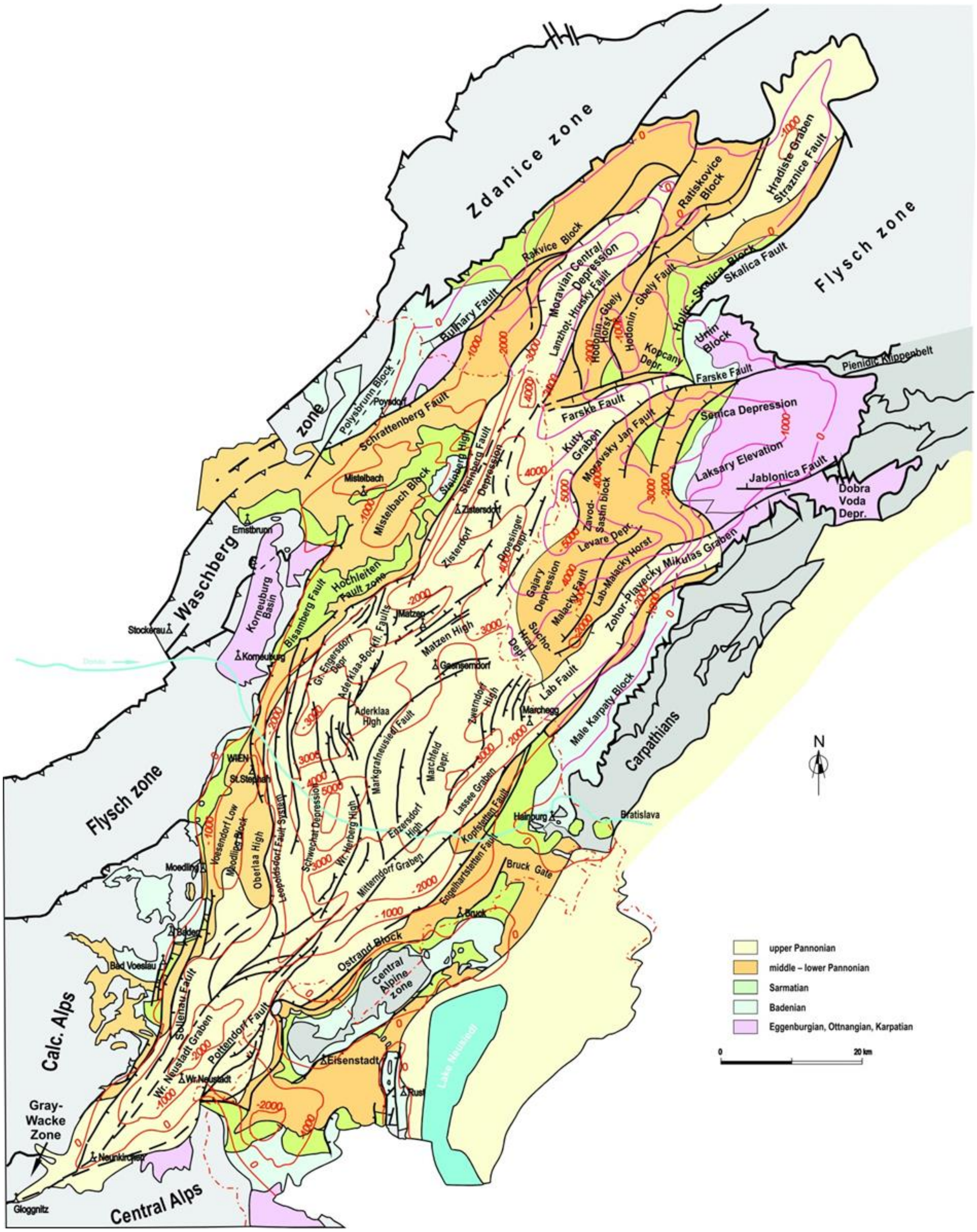

Figure 8. Geological subsurface map of the Vienna Basin shows the main fault systems, depressions, horsts and related structural blocks (Arzmüller et al.2006).

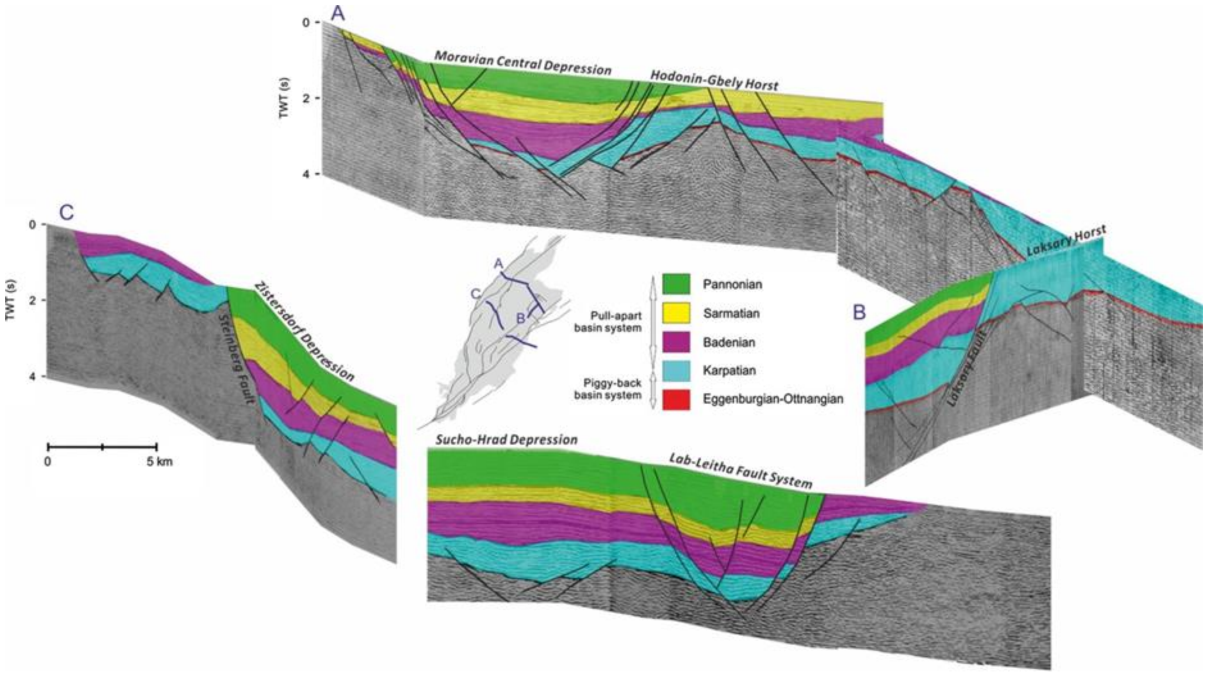

Figure 9. Seismic sections across northern and central part of the Vienna Basin (Lee and Wagreich 2018)

The faults create new traps controlled by discontinuity of lithological horizons. “Open” faults occur, where sands are present on both sides of the fault, while “closed” faults have sand on one side and shale on the other. Many of the oil and gas fields in the VB are tectonically bounded by closed faults, which prevent fluid movement from the lower (hanging wall) to the upper (footwall) block. Tectonic closures of reservoirs are usually combined with additional lithological pinch-outs.

2.2 Oil and gas in the Vienna Basin

2.2.1 Oil and gas occurrences

The occurrence of oil and gas accumulations in the VB reflects the most striking structural elements (Figure 10**Erreur ! Source du renvoi introuvable.**). They are mostly concentrated along the depocentre of the buried Jurassic sediments, especially the Mikulov marls of the Malm age situated in the W and NW part of the basin. The marls are considered to be the main source rock of the VB hydrocarbons. Other potential source rocks, e.g. deeply buried Neogene sediments, Palaeogene, Triassic or Cretaceous of the Alpine thrusts, are only of secondary importance for hydrocarbon formation.

Hydrocarbon accumulations in Neogene sediments are often bound to tectonic traps in sandy layers attached to big fault systems (see above). The transgression-regression cycles in various periods of the Neogene led to deposition of numerous sandy horizons on top of each other, which caused the creation of complex hydrocarbon fields with several production zones. In some cases (e.g. the Matzen, Hrušky or Láb fields), even tens of productive horizons are situated on top of each other. In addition to the tectonic traps, anticline-type traps also occur, bound to elevation structures where faults play only a minor role, as well as lithologically isolated sand lenses.

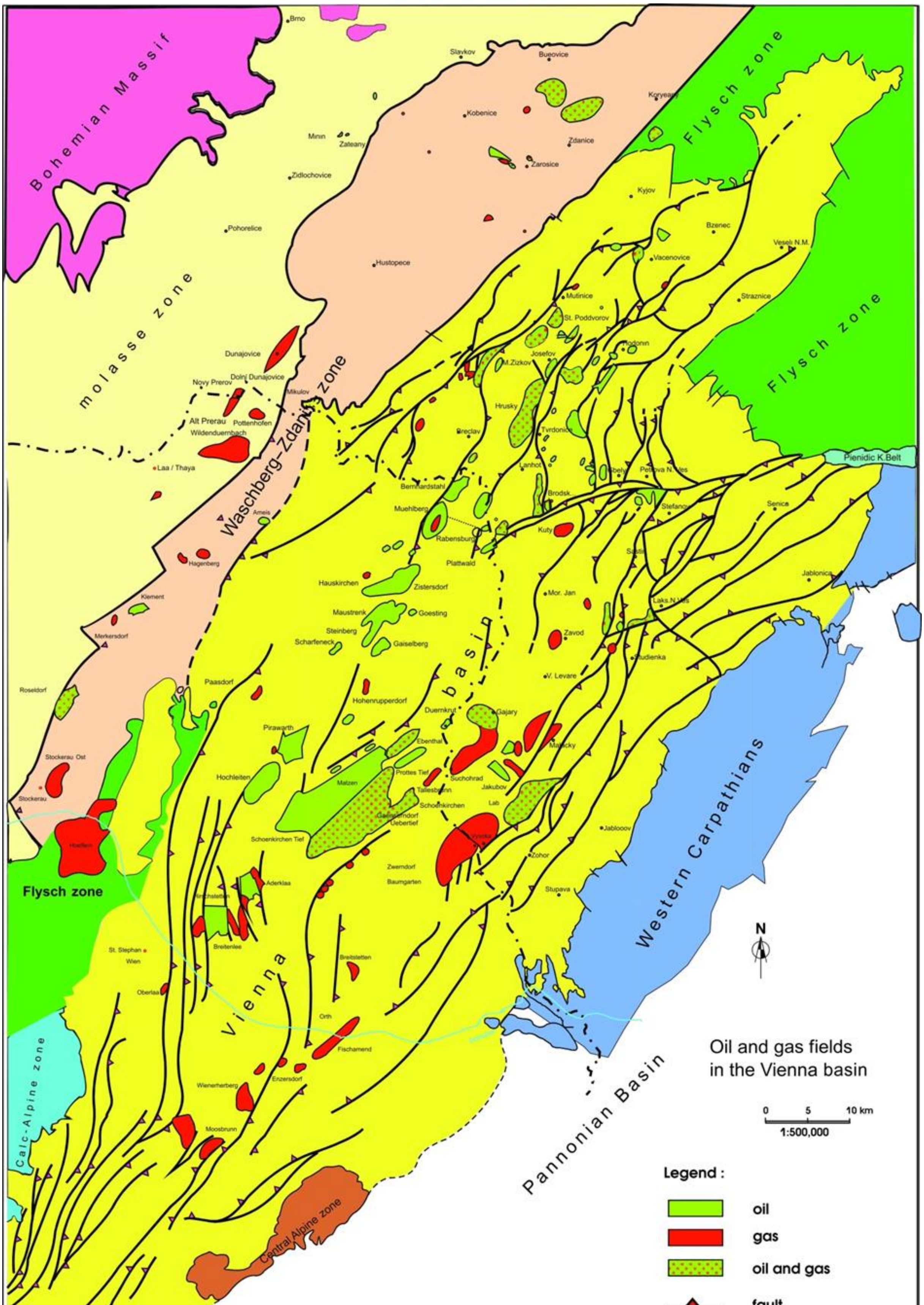

Figure 10. Oil and gas fields in the Vienna Basin (Arzmüller et al. 2006)

From the stratigraphic point of view, oil and gas reservoirs occur from Eggenburgian up to Lower Pannonian. No hydrocarbon accumulation has been discovered in older sediments so far. Most of the fields are located in Badenian and Lower Sarmatian sediments. In the Northern part of the VB, small oil and gas fields can be found in the Flysch basement, bounded by Paleocene and Eocene turbidite sandstones close to the Steinberg fault system. Relatively big hydrocarbon fields can be found in the basement of the central part of the VB, notably in Triassic dolomites of Northern Limestone Alps. Oil and gas accumulates in the so called “buried hills” (e.g. oil fields Schönkirchen Tief and Prottes Tief or gas fields Aderklaa, Baumgarten, Závod and Borský Jur) and in the inner structure of the Flysch nappes (e.g. gas fields Schönkirchen Übertief, Reyersdorf or Aderklaa Tief) that have formed in the imbricated system (Arzmüller et al. 2006).

The caprock of the hydrocarbon reservoirs consists mostly of Neogene claystones. In case of the fields located in the internal structure of the nappes the sealing rocks are clayey shales of Cretaceous and Paleogene age. The oil and gas in the Northern and central parts of the VB are mostly of thermogenic origin while fields with biogenic gas prevail in the Southern and SE part.

2.2.2 History of oil and gas exploration and production

Surface oil-and-gas seeps in the Vienna Basin were known more than hundred years ago. Oil seeps in the Morava River close to Hodonín inspired E. Tietze, a geologist from Vienna, to dig a 6 m deep exploration hole in 1901, which was later filled with oil. In 1901-1902 the first well was drilled ca. 1 km West off the Nesyt farm near Hodonín. Oil shows were encountered at depths of 10 m, 150 m and oil and gas at 192 – 203 m. The total well depth was 217 m but the well did not result in an economic discovery (Bednaříková 1984).

Based on the negative assessment by E. Tietze the area was abandoned for some time. Private explorationists focused at oil impregnations in Quaternary gravels and dug a number of 4-14 m deep holes and collected several litres of oil from the ground water level per day. The beginning of oil industry in the VB is usually associated with the year 1913, when the first exploration well was drilled in the vicinity of Gbely in Slovakia (Figure 11). In 1914, this well produced economically profitable amount of oil from the first oil field in the Vienna Basin, the Gbely (Egbell) Staré Pole. The daily production from Neogene strata at depth of 164 m reached 15 metric tons/day (Bednaříková 1984). In the Czech Republic, the commercial oil production began in 1920 from the Nesyt field (Figure 12) at a depth of 313–338 m. The commercial production in Austria began in 1934 with Gösting–2 well located close to the Steinberg fault near Zistersdorf (Janoschek et al. 1996).

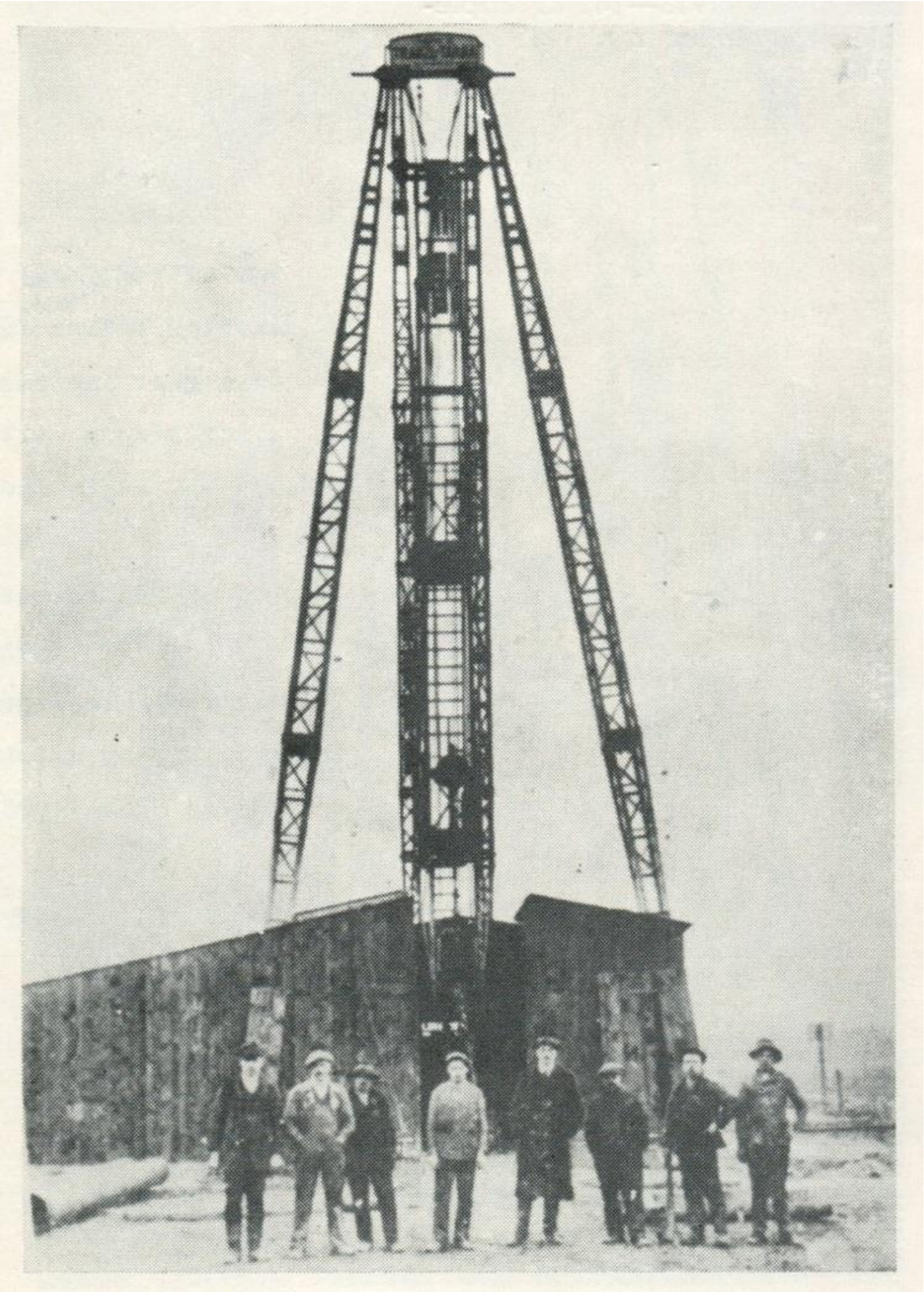

Figure 11. Drilling rig Trauzl-Rapid and oil rig crew from 1913 – 1914. First production well in the Vienna Basin: Gbely – Old Field – Slovakia (Bednaříková and Thon 1984).

Figure 12. Panorama of the Nesyt oil field (Hodonin – Czech Republic) in the 1920s with old derricks and drilling rig on the left (Bednaříková & Thon, 1984).

Extensive geological exploration in the Vienna Basin has been going on for about 150 years, bringing thus a deep insight in the subsurface structure by the early geologists. The knowledge has rapidly grown as about 6000 wells have been drilled and 2D seismic lines and 3D cubes have been acquired. The deepest Zistersdorf UT 2A well was drilled in Austria down to a final depth of 8,553 m (Janoschek et al. 1996). The cumulative oil-and-gas production up to 2018 and in 2018 is shown in Table 1. Figure 13 and Figure 14 show the shares of the three countries in the total production. It is evident that both the historical and current production of hydrocarbons in the Austrian part of the VB is one order of magnitude higher than the production in the two other countries.

Table 1. Total oil and gas production until 2018 and production in 2018 in the Vienna Basin. Source: Balance of Mineral Resources of the Czech Republic and Slovakia, Annual Reports of OMV, MND a.s. and NAFTA.

Country	Total production		Production in 2018	
	Oil production (million tons)	Gas production (billion m^3)	Oil production (thousand tons)	Gas production (million m^3)
Austria	**111.0**	**75.0**	**587.0**	**875.0**
Czech Republic	**4.1**	**4.5**	**28.9**	**82.2**
Slovakia	**4.2**	**26.5**	**6.3**	**47.5**
Vienna Basin	**119.3**	**106**	**622.2**	**1004.7**

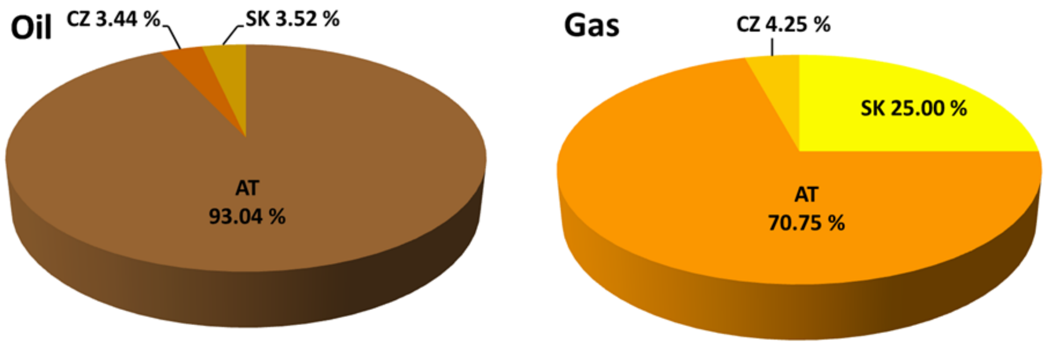

Figure 13. Share of Austria (AT), the Czech Republic (CZ) and Slovakia (SK) in total oil and gas production in the Vienna Basin until 2018.

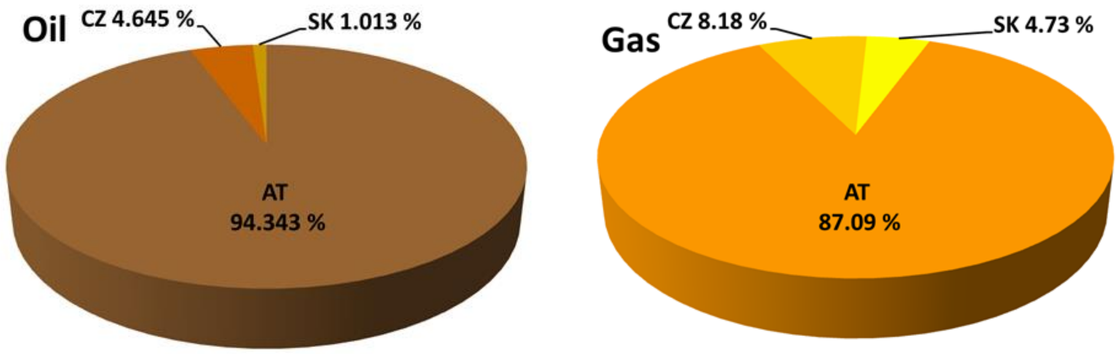

Figure 14. Share of Austria (AT), the Czech Republic (CZ) and Slovakia (SK) in oil and gas production in the Vienna Basin in 2018.

2.2.3 CO_2-EOR potential

The big number of mature, nearly depleted and depleted oil fields in the Vienna Basin represents an interesting potential for CO_2-driven enhanced oil recovery (CO_2-EOR), combined with subsequent CO_2 geological storage. To assess this potential, the characteristics of the oil fields[1] in all three national parts of the Vienna Basin were studied. A brief description of the fields in each country is provided in Chapters 2.3 – 2.5. For the purposes of the study, the oil fields were grouped into geographical clusters (see Chapter 4.2 for more details). Altogether, nine oil field clusters were studied: 3 in the Czech Republic, 3 in Slovakia and 3 in Austria.

[1] Oil fields and combined oil & gas fields were studied; pure gas fields were excluded due to the non-existence of CO_2-EOR potential.

2.3 Oil fields in the Czech part of the Vienna Basin

The Czech part of the VB is the smallest one of the three national parts, and also the remaining oil reserves are relatively limited. Its 14 oil and gas fields can be grouped into three geographical clusters (Figure 15):

- Cluster CZ I: includes Vracov, Vacenovice and Mutěnice oil fields located on the west flank of the Moravian Central depression (MCD).
- Cluster CZ II: includes Poddvorov on the west of MCD, Josefov, east of MCD, and Lužice, Hodonín and Týnec located on the Hodonín-Gbely horst.
- Cluster CZ III: consists of the most important oil and gas fields in the region: Prušánky, Bílovice Žižkov and Poštorná west of MCD, Hrušky and Lanžhot east of MCD, and LBr-1 located on the Hodonín-Gbely horst.

The areal distribution of the fields is controlled by block tectonics, which is expressed in a set of major faults including Schrattenberg, Steinberg, Lanžhot-Hrušky, Hodonín-Gbely, Farské and Brodské. Oil and gas have been produced from the Eggenburgian through Sarmatian, less important oil fields are located in the underlying nappes of the Flysch Belt. Badenian reservoirs, mainly the Middle Badenian Láb horizon (Fig. 16, 17 and 18) have produced the highest amounts of oil and gas. Hrušky is the largest oil and gas field with over 20 producing Eggenburgian to Badenian horizons with recoverable reserves of 2 Mt oil and 2 BCM gas (Fig. 18 and 19). Sarmatian reservoirs contain only gas accumulations.

Most of the fields are mature to exploited, some fields (Poddvorov and Hrušky) were partly converted to underground gas storages. EOR (other methods than CO_2-EOR) was applied to a few of these oil fields.

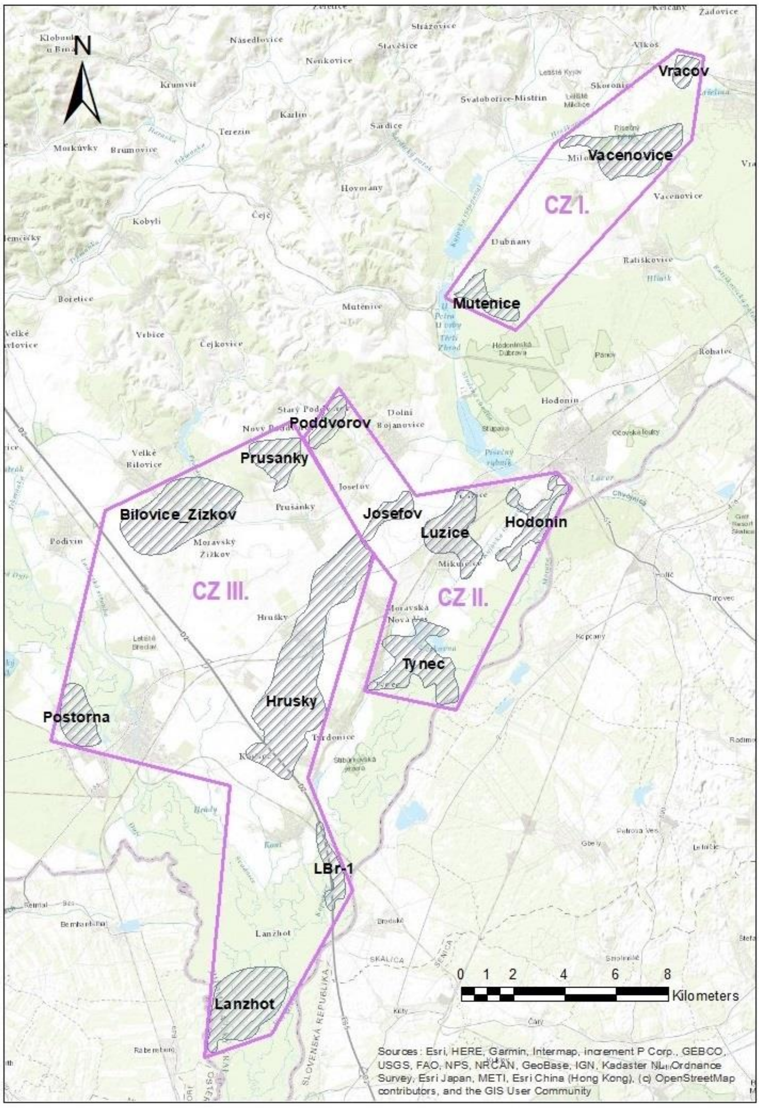

Figure 15. Oil fields in the Czech part of the Vienna Basin: clusters are outlined by purple lines, oil fields by hatched areas.

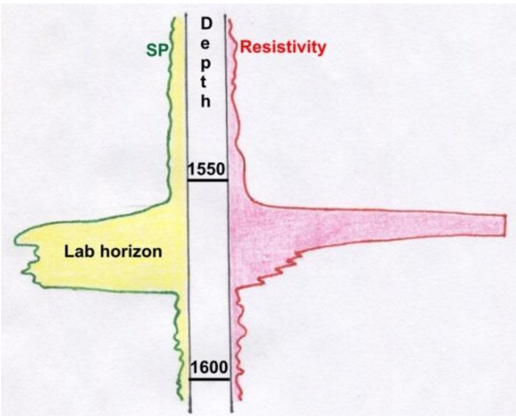

Figure 16. Example of SP and RAG well logs showing typical properties of the Láb horizon – low SP values and high resistivity.

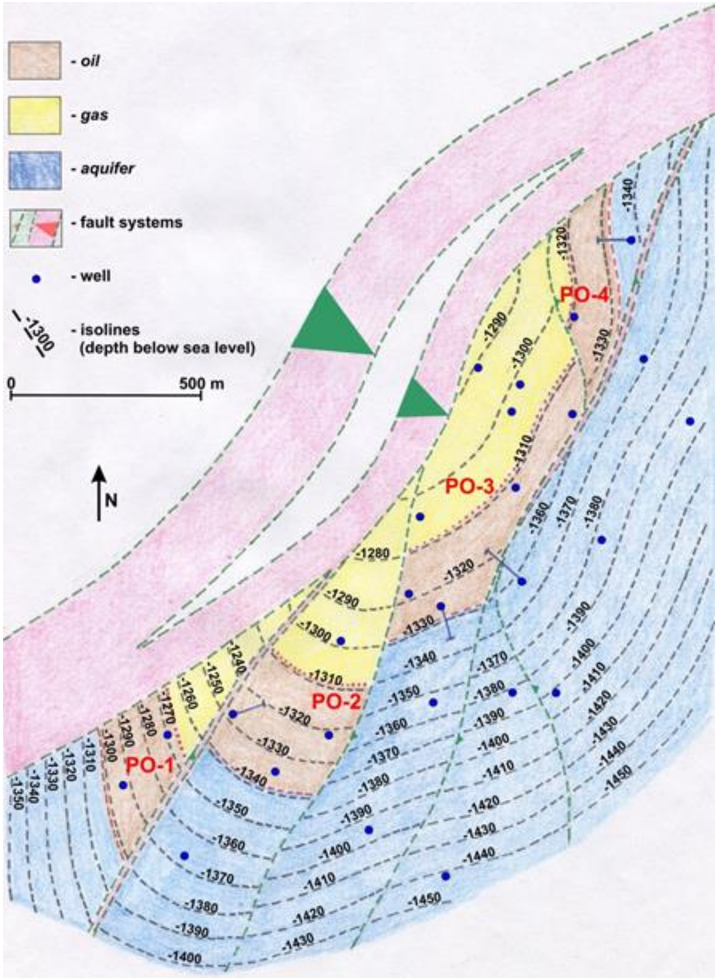

Figure 17.The Vienna Basin - Czech Republic - oil and gas field Poddvorov - West – depth-structure map of the top of the Láb horizon (Middle Badenian). The field consists of four blocks (basic units): PO-1, PO-2, PO-3 and PO-4.

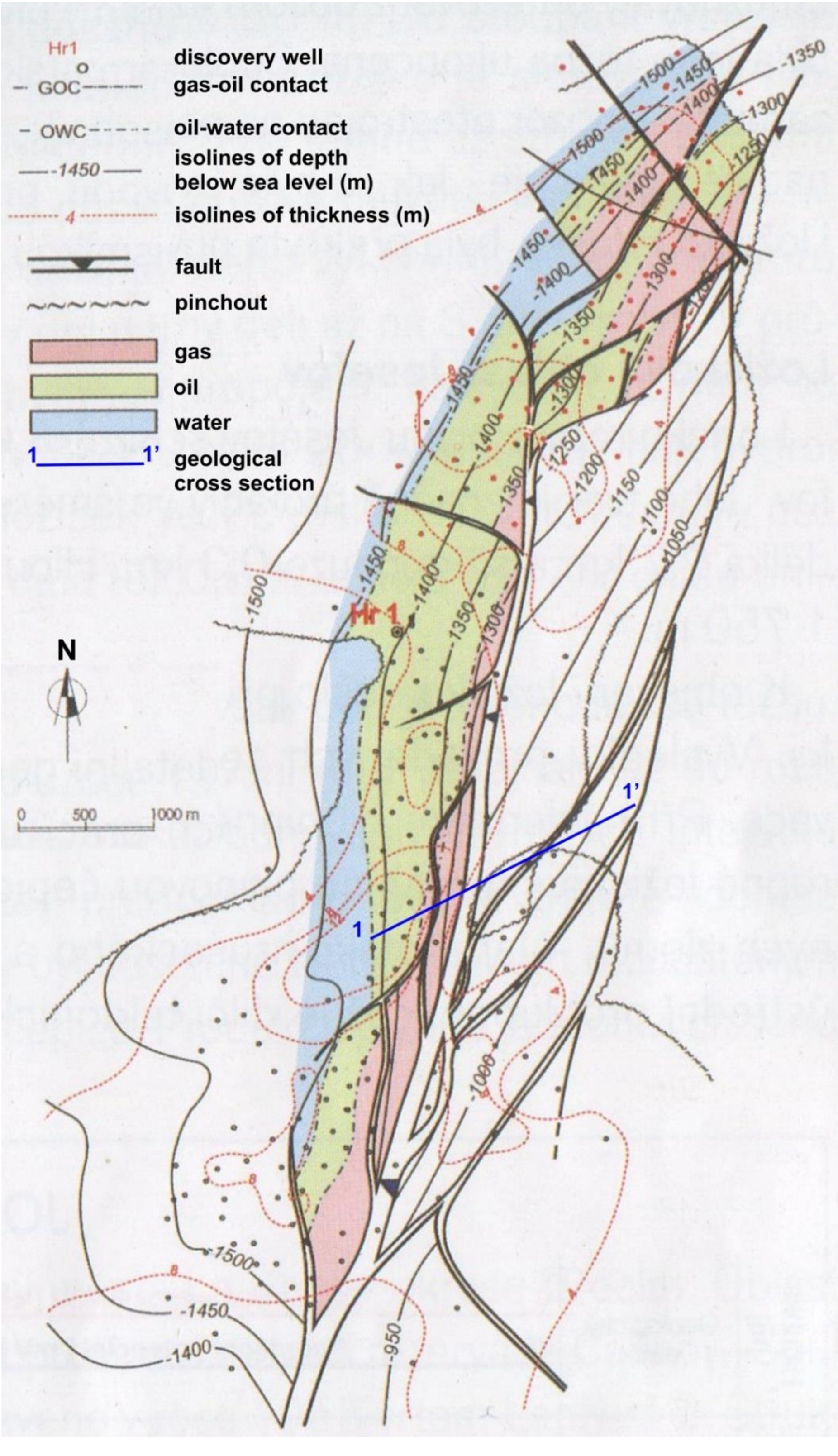

Figure 18.The Vienna Basin - Czech Republic - oil and gas field Hrušky, block (basic unit) HR-4 – depth-structure map of the top of the 7th Badenian horizon (Upper Badenian) (Ďurica et al. 2010).

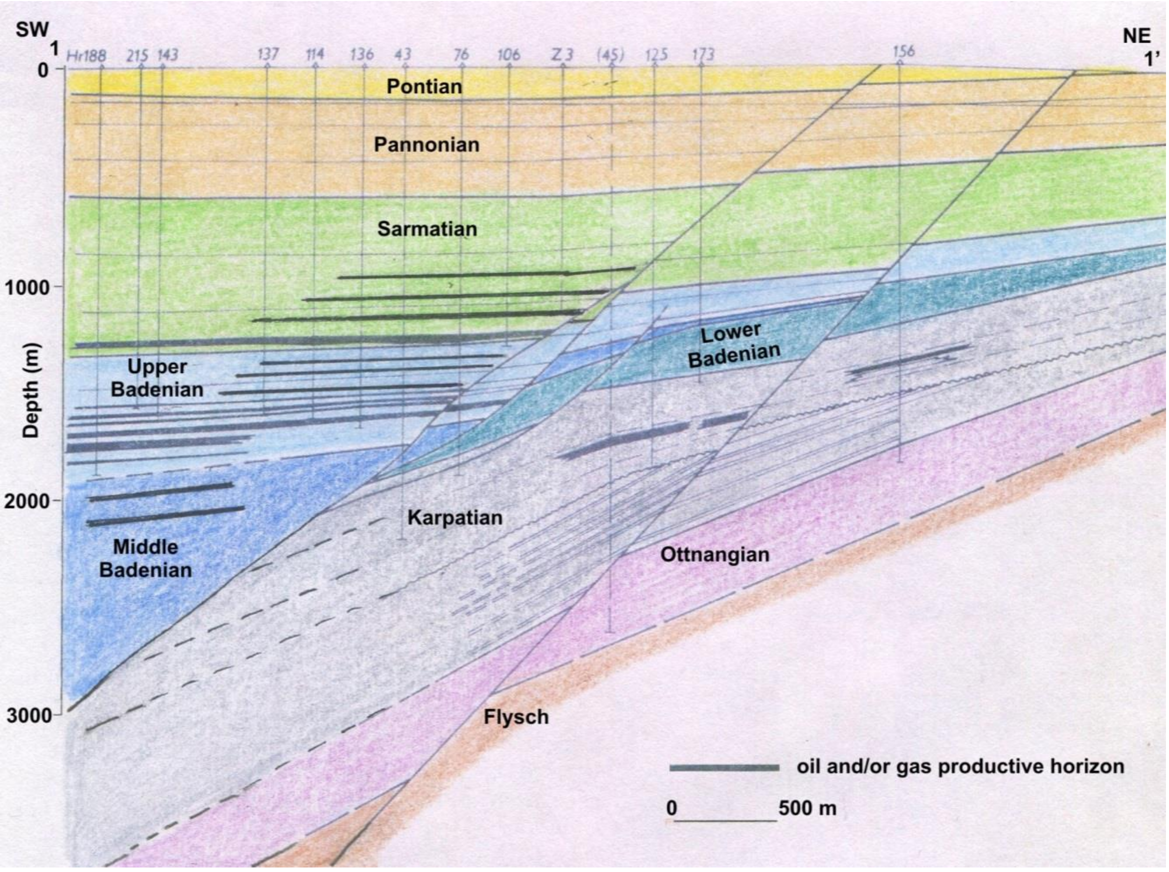

Figure 19. Oil and gas field Hrušky – geological cross section 1 – 1' (Buchta et al. 1984). The location of the section is shown in Fig. 18.

2.4 Oil fields in the Slovak part of the Vienna Basin

Three clusters of oil and gas fields can be delimited in the Slovak part of the Vienna Basin (Figure 20), covering 10 oil fields relevant for the purposes of this study. In the North (cluster SK I.) the fields occur on the Hodonín-Gbely Horst and in the eastern part of the Farské fault system in the pre-Neogene Flysch unit. In the central part, i.e. in the Závod – Šaštín Block, oil and gas fields occur in the Neogene (cluster SK II.) and gas-condensate fields are located in the pre-Neogene Mesozoic dolomite reservoirs of the North-Eastern Calcareous Alps. In the South of the Slovak part of the VB gas fields prevail, many of them were converted to underground gas storages. Only a few oil fields occur (cluster SK III.)

Gbely – Stare pole ("Old Field", cluster SK I.) is the historically first oil field discovered in the Vienna Basin (Figure 20 and Figure 21). Here the basal sand of the Sarmatian at a depth of ca. 170-230 m represents the main oil reservoir. The largest field is the joint Austrian-Slovak Vysoká-Zwerndorf gas field with total recoverable reserves of ca. 27 Mm^3 of gas (9 Mm^3 on the Slovak side). The second major field is Láb (cluster SK III.), where most of the gas horizons were converted to underground gas storage (Figure 23 and 24). Further fields are divided into 17 partial regions with recoverable reserves in Eggenburgian to Pannonian reservoirs. Only microbial gas is accumulated in the Pannonian. Smaller oil fields occur in the Cunín pre-Neogene reservoirs (cluster SK I.) and gas accumulations were found in the Mesozoic floor (Závod and Borský Jur). The most productive stratigraphic unit is the Badenian, mainly the Middle Badenian Láb horizon. The fields are in general mature or in final phase of production. Limited EOR was applied in some of the fields.

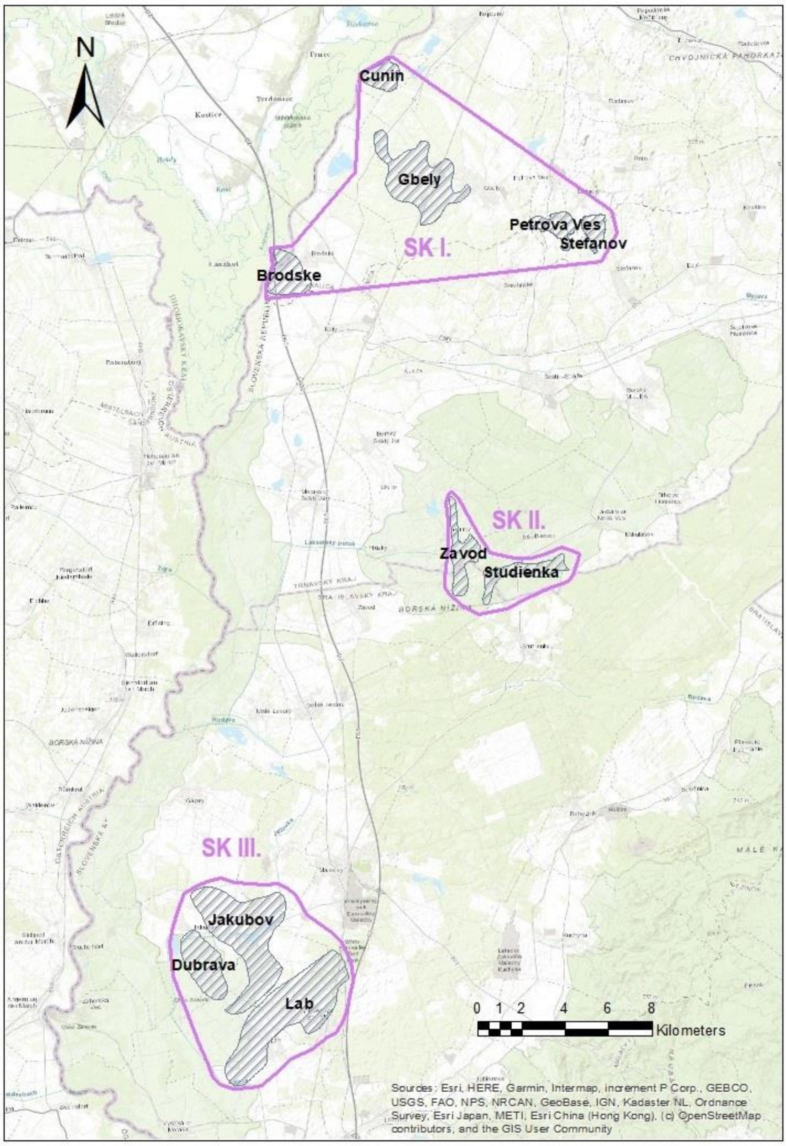

Figure 20. Oil fields in the Slovak part of the Vienna Basin: clusters are outlined by purple lines, oil fields by hatched areas.

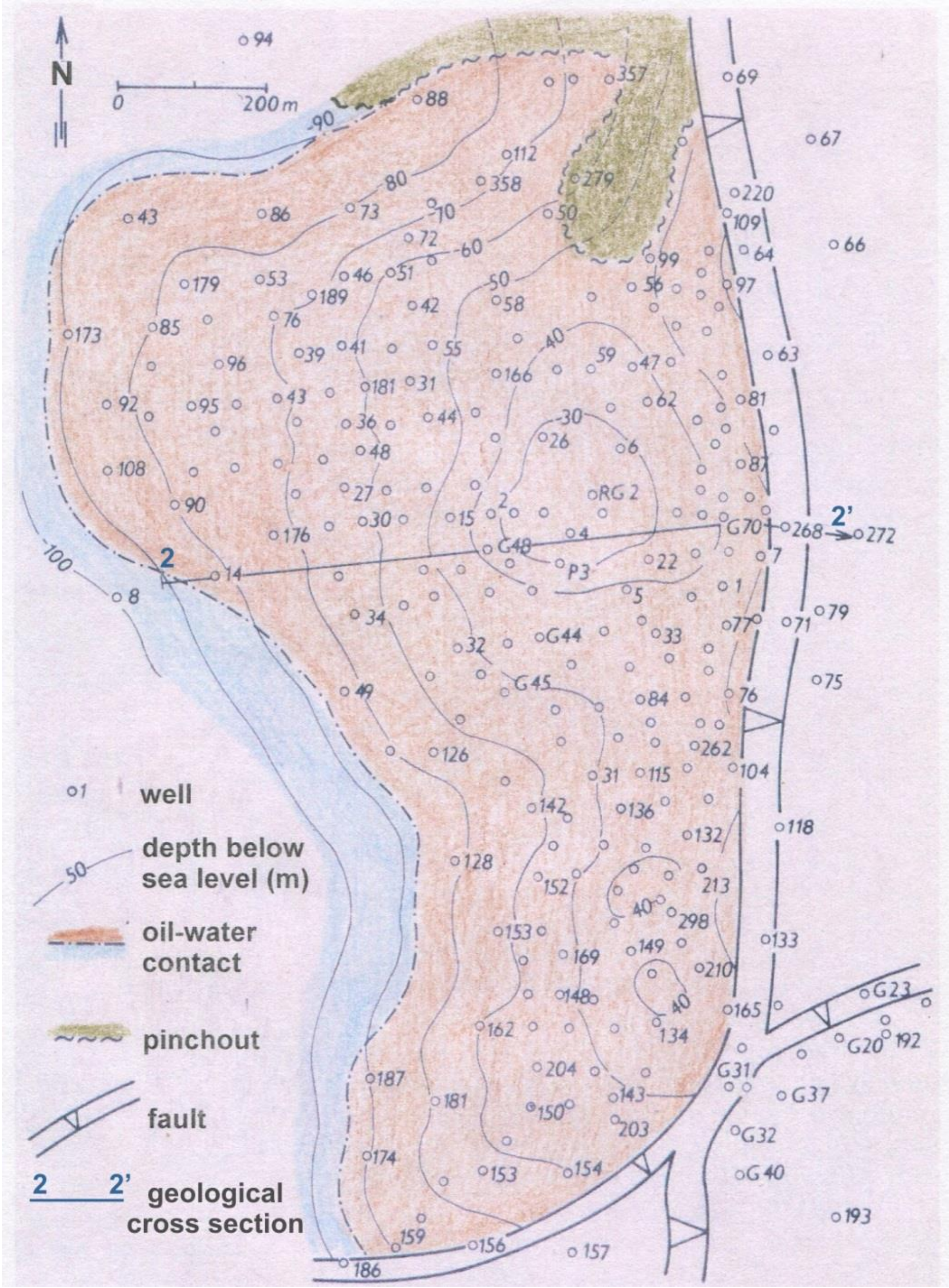

Figure 21. The Vienna Basin - Slovak Republic – Gbely – Old Field; the oldest oil field in the Vienna Basin; depth-structure map of the top of basal Sarmatian horizon; block (basic unit) G1 (Buchta et al. 1984).

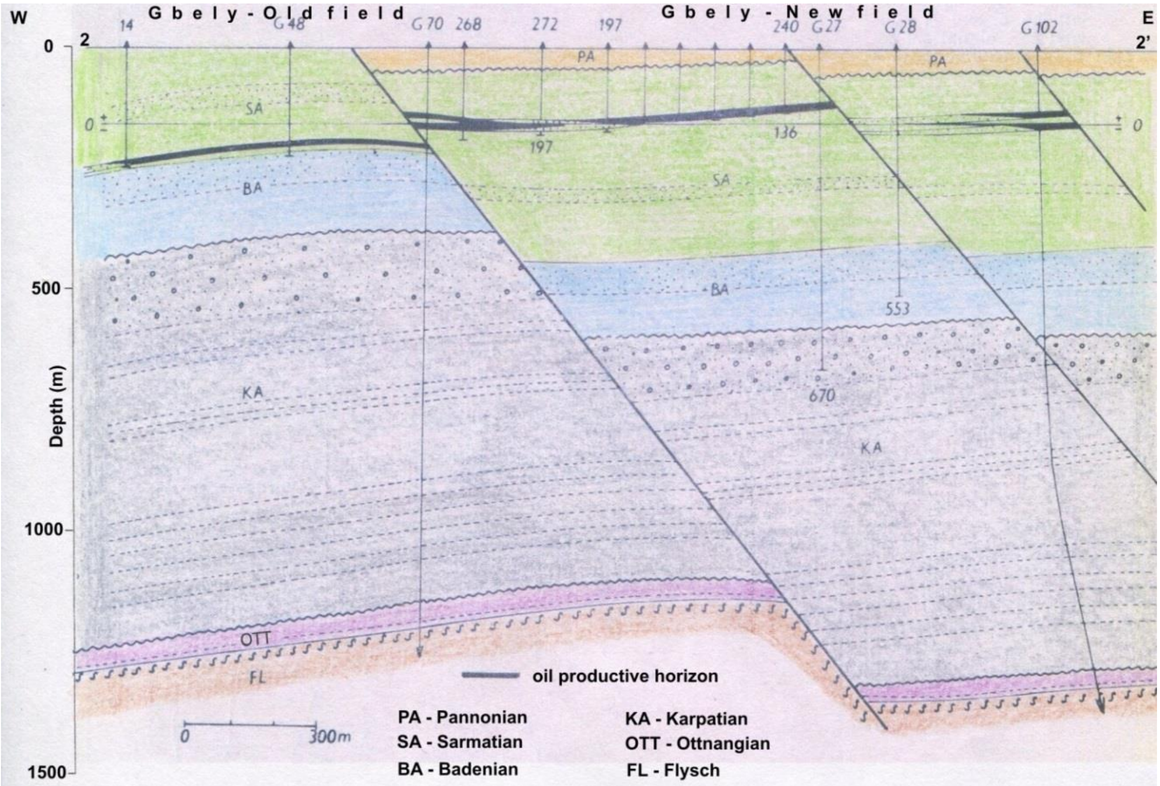

Figure 22. Gbely – Old Field and Gbely – New Field; geological cross section 2 – 2' (Buchta et al. 1984). The location of the section is shown in Figure 20.

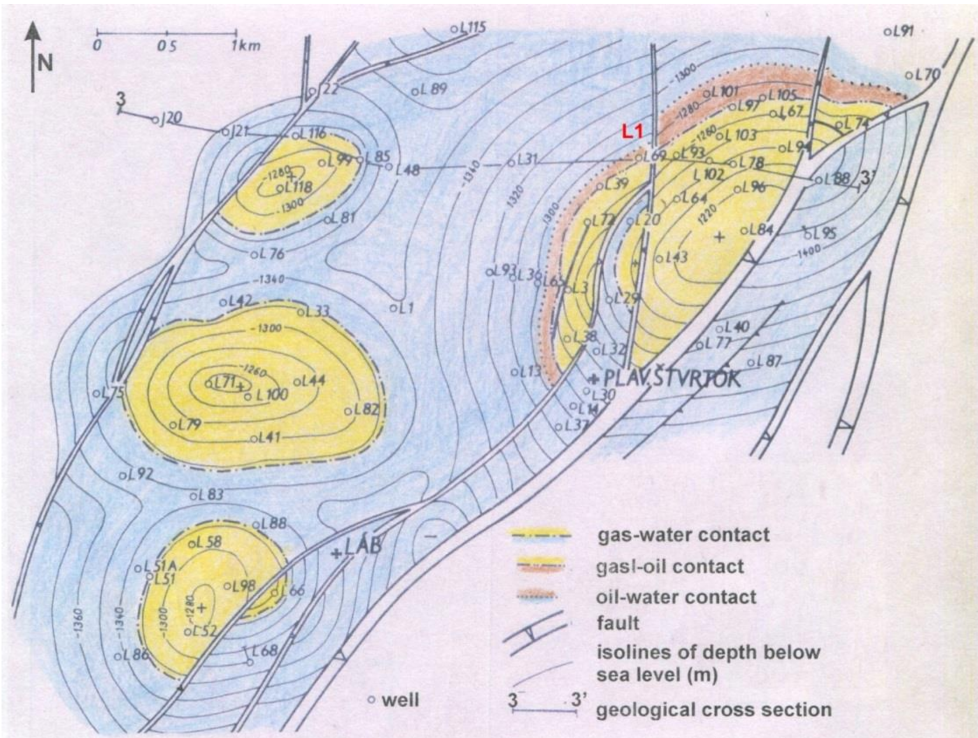

Figure 23.The Vienna Basin - Slovak Republic – Láb oil and gas field; depth-structure map of the top of the Middle Badenian Láb horizon (Buchta et al. 1984).

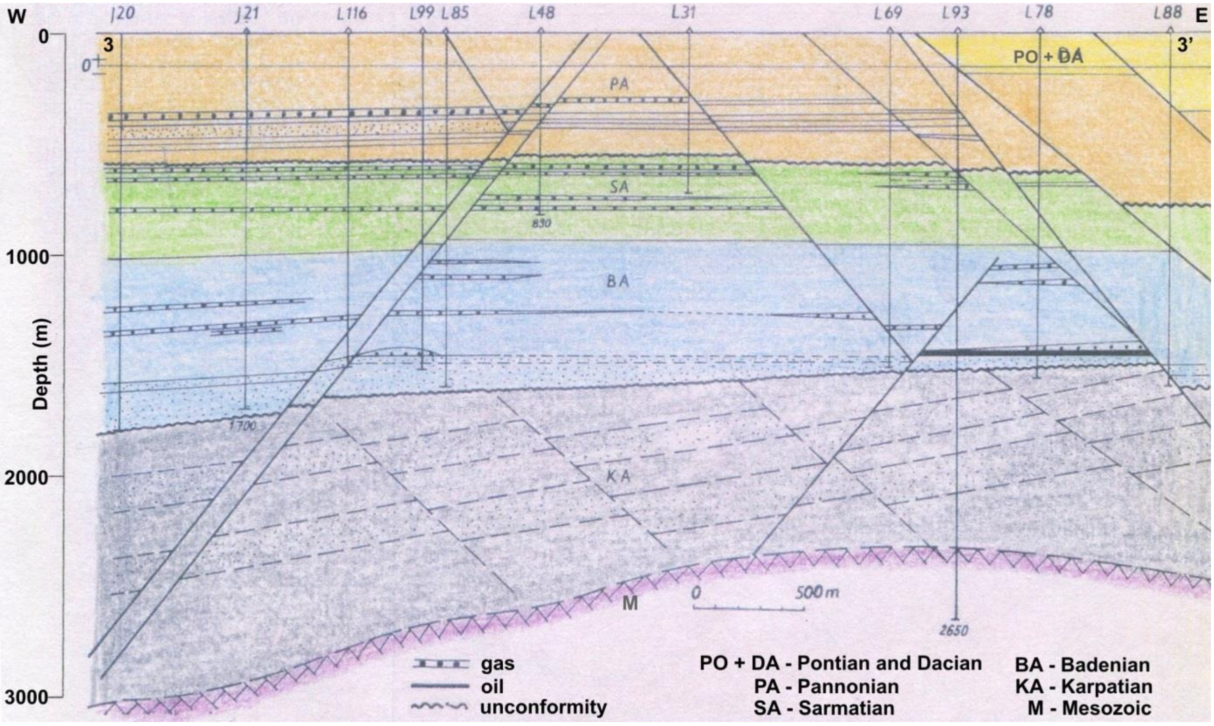

Figure 24. Oil and gas field Lab; geological cross section 3 – 3' (Buchta et al. 1984). The location of the section is shown in Figure 22.

2.5 Oil fields in the Austrian part of the Vienna Basin

The Austrian part of the VB comprises more than 20 separate oil fields relevant for our research. Some fields are very small; therefore, they were merged with larger neighbouring fields, which resulted in the number of 16 project-relevant fields. Three geographical clusters have been determined (Figure 25).

Cluster 1 North

The oil fields of Cluster 1 are arranged along the Steinberg fault system in the northern part of the Austrian Vienna Basin. Cluster 1 consists of the oil fields Goesting, Van Sickle, Maustrenk, St. Ulrich-Hauskirchen, Scharfeneck, Neulichtenwarth, Altlichtenwarth, Muehlberg, Bernhardsthal, Rabensburg, Windisch-Baumgarten, Gaiselberg and Paasdorf as well as the field RAG. Neulichtenwarth, Paasdorf and Scharfeneck each contain only small amounts of oil in place and are therefore not included in this project.

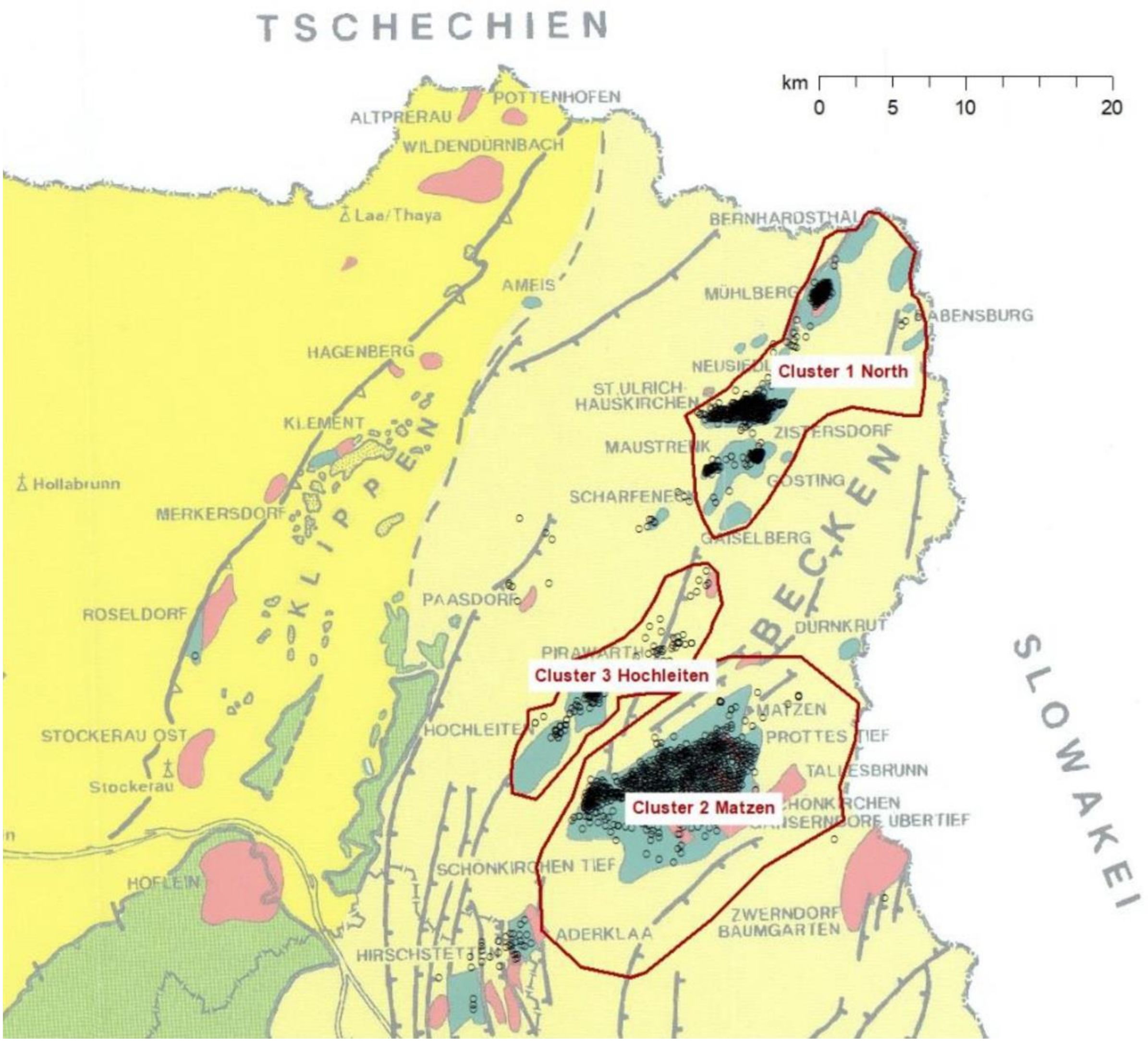

Figure 25. Clusters of oil fields in the Austrian part of the Vienna Basin. Oil fields are marked in dark green. Black circles mark the position of wells. Map adopted from Wessely (1993).

The northernmost oil field is Bernhardsthal, which is located near the Austrian-Czech border. Oil has been produced from Badenian sediments (1,200-1,500 m and 2,000-2,100 m) of a flat dome structure in the downthrown block of the Steinberg fault system (Zistersdorfer Depression) in 1960-1986. In 1986 oil production started in the Eggenburgian strata of the Mistelbacher high, at a depth of 1,750 m. The total cumulative production is less than 1 million tonnes of oil.

Following the south-eastward dipping Steinberg normal fault to the South, the next oil field is Muehlberg (Figure 26). It is heavily fragmented by the SW-NE-striking Steinberg fault system with both north-westward and south-eastward dipping fault planes. Oil reservoirs were found in the Badenian at a depth of 1,000-1,700 m, mostly present in structural traps. Minor oil horizons occur in the so-called Lageniden zone at a depth 1,800-1,900 m.

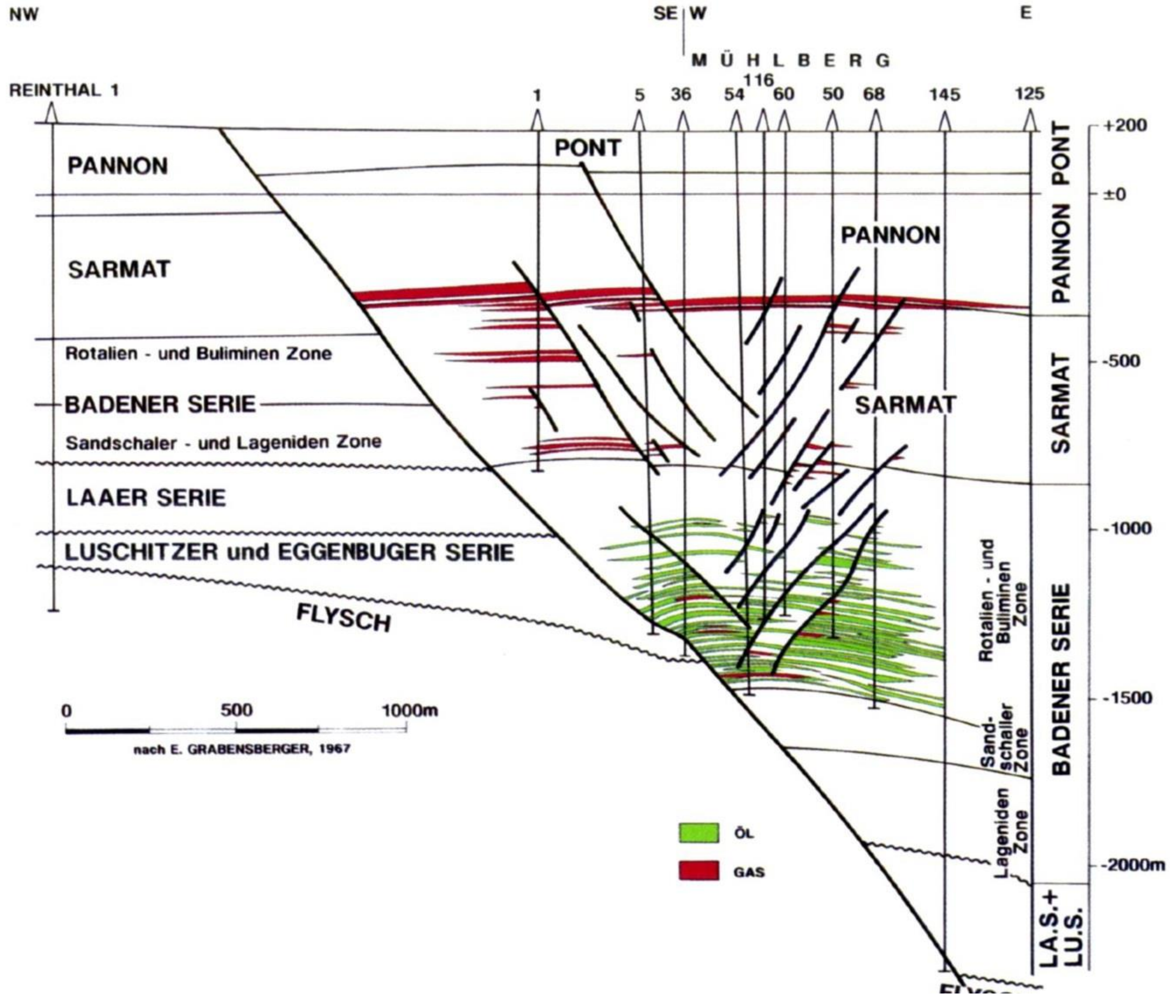

Figure 26. Geological cross-section through the oil field Muehlberg (Kreutzer 1993)

Altlichtenwarth (formerly Altlithenwarth-Neuberg) is an oil field located to the southwest of Muehlberg. The oil-bearing horizons in Altlichtenwarth are situated in a shallow anticline in the Sarmatian (1,000 m) and in numerous blocks of the Badenian (1,400-1,900 m).

Ever further to the southwest are the oil fields St.Ulrich-Hauskirchen and Van Sickle-Plattwald. Both fields share a similar geological setting. Oil in the area of St.Ulrich is found within doming structures in the hanging wall block of the Steinberg fault. The sedimentary succession is split into several blocks. Reservoir horizons in this area start in the lowermost Pannonian (from 450 m) and are found throughout nearly the whole Sarmatian sequence (500-1,000 m) as well as in the upper Badenian (1,000-1,500 m). West of the Steinberg fault system, at the Mistelbach high block, oil production is derived from the Flysch beneath the Neogene basin infill. The oil of this so-called Second Floor reservoir spreads across several fields, reaching from the field St.Ulrich-Hauskirchen throughout RAG, Gaiselberg, Maustrenk, Neusiedl to Windisch-Baumgarten. Fractured Palaeocene glauconite sandstones and the highly porous Eocene Steinberg flysch are underlain by Upper Cretaceous rocks (Altlengbacher Unit). The whole series belongs to the Greifenstein Nappe, which is tectonically separated into the lower Goesting Unit and the higher Zistersdorf Unit. Regarding the fields St.Ulrich-Hauskirchen and Van Sickle-Plattwald, oil is produced from the glauconite sandstone series (900-1,200 m) and the Steinberg flysch series (up to 1,300 m), both part of the Goesting Unit, as well as from the sandstones and conglomerates associated with the “Schlier” base (“Luschitzer series”; 700-1,050 m). The eastern part of the latter is divided into a northern and a southern depositional environment, separated by a zone of W-E striking marls.

South of St.Ulrich-Hauskirchen and along the Steinberg fault system of Cluster 1 are the oil fields Goesting (Figure 27), Neusiedl and RAG. Doming structures in the downthrown block of the Steinberg fault host oil-bearing horizons from the lowermost Pannonian (from 550 m), throughout the whole Sarmatian (800-1,650 m) and in case of the RAG field down to the upper Badenian (1,850-2,305 m). A minor oil reservoir was also found at a depth of 3,145-3,193 m in the so-called Sandschaler zone (Badenian). The Mistelbach high block, directly east of the Steinberg fault, bears oil in the Steinberg flysch series (950-1,150 m) and the glauconite sandstones (1,170-1,700 m) of the Goesting Unit.

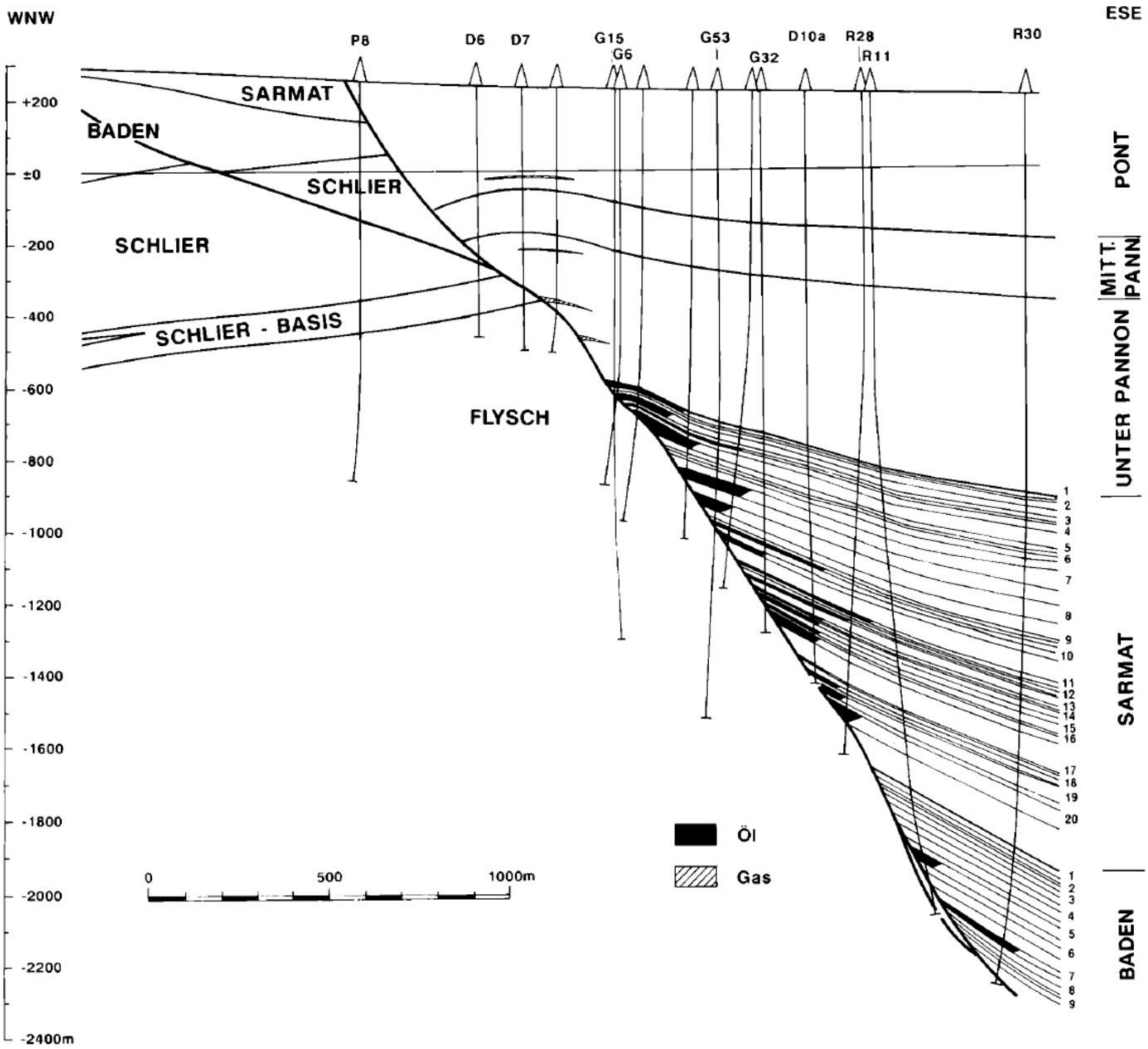

Figure 27. Geological cross-section through the oil field Goesting (Kreutzer 1993).

Maustrenk, formerly called Maustrenk-Kreuzfeld is an oil field associated with the Goesting field. It is located in the block of the Mistelbach high. The main horizon in this area is the aforementioned Luschitzer series of the Ottnangian-Eggenburgian, here found at a depth of 820-1,020 m. It comprises sandstone and conglomerate packages with clay interfingering that generate structural-stratigraphic traps. A thin horizon of so-called “Leitsand” at the base of the Karpartian bears oil too. Further production is derived from the Steinberg flysch and the glauconite sandstones of the Zistersdorfer Unit (tectonically higher part of the Greifenstein Nappe; 900-1,050 m).

The southernmost oil fields of Cluster 1 are Windisch-Baumgarten and Gaiselberg (Figure 28). Sarmatian (930-1,600 m) and Badenian (1,400-2,320 m) sediments of a doming structure in the downthrown block of the Steinberg fault system are oil bearing but they are heavily fragmented. The Steinberg flysch and the glauconite sandstones of the Zistersdorfer Unit of the Mistelbach high block host oil reservoirs as well (500-1,650 m).

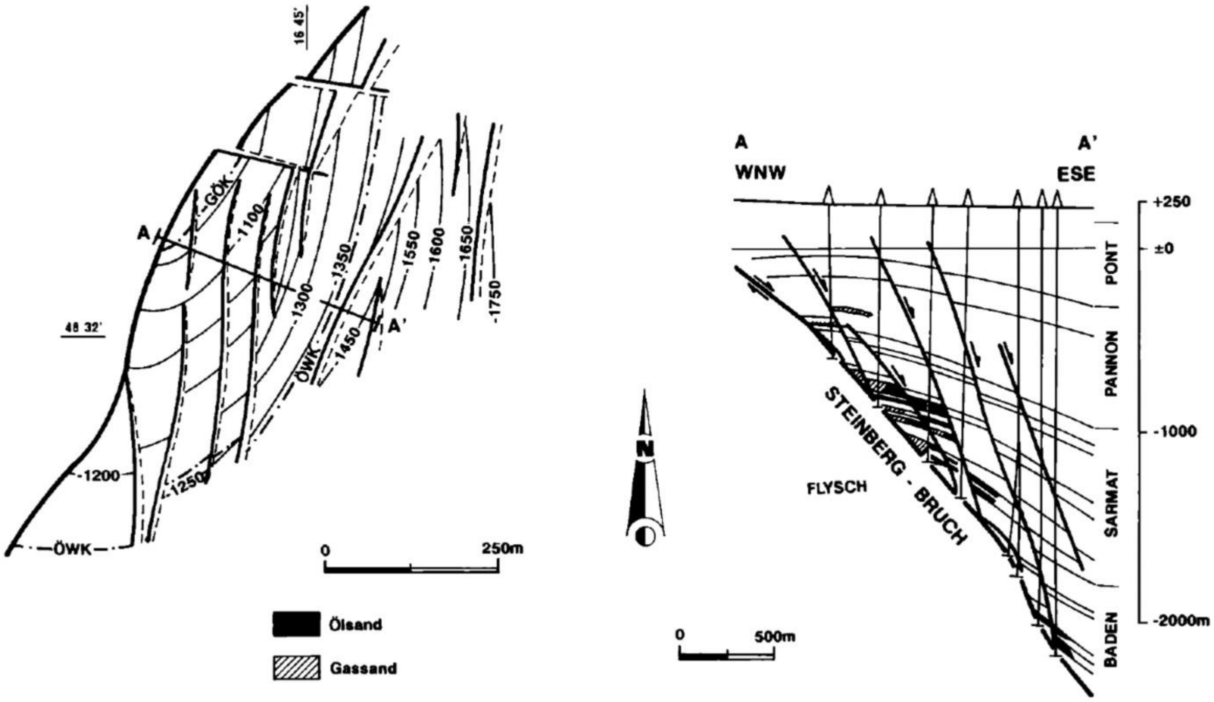

Figure 28. Geological cross-section through the oil field Gaiselberg (Kreutzer 1993).

Cluster 2 Matzen

The only oil field relevant to this study in Cluster 2 is the field Matzen. It is the largest oil field not only in the Vienna Basin but also in all Central Europe. Matzen has a size of approximately 100 km² and more than 200 million tt of initial oil in place. It belongs to the so-called Middle High Zone of the Vienna Basin, a local tectonic high block. To the west, Matzen is bordered by the N-S striking, westward dipping Bockfließer (or Aderklaaer) fault system. It was active during deposition whereas other structures such as the Matzener fault system in the North or the Schönkirchener fault system in the South formed after sedimentation.

Oil and gas in the Matzen field have been produced from 25 important horizons at depths of 900-3,300 m. 10 oil bearing horizons are found in the Badenian (1,100-1,700 m), 2 in the Karpatian (Gänserndorf Unit; 1,900-2,850 m), and 4 in the Ottnangian (Bockfließ Unit; 1,800-2,900 m). Hydrocarbons traps in the Miocene sediments are mostly combined tectonic (due to the three different fault systems) and stratigraphic (local clay accumulations in the sand). The 16th-horizon of the first floor covers around half of the total production of the whole oil field. It is also called “Matzener Sand” and it is the most important oil bearing horizon in the VB.

The reservoirs of the Second Floor (Figure 29) are found in Triassic Hauptdolomites at depths of 2,800-6,000 m, depending on their tectonic setting. Despite their scattered locations and varying oil/water-contact depths, they share a common aquifer and therefore form a coherent hydraulic system. The most important accumulation is the oil reservoir Schönkirchen Tief, which was discovered in 1960. Its initial oil content is about 17.59 million tonnes (Scharf and Clemens, 2006).

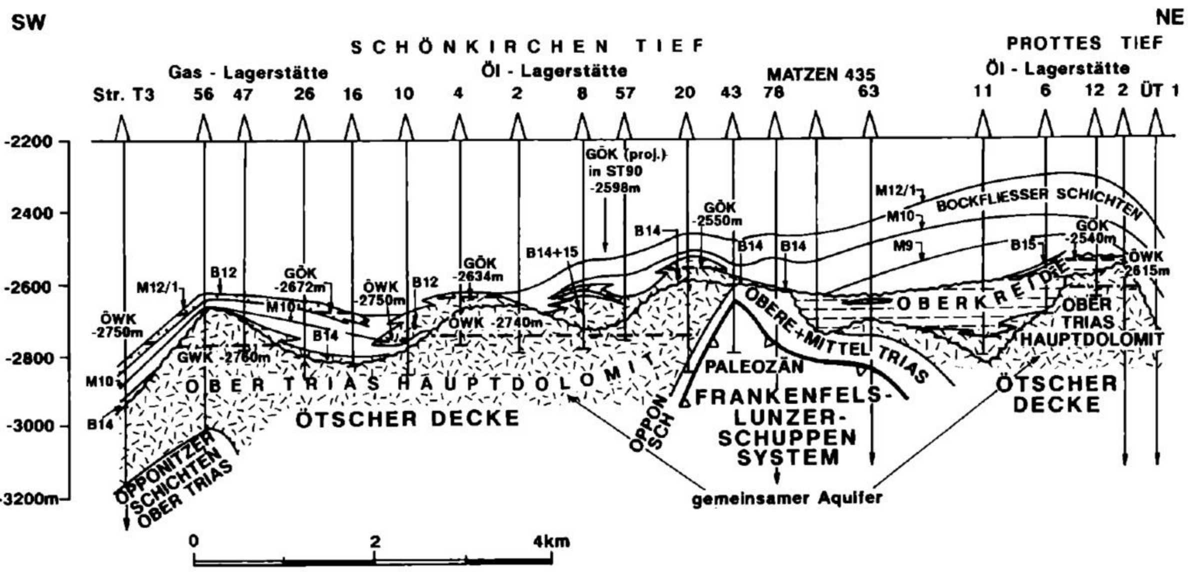

Figure 29. Cross-section through the Second Floor of the Matzen field (Kreutzer 1993).

Cluster 3 Hochleiten

This cluster comprises three oil fields, namely Hohenruppersdorf, Hochleiten, and Pirawarth.

Although still located along the Steinberg fault, the field Hohenruppersdorf (including the field Erdpress) is attributed to Cluster 3 in this study. In this area at the end of the southern Steinberg fault system, the Pirawarth-Hochleiten fault system starts to evolve towards the south-west. Oil-bearing horizons in the downthrown block of the Steinberg fault are found in the Sarmatian (1,050-1,700 m), as well as on the Mistelbach high block (at 750 m) and in one intermediate block (1,300-1,500 m) in the Badenian. Minor production was also derived from the upper Cretaceous Flysch of the Kahlenberg Nappe (1,000 m).

Starting from the upper Badenian, the SW-NE striking Pirawarth-Hochleiten fault system was syn-sedimentary active. A number of tectonic blocks formed, building a sort of stairway toward the Mistelbach high block. The north-easternmost field of this system is Pirawarth. Beginning at the lower Pannonian (480 m) oil is found throughout the whole Neogene sedimentary sequence down to the lower Lageniden zone of the Badenian.

The oil field Hochleiten (Figure 30) is situated just to the south-west of the field Pirawarth, separated by the Hochleiten fault. It is the last oil field of the SE-ward dipping Pirawarth-Hochleiten fault system. Miocene reservoirs are located almost exclusively in the downthrown block of the main Pirawarth fault though on the high block of the eastward dipping Hochleiten fault. Oil is found in the Sarmatian (880-1,140 m), in the Upper Badenian (1,070-1,320 m) and in the Upper Lageniden Zone (885-895 m in intermediate block; 1,450-1,560 m in downthrown block). Below the Neogene sediments, the Second Floor produced some oil from the Upper Cretaceous and Eocene Flysch of the Kahlenberg Nappe (800-2,200 m).

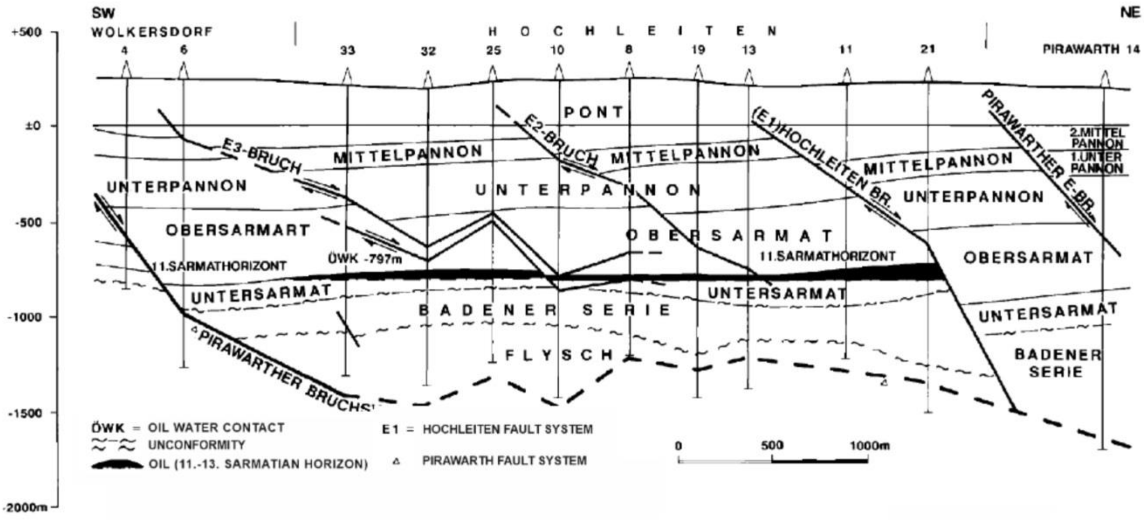

Figure 30. Geological cross-section through the oil field Hochleiten (Kreutzer 1993).

3 Stakeholder mapping and assessment of regional industries and organizations

3.1 Introduction to stakeholder mapping and analysis

In addition to assessing the geological and technical potential for CO_2-EOR in the Vienna Basin, it's also important to understand the broader societal and economic framework of the region. Conducting a stakeholder mapping and analysis is important to identify the organizations that can have an interest in or influence the outcome of a project, in this case realization of a CO_2-EOR project in the Vienna Basin. These regional actors, such as potential investors, government and non-governmental stakeholders can assist in the development of focused recommendations for the development of CO_2-EOR in the Vienna Basin. Stakeholder mapping and analysis have been completed for the Austrian, Czech and Slovakian sectors of the Vienna Basin.

In the following Chapters the results of a simple stakeholder mapping and assessment process for the three regions are presented. In addition to identifying the stakeholders, their interests and possible influence or impact on the potential development of CO_2-EOR in the region is briefly described.

3.2 Austria

In December 2019 Austria presented its long-term strategy on how to reach its climate goals, following up to EU regulation 2018/1999. The strategy comprises several scenarios, where CCS and CCU play an important role to meet Austria's climate obligations. Nevertheless, the underground storage of CO_2 is currently forbidden and the ban is re-evaluated every 5 years (next evaluation in 2023). Research on storage capacity has so far only been carried out for oil and gas reservoirs. The overall capacity is about 500 million tonnes CO_2, of which more than 80 % could be stored in the Vienna Basin. Alternatively, it would also be possible to transport the captured CO_2 to a different country and store it in e.g. large-scale offshore storage sites.

Table 2 presents a broader stakeholder analysis for CO_2-EOR activities in the Austrian part of the Vienna Basin.

We have asked three important industrial stakeholders for an interview and summarized their positions on CCS and CCU.

- *VÖZ*
  The VÖZ (Vereinigung Österreichischer Zementindustrie) forms a lobby for the Austrian cement industry. Its shareholders are CRH, Holcim, Lafarge, Leube, Rohrdorfer, Schretter & Cie, w&p and Baumit. EU ETS CO_2 pricing has a strong influence on the cement industry. A big part of the produced emissions comes from the CO_2 that is released from the carbonates during cement production. Increasing the efficiency by clinker substitution and by using substitute fuels has brought a CO_2 reduction of 25 % in the last 30 years in Austria. According to VÖZ the potential for CO_2 reduction by further efficiency increase is almost exhausted. CCS and CCU would enable a further reduction in accordance with the European Union's objectives. Currently there is no carbon capture project supported by the cement industry in Austria. The implementation of capture technology requires long-term planning and substantial financial investments. So far, research on CCS has only been done by partners in Germany. Should the ban on CCS in Austria continue, then transportation to and storage of CO_2 in other countries could help to achieve the climate goals for the Austrian cement industry.

Table 2. A simple stakeholder analysis for CO_2-EOR activities in the Austrian part of the Vienna Basin. Green = governmental bodies, grey = private companies, blue = non-governmental bodies.

Stakeholder name	Type of organisation	Interests	Influence/impact
Ministry of Agriculture, Regions and Tourism	Governmental body - Ministry	Developing and implementing policies and regulations concerning the use of geological structure	Responsible for the provision of exploration, production and storage licenses of hydrocarbons. Evaluating the CCS ban in Austria every 5 years.
Environmental Agency Austria	Governmental body - independent	Transformation of the economy and society to ensure sustainable living	Recommendations for decision-makers in politics, administration and business in Austria and the EU
OMV	Oil and gas company – partly nationalized	Production of hydrocarbons	Potential CO_2-EOR user and CCS operator, biggest CO_2 producer in the Vienna Basin and potential investor
RAG Austria AG	Oil and gas company	Providing secure, sustainable, competitive and affordable energy	Runs currently power-to-gas system in upper Austria, Experiences with underground CO_2 injection
Wien Energie	Energy supplier	Power plant operator	CO_2 emitter and potential investor
Vereinigung Österreichischer Zementindustrie	Association of the cement industry in Austria	Mining and production of cement	CO_2 emitter and potential investor
EVN	Energy supplier	Power plant operator	CO_2 emitter and potential investor
Agrana Zucker GmbH	Sugar producing company	Production of sugar and sugar products	CO_2 emitter and potential investor
Trans Austria Gasleitung GmbH	Transmission system operator in Austria	Transportation of natural gas via pipeline	CO_2 emitter and potential investor
FCC Zistersdorf Abfall Service GmbH	Waste combustion company	Production of electricity from waste combustion	CO_2 emitter and potential investor
Jungbunzlauer Austria AG	Producer of biodegradable ingredients	Production of biodegradable ingredients of natural origin	CO_2 emitter and potential investor
Fritz Egger GmbH & Co KG	Producer of wood products	Producing wooden construction materials & furniture	CO_2 emitter and potential investor
W. Hamburger GmbH	Paper producing company	Producing paper products	CO_2 emitter and potential investor
Professor Reinhard Sachsenhofer	Montanuniversity Leoben	Research on petroleum geology	Experienced in geology of the Vienna Basin
Professor Holger Ott	Montanuniversity Leoben	Research on CCS and CO_2-EOR	Experienced in CO_2-EOR and underground gas storage
Greenpeace Austria	Non-governmental organization (NGO)	Greenpeace is an independent and international environmental organization.	Holds a negative sentiment regarding the use of hydrocarbons and CCS. Likely to create social and political resistance to a CO_2-EOR project.
Local community next to storage sites			Might lead to public campaign against CCS projects

- *Wien Energie*
  Wien Energie is Austria's biggest energy supplier and one of the biggest CO_2 emitters in the Austrian Vienna Basin. There has been no research on CCS so far, but research on carbon capture with solid sorbents was carried out in the ViennaGreenCO_2 project. Energy suppliers, in contrast to other industrial sectors cannot move to foreign countries and bypass CO_2 pricing. To fulfil its ETS emission reduction goals, Wien Energie will further invest in geothermal energy and perhaps CCU projects. According to Wien Energie, carbon capture technology for thermal power plants or waste incineration

is currently not sufficiently developed, as no large-scale systems have been in operation for the entire life cycle of a plant. CCS investments are not planned and won't be considered unless the legal framework changes and capture technology gets economic.

- *OMV*
  OMV is Austria's biggest oil & gas company and its refinery in Schwechat is the biggest single CO_2 emitting facility in the Vienna Basin. OMV is the most important industrial stakeholder for CCS and CO_2-EOR operations in Austria. On the one hand they are a big CO_2 emitter, on the other hand, if the legal framework should change, they have the necessary technology to realize CCS applications in Austria. Unfortunately, there is currently no clear position on CCS from OMV. A stakeholder interview for the ENOS project could not be realized, as the topic is currently under internal evaluation. According to our research, EOR activities in the Vienna Basin (by OMV) are currently focusing on polymer injection. Whether OMV change their approach to CO_2-EOR if the EU ETS prices rise, is unknown.

3.3 Czech Republic

CCUS does not belong to prioritised climate change mitigation technologies in the Czech Republic, and no national support programmes nor measures have been prepared so far, except for some (limited) support of research and development. Nevertheless, some of the national strategic documents take this technology into account.

The State Energy Policy of the Czech Republic (MPO, 2014) mentions CCS as a technology that may contribute to fulfilling of national climate protection commitments after 2040. It also counts geological storage of carbon dioxide among the basic priorities of energy research and innovation.

The Climate Protection Policy of the Czech Republic (MŽP, 2017) provides three scenarios of achieving 80% GHG emissions reduction by 2050. One of them relies on massive development of CCS in the energy sector, which, unfortunately, cannot be considered realistic any more due to the recent trends of abating fossil fuels combustion in the EU. No considerations of possible role of CCUS in decarbonisation of emission-intensive industries are included.

The National Energy and Climate Plan (NECP) of the Czech Republic for the period 2021-2030 (MPO, 2019) mentions CCS and CCU in combination with possible future utilisation of natural gas for energy and transport purposes, which generally means production of "blue" hydrogen. No concrete plans or measures are suggested. Oil is still considered an important primary energy source up to 2030, with relatively stable input energy value of ca. 370 PJ throughout the period. This would correspond to a 20.5 % share in the mix of primary energy sources in 2030. In this respect, increasing the domestic oil production, including utilisation of CO_2-EOR, can be considered desirable.

Table 3 presents a broader stakeholder analysis for CO_2-EOR activities in the Czech part of the Vienna Basin.

CGS organised a series of meetings and consultations with key stakeholders representing the group of policy makers and regulators to discuss the current national political and regulatory framework of CCUS, including utilisation of CO_2 for EOR. Meetings were held with Ministry of Industry of Trade, Ministry of the Environment – Dept. of Geology and Dept. of Energy and climate protection, and the District Mining Authority in Brno (responsible for the Vienna Basin area in the Czech Republic).

Table 3. A simple stakeholder analysis for CO_2-EOR activities in the Czech part of the Vienna Basin.

Stakeholder name	Type of organisation	Interests	Influence
Ministry of Environment	Governmental body - Ministry	Developing and implementing policies and regulations for Czechia in national environmental affairs. Administrative and supreme inspection authority for nature and landscape protection, waste management, water protection, EIA, national environmental policy and geological works.	Main national CCS policy maker, also influencing related legislation and regulatory framework. Responsible for the award of exploration licenses and CO_2 exploration permits.
Ministry of Industry and Trade	Governmental body - Ministry	Develops national energy and industrial policies, including raw materials and decarbonisation strategies.	Influences political framework and legislation related to CCS.
Czech Mining Authority	Governmental body – Independent regulator of mining activities and production	Implementing the requirements of the Czech Mining Law, particularly with regard to safety, environmental protection and mineral deposits protection.	Responsible for the award of production licenses and CO_2 storage permits, also responsible for CO_2-EOR operations permitting
Building Authorities	Regional level authority	They issue building permits, land use plans, including subsurface use.	Responsible authorities for land use permit (pipelines, CO_2 injection facilities etc.).
Environmental and water departments of regional authorities	Regional level authority	They issue permits for all kind of land use, mining activity including (drilling, geological exploration) from point of view of environmental impacts.	Responsible authorities for environmental requirements related to mining activities (drilling, geological exploration)
MND	Private company – Oil and gas	Exploration, production and storage of oil & gas.	Potential CO_2-EOR project developer or investor. Currently producing oil in multiple fields.
LAMA Gas & Oil	Private company – Oil and gas	Exploration and production of oil & gas	Potential CO_2-EOR project developer or investor. Currently producing oil in the Vienna Basin only.
NET4GAS	Private gas transportation company	The gas transmission system operator in the Czech Republic; operates more than 3,800 km of pipelines.	Potential cooperation in building of CO_2 transportation network
ČeskomoravskýČeskomoravský cement Mokrá - HeidelbergCementMokrá - HeidelbergCement group	Private company – cement plant	Cement producer	Potential source of CO_2. The company is interested in developing CCS.
Carmeuse - Vápenka MokráVápenka Mokrá	Private company – lime works	Quicklime producer	CO_2 emitter and potential investor
Liberty Ostrava	Private company –ironworks	Iron and steel producer	Potential source of CO_2. (long distance but high CO_2 emission) The company is interested in developing CCS.
Greenpeace Czechia	Non-governmental organization (NGO)	Greenpeace is an independent and international environmental organization.	Holds a negative sentiment regarding the use of hydrocarbons and CCS.
ZelenýZelený kruh (Green circle)	Non-governmental organization (NGO)	Zeleny kruh is a national umbrella organization, associating green NGOs, based in the Czech Republic.	Holds a balanced sentiment to CCS, however uncertain regarding EOR.

The position of the Ministries towards CO_2-EOR is rather ambivalent because this technology is considered just a special kind of oil production, fully within the competence of the Mining Authority. Utilisation of depleted hydrocarbon reservoirs for CO_2 storage is acknowledged as the primary opportunity for deployment of the technology in the country because of the higher level of knowledge in comparison with deep saline aquifers. All the consulted authorities are aware of the gaps in the regulatory framework (see chapter 7.1 for details) but are not planning any immediate actions to improve the situation at the moment. They also register the increased interest of the emission-intensive industries in CCUS (see below). The Chairman of the District Mining Authority in Brno is supportive of development of CO_2-EOR with subsequent CO_2 storage in Czechia and does not see any serious regulatory obstacles that should hinder this development.

Consultations were also held with two potential CO_2-EOR project developers – the oil companies MND a.s. and LAMA Gas & Oil s.r.o. MND is a long-term partner of CGS, supporting a number of CO_2-EOR and CCS-related studies in the past and present. MND is member of ENOS End-User Committee and supported ENOS, including this study, by provision of data from the oil fields it has been operating. MND is interested in developing CO_2-EOR projects possibly combined with subsequent CO_2 storage. LAMA Gas & Oil is a smaller operator of two oil fields in the Vienna Basin and their interest in CO_2-EOR remains reserved.

Last but not least, a series of meetings was organised with representatives of CO_2-emission-intensive industries – Liberty Ostrava (iron and steel producer), Českomoravský cement (cement manufacturer) and C-Energy Planá (energy producer). All of them are currently considering CCUS as an option for reduction of their greenhouse gas emissions and are highly interested in concrete possibilities of using hydrocarbon fields (not only in the Vienna Basin) as possible CO_2 storage sites, looking for a competent partner as storage site operator at the same time.

From the geographical point of view, the most interesting partner would be Českomoravský cement, member of the HeidelbergCement Group, operating one of the biggest Czech cement plants at Mokrá, in a distance of ca. 50 km from the oil fields in the Czech part of the Vienna Basin. This facility has been selected for one of the case studies of ENOS Task 6.5 (see chapter 6.2.2) and the information obtained in the meeting were used for elaboration of the study.

3.4 Slovakia

The organisations in Slovakia responsible for granting of provisions for CO_2 storage and CO_2-EOR exploitation fall within Ministry of Environment and Ministry of Economy of the Slovak Republic. Granting of permissions is based on expertise and opinion of the government body Main Mining Authority, as an independent regulator of mining activities in the Slovak Republic.

SGIDS and CGS held a meeting with NAFTA, the private oil and gas exploration and production company, on various topics related to the ENOS project. Regarding CO_2-EOR, NAFTA top management considers the technology currently not relevant and unprofitable.

Potential stakeholders owning sources of CO_2 haven´t been approached. The largest emitters in the region, are Slovnaft a.s., an oil refinery, and cement factories. Only a limited amount of public information on their CO_2 emissions are available. The opinion of non-governmental organisations regarding CCUS and CO_2-EOR is generally unknown; these organisations might, however, have a strong influence on public attitude.

Table 4 presents a broader stakeholder analysis for CO_2-EOR activities in the Slovak part of the Vienna Basin.

Table 4. A simple stakeholder analysis for CO_2-EOR activities in the Slovak part of the Vienna Basin.

Stakeholder name	Type of organisation	Interests	Influence
Ministry of Environment of the Slovak Republic	Governmental body - Ministry	Developing and implementing policies and regulations for Slovak in national environmental affairs. Administrative and supreme inspection authority for nature and landscape protection, waste management, water protection, EIA, geological works, GMOs, national environmental policy	Responsible for the provision of mining area and CO_2 storage permits needed for CO_2-EOR. Also responsible for the provision of subsidies to facilitate possible CCS projects
Ministry of Economy of the Slovak Republic	Governmental body - Ministry	Developing and implementing policies and regulations for Slovak enterprises, energy, agriculture and climate. Central body of state administration for power engineering and nuclear waste storage, heat and gas manufacture, exploitation of natural resources	Responsible for the provision of CO_2 exploitation permits needed for CO_2-EOR
Main Mining Authority	Government body – Independent regulator of mining activities	Providing and administrating of international and national mining activities and supervision of the Mining Act of the Slovak Republic	Will provide expertise and opinion to the Ministry of Environment and to Ministry of Economy regarding the provision of licenses for CO_2-EOR operations.
NAFTA	Private company – Oil and gas	Exploration, production and storage of oil & gas.	Potential CO_2-EOR project developer or investor. Currently producing oil in multiple fields.
SLOVNAFT	Private company – Oil refining plant	Production and storage of petroleum and chemicals.	CO_2 emitter and potential investor
Duslo	Private company – Chemical industry and fertilisers	Chemical production of fertilisers and other technical chemicals	CO_2 emitter and potential investor
CEMMAC	Private company – cement factory	Cement producer	CO_2 emitter and potential investor
CRH (Slovakia)	Private company – cement factory	Cement producer	CO_2 emitter and potential investor
Považská cementáreň, Ladce	Private company – cement factory	Cement producer	CO_2 emitter and potential investor
SPP/Eustream	Private company - gas transportation	Responsible for the transportation of natural gas in the Slovak Republic.	CO_2 emitter and potential investor
Greenpeace Slovakia	Non-governmental organization (NGO)	Greenpeace is an independent and international environmental organization.	Holds a negative sentiment regarding the use of hydrocarbons and CCS.

4 EOR potential by CO_2 injection in the Vienna Basin reservoirs

4.1 Introduction

This section outlines the methodology used and results of a screening of depleted and partially depleted reservoirs in the Vienna Basin in view of investigate the potential for CO_2 based EOR, and subsequent CO_2 storage. This assessment is essential to gain an initial picture of the favourability in economic terms, of the additional oil that could be recovered through the injection of CO_2. Furthermore, given that storing CO_2 in geological formations can have an economic value due to participation in the EU Emission Trading Scheme, the total amount of CO_2 that can be stored after the EOR operations can also be a deciding factor in establishing a business case.

In addition to literature search and some reviews into use of analytical tools, the investigations were primarily based on use of conceptual reservoir simulation models, using compositional, Equation of State (EOS) based reservoir fluid descriptions.

4.2 Data collection

GBA, CGS and SGIDS collected the necessary data from the Austrian, Czech and Slovak oil fields identified in Chapter 2. Where necessary, the fields were subdivided into several “basic units”, corresponding to a part of the field (block or horizon) that can be characterized by a single set of parameters needed for CO_2-EOR suitability screening as described below. The threshold for inclusion of a basic unit in the screening process was the amount of 100,000 Sm^3 OOIP (original oil in place).

In total, input data were prepared for 74 basic units representing 40 oil fields, both producing and abandoned, in all three national parts of the Vienna Basin (see Table 5). For the purposes of the study, and to enable presentation of results under the data confidentiality constraints (see below), the oil fields were grouped into geographical clusters. Three clusters were created in every country, each of them including several oil fields. An overview map of the clusters is provided in Figure 31.

Table 5. Overview of input data provided for CO_2-EOR screening.

Country	No. of clusters	No. of oil fields	No. of basic units
Austria	3	16	24
Czech Republic	3	14	31
Slovakia	3	10	19

Two main data sources were used to collect the necessary input data:

(i) national archives and geological databases maintained by the three project partners (GBA, CGS and SGIDS) within their performance of the duties as national geological surveys, and

(ii) data and information provided by the operators of the fields, i.e. the national oil companies in the three countries concerned – OMV, MND and NAFTA.

The data provided by the oil companies to the project were partly or fully in confidential regime. Due to this, an agreement had to be reached concerning the level of detail to be revealed in the present report which is a public deliverable of the ENOS project. According to this agreement, neither input data for the screening process, nor individual screening results on the basic unit or field levels can be published. It was confirmed that the results will be published on the aggregated cluster level, which in itself is sufficient for the study purposes.

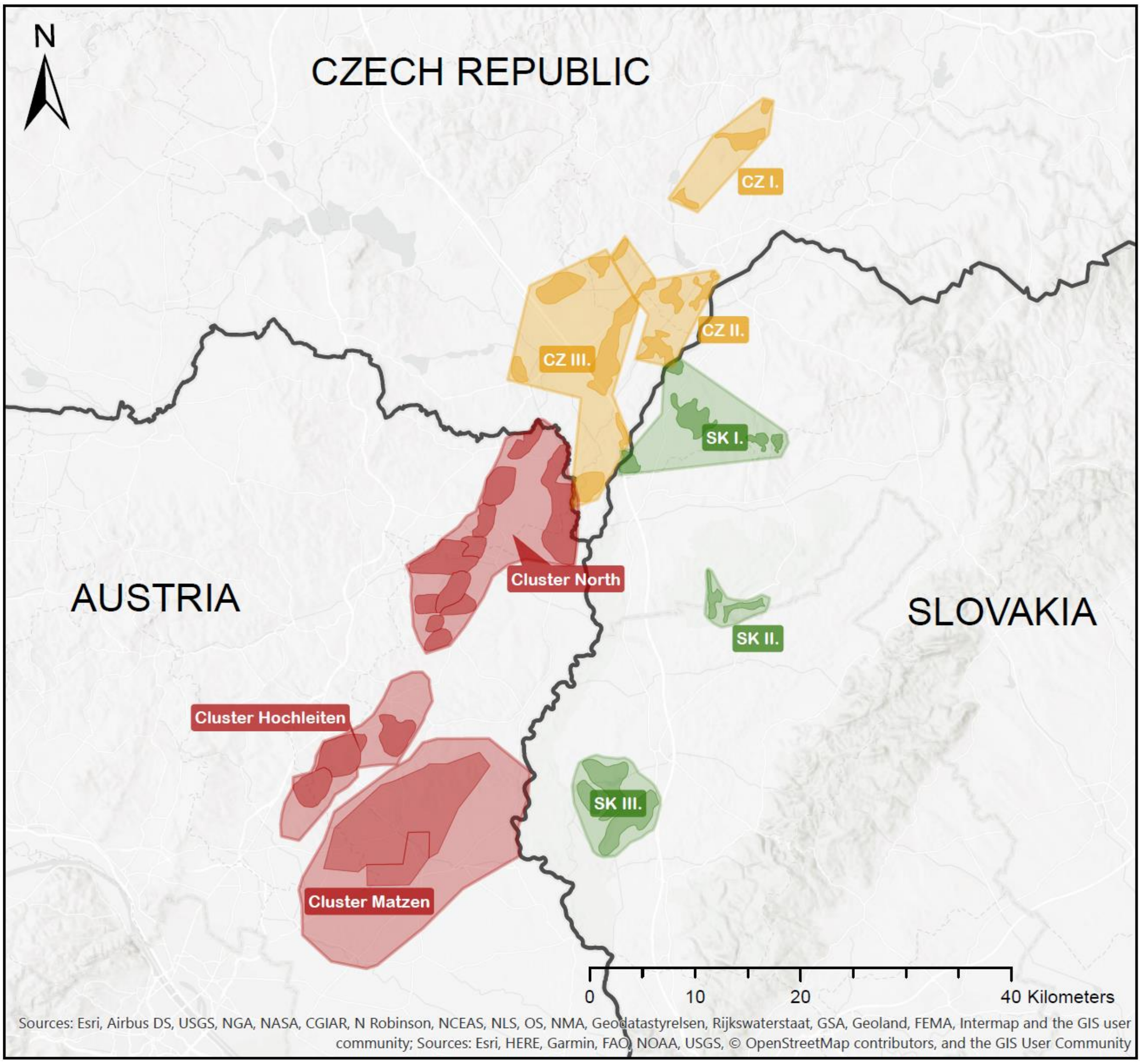

Figure 31. Map of clusters of oil fields in the Vienna Basin used for CO_2-EOR screening.

The collection of information on potential CO_2-EOR candidate reservoirs was done on basic unit level through a questionnaire form (Table 6). In designing the questionnaire, care was taken of balancing the need for data precision versus the field operators need or desire to protect confidential information. The data were therefore asked for within specific intervals or ranges rather than more exact values. This should ease the data confidentiality constraints as well as minimizing the workload for the partners and field operators, while still providing enough information to enable a proper screening of the EOR potential. For many of the reservoirs, particularly in the Czech and Slovak regions, more precise information was nevertheless made available.

Table 6. Data collection form (example).

Parameter	Parameter range selection					More presice value if available
Rock type	Sandstone	Carbonate/Chalk				
Depth (metres to water/oil contact)	< 1000	1000 - 1500	1500 - 2500	> 2500		1560
Effective permeability (mD)	Tight (< 1 md)	Poor (1 - 30 md)	Intermediate (30 - 300)	Good (300 - 3000)	Excellent (3000+)	360 - 860
Permeability variation (max/min)	10 (Homogenious)	100	1000 (Heterogenious)			
Average anisothrophy (kv/kh)	< 0.001	0.001 - 0.01	0.01 - 0.1	> 0.1		
Faults/compartimentalization	Heavy	Intermediate	Fairly open			
Dip angle	< 5 %	5 - 10 %	> 10 %			
Oil zone thickness (m)	< 10	10 - 50	50 - 100	> 100		20
Oil quality (API gravity)	10 - 30	30 - 40	> 40 (volatile)			26
Solution GOR (Rs) (Sm3/Sm3)	< 10	10 - 30	30 - 100	> 100		77
Initial pressure	Hydrostatic	Overpressured < 20 %	Overpressured < 50 %	Overpressured > 50 %		16
Depletion (from initial pressure - %)	< 10	10 - 20	20 - 50	> 50		ca 40
Original oil in place (1000 Sm3)	< 100	100 - 500	500 - 1000	1000 - 5000	> 5000	240
Current recovery factor (%)	< 20	20 - 30	30 - 40	> 40		31
Reservoir oil condition	Saturated	Saturated w/gas cap	Undersaturated			

Only a minimum set of parameters was requested. Parameters for which the values, with sufficient precision, could be derived from the values of other parameters, were omitted. Typical examples would be reservoir temperature to be estimated from depth using a common temperature gradient, or in-situ fluid viscosity determined through standard correlations with API gravity, solution GOR (Rs) and temperature.

4.3 Reservoir information overview

Data from 74 reservoir basic units were collected, 24 in Austria, 31 in the Czech Republic and 19 in Slovakia (see Table 5). The units span quite a wide range in reservoir characteristics such as original in-place hydrocarbon volumes, reservoir quality, fluid properties, formation depth etc. Common to most of them where on the other side that all (but one) are sandstone reservoirs, containing saturated oil, mostly with gas cap, and were originally at hydrostatic or moderately over-pressured condition.

A common denominator for these reservoirs, in particular those in the Czech and Slovak regions, also seems to be that the primary recovery has taken place through natural depletion, where the drive mechanism has been natural aquifer support combined with gas cap expansion. Based on the indicated primary recovery factors, ranging from 20 to 40 percent, it appears that this strategy has worked quite well, despite the relatively thin oil zones found in many of these reservoirs.

A drawback of this primary recovery process might be that the reservoir pressure in some cases has fallen below the supercritical level for CO_2 (74 bar), which means that initial CO_2 injection will be in gas-phase condition. This might have negative consequences, both in handling of the injection process, as well as by reducing the EOR efficiency. In such cases it might be necessary to increase the reservoir pressure by water injection or wait for the aquifer to re-charge the reservoir prior to start-up of the CO_2 flooding.

4.4 Recovery process

The CO_2-EOR process foreseen for the candidate reservoirs in the Vienna Basin will primarily be a form of solution gas drive. Due to the generally fairly shallow reservoirs and ditto pressure limitation, fully miscible displacement cannot be expected. However, both the Equation-of-State (EOS) based compositional simulations as well as the correlations for CO_2 solubility in oil presented in (Emera & Sarma, 2007), suggest that significant dissolution of CO_2 into the oil phase, probably in the order of 50 to 70 % should be possible. This will lead to important swelling of the oil in place, as well as considerable reduction in its viscosity.

The initial simulation experiments convincingly indicate that the best EOR strategy will be to inject CO_2 at a low position relative to the oil zone, probably at the original WOC or even somewhat deeper to ensure good dispersion of the CO_2 and maximizing the contact with the remaining oil. The CO_2 will thus have maximum opportunity to percolate into and through the oil zone and enhance the mixing process.
Injecting CO_2 below the oil zone should also be limiting further influx of water from the aquifer, thus leading to reduced water cut and ditto water production. This effect is clearly demonstrated by the simulation results.

4.5 Screening process

Analytical modelling (e.g. SWARD) and literature search were initially thought to be paramount in this screening exercise. However, most of the examples presented in the literature or serving as data basis for the analytical modelling are founded on the CO_2-EOR experiences from the US and generally subject to the following constraints:

- The CO_2 has come at a cost, both for purchase and transport (rather than being a potential income through the ETS), thus encouraging optimization and minimization of CO_2 usage.
- As a consequence, CO_2-EOR are normally performed through a WAG process, and not as a clean, continuous CO_2 injection.
- Full miscibility has often been considered as a prerequisite for a successful CO_2 flood.

Except for a few reservoirs which could attain full miscibility, none of these conditions apply for the potential projects in the Vienna Basin. The EOR screening process has therefor primarily been based on conceptual modelling, using an 8-component, Equation-of-State (EOS) compositional simulation approach. Literature data have been consulted for qualification and verification purposes.

The base-case concept model is illustrated in Figure 32. The configuration was to some extent based on the experience from modelling of the Lbr-1 reservoir (ENOS D4.5: Reservoir models of novel CO_2-EOR concepts at LBr-1). The grid cell size was set to 50 m by 50 m laterally with 2 m thickness. The model was given 25 layers, resulting in a total formation thickness of 50 m. An alternative model with 25m by 25 m grid cells was established to handle cases with low permeability and/or heavy oil.

Porosity and permeability distribution were somewhat randomised in order to create some basic heterogeneity. In addition, the permeability field could be tailored to meet criteria of heterogeneity in terms of max/min value and Dykstra Parson coefficients.

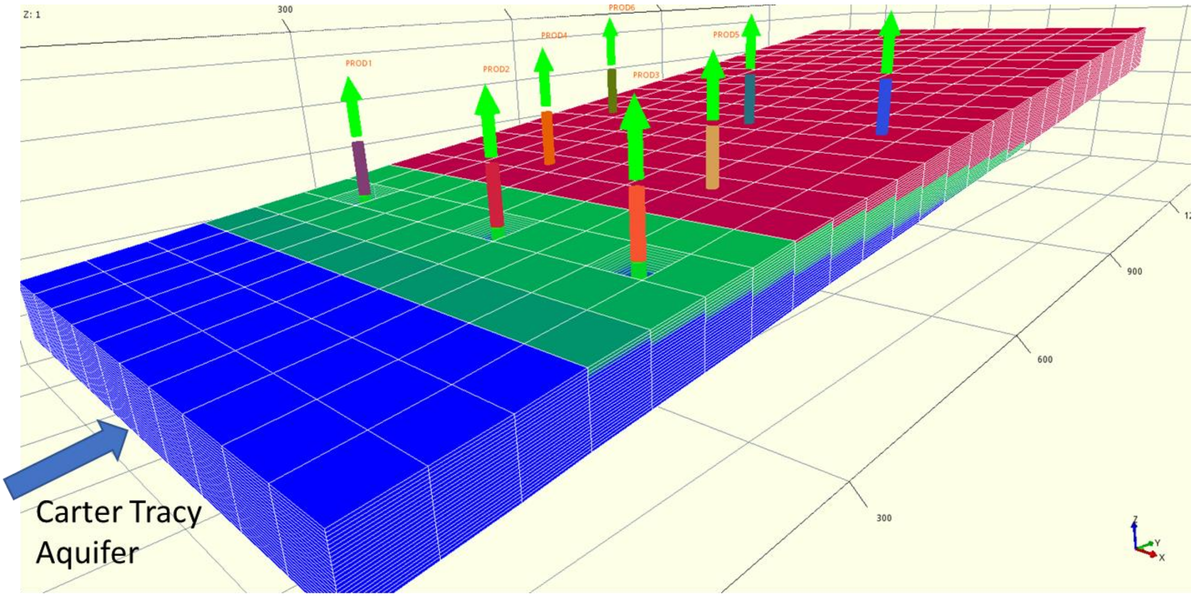

Figure 32. Base case model layout (initial condition)

A set of simulation cases were established in order to investigate the effects of various reservoir configurations and characteristics:

- Dip angle (3, 6 and 12 deg)
- Permeability; low (20 – 50 mD), high (300-1000 mD)
- Heterogeneity (weak, strong)
- Anisotropy (Dykstra Parson coefficient, reservoir zonation, vertical communication)
- Aquifer support (weak, intermediate, strong)
- Fluid properties (heavy, intermediate, light)
- Gas-cap (none, small, larger...)
- Oil zone thickness

It was certainly not achievable to run all combinations of the various configurations, and the different cases were thus set up to cover several aspects at the same time, choosing to vary parameters which were expected to have low interdependence.

4.6 Simulation premises

For all cases, the model was run through a primary recovery process, driven by aquifer support and gas-cap expansion if applicable (no injection). The production took place through vertical wells, covering the oil zone area, with a well spacing of ca 100 m for the low permeability/heavy oil cases, and 200 m for other cases. The wells were set to shut-in when water-cut or gas-oil ratio exceeded pre-set limits (98 % water-cut or 8,000 Sm^3/Sm^3 in GOR). No further optimizations were done, and the models were run until all producers were closed according to the above constraints.

Through the simulation restart facility, the CO_2 injection was launched after all the primary recovery potential was exhausted. The CO_2 was injected into horizontal wells placed approximately at the original WOC, with a direction perpendicular to the strata (i.e. dip direction). The use of horizontal wells was decided in order to reduce modelling complexity, without regard to technical or economic opportunities.

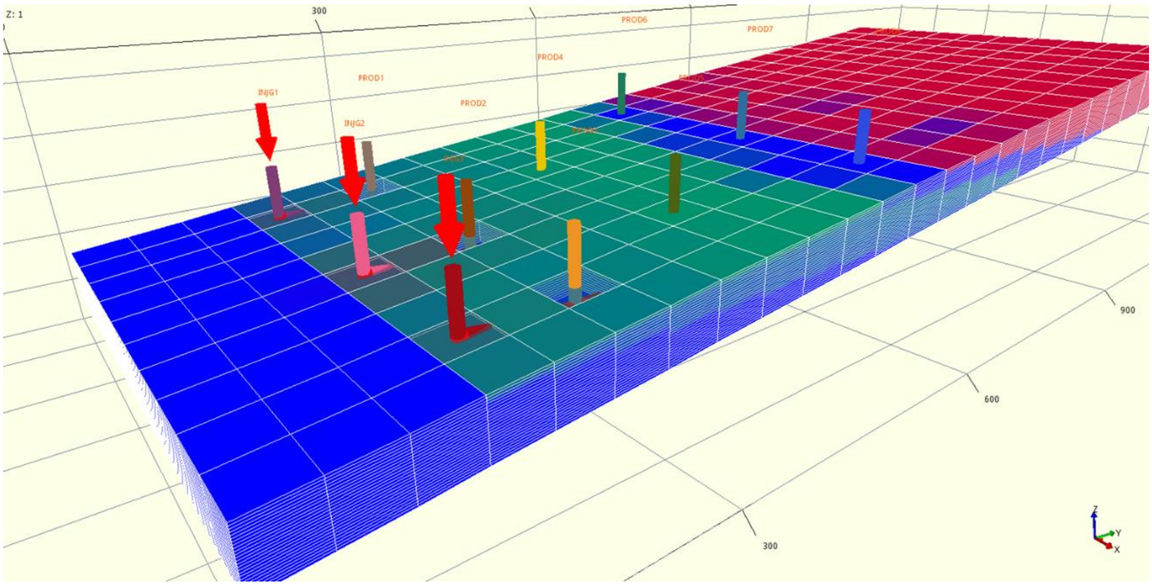

Figure 33. Reservoir model, prior to CO_2 injection.

Figure 34 illustrates a typical model output recovery profile, combining the primary depletion and the CO_2-EOR periods.

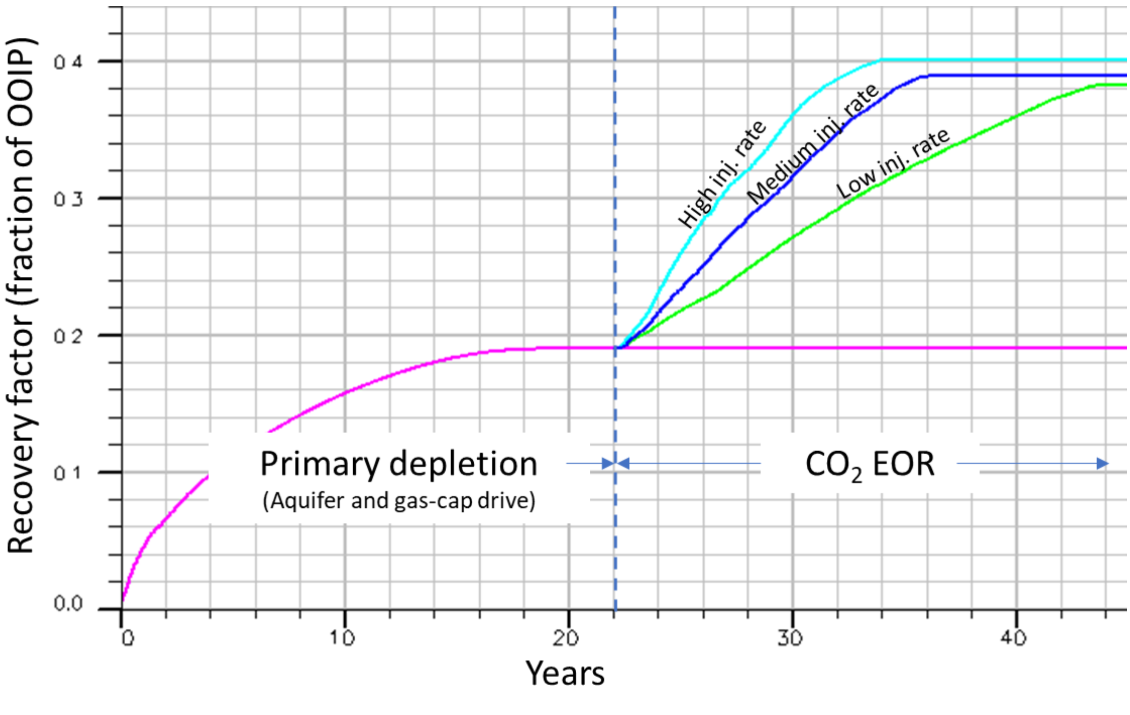

Figure 34. Example recovery profiles exhibited by the concept models.

4.7 EOR scoring

Each reservoir unit was compared with relevant concept models and valuated with respect to some key reservoir parameters, which based on the ensemble of simulation results appeared to be the most influential regarding CO_2-EOR efficiency. These were dip angle, gas cap, anisotropy, oil zone thickness, API gravity, original oil in place (OOIP), faulting, depth and potential for miscibility. Each parameter was given a whole number score value, ranging from -3 to +2, dependent on how it was considered that the parameter value would promote or impede the EOR process.

The scores for the individual parameters were summed-up and normalized (0 – 1) based on the maximum and minimum value for the total score. Further based on the simulation results, literature search (in particular (Azzolina & et al., 37 (2015)) see Figure 35), and general concern with respect to "safety factor" a potential incremental recovery factor span was decided, ranging from 4% to 21% for the Czech and Slovak reservoirs, and 5% to 15% for the Austrian fields (difference mainly due to lesser precision and variation in the Austrian reservoir data). The EOR factor for each reservoir was then decided based on the normalized score value (e.g. 0 = 4%, 1 = 21%). These factors are typically within the range reported in literature (Azzolina & et al., 37 (2015)), (Perera & et al., 2016), (U.S. Geological Survey, 2017).

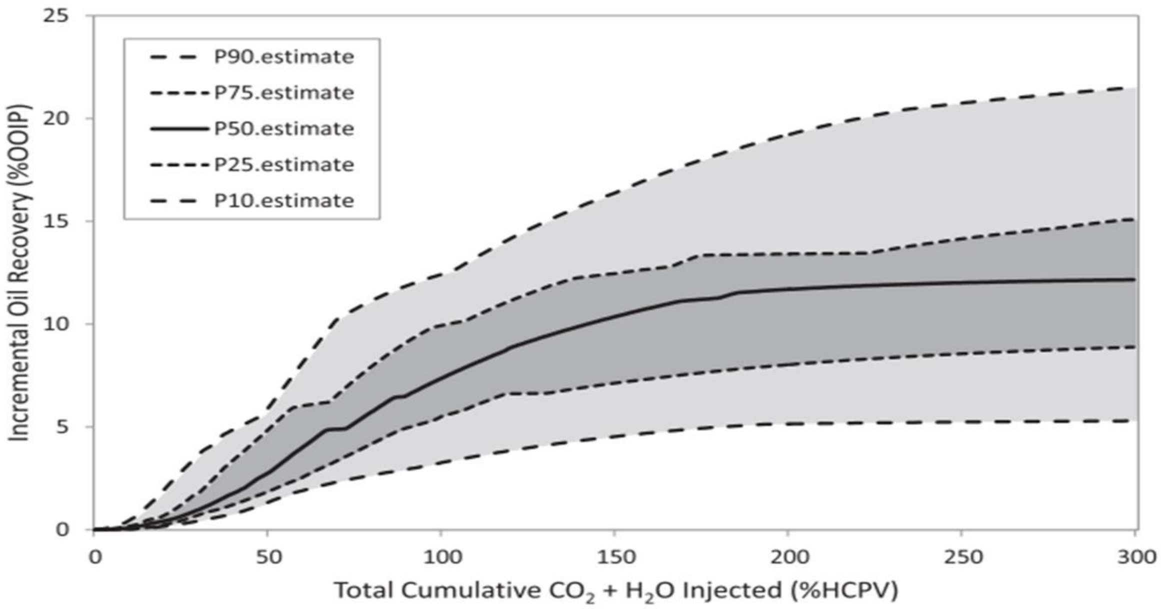

Figure 35. Incremental oil recovery from CO_2-WAG flooding (exerted from Azzolina & et al. 2015).

4.8 CO_2 storage

Estimating the CO_2 storage or retention factor (fraction of the injected CO_2 that will remain in the reservoir) was trickier, as there are more, often unknown factors involved, such as aquifer size and strength, gas-cap volume, and the overall pressure distribution before and during the injection. There is also a question whether the amount of net CO_2 injection should be subject to reservoir pressure constraints only, or if other considerations, such as potential spill points should be taken into account.

The CO_2 storage results presented here are again based on the conceptual simulations, however through a less rigorous approach than those for the EOR estimations. The ensemble of modelling results was evaluated in view of which reservoir and/or fluid characteristics could govern the CO_2 storage potential, and the capacity of each reservoir was judged according to these characteristics. The results are presented in terms of tonnes of CO_2 retained per Sm^3 of Original Oil in Place (OOIP). The OOIP may not be the best scaling parameter for CO_2 storage capacity, but for the current screening process, it is the only volumetric parameter available.

For many cases, the indicated storage quantities far exceed the original hydrocarbon pore volume (HCPV) of the original oil zone. This implies that a lot of CO_2 would be located either in the original gas-cap volumes (as a plume on top of the oil zone) and/or in the underlaying water zone, in addition to the CO_2 in solution with the remaining oil.

4.9 EOR production profiles

The EOR production profiles will naturally vary from reservoir to reservoir, based on actual geology, petrophysical properties, fluid properties and other qualities provided by nature, as well as well spacing, production operations and other man-made constraints. Trying to generate individual profiles for the various reservoirs can thus not be justified and would anyhow have limited credibility and value. However, based on modelling results, a set of five generic profiles were established (Figure 37). These take into account dip-angle, reservoir quality, fluid quality, heterogeneity (Dykstra Parson coefficient) and gas-cap (with or without). The profiles have the general characteristics of an early period of peak or plateau production followed by later decline, but the length of the plateau and shape of decline may vary.

4.10 CO_2 injection and storage profiles

The CO_2 injection has two important aspects; the total injection rates, which includes imported as well as re-circulated CO_2, and the storage or retention rate, which over time should match the import. The total injection may also contain some hydrocarbon gas, either free gas coned in from the gas cap, and/or dissolved gas released from the produced oil. The overall modelling results indicate the HC gas volumes will only constitute a minor part, i.e. less than 3 % of the re-circulation gas handling.

The total gas injection rate will to a great extent be constrained by CO_2 availability (i.e. import), and process, pumping and well capacities, i.e. parameters under human control. Based on review of various modelling results, it seems like the total accumulated injection including re-circulation varies in the range of 3 to 4 tons of CO_2 per Sm^3 of OOIP in order to realize the EOR potential. It also appears that the ultimate EOR is not strongly affected by the injection rate, i.e. the recovery process may be faster or slower without hampering the EOR effect (even though a slower process may be slightly more efficient (see Figure 34 and Figure 36). It is therefore suggested to use 3.5 tons of CO_2 per Sm^3 of OOIP as a standard value for gross CO_2 injected for all prospects, to be distributed linearly as a yearly amount over the anticipated EOR period – maybe with some build-up during the first year or two and some tapering towards the end.

Establishing the CO_2 storage profiles, i.e. import quantities, has been more challenging as these will be mostly governed by the reservoir and fluid characteristics. Typical for these profiles seems however to be an initial period of high net injection, before CO_2 break-through, followed by a period dominated by CO_2 re-circulation and more moderate net storage. Toward the end there could be a slight increase as the producers start closing for economic reasons and less CO_2 is returned from the reservoir, until the injection becomes constrained by reservoir pressure build-up. This late increase may not be achievable if a spill point constraint should apply in which case the rise in reservoir pressure probably should be limited by the reservoirs initial pressure.

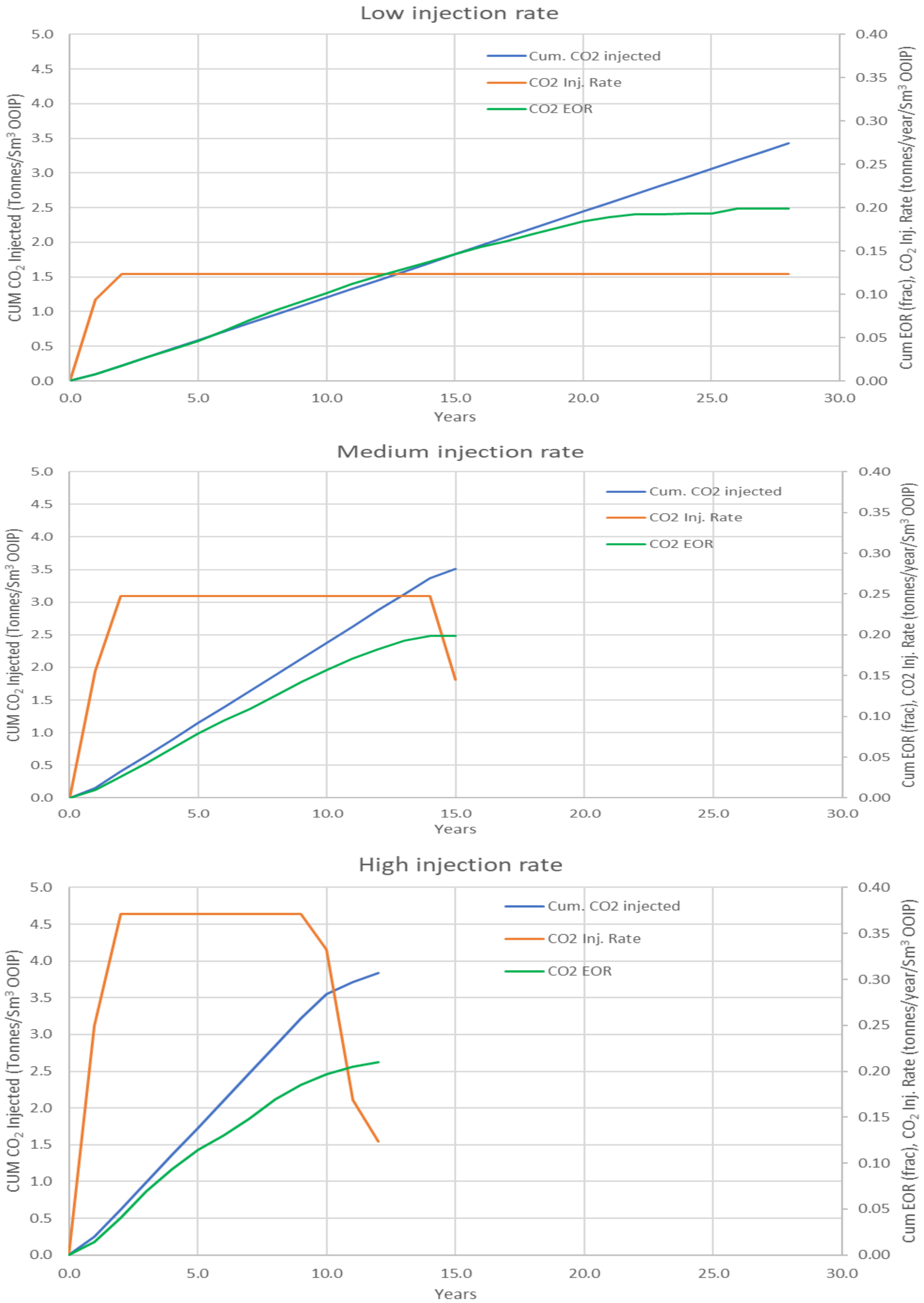

Figure 36. EOR efficiency vs CO_2 injection rate.

4.11 Preparation of results

The generic profiles were connected to the individual reservoirs through an index parameter, based on a judgement as to which of the 5 profiles could be the most likely for the specific units. Together with the OOIP and estimated recovery factor and CO_2 storage factor, this should serve as input to calculate the actual EOR and CO_2 storage profile for each reservoir.

Figure 37 exhibits the 5 generic EOR profiles in terms of the fraction of the ultimate EOR taken out each year over a 15-year period (the integration of each curve should sum to unity).

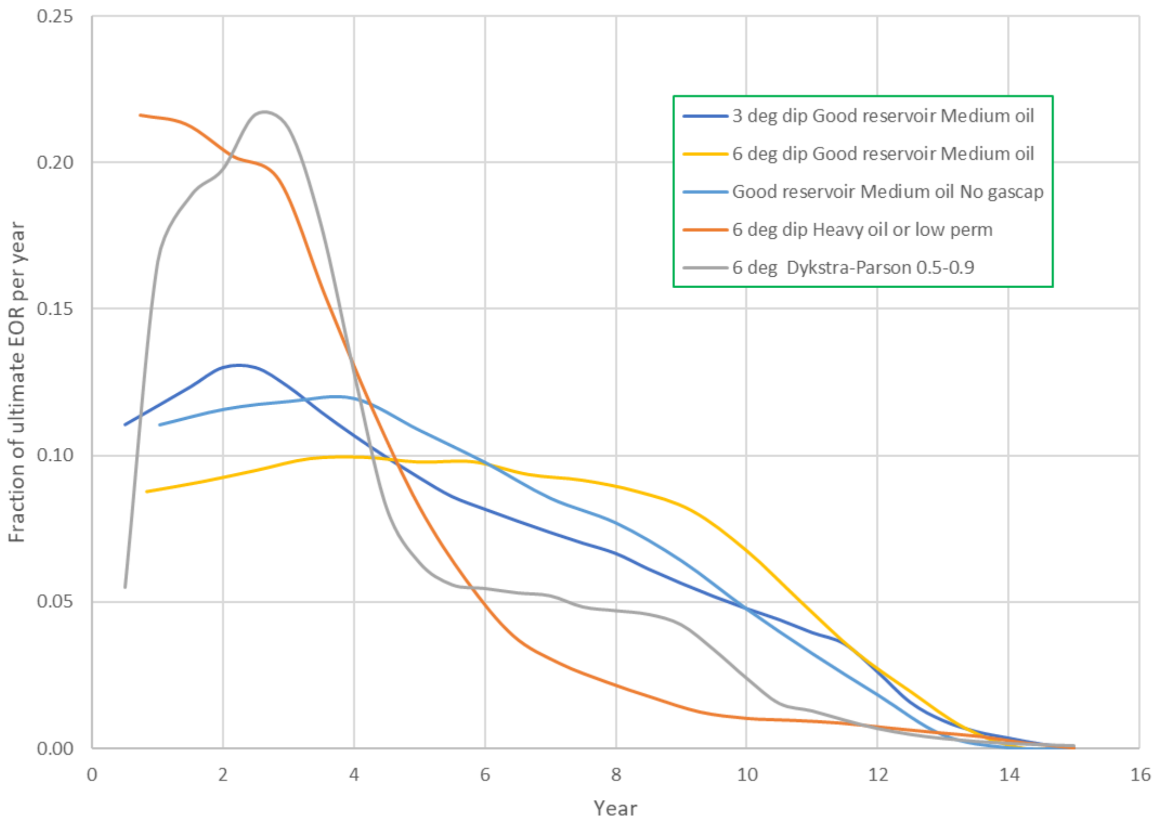

Figure 37. Normalized CO_2-EOR profiles.

4.12 Screening results

From the 74 evaluated basic units, 19 have been eliminated due to unfavourable conditions for CO_2-EOR, mostly too shallow depth that would be insufficient for reaching supercritical status of CO_2 – the basic CO_2-EOR condition.

The remaining 55 basic units were evaluated as potentially suitable for CO_2-EOR, based on the character, quality and level of detail of the data provided. The results of screening, originally provided on the basic unit level, were aggregated first on the field level and then on the cluster level (see Table 7). The data presented in the table represent the main input from the CO_2-EOR screening process to the source-sink matching process in Chapter 6 and subsequent creation of the roadmap.

Table 7. Results of CO_2-EOR screening.

Cluster	**Original oil in place**	**Oil produced so far**	**Incremental oil production by CO_2-EOR**	**CO_2 used for EOR and stored**
	thousand Sm^3	thousand Sm^3	thousand Sm^3	thousand tonnes
AUT I.	71 000	25 000	6 600	82 000
AUT II.	212 800	85 000	22 400	22 000
AUT III.	14 400	2 500	1 600	17 000
Total Austria	**298 200**	**112 500**	**18 700**	**121 000**
CZ I.	150	50	10	100
CZ II.	2 440	790	210	2 590
CZ III.	8 700	1 810	1 430	8 550
Total Czech Republic	**11 290**	**2 650**	**1 650**	**11 240**
SK I.	2 770	530	250	1 720
SK II.	1 820	750	240	2 060
SK III.	2 160	360	310	2 270
Total Slovakia	**6 750**	**1 640**	**800**	**6 050**
Grand total Vienna Basin	**316 240**	**116 790**	**21 150**	**138 290**

Table 7 only includes volumes for those units which have been considered applicable for CO_2-EOR.

The screening results show a theoretical potential of 21 million Sm^3 (130 million barrels) of incremental oil that can be recovered in the Vienna Basin using CO_2-EOR. Using the current oil price of 40 USD/bbl this represents (if produced) a gross value of 5 200 million USD. The amount of CO_2 that would be needed to perform the related CO_2-EOR operations and thereafter stored in the depleted fields is estimated to nearly 140 million tonnes.

It should be strongly emphasized though that these results are based on a screening study, with limited information about individual fields and reservoirs, using conceptual modelling techniques with few possibility to adapt to actual reservoir sizes, structure, faulting and other factors important to the recovery process. It should also be reiterated that the reservoir units included in the study, with few exceptions, may not attain fully miscible conditions during the CO_2 flooding process due to maximum pressure constraints. The results will therefore be hampered with significant uncertainty. The miscibility issue is further elaborated in Chapter 7 (Technical challenges).

5 Analysis of CO_2 point sources in the region

5.1 Potential suitable CO_2 point sources in the Vienna Basin

Of course, CO_2-EOR cannot happen in the absence of a reliable and affordable CO_2 supply. In order to provide an initial insight into potential suitable anthropogenic sources of CO_2 in the Vienna Basin, a simple analysis of CO_2 point sources in the region was conducted.

The analysis of point sources identified 69 CO_2 emitters in a range of up to 70 km away from the closest potential storage field. All emission data were extracted from the climate action ETS (*Emissions Trading System*) database and the E-PRTR (*European Pollutant Release and Transfer Register*) respectively. The cumulative CO_2 emission of all facilities reached 16.6 Mt CO_2 in 2017. The assessment of the emissions in Figure 38 shows that the oil & gas industry, the cement industry and energy suppliers are the greatest emitters, being responsible for 80 % of the emissions in the survey area.

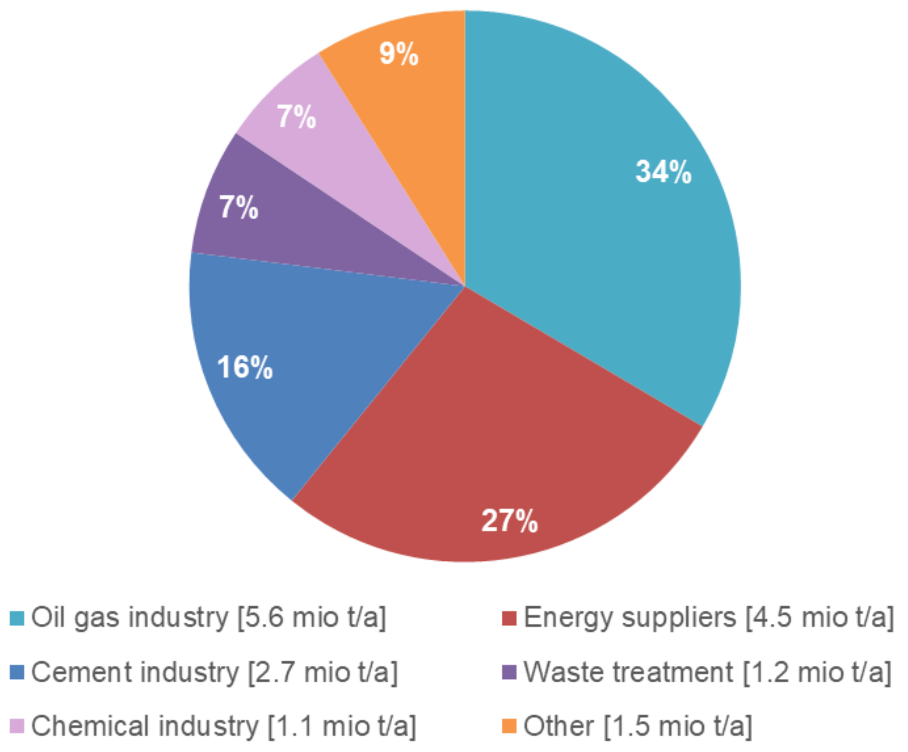

Figure 38. Industrial emissions in the Vienna Basin by sector (in 2017).

5.2 Short-listing CO_2 sources for source-sink matching

In order to select the most favourable prospective CO_2 emitters to include for the source-sink matching exercise (see Chapter 6), the long list of 69 emitters were filtered using a number of criteria. These filters are explained below:

- **Total annual CO_2 emissions:** an initial filtering was conducted to remove smaller emitters, sources which have annual emissions of less than 30 kt CO_2. Installations with annual emissions below this threshold were not considered favourable for large scale CCS projects.

- **Estimated cost of CO_2 capture:** The cost of capturing CO_2 from energy and industrial installations is largely dependent on the composition of the flue gas. Some industrial processes, such as hydrogen production (for use in refineries or for ammonia synthesis), bioethanol production or natural gas processing, result in a very concentrated 'offgas' of CO_2. The highly concentrated stream of CO_2 can be diverted, treated, and compressed if necessary, requiring relatively limited capital and operational expenditures. Many of the existing CCS projects operating globally, such as Sleipner and Snohvit projects in Norway, and the Quest CCS Project in Alberta, Canada, involve CO_2 capture from such 'high-purity' sources.

  Conversely, CO_2 capture from gas or coal-fired power plants, cement kilns, or refinery boilers results in flue gases with a relatively low concentration of CO_2, often between 8-12% (vol.). In order to capture the CO_2, large investments are needed in post-combustion capture systems which include large towers where CO_2 is 'stripped' from the flue gas using chemical solvents. These systems also incur significant energy penalties as the solvent needs to be heated to release the CO_2 and be regenerated.

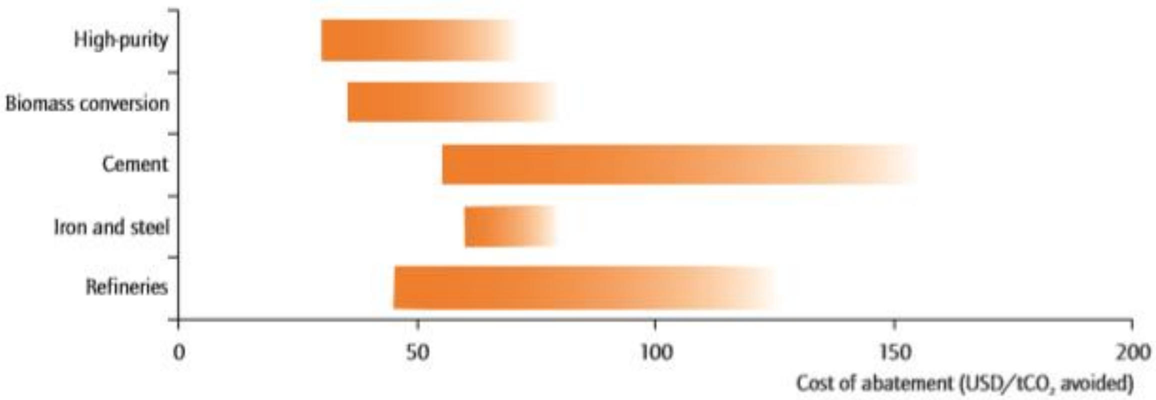

Figure 39. Ranges of estimated cost of CO_2 capture from different industrial processes. 'High purity' includes natural gas processing, hydrogen production and ethylene oxide production (IEA 2011).

In light of this, all potential 'high purity' sources that met the quantity threshold have been included in the short-list of emitters taken to the source-sink matching phase.

- **Alternative options to reduce emissions other than CCS:** For many industrial processes, emitting CO_2 is largely an unavoidable part of the industrial process. Particularly for cement, CO_2 is emitted both for heating the kiln, but also intrinsically during the thermal decomposition of limestone to cement clinker. Because of this, a number of cement plants are included in the short list, even though the cost of capturing CO_2 is likely to be quite high. This justification is also applicable to refineries where CO_2 is released during the hydrocarbon cracking processes.

- **Inclusion in the EU ETS:** All combustion installations in the EU with a capacity above 20 MW are included in the EU Emissions Trading Scheme. Only waste incinerators above this capacity are exempt. This means that for many power and industrial installations, emitting CO_2 can have direct financial consequences. In general, emission allowances will need to be purchased for each tonne of CO_2 emitted. The price for emission allowances is currently €25 (March 11th, 2020). By capturing CO_2, and by storing it in geological formations, companies can avoid purchasing emission allowances. The use of CO_2 for EOR is also possible, so long as any fugitive emissions during the injection and CO_2 recycling process are accounted for. Thus, for companies included in the EU ETS, this can be an important incentive to explore the possibility of using CCS to reduce their emissions.

The application of the criteria listed above resulted in a short-list of emitters that were incorporated into the source-sink matching process. The short list is presented in Table 8.

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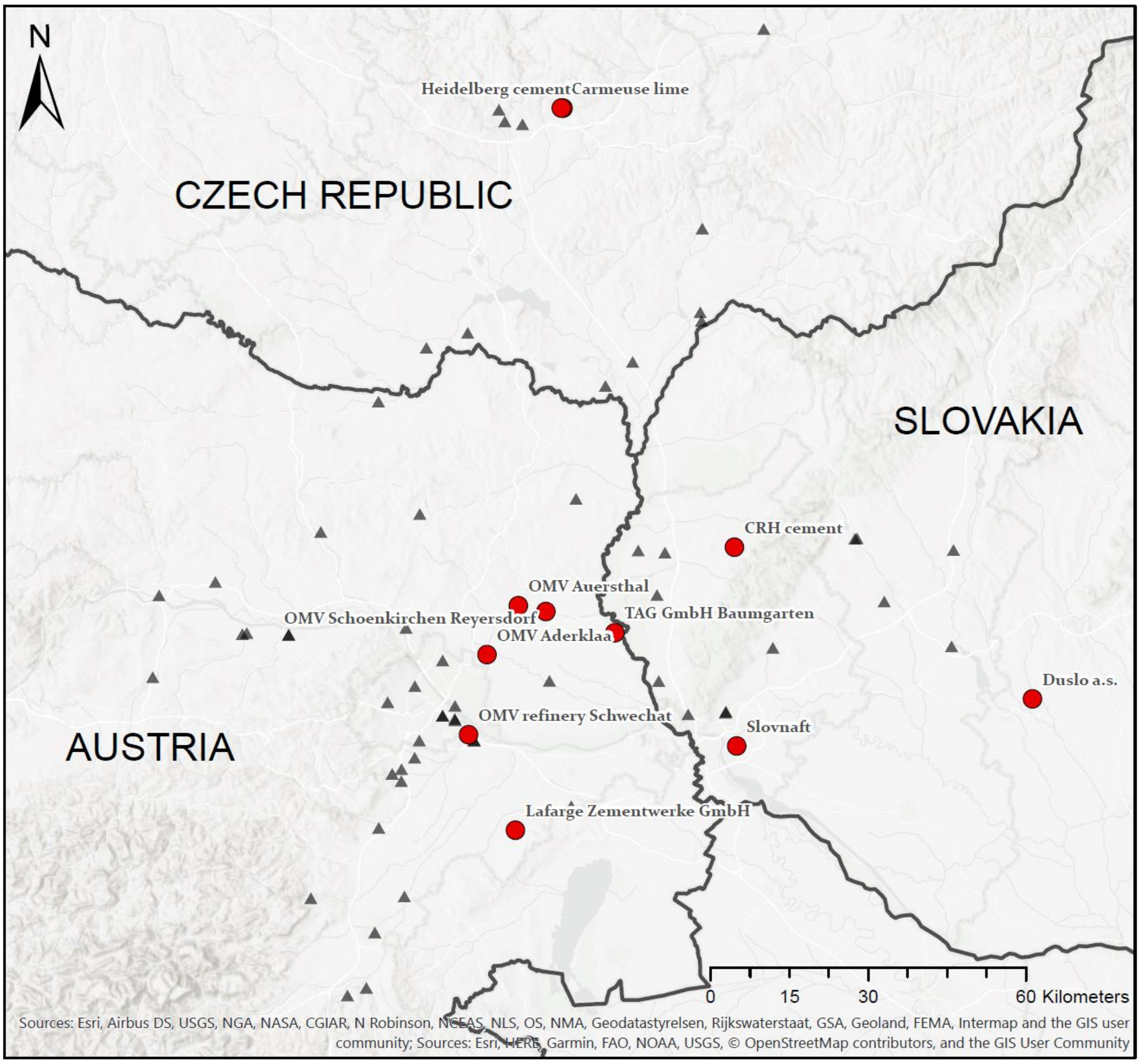

Figure 40. Map of identified CO_2 sources in the survey area. The red dots mark the further evaluated sources for CCS and CO_2-EOR applications, triangles mark other sources.

Table 8. Best suitable emitters for CCS application in the Vienna Basin. CO_2 emissions are extracted from ETS or E-PRTR database and given in tonnes. See next figure for the location of the facilities.

Facility	Source characteristics	CO_2 2017	CO_2 2018	
OMV refinery	oil and gas refinery hydrogen: 30,000 m^3/h	2,740,000	2,824,369	Austria
OMV Aderklaa	gas production from the gas fields Schönkirchen (sour gas) and Höflein. Emissions from combustion for compressors	190,000		Austria
OMV Auersthal	oil and gas extraction station. Emissions from combustion for compressors	78,119	71,219	Austria
OMV Schönkirchen Reyersdorf	gas storage (1.8 bn. m^3), Emissions from combustion for compressors	38,879	37,485	Austria
Lafarge	cement factory	596,000	601,756	Austria
Trans Austria Gasleitung	gas distribution centre	185,000	189,000	Austria
Slovnaft	oil and gas refinery, petrochemical plant, heat generation hydrogen: 37,000 m^3/h emission: 50% from refinery 30% from heating plant 20% for petrochemical usage	2,198,678	2,209234	Slovakia
Duslo a. s.	fertilizer production ammonia: 433,000 m^3/h	1,054,051	1,241,724	Slovakia
CRH (Rohožník)	cement factory	927,494	875,541	Slovakia
Carmeuse lime works Mokrá (same location as HeidelbergCement)	limestone mining	119,000	141,700	Czech Republic
HeidelbergCement group plant Mokrá	cement factory	657,000	760,000	Czech Republic

6 Regional CO_2 source-sink matching

6.1 Development of GIS database

ArcGIS Pro is the most recent desktop geographic information system from ESRI. It was used to visualize outlines of reservoir fields and clusters, the position of CO_2 sources and to calculate the pathways of the pipelines connecting sources and sinks. All data is georeferenced in WGS 1984 UTM Zone 33N coordinate system. Instead of drawing straight lines to connect sources and sinks, a more sophisticated approach was used. By combing the CORINE Land Cover 2018 dataset from the Copernicus observation program and the slope terrain of the survey area, we created a cost surface (Figure 41), which depicts possible pipeline pathways in a more realistic way. Industrial sites, protected regions or areas with steep slopes were assigned with high costs to minimize their crossing. Then, the spatial analysist distance-tool was used to calculate the cost allocation and cost back link for each of the evaluated CO_2 sources. Based on them, we calculated pipeline pathways to the closest suitable reservoir.

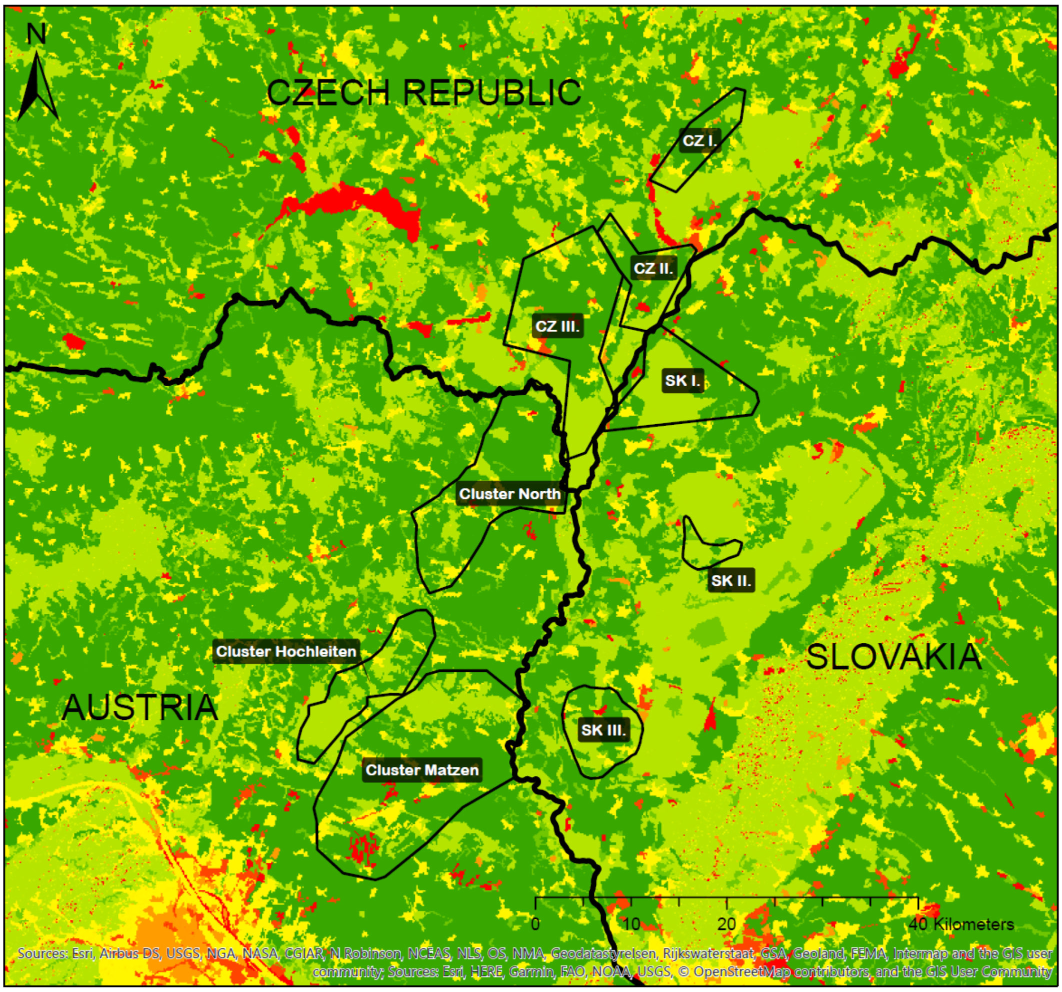

Figure 41. Cost function based on land use and slope of the survey area. Red regions indicate high costs, green areas low costs.

6.2 Source-sink matching case studies

Transportation of the CO_2 in the source-sink matching was limited to transport via pipeline. The sources in the Vienna Basin are rather small, compared to the pipeline capacities of international projects (Table 9). Nevertheless, pipelines with capacities less than 1 million tonnes CO_2 per year do exist. Based on the results of the source-sink matching exercise, two case studies in the survey area were suggested for further elaboration. The outcomes of the source-sink matching assessment can be found in Figure 42.

Table 9. Overview of CO_2 pipeline projects (Pelitri et al. 2018)

Pipeline Name	Length (km)	Capacity (Mt/y)	Diameter (mm)	Status	Country
Quest	84	1.2	324	Planned	Canada
Alberta Trunkline	240	15	406	Planned	Canada
Weyburn	330	2.0	305–356	Operational	Canada
Saskpower Boundary Dam	66	1.2		Planned	Canada
Beaver Creek	76		457	Operational	USA
Monell	52.6	1.6	203	Operational	USA
Bairoil	258	23		Operational	USA
West Texas	204	1.9	203–305	Operational	USA
Transpetco	193	7.3	324	Operational	USA
Salt Creek	201	4.3		Operational	USA
Sheep Mountain	656	11	610	Operational	USA
Val verde	130	2.5		Operational	USA
Slaughter	56	2.6	305	Operational	USA
Cortez	808	24	762	Operational	USA
Central Basin	231.75	27	406	Operational	USA
Canyon Reef Carriers	225		324–420	Operational	USA
Chowtaw (NEJD)	294	7	508	Operational	USA
Decatur	1.9	1.1		Operational	USA
Snohvit	153	0.7		Operational	Norway
Peterhead [a]	116	10		Cancelled	UK
White Rose [a]	165	20		Cancelled	UK
ROAD [a]	25	5	450	Cancelled	The Netherlands
OCAP	97	0.4		Operational	The Netherlands
Lacq	27	0.06	203–305	Operational	France
Rhourde Nouss-Quartzites	30	0.5		Planned	Algeria
Qinshui	116	0.5	152	Planned	China
Gorgon	8.4	4	269–319	Planned	Australia
Bravo	350	7.3	510	Operational	USA
Bati Raman	90	1.1		Operational	Turkey
SACROC	354	4.2	406	operational	USA
Este	191	4.8	305–356	Operational	USA

[a] Reported as planned but now cancelled.

Austria has the biggest storage capacities and two big CO_2 emitters (OMV refinery and Lafarge cement plant). Connecting the two biggest sources mentioned above via a pipeline and transporting the CO_2 to the Matzen cluster is suggested as the best source-sink scenario. Several small CO_2 sources (OMV Schönkirchen-Reyersdorf, OMV Aderklaa, OMV Auersthal and TAG Baumgarten) which are operated by companies in the oil & gas sector are in proximity to storage sites and might represent additional suitable CO_2 sources. Connecting the two biggest sources mentioned above via a pipeline transporting the CO_2 to the Matzen cluster is suggested as the best source-sink scenario.

In terms of sources and sinks suitability, Austria has the best prerequisites out of the three Vienna Basin countries. Unfortunately, data uncertainty regarding storage capacity and incremental oil production is the biggest for this country.

Slovakia has three large CO_2 sources in the survey area; e.g., the Duslo fertilizer plant has a very pure CO_2 emission stream but is quite far away from suitable storage sites. The oil reservoirs in Slovakia have low CO_2 storage capacities and are therefore not very suitable for CCUS application. In addition, the potential for oil production from EOR operation seems to be minor. Nevertheless, the Slovnaft oil refinery in Bratislava is a big and steady CO_2 emitter. The refinery emissions can only be stored in a foreign reservoir and therefore we suggest transportation to Austria. It should be noted, that the legal framework of CO_2 export or import for CCS application into foreign countries is unknown and difficult to be estimated.

The Czech Republic has one big emission source in the survey area – the Mokrá cement plant belonging to the HeidelbergCement Group. Its CO_2 can be captured and transported via pipeline to the oil fields of the Czech CZ III cluster. With around 8 million tonnes storage capacity, it is the only sufficiently large storage cluster in this country. In addition, the Carmeuse lime works are located next to the cement plant and their CO_2 sources could be possibly combined with those of the cement plant to increase the size of the CCUS project and support thus the economy-of-scale effect.

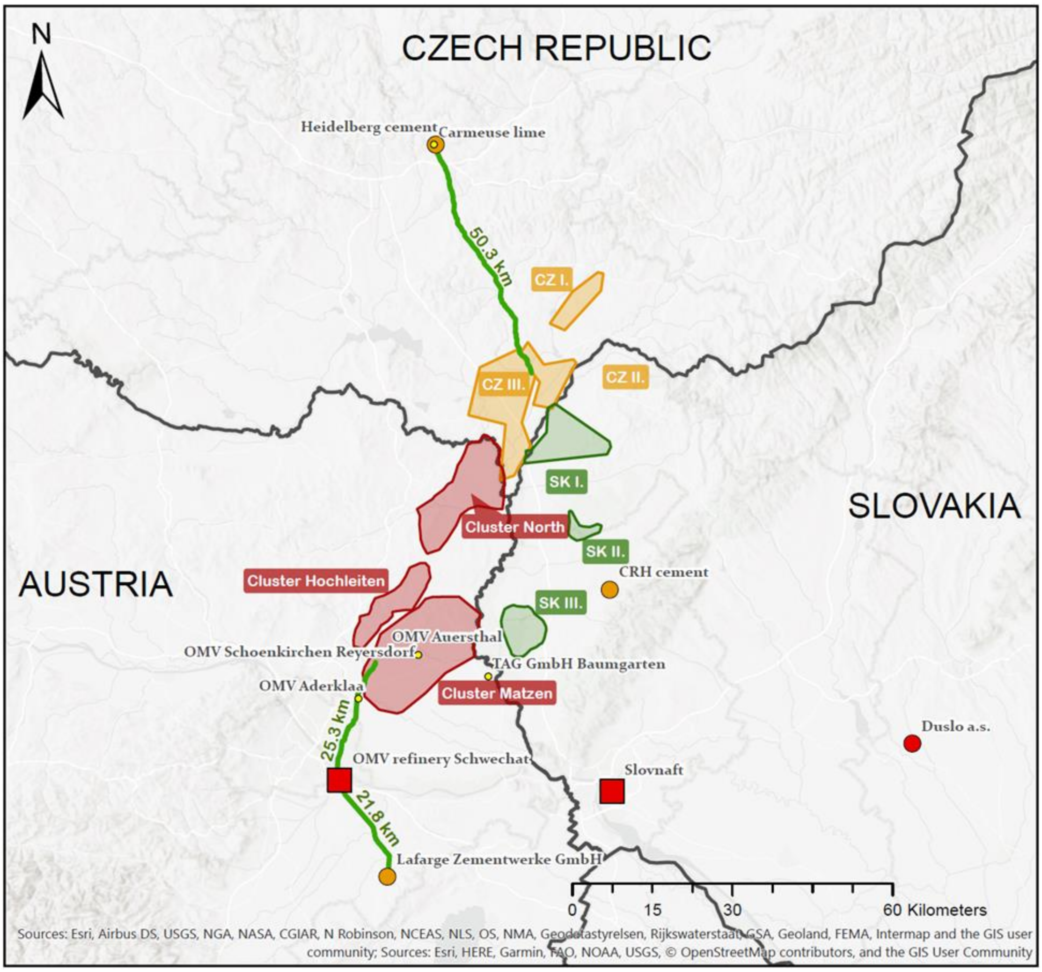

Figure 42. Results of source sink matching showing the locations of the selected sources (the Czech HeidelbergCement plant, the OMV refinery and the Lafarge cement plant in Austria), as well as the oil fields clusters. Green lines depict the calculated indicative pipelines based on considerations explained in Chapter 6.1. Note that pathways might differ for the case study No. 2 as existing pipeline networks were not evaluated in Chapter 6.1.

6.2.1 Case study 1 – OMV Refinery / Lafarge cement plant / Matzen cluster

Emission sources

The OMV refinery is in operation since 1960, it comprises oil refining and a petrochemical production and processes 9.6 million tonnes of crude each year. It is located in Schwechat, southeast of Vienna in proximity of the Danube river. The plant is the biggest single allocation in terms of CO_2 emissions in our survey area with emission of approximately 2.8 million tonnes CO_2 per year. As stated by several reports (Valdenaire 2018; Van Straelen et al. 2009; Allevi et al. 2011) carbon capture in a refinery is rather challenging as multiple CO_2 sources exist that are strongly varying in size and CO_2 flue gas concentration. The OMV refinery comprises hydrogen production with a capacity of 30,000 m^3/h, which is a well-suited CO_2 source for carbon capture processes.

The Lafarge plant in Mannersdorf is Austria's biggest cement clinker factory. It is located 40 km southwest of Vienna close to the Leitha Gebirge. The plant was founded in 1984, nowadays it produces 1.1 million tonnes of cement each year and emitted 0.6 million tonnes CO_2 in 2018. Flue gas concentration in Austrian cement factories is estimated to be in the range of 20 % according to VÖZ.

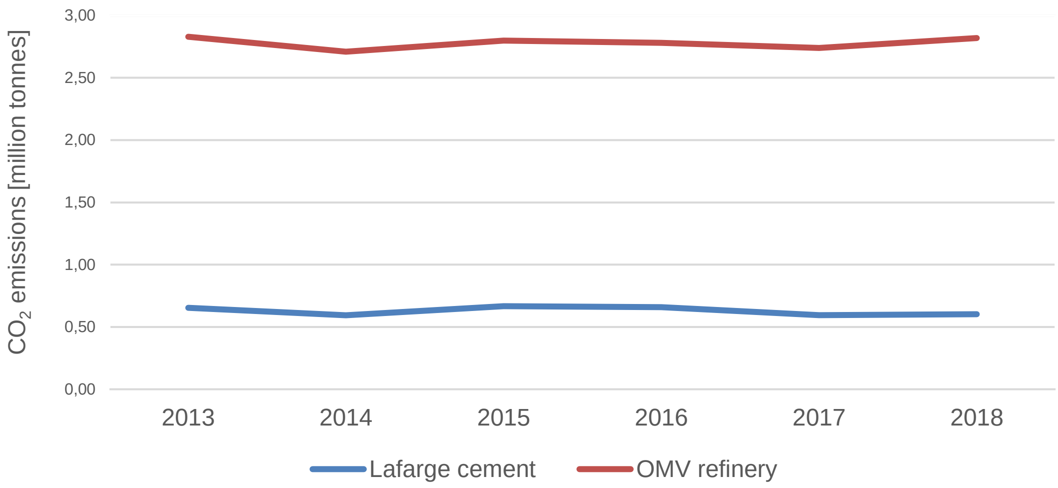

Figure 43. Annual CO_2 emissions from the Lafarge cement plant and OMV refinery between 2013 and 2018.

Assessment of the quantity of CO_2 emissions from these two sources that can be used for carbon capture would require more detailed knowledge on the facilities equipment and cannot be answered in our study. Nevertheless, both sources are affected by EU ETS regulations, they had steady emissions over the last years (see Figure 43) and will most likely continue to emit CO_2 in the future. In our case study we assume that 400,000 tonnes CO_2 per year from the cement plant and 200,000 tonnes CO_2 per year from hydrogen production can be captured and transported for CO_2-EOR and storage.

EOR / storage location

The Matzen cluster was chosen as a potential CO_2-EOR/CO_2 storage site. It is the closest one to the sources with reasonable storage capacities of 22.4 million tonnes CO_2 and the most promising EOR potential with 10.5 million m^3 of oil that could be recovered (see Table 6). The cluster consists of various oil reservoirs in the Neogene first floor and in the Triassic second floor. While the Neogene reservoirs have better potential for EOR, the deeper ones are more promising for CO_2 storage. Furthermore, there are additional big gas reservoirs in proximity to the Matzen cluster that might be used for possible Enhanced Gas Recovery and/or CO_2 storage (Scharf and Clemens 2006).

Transport

Generally, various modes of CO_2 transport means, e.g. truck load, rail cargo, ship or pipeline or a combination of these, are possible. However, according to the European Directive 2003/87/EC, installations that are planning to store CO_2 in geological media and are covered by the EU ETS don't need to surrender CO_2 credits for carbon capture only in the case that the transport is realized via pipelines. This law might be changed in the future as currently developed CCS projects in Europe plan to transport their emissions by ships. Nevertheless, transport via trucks puts additional burden on the local infrastructure. We therefore suggest pipeline transportation for this case study. A pipeline from the cement factory to the refinery would be 21.8 km long (Figure 42). The additional pipeline from the refinery to one of the oil reservoirs in the Matzen cluster would need to have a length of about 25.3 km. The pipeline pathway is flat without any major crossing of big cities or additional industrial sites except for the crossing of the Danube river between the refinery and the storage site.

Economic evaluation

A detailed economic evaluation for this case study would require further research and will not be presented in this project. Nevertheless, the following general economic considerations can be made:

- Capture costs for cement plants by traditional chemical absorption are in the order of 36$ - 101$ per tonne CO_2 (IEAGHG 2018). Capture costs for refineries can strongly differ as shown in figure 9. The costs for retrofitting CO_2 capture in refineries lie between $ 160-210 per tonne CO_2 (Valdenaire 2018). However, using CO_2 from hydrogen production will result in much smaller costs in the order of $ 35-45 per tonne CO_2.
- Pipeline transportation requires high investment in the beginning, but often outruns other transport possibilities when accounting for longer time periods (ZEP 2011, Gao et al. 2018). The surrounding area is non-challenging for pipeline construction. The capacity of the CO_2 pipeline would be rather small compared to international projects. According to our consideration on the sources, an 8" diameter pipeline would have sufficient capacities for transportation in both pipeline sections. The cost for such pipeline would be in the range of $ 5-10 per tonne CO_2 (IEAGHG 2013; McCoy and Rubin 2007; Gao et al. 2018; ZEP 2011), considering a lifespan of 20 years.
- Storage costs will be in the range of € 1-10 per tonne CO_2 (ZEP 2011)
- The calculated recoverable oil corresponds to 66 million barrels. However, revenues from EOR application need further evaluation as existing infrastructure needs to be treated and abandoned wells need to be monitored for CO_2 leakage.

An overview of this case study is provided in Table 10. Further CO_2 sources could be added to increase efficiency and reduce transportation costs. A suitable emitter would be the Aderklaa processing plant located next to the proposed pipeline (Figure 42). Several newspaper articles[2] published in the last couple of months mention the interest of OMV in storing CO_2 from the processing plant into the depleted Aderklaa gas reservoir next to the Matzen cluster. Additionally, emission from the Slovakian Slovnaft refinery in Bratislava could be used to create a CO_2 source cluster. Although the refinery is a bit smaller compared to OMV, it also comprises hydrogen production and hence cheap CO_2 source. As reservoirs in Slovakia are too small for storage application, transportation and storage abroad could be one way of meeting the refinery ETS obligations. Nevertheless, an additional 48 km pipeline would be needed to build.

[2] https://www.energate-messenger.ch/news/200261/omv-treibt-ccs-projekt-im-marchfeld-voran
https://www.derstandard.at/story/2000110803720/omv-will-co2-unter-die-erde-befoerdern

Table 10. Overview of the Case Study - Lafarge cement plant / OMV refinery / Cluster Matzen.

General details	
Case study name:	Lafarge cement plant – OMV refinery – Cluster Matzen
Source details	
Name of source	Lafarge cement plant OMV refinery
Country	AUT
Type of industry	Cement industry Oil refinery (with hydrogen production)
Total CO_2 emissions (Mt /year)	3.4
Proposed CO_2 capture rate (Mt/year)	0.4 – cement plant 0.2 - refinery
High or low purity CO_2	20% concentration in flue gas from cement industry >50% for hydrogen production (high purity)
ETS applicable (yes/no)	yes
Sink details	
Cluster name	Matzen
Additional incremental oil production (thousand Sm^3)	10,500
Total CO_2-EOR/storage potential (Mt)	22.4
Transport details	
Distance between source and sink	21.8 km cement plant - refinery 25.3 km refinery – oil reservoir
Geographical challenges	Crossing of the Danube (~500 m)

6.2.2 Case study 2 – Mokrá cement plant / cluster CZ III

Emission source

The cement plant Mokrá (part of the company Českomoravský cement, HeidelbergCement Group member) is the biggest cement producer in the Czech Republic. In 2018, the annual cement production was estimated at 1.1 million tonnes while the total Czech cement production of all 5 active cement plants was reported to be 4.4 million tonnes[3].

The cement plant Mokrá is located near Brno, in the eastern part of the Czech Republic. From geological point of view, this plant is located just on the border between the two main European geological units - Bohemian Massif and Carpathians. The cement plant was established in 1967 and the cement production started in 1969. As the basic raw material, the limestones (Middle Devonian age) from a nearby (1.5 km) quarry are used for clinker and subsequent cement production; the limestones consumption was about 1.4 million tonnes in 2018. The average fuel composition, used in the rotary kiln, is shown in Table 11.

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[3]Source: Svaz výrobců cementu ČR - Cement Producers Union of the Czech Republic, https://www.svcement.cz/ (in Czech only)

Table 11. Fuels used for clinker production in the rotary kiln[3].

Hard coal	Solid alternative fuels (waste residues)	Biomass	Used tyres
30 %	38 %	24 %	8 %

The average ratio between the produced amount of cement and the emitted amount of CO_2 depends on the type of reported emission – either excluding biomass as reported by European Union Transaction Log[4] or including biomass as reported by the Czech Integrated Register of Polluters (IRZ)[5]. If CO_2 emissions are reported including the combusted biomass, about 0.67 tonnes CO_2 is emitted per tonne of produced cement; in case of emissions excluding biomass, about 0.63 tonnes CO_2 is emitted per tonne of produced cement. About 65 - 70 % of the CO_2 emissions are "process -related", i.e. from decomposition of the carbonate mineral (limestone), and the rest is from fuel combustion. The CO_2 concentration in the flue gas is estimated at 20 %[6]. This number fits the literature values of 14 - 33 % (e.g. Bosoaga et al. 2009). The annual CO_2 emissions and CO_2 emission allowances of the plant are shown in Table 12.

Table 12. Annual CO_2 emissions and allowances in allocation; emissions excluding biomass according to the European Union Transaction Log[1]; emissions including biomass according to the Integrated Register of Polluters[2].

	Allowances in allocation	CO_2 emissions excluding biomass	CO_2 emissions including biomass
	tonnes	tonnes	tonnes
2010	657,200	593,592	660,091
2011	657,200	636,093	704,258
2012	657,200	551,237	603,207
2013	644,075	453,821	516,076
2014	632,888	511,690	582,374
2015	621,569	558,389	605,459
2016	610,133	626,166	679,837
2017	598,573	610,490	656,884
2018	586,901	708,533	759,893

The management of the Mokrá cement plant is very interested in potential CO_2 capture and storage/use. As a member of the HeidelbergCement Group, the management follows the study and research on CCS application for the Norwegian cement plant in Brevik, which shows many similarities with the Mokrá plant from the CO_2 emissions point of view. The Brevik plant belongs to the Norcem company, which is also a member of the HeidelbergCement Group. Norcem and Heidelberg have a vision of achieving zero emissions from concrete production by 2030, seen from a life cycle perspective[7]. This vision will be realised through the development of new types of cement, increasing the percentage of alternative fuels and deployment of carbon capture in cement production. An essential element in the planned carbon

[4]https://ec.europa.eu/clima/ets/napMgt.do
[5]https://portal.cenia.cz/irz/
[6]Information kindly provided by Českomoravský cement staff
[7]https://www.norcem.no/en/CCS

capture is to make use of the residual heat from the cement factory. There is enough residual heat to capture approximately 400,000 tonnes of CO_2 annually, which corresponds to 50 % of the Brevik plant emissions. Post-combustion capture using liquid amine absorption was selected as the most appropriate technology. The same capture technology and the same amount of captured CO_2, i.e. ca. 400,000 tonnes, is (very preliminary) planned also for the Mokrá plant. According to the IEAGHG Technical Review of CO_2 capture costs in industry (IEAGHG 2018), the expected capture cost of 1 tonne of CO_2 can be in the range 31 - 92 EUR / tonne using traditional chemical absorption and 41 – 54 EUR / tonne using advanced chemical absorption (which is the expected technology in our case).

EOR / storage location

As a potential storage/EOR location for captured CO_2 emissions from the Mokrá cement plant, the cluster CZ III was selected in this case study. The cluster CZ III consists of 6 oil fields, located in southern Moravia, about 50 km away from the Mokrá plant. Another potential storage/EOR location represents the nearby located cluster CZ II, which consists of 4 oil fields. The amount of expected incremental oil production by CO_2-EOR and expected storage amounts in the clusters CZ III and CZ II are shown in Table 13.

Table 13. Expected incremental oil production and CO_2 storage capacity.

Cluster	**Incremental oil production by CO_2-EOR**	**CO_2 used for EOR and stored**
	thousand Sm^3	thousand tonnes
CZ III.	1,430	8,550
CZ II	210	2,590

According to Table 13, the storage capacity of the cluster CZ III is about 8.5 Mt of CO_2. The planned CO_2 flow from the Mokrá cement plant is estimated at 400 kt per year, so that the capacity of the cluster CZ III could be suitable for CO_2 utilisation and storage for 21 years with potential prolongation (using cluster CZ II) for next 6.5 years.

Without a detailed CO_2-EOR & storage implementation plan for each field of the cluster it is impossible to calculate the exact CO_2 injection and storage costs. Literature data (e.g. ZEP 2011) provide some guidance regarding possible cost range; for the case of CO_2 storage in an onshore abandoned hydrocarbon field without using legacy wells the values range between 1 and 10 EUR / tonne of CO_2 stored.

Transport

The aerial distance from the Mokrá cement plant to the edge of the CZ III cluster is less than 50 km but the potential transport trajectories would be longer; a pipeline distance of about 80 km needs to be considered (Figure 44) because of geographical conditions. A shorter route is complicated because of crossing the Ždánický les hills; a less complicated trajectory (without altitude changes) runs along the rivers Rokytnice, Říčka, Litava and Svratka up to the Vranovice village. Here, the potential CO_2 pipeline could be added to the existing gas pipeline corridor "Tranzit" (operator NET4GAS) to Břeclav and then up to a potential CO_2 hub in Moravská Nová Ves (theoretical centre point of the CZ III cluster).

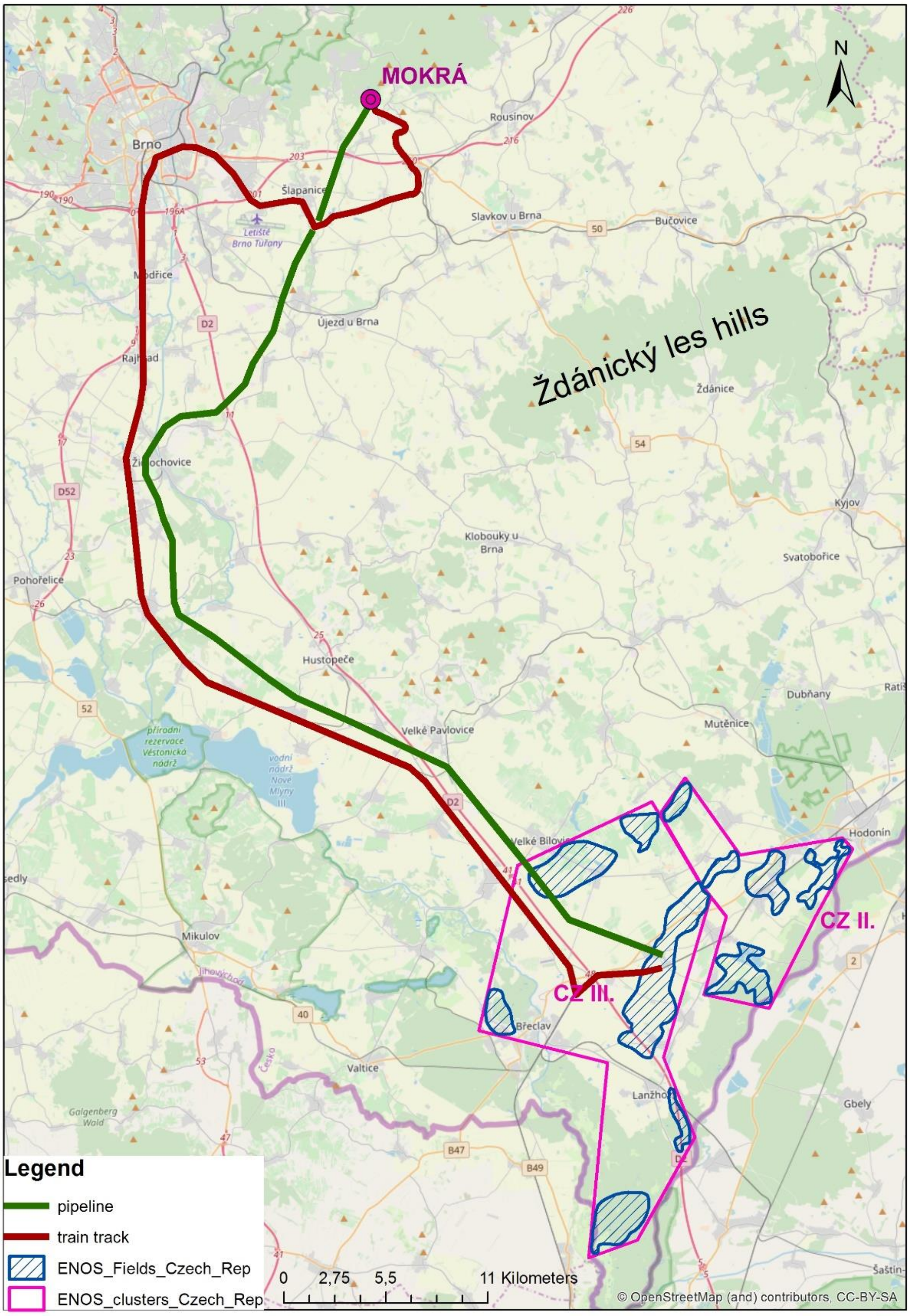

Figure 44. Possible CO_2 transport routes between the Mokrá cement plant and cluster CZ III.

In compliance with literature (McCoy & Rubin 2005 and 2008, McCoy 2009, CO2Europipe 2011) and results of the earlier REPP-CO_2 project (Štván et al. 2016), we suppose that CO_2 will be transported by pipeline in liquid stage. It is recommended to use higher than supercritical pressure (8.6 MPa as a minimum) because some impurities (especially H_2S) can cause two-phase flow at the pressure interval of

7.4 - 8.6 MPa. For the supposed CO_2 amount of 400,000 tonnes per year, the suitable pipe diameter is 8", i.e. 203 mm with an input pressure of 12 MPa. The output pressure (pipe length 80 km) is estimated at 10 MPa at 10° - 12° C (average shallow subsurface temperature). Based on REPP-CO_2 results, the costs (CAPEX + 1 year OPEX) of such a pipeline come up to 3 billion CZK or 120 million EUR. If the pipeline is active for 20 years, the cost per 1 tonne of transported CO_2 is ca. 15 EUR.

In spite of the fact that CO_2 transport for EU-ETS purposes is allowed only by pipeline, we also considered potential CO_2 transport by train that could be used in case the CO_2 is solely used for CO_2-EOR, or if the related legislation is changed. Another reason is the favourable existing transport infrastructure - the Mokrá plant has got its own railway connection to the state-owned railway network.

Analogously to ship-based transport, CO_2 can be transported by train under divers conditions, from cold liquid state at sub-zero temperatures and low pressures to dense phase at high pressures and ambient temperature. Similarly to the majority of the recent studies on ship based CO_2 transport (Aspelund et al. 2006, Jakobsen et al. 2016, Yara 2015, Roussanaly et al. 2013, Gao et al. 2011, Jung et al.2013), the preferred mode of train-based CO_2 transport is assumed to be in liquid form at 0.65 MPa and about -50.3 °C. While the train supply chain (including number of trains and number of wagons) can be optimised in order to minimise the transport cost, the tank dimensions of wagon are limited. The assumed size is ca. 3 m x 3.5 m in section and 21 m in length (based on the CMGV 11-9733 model wagon[8]). Considering that 90% of the transport volume is used, each wagon has an overall transport capacity of 240 tonnes of CO_2. The maximum number of wagons per train is assumed here to be 20 (i.e. 4,800 tonnes per train), in order to have a maximum train length of 600 m including locomotive. For the annual amount of 400,000 tonnes CO_2 to be stored, about 84 trains per year would be needed. The length of the railway connection from the Mokrá plant to the potential hub close to the Moravská Nová Ves railway station represents 97 km (Figure 44), including 7 km of a private railway siding. It is difficult to calculate the costs of CO_2 transport by train because of lack of data relevant to European conditions. As an exception, Roussanaly et al. (2017) calculated the average cost of 1 tonne CO_2 transported by train to a distance of 100 km to be between 15 and 20 EUR, including conditioning.

Economic evaluation

The combination of the relatively high costs of CO_2 capture in the cement industry and the limited amount of CO_2 to be captured, transported and stored annually with the currently low price of both oil and CO_2 emission allowances (EUA) make a business case based on the above-described scenario impossible in case CO_2-EOR and CO_2 storage are considered separately. However, a rough estimate of costs and revenues can be made to illustrate the basic economy of a possible project that could become viable in case CO_2-EOR and CO_2 storage can be combined, or if sufficient amount of subsidies is available, or if the value of one or more of the major cost / revenue items significantly changes. A combination of these factors is of course also a possible option.

The estimated cost of CO_2 capture at the cement plant, its conditioning, transporting to the storage site and injection in the hydrocarbon fields of the CZ III cluster ranges between 57 and 84 EUR per tonne (Table 14), which means that the total CCS project costs might be in the range of 488 – 719 million EUR.

[6]http://www.eurofire.lt/en/rail-wagons

Table 14. Rough estimation of CCS costs (in EUR) for the Mokrá – CZ III case study

	Capture	Transport	Storage	Total
Unit cost per tonne CO_2	41 - 54	15 - 20	1 - 10	57 - 84
Total cost for complete amount of CO_2 captured, transported, used and stored (8.55 million tonnes)	351 – 462 million	128 – 171 million	9 – 86 million	488 – 719 million
Cost of CO_2 captured, transported and used for CO_2-EOR (4.72 million tonnes)	194 – 255 million	71 – 94 million	5 – 47 million	270 – 396 million
Cost of CO_2 captured, transported and stored after CO_2-EOR termination (3.83 million tonnes)	158 – 207 million	57 – 77 million	4 – 38 million	219 – 322 million

Based on the statistical CO_2-EOR data published by Azzolina et al. (2015) and the suggested average net CO_2 utilisation factor of ca. 10 Mscf CO_2/bbl oil, it can be estimated that ca. 55 % (4.72 million tonnes) of the total CO_2 amount that can be used and stored in the CZ III cluster would be needed for the additional oil extraction by means of CO_2-EOR, while the remaining 45 % (3.83 million tonnes) represent CO_2 that will be delivered for geological storage only. The related cost estimates are shown in Table 14.

The CCS cost estimates shown above can be compared with possible revenues. These need to be divided into two different business models – CO_2-EOR and CO_2 storage – that are completely different but – based on current interpretation of the existing legislation and regulatory framework – can possibly be combined, depending on corresponding approval of the responsible Mining Authority.

In the pure CO_2-EOR model, the revenues are represented by the value of the incremental oil produced. For cluster CZ III, 1.43 million Sm^3, i.e. ca. 9 million barrels of incremental oil production was estimated. Using the average Brent crude oil price for 2015 – 2019[9], i.e. 59 USD/bbl, we can estimate the total theoretical value of the incremental oil that can be produced from the oil fields of cluster CZ III at 531 million USD (ca. 486 million EUR[10]). These figures can be compared with the estimated costs of the 4.72 million tonnes CO_2 needed for the CO_2-EOR process, which are in the range of 270 – 396 million EUR. The comparison shows a positive balance of 90 – 216 million EUR, corresponding to 10.93 – 26.24 USD per barrel. This margin is definitely too low to cover the costs of oil production, separation and re-injection of co-produced CO_2, additional CO_2 handling, overheads and possible profit but can rise in case the oil price increases and/or the CCS costs decrease.

It also needs to be stated that some other studies (e.g. Stewart & Haszeldine 2014) suggest lower net CO_2 utilisation factors than those published by Azzolina et al., which would result in lower amount of CO_2 needed for the production of the estimated amount of oil and, consequently, in more favourable economic balance. To calculate a more exact value of a breakdown oil price versus amount and cost of CO_2 delivered would require performing a more detailed dedicated study.

If CO_2-EOR is combined with CO_2 storage perfomed in accord with the regulatory framework of the EU CCS Directive, the revenues can be increased by the value of of EU-ETS emission allowances (EUA) that would not need to be surrendered if the CO_2 is captured, transported and stored according to the relevant legislation. If we consider the amount of CO_2 needed to perform the CO_2-EOR job in cluster CZ III (4.72 million tonnes), this additional revenues can be as high as 117 million EUR, using the estimated EUA price for 2020 (26.50 EUR / tonne CO2[11]). This would theoretically increase the above-mentioned positive economic balance to 207 – 333 million EUR, corresponding to 25.15 – 40.45 USD per barrel.

[9] https://www.patria.cz/komodity/energie/IPE+BRENT/ipe-brent.html
[10] using exchange rate of 18 March 2020 - 1 USD = 0.9146 EUR; source https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html
[11] https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/121819-commodities-2020-near-term-weakness-for-eu-co2-prices-but-gains-seen-in-late-2020

These values, especially those in the upper part of this interval, might possibly be close to or even exceed the marginal oil production costs for some of the oil fields in the region[12]. It needs, however, to be stressed that the EU ETS regime will introduce some additional requirements related to CO2 storage that will reflect on increased total project costs. This especially concerns the administrative costs related to acquisition of the storage permit, the related reporting, provision of financial security and the required measurement, monitoring and verificatiojn of the CO_2 stored. The possible emerging business case related to this scenario can be strengthened by provision of subsidies related to CO_2 emissions reduction, increased price of oil and/or emission allowances and decrease of CCS costs.

Delivery of additional CO_2 (beyond the amount that would be needed for CO_2-EOR) for storage in the depleted oil fields after cessation of the oil production would, ironically, worsen the overall economy of the project and would need to be compensated by subsidies.

The revenues in the pure CO_2 storage scenario are represented only by the value of EU-ETS emission allowances that would not need to be surrendered if the CO_2 is captured, transported and stored according to the relevant European legislation. If the total amount of CO_2 delivered from the Mokrá plant (8.55 million tonnes) is considered, the value of the allowances in question is ca. 227 million EUR, using the estimated EUA price for 2020 (26.50 EUR / tonne CO_2[13]). This is far below the cost of CO_2 emissions avoided by means of CCS (488 – 719 million EUR) and signals that if the project relied only on the value of emission allowances, it would need to be heavily subsidized. A possible business case would require a significant increase in the EUA price combined with a decreased cost of CCS. An overview of this case study is provided in Table 15.

Table 15. Overview of the Case Study - Mokrá cement plant – cluster CZ III.

General details	
Case study name:	Mokrá cement plant – cluster CZ III
Source details	
Name of source	Mokrá cement plant (company Českomoravský cement, HeidelbergCement Group member)
Country	Czech Republic
Type of industry	Cement industry
Total CO_2 emissions (Mt /year)	0.76
Proposed CO_2 capture rate (Mt/year)	0.4
High or low purity CO_2	20 %
ETS applicable (yes/no)	yes
Sink details	
Cluster name	CZ III
Additional incremental oil production (thousand Sm^3)	1,430
Total CO_2-EOR/storage potential (Mt)	8.55
Transport details	
Distance between source and sink	50 km (direct), 80 km (pipeline)
Geographical challenges	Longer pipeline distance due to hilly terrain in the direct connection line

[12]Exact oil prduction cost figures related to individual oilfierlds are subject of business secret protection and are hence not avialble for the study.
[13]https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/121819-commodities-2020-near-term-weakness-for-eu-co2-prices-but-gains-seen-in-late-2020

7 Identification of regulatory, technical and conflicting interest challenges

7.1 Regulatory challenges

Legislation and regulations related to hydrocarbon exploration and production, CCS and emission trading are the most important parts of the regulatory framework influencing the planning of CO_2-EOR activities.

7.1.1 The Czech Republic

The hydrocarbon exploration is allowed only in the area of a valid exploration block, i.e. with a valid exploration licence (permit). The responsible governmental body is the Ministry of Environment through its regional Departments of State Administration; they award the exploration licences. The conditions and requirements for exploration licence applications as well as the follow-up steps are defined by the Geological Act No 62/1988 (in valid wording). he Geological Act does not limit the acreage of the potential hydrocarbon exploration permit (block), the duration (expiration date) is also not limited. In the Czech Republic, a charge is imposed on use of the exploration permit. The fee for the first year is 2,000 CZK (78 EUR) per square kilometre (km^2) and each following year the fee increases by 1,000 CZK (39 EUR) per km^2; i.e. the fee will be 11,000 CZK (431 EUR) per km^2 in the tenth year. The revenue from this fee is an income (100 %) of municipalities located in the area of the exploration block.

The hydrocarbon production is allowed only in the area of a valid production licence. The operator of the production licence must be simultaneously a holder of the valid authorization for specific mining activities (drilling, production, etc.). The responsible governmental body is the Czech Mining Authority and its regional District Mining Authorities; they award the production licences and authorize all kinds of mining activities. The conditions and requirements for production licence applications as well as the follow-up steps are defined by the Mining Act No 44/1988 (in valid wording); to mining activities, the Mining Activity Act No 61/1988 (in valid wording) is related. The Mining Act does not limit the acreage of the potential production licence, the expiration date is not given. There are 2 kinds of payments related to the production licence in the Czech Republic; fee per hectare of the production licence area and royalty (fee per m^3 of produced oil and/or gas). The fee per hectare (1 hectare = 10,000 m^2) is 1,000 CZK (39 EUR, minimum fee) and is still the same for each following year; the revenue from this fee is an income (100 %) of municipalities located in the area of the production licence. The royalty is defined by fixed rate in the Czech Republic; for crude oil = 558 CZK (22 EUR) per m^3 and for natural gas = 0.27 CZK (0.01 EUR) per m^3; the revenue from this fee is an income (75 %) of municipalities located in the area of the production licence, the rest is an income of the State Environmental Fund.

There is no special legislation related to CO_2-EOR in the Czech Republic. The Decree No 104/1988 of the Czech Mining Authority contains very undetailed information about EOR in general. Simultaneously with implementation of the EU CCS Directive (EC, 2009) into the Czech legislation framework (CO_2 Storage Act No 85/2012 on storage of carbon dioxide into natural rock structures), the Mining Act has been changed. According to the current wording of the Mining Act, it is forbidden to store CO_2 in reserved mineral deposits or anticipated reserved mineral deposits with the exception of oil and gas fields; it is possible to allow (remit of the Mining Authority) storing CO_2 in oil and gas fields according to the CO_2 Storage Act in connection with their overall enhanced oil and/or gas recovery. The CO_2 injection solely for the purposes of enhanced oil and gas recovery and carbon dioxide injection into coal seems for enhanced coal bed methane recovery are not regarded as CO_2 storage according to the Czech Storage Act (§ 30 Economical exploitation of reserved deposits; similarly to the EU CCS Directive). The details of combining the hydrocarbon production using CO_2-driven enhanced recovery with CO_2 storage according to the CO_2 Storage Act are unclear and generally almost entirely depending on the ad-hoc decisions of the responsible Mining Authority.

The selection of storage sites as well as the exploration permits procedure for CO_2 storage (in sense of the CO_2 Storage Act) are very similar to the exploration licence awarding procedure for hydrocarbons. The Geological Act defines the procedure for CO_2 site selection and awarding of CO_2 storage exploration permits (licences). Similarly to hydrocarbon exploration, the acreage of a potential CO_2 exploration permit as well as the duration (expiration date) are not limited. The licence fee is the same as in the case of hydrocarbons.

The award of a CO_2 storage permit is fully within the remit of the Czech Mining Authority. The procedure is described in detail in the CO_2 Storage Act. Unlike EU CCS Directive, the injected amount of carbon dioxide is limited by the CO_2 Storage Act; § 6 limits the amount to 1 million tonnes of CO_2 per year and per storage site. The CO_2 Storage Act defines also (in § 14) the fee of 1 CZK (0.04 EUR) per tonne of stored CO_2. The revenue from this payment is an income of the municipalities in the storage site area; the payer is the operator of the storage site.

The CO_2 Storage Act includes a temporary ban of industrial-scale CO_2 storage (exceeding 100,000 t) until 1 January 2020; this has now, fortunately, expired without prolongation. Nevertheless, some pieces of the regulatory framework are not yet in place; like, e.g., the governmental decree setting the provisions of financial security pursuant to Article 19 of the EU CCS Directive.

A planned CO_2 storage site must be evaluated by full-scale EIA (Environmental Impact Assessment) process according to the EIA Act No 100/2001.

7.1.2 Slovakia

The Slovak legislation regulating hydrocarbon exploration, is still very similar to the Czech legislation (even after 27 years from division). For hydrocarbon exploration, a valid exploration block is needed, i.e. a valid exploration licence (permit) must be awarded. The Geological Act No 569/2007 limits neither the acreage, nor the duration (expiration date). The responsible governmental body is the Ministry of Environment. The exploration permit fee for the first four years is 100 EUR per km^2 per year, for next four years it is 200 EUR per km^2 per year and for next two years 350 EUR per km^2 per year; for next years (the tenth and more), the fee is 700 EUR per km^2 and year. The revenue from this fee is an income of the Environmental Fund (50 %) and of the municipalities in the area of the exploration permit (50 %).

Similarly to the Czech legislation, the hydrocarbon production is allowed only in the area of a valid production licence. The operator of the production licence must be simultaneously a holder of the valid authorization for specific mining activities (drilling, production, etc.). The responsible governmental body is the Main Mining Authority of the Slovak Republic and its regional District Mining Authorities; they award the production licences and authorize all kinds of mining activities. The conditions and requirements for production licence applications as well as the follow-up steps are defined by the Mining Act No 44/1988 (the name and number of the Mining Act is the same in both Czechia and Slovakia, the current Slovak wording slightly differs from the Czech one); to mining activities, the Mining Activity Act No 51/1988 (in valid wording) is related. The Mining Act does not limit the acreage of the production licence, the expiration date is not given. There are two types of payments related to the production licence in Slovakia; a fee per km^2 of the production licence area and a royalty (fee from produced oil and/or gas). The fee per km^2 and per year is 600 EUR (minimum fee) and is still the same for each following year; the revenue from this fee is an income of municipalities (80 %) located in the area of the production licence, the rest is income of the state budget. The royalty for oil as well as natural gas is 5 % of current price of produced oil or gas, revenue from this fee is an income (100 %) of the Environmental Fund.

There is no special legislation related to CO_2-EOR in Slovakia. Simultaneously with implementation of the EU CCS Directive (EC, 2009) into the Slovak legislation system (CO_2 Storage Act No 258/2011, on permanent storage of carbon dioxide into geological environment), the Slovak wording of the Mining Act has been changed. According to the current wording of the Mining Act, the conversion of hydrocarbon fields (or salt deposits) into CO_2 storage sites means a changeover from hydrocarbon production or salt extraction into utilization of these fields or deposits as permanent carbon dioxide storage site (§ 34a). This conversion must be permitted and approved by the relevant District Mining Authority and the operator must cope with the registered hydrocarbon or salt reserves from the point of view of their next utilization; e.g. he can ask for the reserves write-off. It is unclear, if the operator can continue with oil production using CO_2-EOR before starting "pure" CO_2 storage or can ask for writing-off the remaining reserves.

The selection of storage sites as well as the exploration permits procedure for CO_2 storage (in the sense of the CO_2 Storage Act) are very similar to the exploration licence procedure for hydrocarbons. But according § 3 of the CO_2 Storage Act, the location of a potential storage site is limited by the following text: "…*as storage site, the following structures are not considered: natural rock structure and subsurface space, reasonably preferred for exploration, production and storage of hydrocarbons, for geothermal use, for radioactive waste storage …".* This is in fact protection of suitable geothermal, hydrocarbon-bearing and similar structures from setting up a CO_2 storage site that has the lowest priority. The Geological Act defines the procedure for CO_2 site selection and CO_2 storage exploration permits (licences). Similarly to hydrocarbon exploration, the acreage of the potential CO_2 exploration permit as well as the duration (expiration date) is not limited. The licence fee is the same as in the case of hydrocarbons.

The award of a CO_2 storage permit is fully within the remit of the Main Mining Authority of the Slovak Republic. The procedure is described in detail in the CO_2 Storage Act. Unlike EU CCS Directive, CO_2 Storage Act defines (in § 9) very minutely the purity of injected CO_2 stream; the carbon dioxide stream must be dry and must contain at minimum 95 % CO_2 and at maximum 0.01 % of hydrogen sulphide, 0.01 % of sulphur dioxide, 0.01 % of nitrogen oxides (NOx), 0.03 % of carbon monoxide and 0.03 % of methane - compare with EU Directive, A 21: "*A CO_2 stream shall consist overwhelmingly of carbon dioxide*". It is unclear who is responsible for checking these limitations.

A planned CO_2 storage site must be evaluated by full-scale EIA (Environmental Impact Assessment) process according to the EIA Act No 24/2006.

7.1.3 Austria

The Mining Act – *MinroG (Mineralrohstoffgesetz)* – defines exploration, mining and processing of hydrocarbons, as well as the exploration and research of storage sites for hydrocarbons in geological structures. Hydrocarbons in Austria are deemed as national resources, meaning they are exclusive property of Austria regardless of any claims by landowners. The responsible governmental body is the Federal Ministry of Agriculture, Regions and Tourism and its '*Montanbehörde*' is the competent mining authority. Mining and exploration rights can be transferred to suitable third parties according to Mining Act §69 (1). Austria imposes a charge on exploring, mining and storing hydrocarbons based on the amount and value of imported oil and gas into the country. The hydrocarbon production is only allowed in the area of a valid production licence.

3 years after implementation of the EU CCS Directive (2009/31/EC) Austria has made use of its right to ban CO_2 storage according to article 4 §1. Since then, as stated by Federal Law Act No 144/2011 §2, the underground storage of CO_2 as well as the exploration for geological CO_2 storage sights are forbidden throughout the country. The only exceptions are research projects with a maximum storage capacity of 100,000 tonnes CO_2 and the exploration of storage sites for development or testing of new products or

processes. This prohibition needs to be revaluated every 5 years. The following concerns that led to the prohibition of CCS in Austria were expressed:

- CO_2 capture and storage are still in development and not ready for broad-scale application. Following technical issues should be further addressed:
    - numerical simulations for prediction of underground CO_2 behaviour, displacement processes, reaction of CO_2 with its surrounding, prediction of risks related to cracking and seismic activities as well as the evaluation of long-term safety.
    - borehole integrity, especially regarding the corrosion of metals and cement as well as long-term borehole integrity.
    - monitoring of the stored CO_2 and its migration pathways.
    - procedures and measures in case of irregularities or leakage are not sufficiently defined.
- CO_2 Storage in Austria is mostly likely bound to depleted hydrocarbon fields. They have a lower storage capacity compared to saline aquifers. Furthermore, depleted hydrocarbon reservoirs can be used for production of oil and gas as well as storage of artificial and natural gas. Possible future utilisations might be hydrogen storage and compressed air reservoirs. Permanent CO_2 storage represents a competitive use of the subsurface.
- Worldwide CCS storage sites, in contrast to Austria's hydrocarbon reservoirs, are predominately located in sparsely populated or uninhabited areas (e.g. deserts or offshore).

The last evaluation was in 2018 where the continuation of the prohibition was decided. There is no special regulation regarding CO_2-EOR in Austria. The annotation of Federal Law Act No 144/2011 as well as the evaluation report in 2018 (III-238 d.B.) emphasize that enhanced hydrocarbon recovery with CO_2 does not count as geological storage of CO_2 and is therefore not affected by the ban. Although CO_2-EOR is allowed, the combination with CCS is explicitly mentioned in the annotation and prohibited according to Act No 144/2011 §2.

In conclusion

In general, performing of CO_2-EOR to increase oil production is legal in all three countries. In Austria, the ban of CO_2 storage makes it impossible to combine CO_2-EOR with CO_2 storage within the meaning of the EU CCS Directive, while the Czech and Slovak legislations in principle allow combining these two activities, even though there is a lot of unclearness and uncertainty regarding detailed provisions and rules for this procedure. Moreover, some parts of the regulatory framework are not yet in place. This situation gives in fact an unlimited power to the responsible Mining Authority to decide upon all aspects of site development, which represents a big uncertainty for possible investors and operators.

An additional, pan-European regulatory barrier has been identified concerning the provisions for CO_2 transport. The Commission Decision 2010/345/EU as regards the inclusion of monitoring and reporting guidelines for greenhouse gas emissions from the capture, transport and geological storage of carbon dioxide (EC 2010) assumes transport by pipelines as the only way of transport compliant with the EU ETS framework. This provision significantly limits the possibilities of flexible transport of CO_2 within capture and/or storage clusters where also other transport means like trains or trucks would need to be applied for short-distance transport of smaller CO_2 volumes.

7.2 Competitive use of the subsurface

Possible conflicts of interest regarding the use of the pore space in the subsurface include competition between CO_2 storage sites and underground gas storages, exploitation of geothermal energy, etc.

7.2.1 The Czech Republic

The preference of underground gas storages to CO_2 storage sites and/or CO_2-EOR is a typical conflict of subsurface use in the Czech Republic. About 10 years ago, only pure gas fields were transformed into gas storages; but recently, also oil fields have been used as underground gas storage sites. In such cases, field operators (investors) usually prefer a gas storage to CO_2-EOR as well as pure CO_2 storage. The reason for this practice is economic; the gas storage business is still profitable, while CO_2-EOR is still expensive (no CO_2 market) and so far untested in the Czech Republic.

There have not been any conflicts of interest between CO_2 storage and geothermal energy utilisation of deep geological structures so far, mostly due to a limited development of these technologies in the country so far. This can, however, change in future because both technologies can target similar geological structures. There are no rules, procedures or guidelines in place to handle this type of competitive use of the subsurface.

7.2.2 Slovakia

As stated in Chapter 8.1, there is no special legislation related to the CO_2-EOR in Slovakia. According to § 3 of the CO_2 Storage Act, the following structures cannot be considered as CO_2 storage sites: structures preferred for exploration, production and storage of hydrocarbons, for geothermal use, for radioactive waste storage and other waste storage in subsurface space or any other utilization of the subsurface space for energy purpose including possibilities, which are strategical for security of energy supply or development of renewable energy sources. It means that a CO_2 storage site has the lowest priority in the whole ranking of priorities. This paragraph implies that the “contamination” of the reservoir after CO_2-EOR and before transformation into potential underground gas storage acts as a barrier for CO_2-EOR application. On the other hand, the total capacity of Slovak underground gas storages represents currently about 4 billion m^3; this number represents about 85 % of the domestic consumption (4.7 billion m^3 in 2018 according the Ministry of Economy). It seems that new underground gas storage sites will not be needed anymore and this type of conflict will not be common in future. The main current barrier for CO_2-EOR is the limited availability and high price of CO_2 and relatively low reserves of the Slovak oil fields.

7.2.3 Austria

Until now, there is no special regulation that prioritizes the different usage possibilities of the underground in Austria. As mentioned in the previous chapter, storage of CO_2 in geological reservoirs for economic purpose is against the regulations. Apart of safety concerns, one of the justifications for the ban is the competitive use of the subsurface e.g. gas production or gas and hydrogen storage. Currently there are 8 underground gas storages in Austria with a storage volume of approximately 8.4 bn m^3. Hydrogen storage is still in development and might become more important in the future.

In addition, further competitive underground uses might cover in the following order:

- Geothermal energy use including underground thermal energy storage (UTES) in saline aquifers,
- Power-to-gas systems[14] including subsurface storage
- Compressed air storage linked to wind mill farms (currently not in the focus of neither the Austrian government nor the industry).

[14] Pilots in Austria: UNDERGROUND SUN.CONVERSION project or Wind2Hydrogen project

7.3 Conflicts of interest

CO_2-EOR and CO_2 storage generally fall into the category of geological exploration and mining activities. As such, the usual procedures for handling of conflicts of interest with the protection of environment, water and infrastructure, as well as regional land-use planning, etc. need to be performed. In some cases, these conflicts can prove difficult to handle and can represent an unsurmountable barrier for implementation of a new project.

7.3.1 The Czech Republic

The Geological Act (No 62/1988, in valid wording) defines (§ 6) a "list" of potential conflict of interests for exploration (geological works) and mining activities, containing names and numbers of relevant acts; the experience of "permitmen" shows that this "list" does not fully cover all potential conflict of interests. According to § 22, "*The potential conflicts of interest have to be identified during the project preparation. If any conflict of interest protected by another law has been identified, the project has to be prepared according these laws*".

The most important and crucial potential conflict of interest is nature protection according to Act No 114/1992 (on Nature and Landscape Protection, in valid wording). This Act limits and/or forbids exploration works and mining activities in the protected areas (for example National Parks, Protected Landscape Areas, Natura 2000 etc.).The responsible authority for approval and permission of any kind of exploration and mining activity in any area is the Environmental Department of the relevant Regional Authority; without its approval, no geological and/or mining activity is allowed. In disputable cases, the Ministry of Environment is the appellate authority. Other acts related to landscape protection are the Forest Act (No 289/1995, in valid wording) and the Agriculture Land Resources Act (No 334/1991, in valid wording). These acts limited the geological works and mining activities but do not forbid them.

The Water Act (No 254/2001, in valid wording) represents the water protection, both subsurface and surface. This Act defines special protected areas for drinking water resources and drinking water reservoirs, where no exploration and mining activities are allowed and protected areas for potential drinking water resources, where exploration and mining activity are limited. Similar protection of mineral and healing water resources is defined in the Spa Act (164/2001, in valid wording).

The Mining Act (No 44/1988, in valid wording) protects the areas of production licences. Only operator of the production licence is authorized for exploration and mining activity in the area of the production licence; for other investors, any activity inside the area of the production licence is forbidden.

The protective and safety areas of linear constructions (networking industry) like pipelines, motorways, railways and high-voltage electric lines represent another limitation for geological works as well as E&P activities. The protective and safety areas are defined by special laws and represent typical "industrial" conflicts of interests. The protective and safety areas for electric lines and gas pipelines are defined by Energy Act (No 458/2000, in valid wording). For electric lines, the protective area depends on voltage and is relatively small; the largest is 30 m on both sides of line for electric lines with voltage of 400 kV. For gas pipelines, the protective area depends on a pressure; the largest area is 4 m for the pressure 40 bars and more. The safety areas are defined for gas pipelines only, depends on both, pressures and diameters; the largest is 160 m for pressure 40 bars and more and diameter 700 mm and more. In the safety area, it is possible to carry out some geological exploration with a writing permission of the pipeline operator. According the Act No 189/1999 (on Crude Oil Emergency Reserves, in valid wording), the protective area for crude oil pipelines is 150 m. For gasoline pipelines, the protective area is 300 m (according governmental decree No 29/1959). The largest protective area for railways is 60 m according the Railway Act (No 266/1994, in valid wording). According the Road Act (No 13/1997, in valid wording), the protective area for motorways is 100 m.

7.3.2 Slovakia

Similarly to the Czech legislation, the Geological Act (No 569/2007, in valid wording) defines (§ 12) a “list” of potential conflict of interests during exploration works and mining activities. “*During a project preparation, the potential conflict of interest protected by other laws has to be identified and suitable measures for protection of such interests has to be suggested”.*

The most important and crucial potential conflict of interest is nature protection according Act No 543/2002 (on Nature and Landscape Protection, in valid wording). This Act limits (or forbids) exploration works and mining activities in the same way as in the Czech Republic (National Parks, Protected Landscape Areas, Natura 2000 etc.). The responsible authority for approval and permission of any kind of exploration and mining activity is also the Environmental Department of the relevant Regional Authority. Without its approval, no geological and/or mining activity is allowed. Other acts related to landscape protection are the Forest Act (No 326/2005, in valid wording) and the Agriculture Land Resources Act (No 220/2004, in valid wording). These acts limited the geological works and mining activities but do not forbid them.

The Water Act (No 364/2004, in valid wording) represents the water protection, both subsurface and surface. This Act defines special protected areas for drinking water resources and drinking water reservoirs, where no exploration and mining activities are allowed and protected areas for potential drinking water resources, where exploration and mining activity are limited. Similar protection of mineral and healing water resources is defined in the Spa Act (538/2005, in valid wording).

The protection of production licence areas defines the same act as in the Czech Republic - the Mining Act (No 44/1988, in valid wording).

Also in Slovakia, the protective and safety areas of linear constructions (networking industry) like pipelines, motorways, railways and high-voltage electric lines represent a limitation for geological works as well as mining activities. There are only small differences between the Czech and Slovak legislation. The protective and safety areas for electric lines and gas pipelines are defined by Energy Act (No 251/2012, in valid wording). For electric lines, the protective area depends on voltage and is relatively small; the largest is 35 m on both sides of line for electric lines with voltage of 400 kV. For gas pipelines, the protective area depends on a diameter; the largest area is 50 m for the diameter 700 mm and more. The safety areas are defined for gas pipelines only, depends on both, pressures and diameters; the largest is 200 m for pressure 40 bars and more and diameter 500 mm and more. In the safety area, it is possible to carry out some geological exploration with a writing permission of the pipeline operator. The largest protected area for both crude oil and gasoline pipelines is 300 m according Slovak technical standard No 650204 and governmental decree No 29/1959 of the former Czechoslovakia. According the Railway Act No (513/2009, in valid wording), the largest protective area for railways is 60 m. For motorways, the protective area is 100 m (according the Road Act No 135/1961, in valid wording).

7.3.3 Austria

Apart of the previously mentioned competitive use of the subsurface, carbon capture, its transportation and storage might pose additional conflicts of interests with nature protection and local infrastructure. Deep aquifers that comprise drinking water are under special protection in Austria and must not be harmed or contaminated by drilling and storage operations. Carbon capture facilities with the aim of storing CO_2 in geological reservoirs or with a carbon capture volume of at least 1.5 million tonnes CO_2 per year would need a full-scale Environmental Impact Assessment (Act No 697/1993 attachment 1 Z4). The same is valid for CO_2 pipelines with a length of at least 40 km and an internal diameter bigger than 300 mm (Act No 697/1993 attachment 1 Z13). Furthermore, all industrial emissions produced by carbon capture processes underlying the European Directive 2010/75/EU need to be classified as IPPC facilities according to Federal Law Act No 194/1994 attachment 3 (6.8). If transportation of the CO_2 is realized via truck and/or rail instead of pipelines, infrastructure will need to shoulder additional burden. According to (Acatech, 2018), transportation of 1 million tonnes of CO_2 via pipeline is equivalent to 50,000 truckloads or 1,000 cargo trains.

Before introducing the legal ban of CO_2 storage in Austria, the public opinion on CCS was very critical. However, since then topics linked to CCS disappeared from the public discourse and lost the interest of journalists. The raised public awareness concerning the climate crisis might lead to a turn of public perception and to a, at least, slightly higher public acceptance. Although no public acceptance studies have been performed in Austria in the framework of ENOS, an indication of a presumed higher public acceptance might have been the reason for several press releases published by the Austrian hydrocarbon producer OMV on the relevance and necessity for CO_2 storage.

7.4 Technical challenges related to CO_2-EOR and CO_2 storage

7.4.1 Supercritical conditions

In order to work as an EOR agent, the CO_2 must reach supercritical condition in the reservoir, i.e. the general flooding and storage pressure must exceed 74 bar. Applying normal hydrostatic conditions and a decent safety margin, this means that the reservoir depth should be at least 800-900 m sub-surface (3000 ft is often referred to in regions where customary field units are used). If the reservoir pressure has fallen below supercritical conditions as a result of the earlier depletion process, it may be necessary to do water injection or wait for the reservoir to re-charge through natural aquifer influx.

7.4.2 Miscibility

CO_2-EOR works best under fully miscible conditions, meaning that the CO_2 and the in-situ oil can be mixed in all propulsions with no interfacial tension between the two fluids. Historically this has often been considered a prerequisite for a successful CO_2 flooding, particularly in combination with water injection (CO_2 WAG). In many cases operators have applied extra water injection to boost pressure beyond miscibility level prior to CO_2 injection. The minimum miscibility pressure (MMP) increases when the API gravity (related to level and distribution of heavy (C5+) components in the oil) decreases and reservoir temperature increases as illustrated in Figure 45. Due to the oil quality (low API gravity) and the general shallowness, with formation depths often less than 1,500 m, only a few of the Vienna Basin reservoirs screened in this study will have potential for fully miscible CO_2 flooding conditions.

However, even though full miscibility cannot be achieved, CO_2 may still to a great extent be soluble in the oil. Equation of State (EOS) modelling as well as published correlations (Emera & Sarma, 2007) indicate that as much as 50 to 60 % CO_2 may be attained in the oil on molar basis. This should lead to enhanced recovery through swelling of the oil and reduction in in-situ oil viscosity. It should nevertheless be noted that the general lack of fully miscibility conditions (in most reservoirs) could pose an additional uncertainty on the results of this screening study.

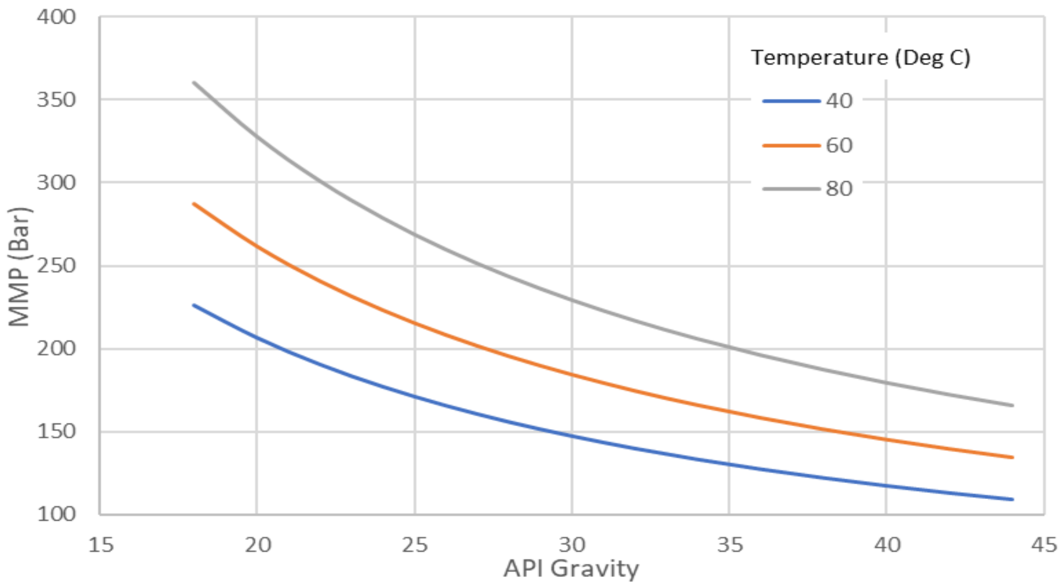

Figure 45. Minimum miscibility pressure for CO_2 in oil (reproduced from (Bachu, 2016).

7.4.3 Maximum injection pressure (attainable rates)

Maximum bottom hole pressure for wells injecting CO_2 is usually constrained by fracturing pressure. In most of the cases it is assumed that induced fracturing should be prevented (Hansen, et al., 2013) due to risk of cracking of the cap rocks and possibility for the formation fluids to leak out of the target formation. The geomechanical assessments carried out for one the Vienna basin fields in the Czech Republic, LBr-1 (Berenblyum, et al., 2017) reported that the fracturing pressure is approximately 30% above the hydrostatic pressure. This estimate for the LBr-1 field was however obtained with quite limited knowledge of the regional geomechanics, the stresses and geomechanical parameters (approximated from simplified approaches and literature) causing large uncertainty of the assessments. Studies of geomechanics (in-situ stress distributions and geomechanical parameters) in the region are therefore of high importance, since such parameters such as fracturing pressure determine potential injection rates and feasibility and economics of CCUS projects.

7.4.4 Injectivity issues

Dependent on the salinity of the formation water, early time well damage may occur due to salt precipitation in the vicinity of the CO_2 injection wells. During the early injection period, CO_2 will tend to dry out the local brine, leaving salt crystals behind to reduce pore sizes. This phenomenon was clearly observed during the sequestration of CO_2 at the Snøhvit field in the Barents Sea. This damage may however be repaired once and for all by treating the well with MEG (Mono Ethylene Glycol) injection (Hansen, et al., 2013).

7.4.5 Productivity and flow assurance

Asphaltenes precipitation has been considered as one of the major challenges during CO_2 injection to enhance recovery. Onset of asphaltene precipitation is a function of pressure and thus prone to happen near or in the production wells where it may cause considerable damage. Injection of solvents such as xylene and toluene are commonly used to dissolve asphaltene deposits in both the wellbore and formation, but these substances have recently become less attractive for environmental reasons. How CO_2 changes the asphaltene structure and thus accelerates the precipitation process is still not well known (Golshahi et al. 2019), and further research into these mechanisms as well as quest for better solvents should be warranted.

Paraffin wax is present in many of the oil reservoirs in the Vienna Basin. In the Czech region, up to 8.5 % has been reported. Paraffinic waxes can precipitate when temperature decreases during oil production, transportation through pipelines, and oil storage. In production wells, wax depositions may cause important flow impairment, which requires frequent well interventions to rectify. Typical remedies are injection of solvents such as methyl-ethyl ketone and toluene.

Wax precipitation may be characterized by the Wax Appearance Temperature (WAT) at which, with falling temperature, solid wax starts to appear. The WAT is also pressure dependent. The effect of CO_2 in this process does not seem to be strongly addressed in the literature and only one directly relevant paper has been identified (Arya Hosseinipoura, 2016). This research indicates that CO_2 in the well stream will actually contribute to lower the WAT and thus help to reduce, or potentially prevent an eventual wax problem. On the other hand, a lot of CO_2 in the stream may cause a stronger Joule-Thomson effect (adiabatic expansion), with more temperature reduction as the CO_2 is released from the oil phase when entering the well or flowing up the tubing.

7.4.6 Corrosion

CO_2 and water together form carbonic acid (H_2CO_3) which causes aggressive corrosion in steel material unless remedial measures are implemented. These measures may be coating of pipes and tubing and use of stainless steel in exposed equipment.

7.4.7 Leakage

The potential for leakage of CO_2 from the reservoir is not limited by induced fracturing of the reservoir and caprock by CO_2 injection as described above (Shchipanov, Kollbotn, & Berenblyum, 2019). Uncontrolled leakage into the overburden may also happen through wells due to unsealed bounds between the formation and the cement in the borehole and through faults that could be re-activated due to pressure build-up and effective stress changes in the reservoir. Studies of geomechanics help in evaluating injection conditions preventing fault reactivation (Chiaramonte et al. 2015) (Chiaramonte, White, & Trainor-Guitton, 2015), (Choi et al. 2015) (Choi, Skurtveit, Bohloli, & Grande, 2015). Leakage risks caused by the reasons described above have been evaluated in ENOS WP3 using data for the LBr-1 field also mentioned above.

7.5 Technical challenges related to CO_2 capture

The potential sources of CO_2 capture that have been included in this study are primarily based on the emissions data collected from the EU E-PRTR database. Some additional calculations have been made on the potential availability of high concentration CO_2 from the hydrogen production plant at the OMV Schwechat Refinery in Austria, and some assumptions have been made regarding the capture potential at the Mokrá cement plant in the Czech Republic. However, in order to take the business case of CO_2-EOR further, more plant specific details regarding the possible application of CO_2 capture at selected sites will be necessary. Information on the types of production processes, the age of the installation, availability of waste heat and the availability of space for capture systems are important factors. Experience in CO_2 capture from industrial emissions, particularly cements plants, is currently limited.

8 Conclusions and recommendations

8.1 Conclusions

This report has studied a number of critical factors to assess the potential for CO_2-EOR in the Vienna Basin. All the three countries of the Vienna Basin have potential for both CO_2-EOR and CO_2 storage. By far the greatest potential for these can be found in the Austrian part of the Vienna Basin, in the large Matzen cluster. For the entire basin, the theoretical incremental recovery of additional oil due to CO_2 injection has been calculated as of 21 million Sm^3 (130 million barrels), which, using the current (February 2020) oil price of 40 USD/bbl, represents (if produced) a gross value of 5,200 million USD. The amount of CO_2 that would be needed to perform the related CO_2-EOR operations and thereafter stored in the depleted fields is estimated to nearly 140 million tonnes. Therefore, from this initial analysis, at least from a theoretical perspective, the potential for CO_2-EOR combined with CO_2 storage warrants further investigation. What is also clear is that there is sufficient theoretical CO_2 storage potential in the region to accommodate many years of emissions from the CO_2 sources identified. One exception here are the oil field clusters in the Slovakian section of the Vienna Basin, which, with a total storage capacity of 6 million tonnes CO_2, are not considered large enough to store industrial scale levels of CO_2.

Despite this theoretical potential, there are a number of technical, regulatory and economic challenges that need to be highlighted. Some of these challenges are specific to the region, others are applicable to all CCS and CO_2-EOR projects. The challenges are outlined below.

8.1.1 Technical aspects

CO_2-EOR works best under fully miscible conditions, meaning that the CO_2 and the in-situ oil can be mixed in all propulsions with no interfacial tension between the two fluids. Due to the oil quality (low API gravity) and the general shallowness, with formation depths often less than 1500 m, only a few of the Vienna Basin reservoirs screened in this study will have potential for fully miscible CO_2 flooding conditions. However, CO_2-EOR can still be feasible even if full miscibility may not be achieved.

Many of the fields investigated have been perforated several hundred times during the exploration and production phases. This is not ideal for CO_2 storage operations, as this will require extensive risk management of potential leakage through legacy wells. Although the potential for using existing wells could reduce the capital costs of CO_2 injection projects, the well infrastructure of many fields may not be suitable for CO_2 injection due to corrosion issues.

This analysis identified approximately 10 point sources of CO_2 that could be considered for CO_2 capture, usage and storage, within a 70 km radius of the oil field clusters. By far the largest point sources are in the oil refining and cement sectors. Generally speaking, the sources face relatively high costs for CO_2 capture, above 60 USD / tonne CO_2. One potential source of relatively low-cost CO_2 has been identified, at a hydrogen production plant at the Schwechat Refinery in Austria. This source produces approximately 200 kt CO_2 per year of potentially high-purity CO_2, which could be efficiently captured for CO_2 storage. It must also be mentioned that the cement plant owners are seriously considering CCS for reducing process emissions, as cement plants have no other options for significant CO_2 reductions.

8.1.2 Regulatory aspects

CO_2-EOR is permitted in all countries, however geological CO_2 storage under the EU CCS Directive is prohibited in Austria. This represents a potential showstopper for the combination of CO_2-EOR with long-term CO_2 storage for the purposes of climate change mitigation. Another area that presents some uncertainty, is the combination of CO_2-EOR with CO_2 storage. Although the EU CCS Directive does not prohibit CO_2-EOR with CO_2 storage, the current regulatory status of this in the Czech Republic and Slovakia is rather unclear. Furthermore, there are no examples of existing or proposed CO_2 injection projects in the EU that have developed a monitoring and reporting plan for a CO_2-EOR project under the EU CCS Directive. The monitoring and reporting guidelines of the EU ETS currently assume only pipeline transport for CO_2, which represents a barrier for implementation of CCS in small clusters which may consider transport by train or truck. Finally, it has been identified in certain countries that CCS developments may be hindered by various conflicts of interest, and regulatory restrictions.

8.1.3 Economic aspects

Cost estimates have been developed for Case study 2, involving CO_2 capture from a cement plant for use for EOR. The combination of the relatively high costs of CO_2 capture in the cement industry and the limited amount of CO_2 to be captured, transported and stored annually with the currently low price of both oil and CO_2 emission allowances (EUA) presents challenges for the development of a sound business case. The most favourable business model is the combination of CO_2-EOR with CO_2 storage performed under EU ETS regime but without storage of additional CO_2, which has a negative economic balance. Whereas the value of the additional incremental oil produced through CO_2 injection can offset the operational costs of capturing the CO_2, the costs of capturing and storing the CO_2 for the sole purpose of CO_2 storage are currently far higher than the expected EU ETS price (26.50 EUR / tonne CO2 in 2020[15]). Therefore, either EU ETS prices must increase, or additional forms of subsidy or grant schemes must be made available to allow CO_2 capture to take place in the cement and refining industries present in the Vienna Basin region.

8.2 Recommendations

In order to take the concept for CO_2-EOR in the Vienna Basin forward, a number of recommendations are proposed.

- *Awareness raising* - The preliminary results of this analysis should be brought to the attention of both policy makers and industry stakeholders, in particular oil producers and CO_2 emitters, in the Vienna Basin region. This can help to raise interests of the economic and environmental benefits this concept could bring. Next steps could involve additional meetings with stakeholders, organizing a series of workshops or establishing a 'CCS in the Vienna Basin' working group.

- *Removing regulatory barriers* - The prohibition of CO_2 storage in Austria is an obvious barrier to the developments of CCS in the country. Austria has both the greatest potential for CO_2-EOR and CO_2 storage. Dialogue with regulators needs to take place to identify why CO_2 storage is prohibited, and whether this prohibition threatens the timely decarbonization of heavy industry by 2050 as required under the Paris Agreement. In addition, the existing regulatory framework in the Czech Republic and Slovakia should be fine-tuned to be more supportive of CCS and its combination with CO_2-EOR. Last but not least, the barrier of limiting CO_2 transport options under EU ETS to pipelines only needs to be removed to allow for other means of transport in smaller clusters.

- *Feasibility studies using site-specific data* - This analysis has provided an initial analysis based on field data aggregated into clusters (due to confidentiality reasons), and publicly available data on CO_2 sources. The next step in this research could be to take the case studies identified in

[15] https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/121819-commodities-2020-near-term-weakness-for-eu-co2-prices-but-gains-seen-in-late-2020

chapter 6 to the next level of detail. Hereby more detailed information could be requested from the oil operators and CO_2 emitters to improve the cost estimates of the case studies and provide a clear picture of the potential business cases.

- *Identifying supportive policy mechanisms* - This concept, if taken forward, has the potential to contribute to the European economy and environmental protection. However, the necessary financial incentives are not yet in place. An inventory of potentially applicable national and European policy mechanisms could help identify potential funding sources to advance both the preparatory research and possible investments needed to realise CO_2-EOR in the Vienna Basin. Possibilities include the European Commission's Cohesion Fund, Innovation Fund, Modernisation Fund, or if a cross-border project was considered, the Connecting Europe Facility (CEF).

Finally, it will be important for the geological surveys and R&D institutes, but also industrial stakeholders in the countries of the Vienna Basin to gain knowledge and experience by developing partnerships (both industrial and research) with countries with practical CO_2-EOR experience (Hungary, Croatia, USA, Canada, Turkey). Through this knowledge sharing, some of the technical challenges relating to CO_2-EOR can be addressed.

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This deliverable is prepared as a part of ENOS project
More information about the project could be found at http://www.enos-project.eu

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This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653718