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Assessment of transboundary effects at LBr-1 and regulatory solutions

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Contents

Executive Summary

The national transpositions of the EU CCS Directive do not fully address transboundary issues, which creates hurdles for utilization of promising storage sites situated on or near Member States boundaries. To understand how these hurdles could look like in practice, ENOS WP4 team carried out a study using the practical example of the Czech LBr-1 site. LBr-1 – one of the ENOS research sites – is an abandoned hydrocarbon field situated in the Czech part of the Vienna Basin, close to the Czech-Slovak border. Thus, it represents a very suitable subject for studying various transboundary issues related to geological storage of CO_2. LBr-1 is now subject of continued detailed site assessment, with the vision to turn the field into a research CO_2 storage pilot site with or without CO_2-EOR.

The main objective of the study was to evaluate any transboundary issues that might arise from geological storage of CO_2 in the LBr-1 field, identify cases that are difficult to handle, including those where existing legislation and regulations is unclear or lacking, and suggest solutions. The assessment was focussed on three potential storage scenarios: small-scale storage pilot, large-scale storage and CO_2-EOR with permanent storage.

At first, currently valid national legislations relevant to CO_2 geological storage in the Czech Republic and Slovakia were examined and several legislative and regulatory barriers for CCUS were identified. In general, the current status of CCUS legislation in both countries reflects the position of the technology in their decarbonisation strategies. This position is currently weak and the technology is not considered as a priority for the use of the subsurface. As a consequence, the relevant legislation and regulations are rather focusing on creating barriers and obstacles, rather than supporting CCUS deployment. This needs to be changed if the potential of the technology to decarbonise the national economies shall be utilised.

In the Czech Republic, the identified barriers (temporary ban of CO_2 storage until 01/01/2020, limitation of the amount of stored CO_2 per site per year and missing provisions for the financial security) can be removed by relatively easy and simple improvements of legislation. In Slovakia, however, the overall regulatory approach needs to be changed to enable CO_2 storage on its territory. This especially concerns re-considering the priorities for subsurface use and the approach to the solution of conflicts of interest.

In both countries there are unclear or missing regulations governing the CO_2-EOR activity and possible transfer of the oilfield produced with help of CO_2-EOR into a CO_2 storage site, which represents a big uncertainty for possible investors and operators.

In the second step, implications of the current legislation and regulatory regimes on the LBr-1 site itself were studied. The most important finding is that both the storage site and storage complex are located entirely on the territory of the Czech Republic. However, several transboundary issues were identified, especially those that are related to possible (even if highly unlikely) leakage of CO_2 from the storage complex.

Four possible types of transboundary issues were examined in detail – pressure build-up, possible leakage through boreholes, possible leakage through faults and possible migration of fluids out of the reservoir due to exceeding spill points. While pressure build-up and leakage through faults do not appear to cause transboundary issues, the other two phenomena need to be carefully considered. In case CO_2 leakage appears either through abandoned wells or due to exceeding the southern spill point, the analysis of possible leakage pathways shows that the CO_2 could migrate into the territory of Slovakia. There are three main factors that limit the level of concern: the probability of large leakage occurrence is low, the amount of possibly leaked CO_2 would be very limited, and the spill point is reached only in case the reservoir is filled up to its limit.

Nevertheless, these findings mean that a cooperation of regulatory authorities from both Czech and Slovak Republics will be necessary to prepare and operate the storage site. The main reason is that many parts of the site preparation, injection, closure and post-closure phases will be transboundary, especially the risk assessment, monitoring (all phases) and possible leakage mitigation measures. This is a significant complicating factor for possible injection of CO_2 at LBr-1.

Despite of this, the realisation of a CO_2 storage project on the site is considered viable, especially in the basic pilot storage scenario. This case avoids the spill-point related concerns (because of the limited extent of CO_2 plume) and involves only a limited number of abandoned wells that need to be taken care of concerning their abandonment status. The lack of experience with CO_2 storage sites and absence of any regulatory precedents in both countries will require a lot of pioneering work do be done by both the project developer and the relevant authorities. This process, however, cannot be avoided, simply because both sides need to gain the necessary experience that can be utilised in future, when preparing, operating and regulating next CO_2 storage projects.

1 Introduction

The national transpositions of the EU CCS Directive (Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006) do not fully address transboundary issues, which creates hurdles for utilization of promising storage sites situated on or near Member States boundaries. To understand how these hurdles could look like in practice, ENOS WP4 team carried out a study using the practical example of the Czech LBr-1 site.

LBr-1 – one of the ENOS research sites – is an abandoned hydrocarbon field situated in the Czech part of the Vienna Basin, near the town of Lanžhot, and close to the Czech-Slovak border (see Figure 1). Thus, it represents a very suitable subject for studying various transboundary issues related to geological storage of CO_2. LBr-1 is now subject of continued detailed site assessment, with the vision to turn the field into a research CO_2 storage pilot site with or without CO_2-EOR. This work was started in the previous project REPP-CO2 (Hladik et al., 2017) and is now continuing within ENOS.

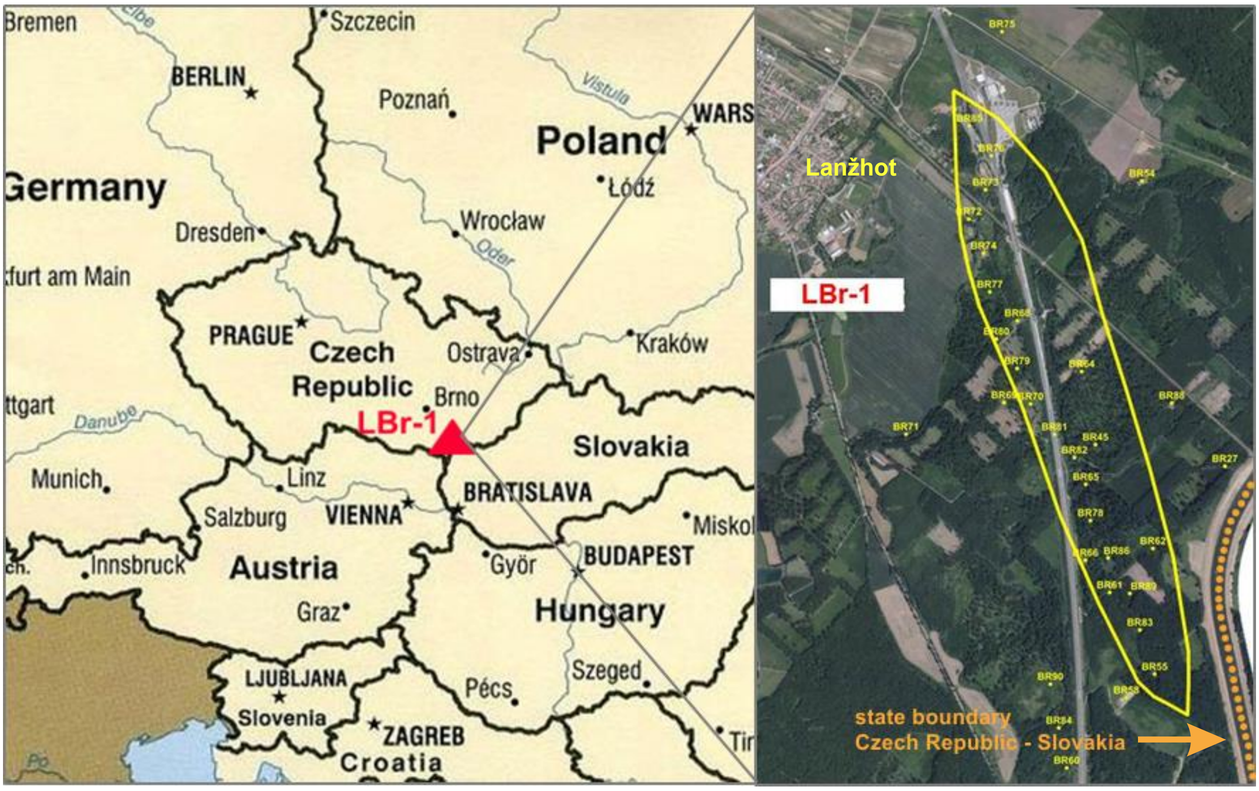

Figure 1 Location of the LBr-1 site (left) and satellite image of the site (right) with outline of the reservoir area (yellow polygon), Czech-Slovak boundary (orange dotted line) and legacy wells (yellow dots). The reservoir is ca. 3 km long and max. 600 m wide.

The study on transboundary issues at LBr-1 has been performed by ENOS partners CGS (lead partner), SGIDS and NORCE. The main objective of the study is to evaluate any transboundary issues that might arise from geological storage of CO_2 in the LBr-1 field, identify situations that are difficult to handle, including those where existing legislation and regulations are unclear or lacking, and suggest solutions.

The assessment considers three scenarios: small scale storage pilot with limited CO_2 storage, full scale storage and CO_2-EOR with permanent storage.

The approach used was to compare the currently valid national legislations relevant to CO_2 geological storage in the Czech Republic and Slovakia with practical issues that appeared during the preparatory stages of the LBr-1 storage pilot. The first step was to define – as precisely as possible – the extent of the CO_2 storage complex at LBr-1, as described in legislation and relevant guidance documents. This answers the basic question if the storage complex is situated entirely on the territory of the Czech Republic, or extends to the territory of Slovakia.

In the second step, any possible influences of CO_2 storage that would reach across the border were studied. These included the spreading of the CO_2 plume, pressure footprint, possible leakage pathways and leakage rates for CO_2 escaping from the reservoir and risk management. The results of reservoir simulations performed in the previous REPP-CO2 project and in ENOS deliverable D4.5, and the risk assessment from the REPP-CO2 project and ENOS deliverable D3.2 were used as input for the current study.

Finally, all findings were summarised and main issues were listed, as well as all related uncertainties. Based on these findings, recommendations were drawn describing possible improvements of the regulatory framework in order to better deal with CO_2 storage sites at or close to boundaries between countries.

2 Legislation and regulations

The EU CCS Directive (EC, 2009) represents the most important legislation for CO_2 geological storage in the EU. Its Czech and Slovak national transpositions (implementations) are the Act No 85/2012 (on storage of carbon dioxide into natural rock structures and on changes of some acts) in the Czech Republic and Act No 258/2011 (on permanent storage of carbon dioxide into geological environment and on changes and amendments of some acts) in the Slovak Republic. The comparison between the EU Directive, the Czech Storage Act No 85/201 and the Slovak Storage Act No 258/2011 is shown in Table 1.

Table 1: Comparison of articles of the EU Directive, Czech Act No 85/201 and Slovak Act No 258/2011

EU CCS Directive	**Czech Act No 85/2012**	**Slovak Act No 258/2011**
A1 Subject matter and purpose	§1 Subject matter	§1 Subject matter
A2 Scope and prohibition	§24 (*storage is not allowed till 1 January 2020*)	§3 Storage site
A3 Definitions	§2 Definitions	§2 Definitions
A4 Selection of storage sites	Part III Amendment of the Geological Act No 62/1988	Part XI Amendment of the Geological Act No 569/2007
A5 Exploration permits	Part III Amendment of the Geological Act No 62/1988	Part XI Amendment of the Geological Act No 569/2007
A6 Storage permits	§3 CO_2 storage operation permits + §4 CO_2 storage operation permits proceeding	§3 Storage site
A7 Applications for storage permits	§5 Applications for storage operation permits	§4 Applications for storage permits
A8 Conditions for storage permits	§6 Storage operation permits decision	§6 Conditions for issue of storage permits
A9 Contents of storage permits	§6 Storage operation permits decision	§7 Contents of storage permits
A10 Commission review of draft storage permits	§6 Storage operation permits decision	§5 Review of storage permit issue application
A11 Changes, review, update and withdrawal of storage permits	§7 Changes, review, update and withdrawal of storage operation permits	§8 Update and withdrawal of storage permits
A12 CO_2 stream acceptance criteria and procedure	§8 CO_2 stream acceptance criteria and procedure	§9 Criteria and procedure for storage
A13 Monitoring	§9 Monitoring	§10 Monitoring
A14 Reporting by the operator	§10 Submission of reports	§11 Submission of reports

EU CCS Directive	Czech Act No 85/2012	Slovak Act No 258/2011
A15 Inspections	§21 Inspecting activity	§12 Running and consequent inspections
A16 Measures in case of leakages or significant irregularities	§11 Measures in case of leakages or significant irregularities	§13 Remedy and needed remedy
A17 Closure and post-closure obligations	§12 Obligations at CO_2 storage closure and post-closure	§14 Storage closure and post-closure procedure
A18 Transfer of responsibility	§13 Transfer of responsibility	§15 Transfer of responsibility
A19 Financial security	§15 Financial security + §16 Financial security for risks + §17 Financial reserve (fund)	§16 Adequate financial security
A20 Financial mechanism	§14 Payment for CO_2 storage *(1 CZK/ton)* + §18 Fees	§17 Payment
A21 Access to transport network and storage sites	§19 Access to transport network and CO_2 storage sites	§18 Access
A22 Dispute settlement	§19 Access to transport network and CO_2 storage sites	§18 Access
A23 Competent authority	§20 Public administration dispensation + §21 Inspection activity	§20 State administration bodies + §21 State control
A24 Transboundary cooperation	§20 Public administration dispensation	§24 Transboundary cooperation
A25 Registers	§20 Public administration dispensation	§19 CO_2 storage information system
A26 Information to the public	§20 Public administration dispensation	§19 CO_2 storage information system
A27 Reporting by Member States	§20 Public administration dispensation	§20 State administration bodies
A28 Penalties	§22 Offences of legal and self-employed persons (sole proprietors) + §23 Common provisions to offences	§22 Administrative offences + §23 Proceedings

The Czech and Slovak EU CCS Directive transpositions (implementations) are more or less similar but some differences can be found. According § 24 of the Czech Act No 85/2012 (Czech Storage Act), "*The carbon dioxide storage into natural rock structures in the area of the Czech Republic in accordance with this Act is not allowed up to January 1, 2020.*" Another difference is represented by § 6 of the Czech Storage Act; this § limits the injected amount of carbon dioxide to 1 million tonnes of CO_2 per year and per storage site. Unlike the EU Directive, the Czech storage Act defines (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.

According § 3 of the Slovak Act No 258/2011 (Slovak Storage Act), the location of a potential storage site is limited by the following text: "…*as storage site, 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 Slovak 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 of these limitations.

The selection of storage sites as well as exploration permits proceeding are very similar to the exploration licence proceeding for hydrocarbons in both Slovak and Czech legislation. The Geological Acts (Czech No 62/1988, Slovak No 569/2007) define, beside other things, the proceeding for CO_2 site selection and CO_2 storage exploration permits (licences). Neither the Czech Geological Act, nor the Slovak Geological Act limit the acreage of the potential exploration permit (block); the duration (expiration date) is not limited either. In both countries, a charge is imposed on use of the exploration permit. In the Czech Republic, the fee for the first year is 2,000 CZK (78.46 EUR) per square kilometre (km^2) and each following year the fee increases by 1,000 CZK (39.23 EUR) per km^2; i.e. the fee will be 11,000 CZK (431.40 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 permit. In Slovakia, the 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 Slovak Environmental Fund (50 %) and of the municipalities in the area of the exploration permit (50 %).

The Annex I of the EU CCS Directive (Criteria for the Characterisation and Assessment of the Potential Storage Complex and Surrounding Area) was included into the Czech Geological Act while in Slovakia it is part of the Storage Act. In both cases, the same wording as stated in the EU Directive is used.

The possibility to explore for a possible CO_2 storage site is limited by Articles of both national Geological Acts. These issues are discussed in Chapter 5.

The name and act number of the Mining Act No 44/1988 is the same for both the Czech Republic and Slovakia but its current wording (26 years after dividing of former Czechoslovakia) is different. Nevertheless, in both countries carbon dioxide storage belongs to the group of mining activity named "Special intervention into the Earth´s crust" (§ 34, both Czech and Slovak wording). From CO_2 storage point of view, the chapters dealing with Enhanced Oil Recovery (EOR) are the most important ones. In the Czech wording, CO_2-EOR is explicitly mentioned as a measure for enhanced hydrocarbon recovery and represents the only option when CO_2 injection in a hydrocarbon field is allowed. In Slovakia, CO_2-EOR is not explicitly mentioned.

Potential transformation from CO_2-EOR operations to CO_2 permanent storage is defined in the Czech Mining Act, while in the Slovak wording the conversion is only mentioned as a transformation from an oil and/or gas producing field directly into a CO_2 storage site. No EOR stage is defined, which creates uncertainty.

According to the Czech 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 Czech Mining Authority) storing CO_2 in oil and gas fields according to the Czech 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 the Czech Storage Act (§ 30 Economical exploitation of reserved deposits; similarly to the EU Directive*: "Enhanced Hydrocarbon Recovery (EHR)* *refers to the recovery of hydrocarbons in addition to those extracted by water injection or other means. EHR is not in itself included in the scope of the EU CCS Directive".*

According to the Slovak 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 only has to write off the remaining reserves.)

A planned CO_2 storage site must be evaluated by full-scale EIA (Environmental Impact Assessment) process in both countries; in the Czech Republic according to the EIA Act No 100/2001 and in Slovakia according to the EIA Act No 24/2006.

Similarly to other geological and mining activities, CO_2 storage site exploration and construction (including drilling) is limited by nature and water protection legislation and by regulations defining safety and protection zones of linear (networking) constructions like pipelines, high-voltage electric lines, railways and motorways.

3 Definition of the storage complex

3.1 Geological structure – reservoir and overburden

The LBr-1 structure represents the northern part of the Brodske complex – several small hydrocarbon accumulations located at both sides of the Czech-Slovak border. Originally, the whole complex was called the Brodske field. After the splitting of Czechoslovakia in 1993, the northern part of the complex was re-named to “Lanzhot-Brodske” (field No. 3241900 according to the CGS-Geofond register), and its area was covered by the production licence 40010 “Lanzhot I”.

The main volumes of oil and gas were produced from LBr-1 in 1959-1969, but sporadic production continued until 2000 (registered production 200 tonnes of oil). The site operator was the state company “Moravske naftove doly” (nowadays MND a.s.). In 2004 the site operator asked for a write-off of the remaining reserves, by which the field was declared abandoned. In 2016 the Czech Mining Authority decided to cancel the production licence “Lanzhot I”. Nevertheless, the whole area is still covered by the oil and gas exploration licence “Vienna Basin VIII” held by MND a.s.

The position of the LBr-1 field within the Brodske complex area is shown in Figure 4. LBr-1 represents the northern oil and gas accumulation. Brodske-South is tectonically bound by the extensional Brodske fault in the South-East and due to subsidence forms the hanging wall-block situated deeper than the other structures. Brodske-Middle is a relatively independent hydrocarbon lens, primarily connected with Brodske-South through the adjacent aquifer. The shallower Brodske-Upper Block is situated on the footwall of the Brodske fault, with a throw of around 120 m.

LBr-1 reservoir is a combination of a lithological and tectonic trap. The Lab horizon pinches out at the East/North-East edge of the field, still on the territory of the Czech Republic but relatively close to the Czech-Slovak border

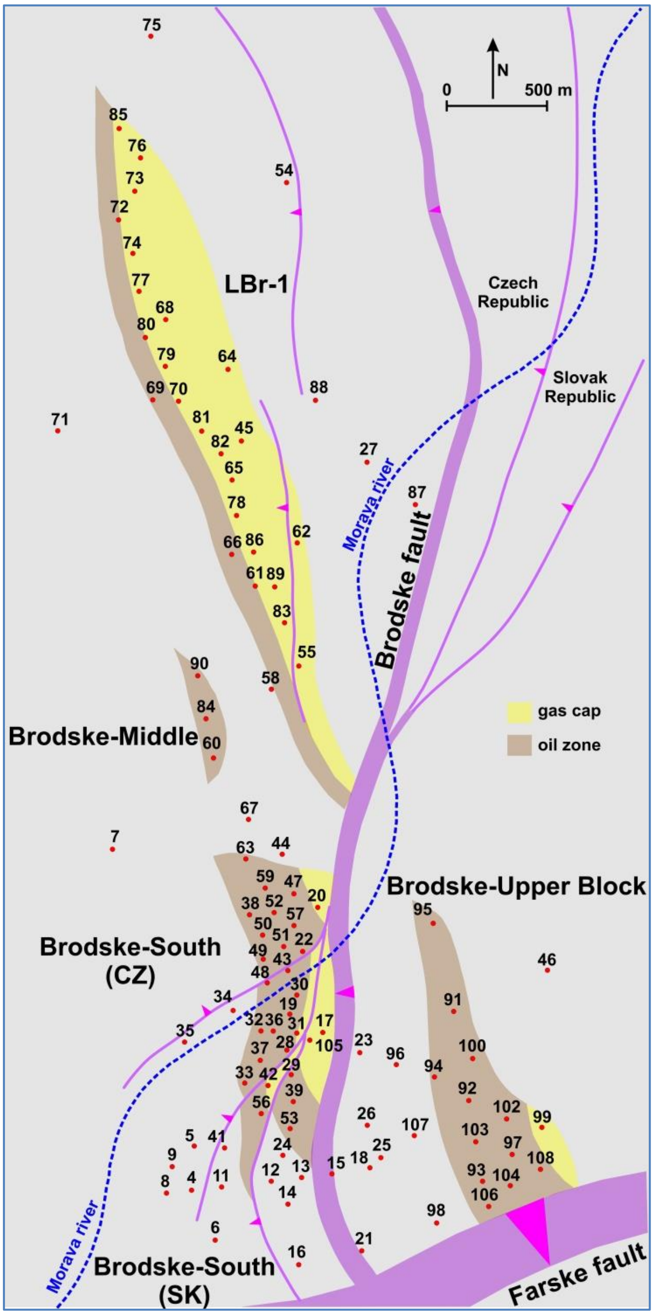

Figure 2 Map of the Brodske hydrocarbon complex. The numbered dots depict the position of wells (the “Br-“ part of the well names was left out; e.g., 85 corresponds to well Br-85). The Morava river also represents the state boundary between the Czech Republic and Slovakia. The initial gas zones are marked in yellow and the initial oil zones in brown. Faults are drawn in violet.

in some places (see Figure 3, Figure 24 and Figure 26), while the faults of the Brodske fault system confine the field in the South and partly in the South-East. The faults are subject of closer evaluation in ENOS Task 3.2.1. Note that in Figure 3 the Lab horizon is juxtaposed across Fault 1 against the impermeable underburden of the Lower Badenian, whereas further South the offset along the fault is smaller and connection between the Lab horizon at both sides of the fault exists (Figure 32).

The main targeted reservoir horizon of the field (originally hydrocarbon-bearing) comprises the Middle-Badenian sands, known as the Lab horizon. It represents the storage structure in the sense of the EU CCS Directive (EC 2009) - '*a defined volume area within a geological formation used for the geological storage of* CO_2'. The horizon is constrained by the underlying impermeable Lower Badenian clays at the bottom and by a good-quality caprock – the Middle-Badenian shale – on the top. The thickness of the horizon is up to 30 m in the western part of the reservoir.

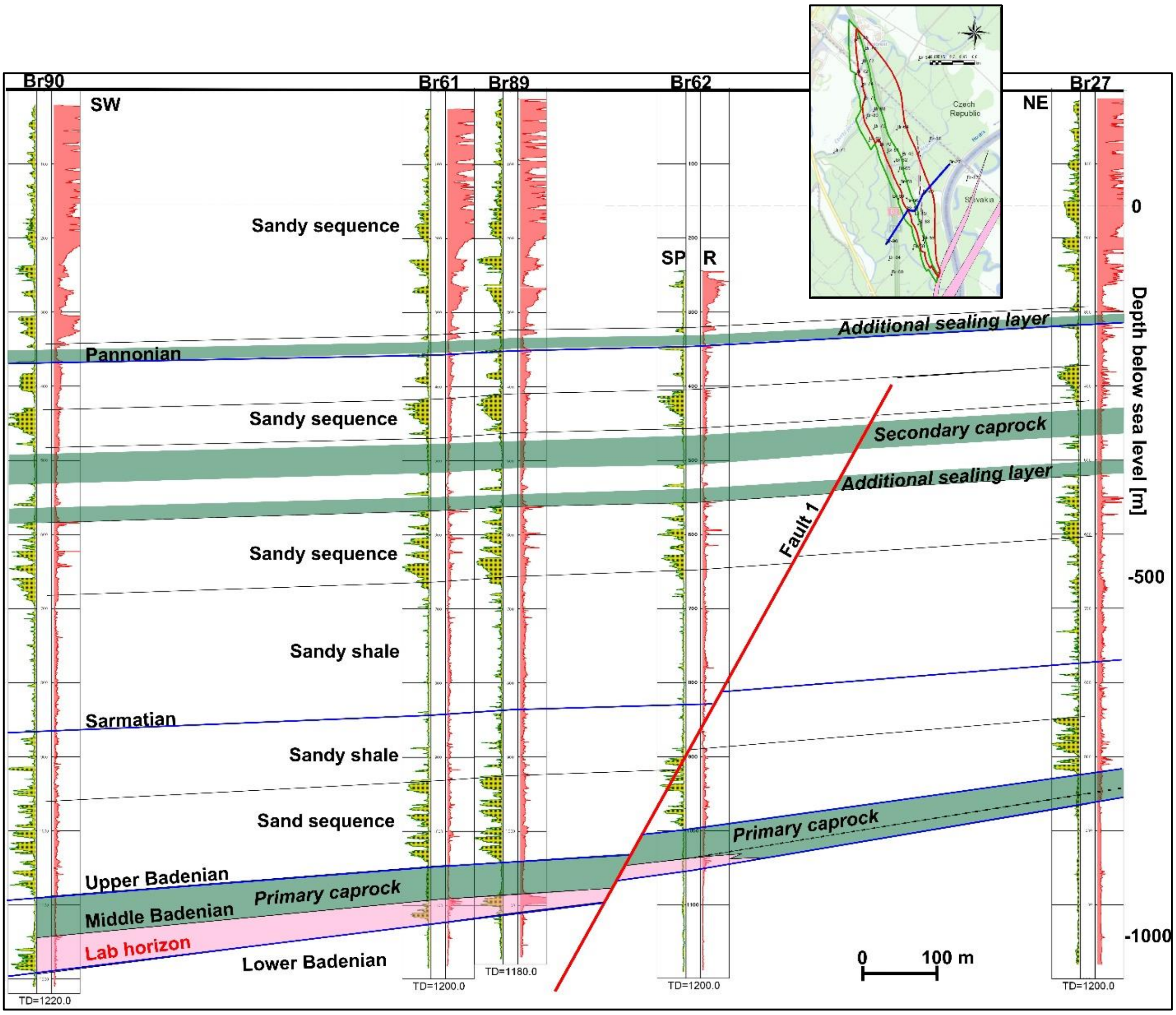

Figure 3 Schematic cross-section through the southern part of LBr-1 based on SP (green) and RAG2 (red) well-log correlation showing Lab horizon pinch-out in the East and the position of the caprocks. The small map in the top right corner shows the position of the cross-section.

The Lab horizon can be divided into four partial collector bodies – sand layers deposited on top of each other (L1, L2, L3 and L4) that are separated by less permeable clayey intercalations with occasional interconnections. The sands are medium to fine grained and generally poorly consolidated. They are situated at a depth of ca. 1,000 m below surface and have outstanding reservoir properties with a porosity up to 25 % and permeability up to 500 mD. This fact, in combination with relatively good knowledge of the geology and presence of a good caprock, is the main reason why LBr-1 is considered a good candidate for a pilot reservoir for geological storage of CO_2, potentially combined with CO_2-EOR.

The primary caprock is formed by Middle Badenian clays, a 35 – 55 m thick uninterrupted layer (see Figure 3) with excellent sealing properties that have been confirmed by the existence of the hydrocarbon accumulation itself (consisting of oil zone and a gas cap). In the overburden – Upper Badenian, Sarmatian and Pannonian – sandy and shale sequences alternate. Three additional clayey sealing layers can be identified in Sarmatian and Pannonian (see Figure 3); the middle one (at depths of 440-500 m and 30 – 40 m thick) has the properties of a regional seal and can be defined as the secondary reservoir caprock. As such, it can be considered to be the upper boundary of the CO_2 storage complex.

While the above-described geological features mainly determine the vertical extent of the storage structure (as the main component of the storage site) and the storage complex, the definition of their lateral extent needs to take the volumes of the injected CO_2 and its behaviour in the reservoir, during and after oil production, into account. This has been investigated by means of dynamic reservoir modelling and numerical simulations of CO_2 injections in the reservoir, both in ENOS WP4 (Berenblyum et al., 2019) and in the previous REPP-CO2 project (Hladík et al., 2017). The main simulation result to be considered in this respect is the extent of the CO_2 plume in the reservoir.

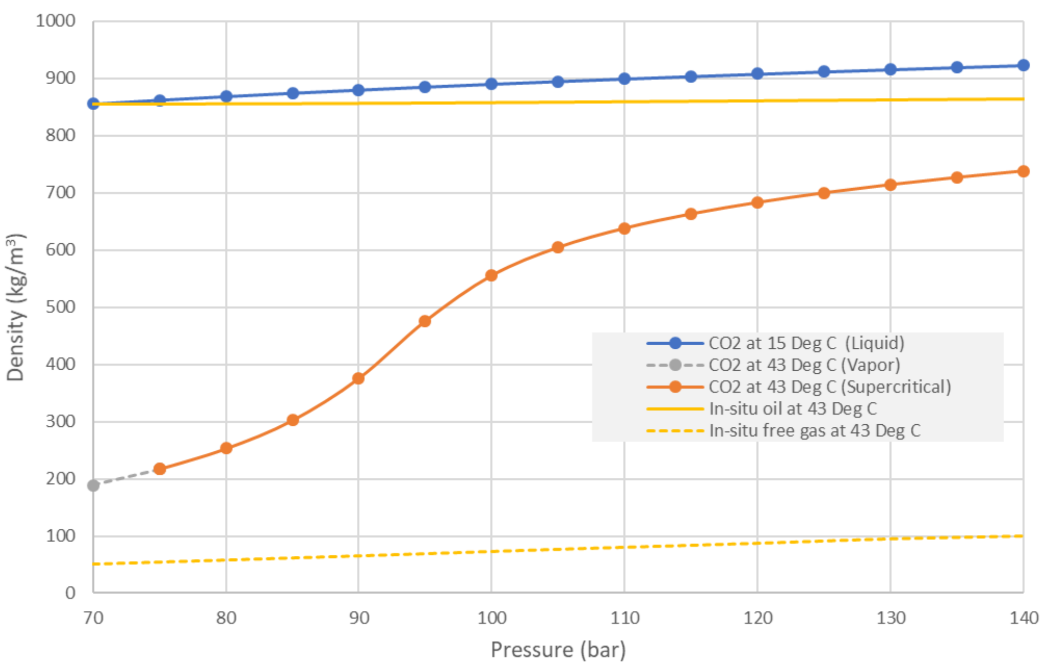

Figure 4 Density of CO_2 at 15°C and 43°C under varying pressure (NIST Chemistry WebBook, Standard Reference Database Number 69), compared with estimated in-situ oil and gas densities

3.2 CO_2 plume extension

CO_2 injected into the LBr-1 reservoir should be stored under liquid or supercritical conditions, i.e. pressure above 74 bar. The CO_2 density at 15°C and 43°C (the latter being the LBr-1 reservoir temperature) for various pressures is shown in Figure 4. As this figure indicates, the density of the CO_2 fluid under normal reservoir conditions (43°C), before eventually mixing with water and remaining oil, will be in the range from roughly 300 to 700 kg/m³. This means that it is less dense than the reservoir oil in situ (estimated to be around 850 kg/m³), and denser than the reservoir gas (50 – 100 kg/m³).

At the prevailing reservoir condition, CO_2 injected into LBr-1 will not be miscible with the in-situ oil (in all proportions). However, CO_2 is still soluble in the oil, and through condensation, vaporisation and diffusion processes the CO_2 will partly become an “oil” component, and partly stay as an independent phase. If there is enough CO_2 in contact with the oil, this process will continue until the oil is saturated with CO_2. As the CO_2 mixes with the oil, the oil viscosity is reduced, leading to EOR potential through better flow properties and improved displacement efficiency.

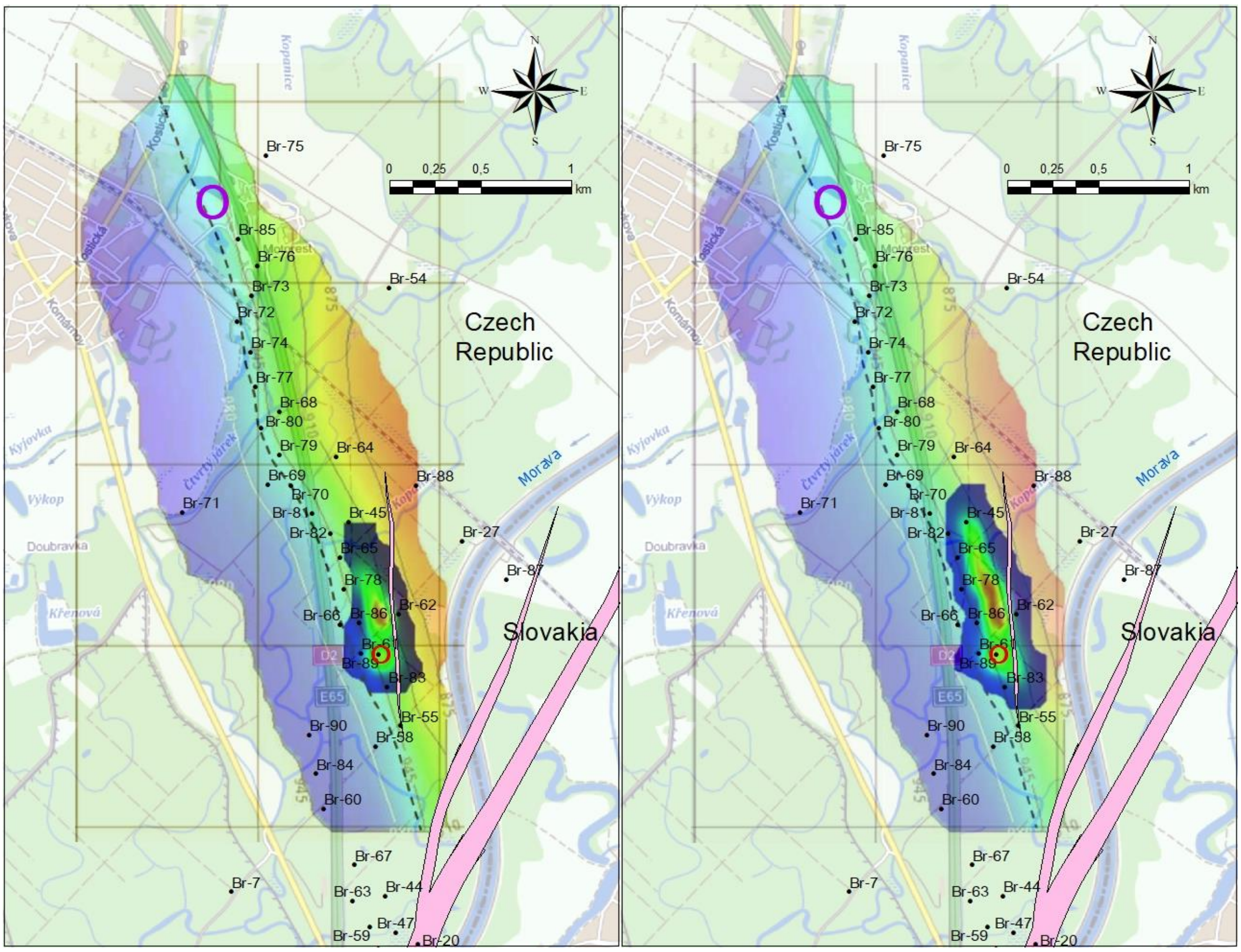

Figure 5 Maps showing CO_2 plume extension for the base case storage pilot scenario after injection of 11,500 t in year 1 (left) and 23,000 t at the end of year 2 (right) of CO_2. Warmer (more reddish) colours indicate thicker plume and higher CO_2 concentration. Structural maps of the top of the Lab horizon are displayed in the background (depths contours in meters below mean sea level). Faults are drawn in violet. The dashed line depicts the estimated original water-oil contact according to results of dynamic history match. The injection well Br-89 is marked by red circle. Approximate position of the northern spill point is marked by a dark-violet circle. The Morava river also represents the state boundary between the Czech Republic and Slovakia.

If injected into the oil zone, for instance through any of the existing producers, the CO_2 plume is therefor expected to extend itself laterally, in or at the top of the remaining oil zone, both in free form and in solution with the oil. In case the CO_2 reaches the reservoir at low temperature, e.g. 10 to 15°C, pure CO_2 might be heavier than the in-situ oil and tend to migrate downward toward the water zone. However, solubility of CO_2 in water is relatively low, and the CO_2 will over time be re-heated towards reservoir temperature. Injection temperature is thus not expected to have any noticeable impact on plume extension.

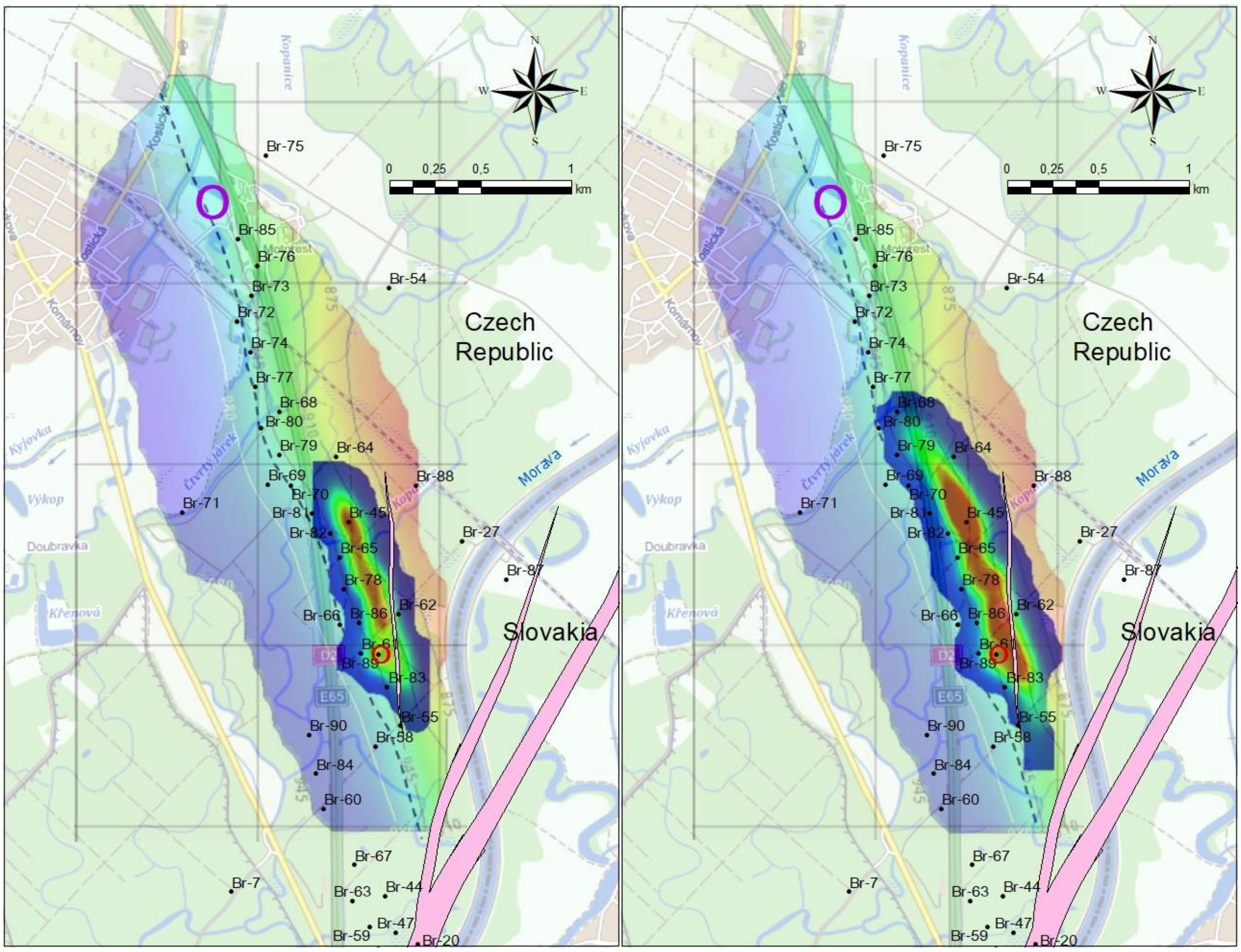

Figure 6 Maps showing CO_2 plume extension for the base case storage pilot scenario after injection of 35,000 t at the end of year 3 (left) and 70,000 t after 6 years of injection (right) of CO_2. Warmer (more reddish) colours indicate thicker plume and higher CO_2 concentration. Structural maps of the top of the Lab horizon are displayed in the background (depths contours in meters below mean sea level). Faults are drawn in violet. The dashed line depicts the estimated original water-oil contact according to results of dynamic history match. The injection well Br-89 is marked by red circle. Approximate position of the northern spill point is marked by a dark-violet circle. The Morava river represents the state boundary between the Czech Republic and Slovakia.

Figure 5 and
Figure 6 show the modelled distribution of the CO_2 plume in the base case storage pilot scenario (Kollbotn & Berenbluym, 2016). This is a storage only case where approximately 30 tons/day of CO_2 were injected at reservoir temperature for 6 years. The CO_2 was injected at a single well point (reusing the existing well Br-89, located in the southern part of the reservoir). As expected, the plume is spreading out at the level of the oil zone, with only marginal invasion into the water zone in the vicinity of the injector. The simulations also show that CO_2 does not enter significantly into the gas-cap area in the east. This may be explained by the strong density contrast between CO_2 and the natural gas, causing a gravity-stable interface between the two fluids. It may thus be anticipated that any migration of CO_2 into the gas-cap will happen chiefly by diffusion.

As can be observed, the plume has not yet reached any potential spill points after 70,000 tons injected, neither in the North, nor at the Brodske fault system in the south. The eastern reservoir margin (mainly formed by the pinch-out of the Lab horizon), which is the part of the reservoir that is closest to the Czech-

Slovak border, remains untouched by CO_2 in the first three cases (up to 35,000 tons injected) and is just about to be reached by the CO_2 plume at 70,000 tons injected.

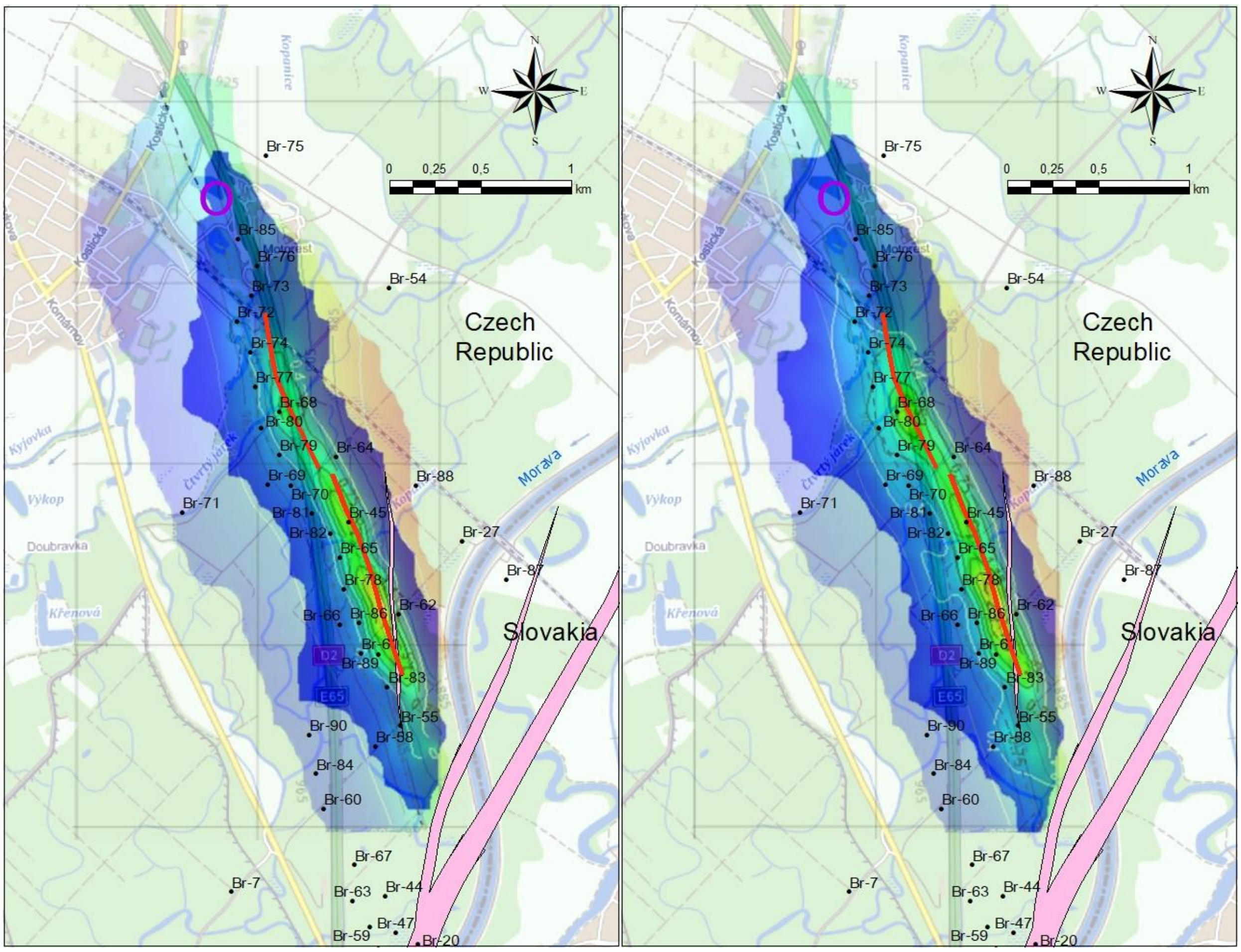

Figure 7 Maps showing CO_2 plume extension for the "full-scale" storage scenario, following 6 years of moderate injection, after injection of 160,000 t at the end of year 7 (left) and 260,000 t at the end of year 8 (right) of CO_2. In this case, horizontal injectors were used (positions indicated by red lines)

Figure 7 shows simulated lateral extension of the CO_2 plume in the "full storage" scenario when, following the first 6 years' moderate injection of the pilot phase, the rate was increased to 270 tons/day (150,000 Sm^3/day) through two horizontal wells drilled in the north-south direction. The calculated extension of the CO_2 plume after 160,000 tonnes and 260,000 tonnes injected is illustrated in the figure. As seen, already after 160 kt injected, the plume will probably have reached both the northern spill point and the Brodske fault system in the south end of the reservoir where possible leakage through the fault plane cannot be excluded (see Chapter 4.4 for details).

As shown in Figure 7, continued, large scale injection will probably also force CO_2 encroachment into the water zone and aquifer. This effect is likely to be controlled by local pressure gradients and by reservoir quality and heterogeneity. Lower temperature of the injected CO_2 (not included in the modelling) may also promote CO_2 migration toward the aquifer, as CO_2 being potentially denser than the in-situ oil (Figure 4)

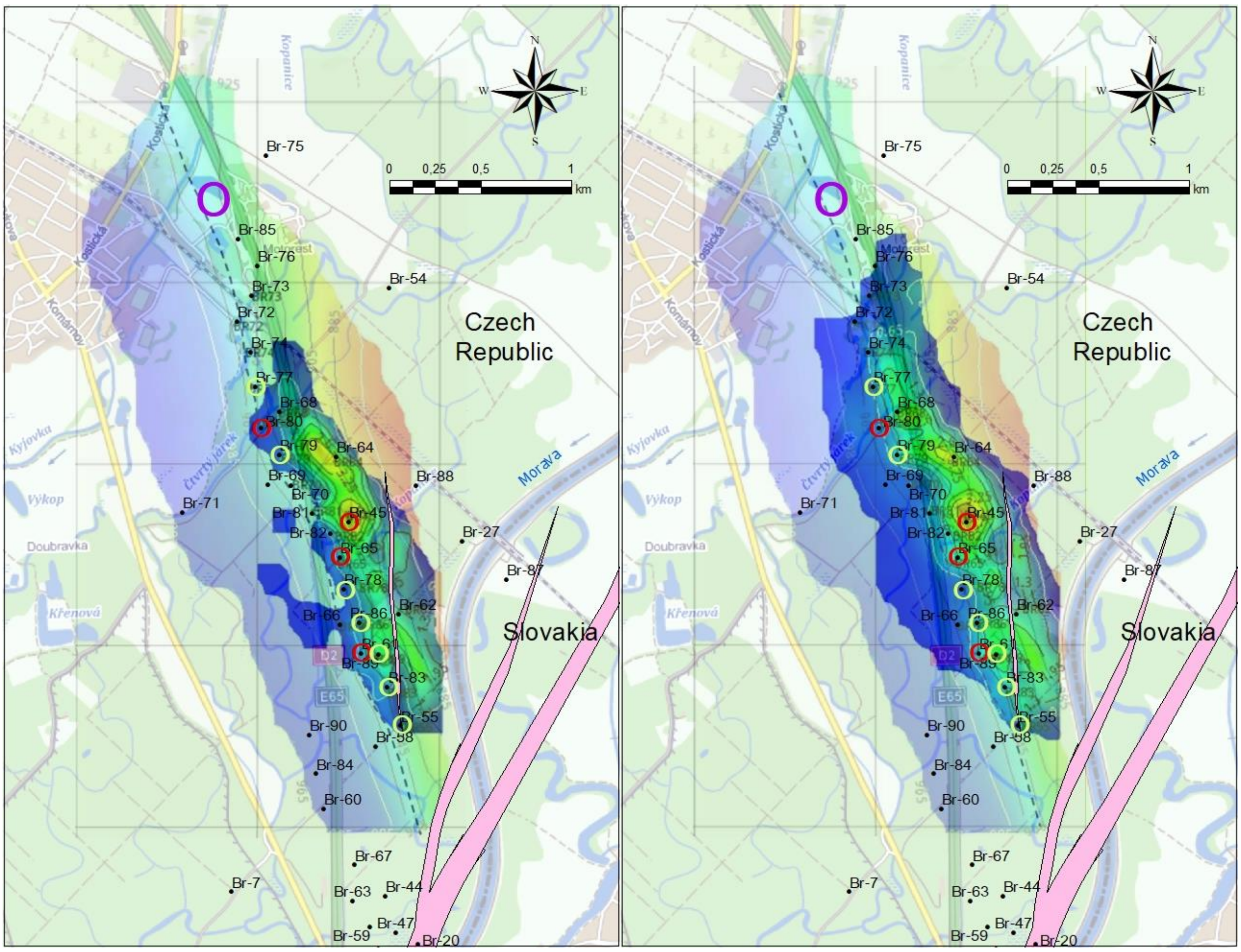

Figure 8 Maps showing the CO_2 plume extension for the CO_2-EOR case after storing of 60,000 t (left) and 140,000 t (right) of CO_2. The red circles represent injectors, the yellow circles producers.

exhibits the extension of the CO_2 plume in a case where CO_2 is injected for the purpose of EOR. This scenario was subject of ENOS Deliverable D4.5 (Berenblyum et al., 2019) where project partners TNO and NORCE simulated various CO_2-EOR scenarios and performed co-optimization of enhanced oil recovery *and* CO_2 storage based on economic criteria (maximizing Net Present Value). Optimization parameters included (timing of) wells to be used as producer or injector. The case shown here is taken from the ensemble of cases used in the optimization procedure and represents a valid example of a CO_2-EOR-storage case. It estimates that this case will store approximately 140 kt of CO_2 with around 100,000 Sm^3 of oil to be produced by EOR over a 20 years period.

In this case the CO_2 was injected using 4 injectors, while oil production took place through 7 producers, all vertical wells. One of the producers was converted to injector after 12 years of operation. Comparing
and
Figure 6 (60,000 t stored by CO_2-EOR vs 70,000 tons stored within the "pure" storage pilot) it appears that whether injection is for EOR purpose, or for storage only does not have a strong impact on the plume distribution. The results also suggest that the CO_2 seems to remain in the area of injection – at least in the short time span. Locating injectors towards the centre of the reservoir may thus help avoiding the plume to reach potential spill points. This is demonstrated by the CO_2 plume maps in Figure 8 – the plume touches the pinch-out zone in the east but does not reach to the northern spill point or the fault system delineating the reservoir in the south.

The CO_2 plume extension maps show that for the basic CO_2 storage pilot scenario (up to 70 kt CO_2 stored) and the discussed CO_2-EOR scenario, the CO_2 safely stays within the reservoir, not reaching the northern spill point or the fault system at the southern reservoir margin. A different situation is, however, observed in the “full storage” scenario, when the CO_2 approaches both the northern spill point and the faults on the southern margin of LBr-1. Here, the existence of a possible spill point needs to be evaluated, taking the fault properties and the juxtaposition of layers into account. This would also be true for a scenario in which additional CO_2 would be injected for storage at the end of the EOR phase. These items are discussed in Chapter 4.4 in detail.

3.3 Delimitation of the storage complex

The storage complex is defined by the EU CCS Directive (EC, 2009) as the storage site and surrounding geological domain which can have an effect on overall storage integrity and security; that is, secondary containment formations. The storage site itself means a defined volume area within a geological formation used for the geological storage of CO_2 and associated surface and injection facilities (Figure 9).

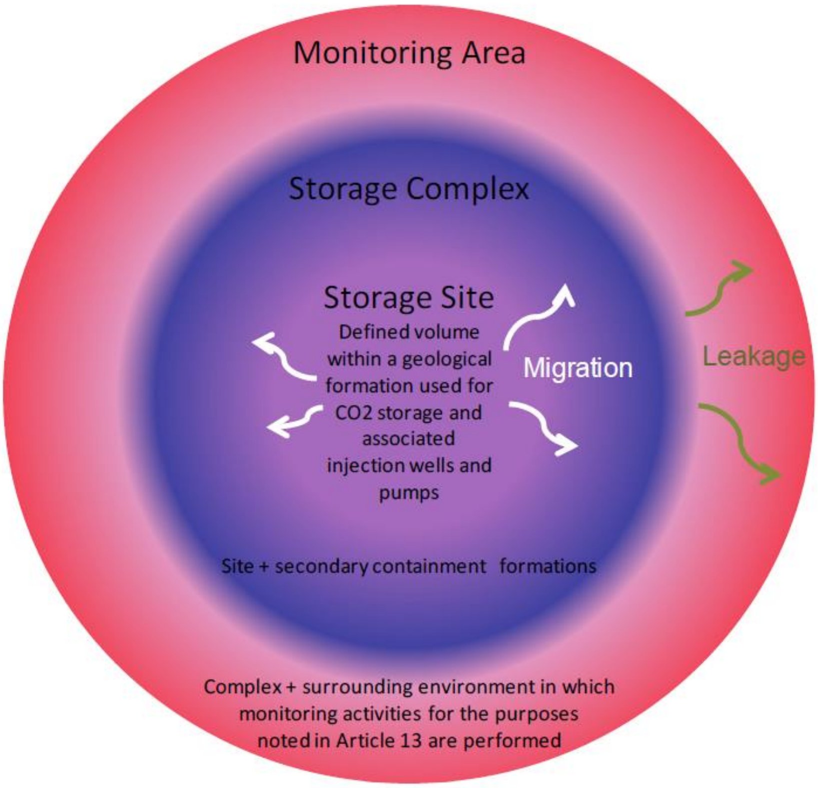

Figure 9 Schematic representation of the Storage Site, Storage Complex and Leakage as defined by the EU CCS Directive (adopted from ICF International, 2010)

According to the Guidance Document 2 on the EU CCS Directive (ICF International, 2010), the definition of the storage complex includes:

- the immediate surface and sub-surface facilities at the storage site;
- only the targeted seal(s) and reservoir(s), where the CO_2 is physically injected into and is expected to migrate and be stored, i.e. the geological formations which comprise the physically invaded rock volume from the CO_2 plume migration; and

- secondary seal(s) and reservoirs(s) that may contain the CO_2, in case the CO_2 plume migrates beyond the primary seal.

What remains unclear, is how the definition of the storage complex is related to the time period to be considered, especially taking the evolution of the CO_2 plume extension in time into account, as well as how additional effects not directly associated with the actual physical CO_2 plume location should be considered (especially pressure footprint of CO_2 injection and displacement of formation water and/or other fluids from the storage site).

Using the definition in the Guidance Document (see above), the lateral extent of the storage complex is defined by the extent of the CO_2 plume; this is discussed in Chapter 3.2. The vertical extent of the complex is outlined in Figure 10. The complex comprises the target reservoir (Lab horizon), the primary caprock (Middle Badenian clays), the overlying sandy and shale sequences of Upper Badenian and Sarmatian and the secondary caprock – the clay layer in the upper part of the Sarmatian sequence.

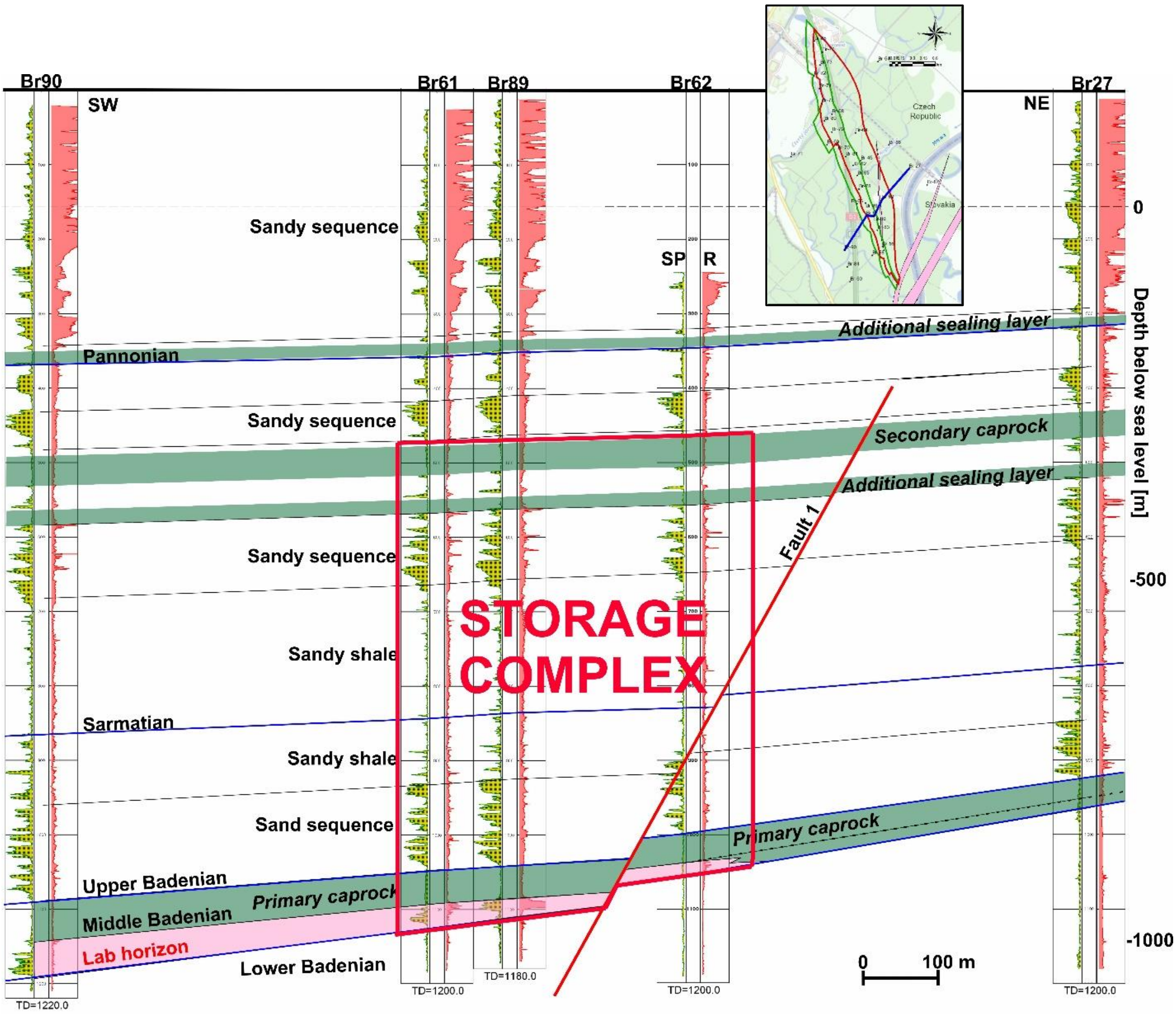

Figure 10 Schematic outline of vertical extent of the storage complex in a SW-NE cross-section through the southern part of LBr-1. The small map in the top right corner shows the position of the cross-section.

From the transboundary point of view, the main conclusion is that the storage complex itself is situated entirely on the territory of the Czech Republic, even though very close to the Czech-Slovak border. Possible transboundary issues are thus not connected with the location of the storage complex itself but rather with other phenomena that are discussed in Chapter 4 below.

4 Possible transboundary issues

4.1 Pressure build-up

Even if the pressure footprint is not explicitly defined as a phenomenon that must be considered when defining the storage site and storage complex, it represents an important attribute of every CO_2 storage project that needs to be considered if the storage reservoir is connected to an aquifer. In the particular case of LBr-1, where the distance between the eastern margin of the storage complex and the Czech-Slovak state boundary is very small (less than 100 m), possible pressure build-up in the reservoir and in its surrounding can easily become a transboundary issue.

The overall reservoir quality of the LBr-1 field is considered to be generally good, with typical permeabilities in the 100 mD to 500 mD range. Even though the net-to-gross ratio is interpreted to be low in some parts of the reservoir, the geological understanding and the historical production performance suggest that the individual sand bodies are generally connected to each other. Except for the one noteworthy fault observed within the reservoir, important lateral barriers which might lead to local pressure build-up thus appear dubious.

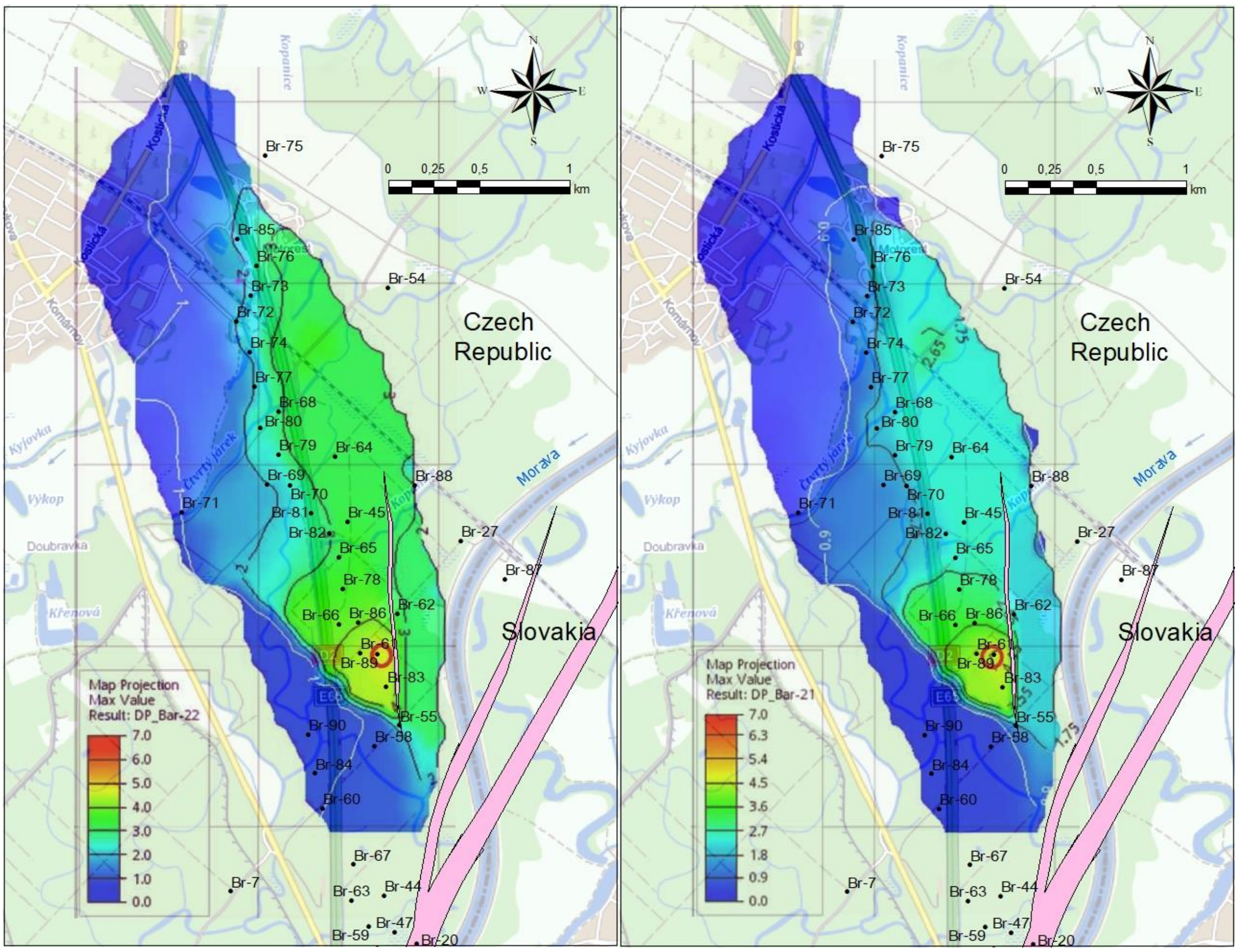

Figure 11 Distribution of pressure changes (bars) for the base case storage pilot scenario after injection of 11,500 t (left) and 23,000 t (right) of CO_2. The injection well Br-89 is marked by red circle.

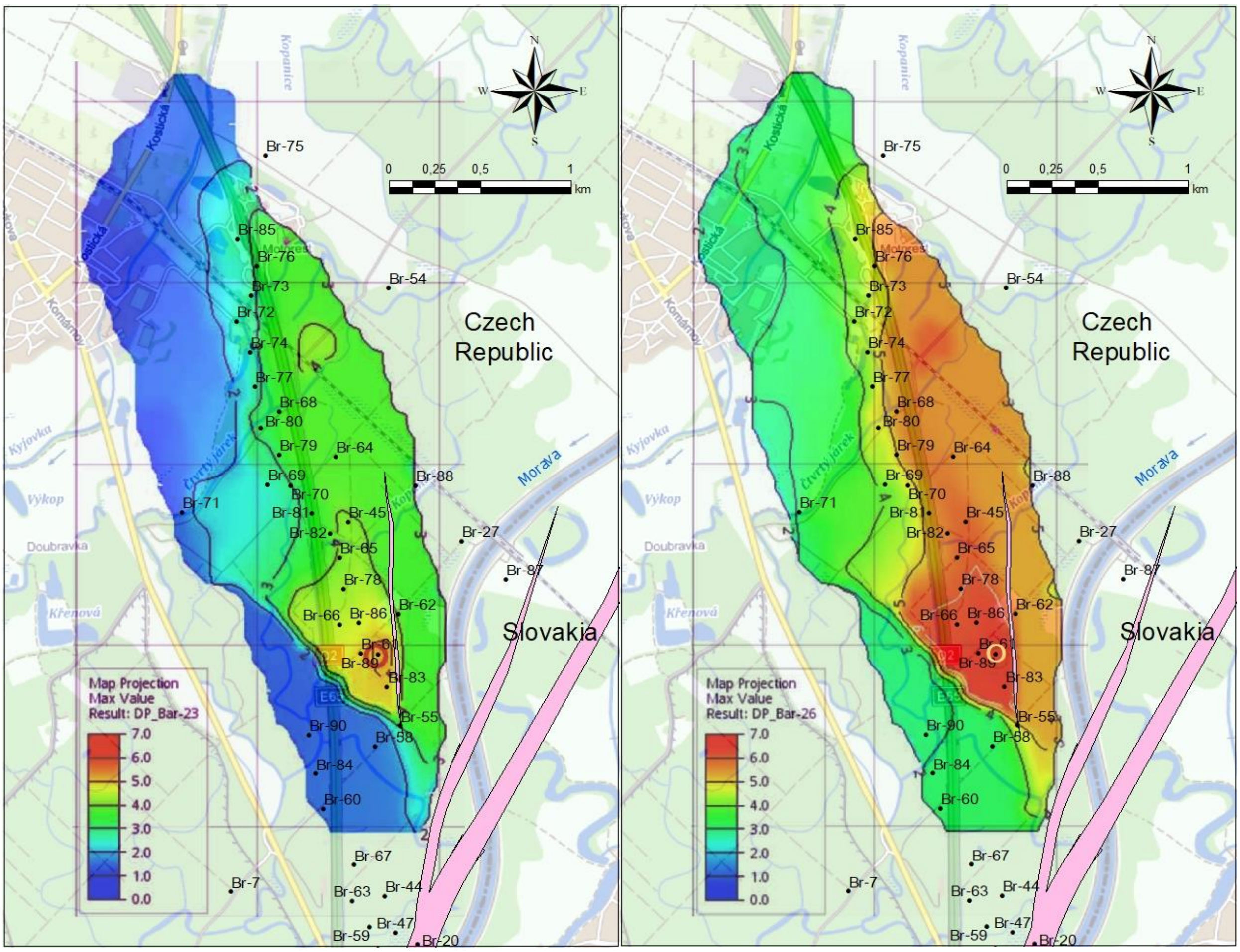

Figure 12 Distribution of pressure changes (bars) for the base case storage pilot scenario after injection of 35,000 t (left) and 70,000 t (right) of CO_2. The injection well Br-89 is marked by red/orange circle.

Pure supercritical CO_2 at the prevailing LBr-1 reservoir condition (100 bar/43ºC) has low viscosity – typically in the order of 0.05 cP. Combined with the relatively good quality and connectivity of the reservoir, the injected CO_2 should have an excellent mobility. Also, the CO_2 injection is in short distance to the gas cap, in which the fluid has even lower viscosity (in the order of 0.015 cP). Both these aspects should contribute to rapid equalization of the reservoir pressure and help to avoid local anomalies.

Based on the history matched dynamic reservoir model, the average reservoir pressure today should be around 110 bars, with a variation in the order of ±5 bar due to depth differences (vertical pressure gradient). Figures 11-14 illustrate changes in reservoir pressure upon CO_2 injection compared to the current state. The same scenarios as in the CO_2 plume extension assessment in chapter 3.2 are considered.

The reservoir pressure responses to the base-case storage pilot scenario are shown in Figure 11 and Figure 12. As might be expected, the pressure changes increase with increasing volume of CO_2 injected. The pressure footprint of CO_2 injection is mostly concentrated to the area around the injection well. It should be noted however that the figures represent snap-shots of pressure response during active injection, and thus include dynamic effects. Due to the good reservoir connectivity mentioned above, the pressure should be expected to level out rapidly once the injection is ended.

In the 70 kt case, the whole reservoir volume starts to be affected by pressure increase, even though the increase is still low – max. 7 bars in the area of the injection well.

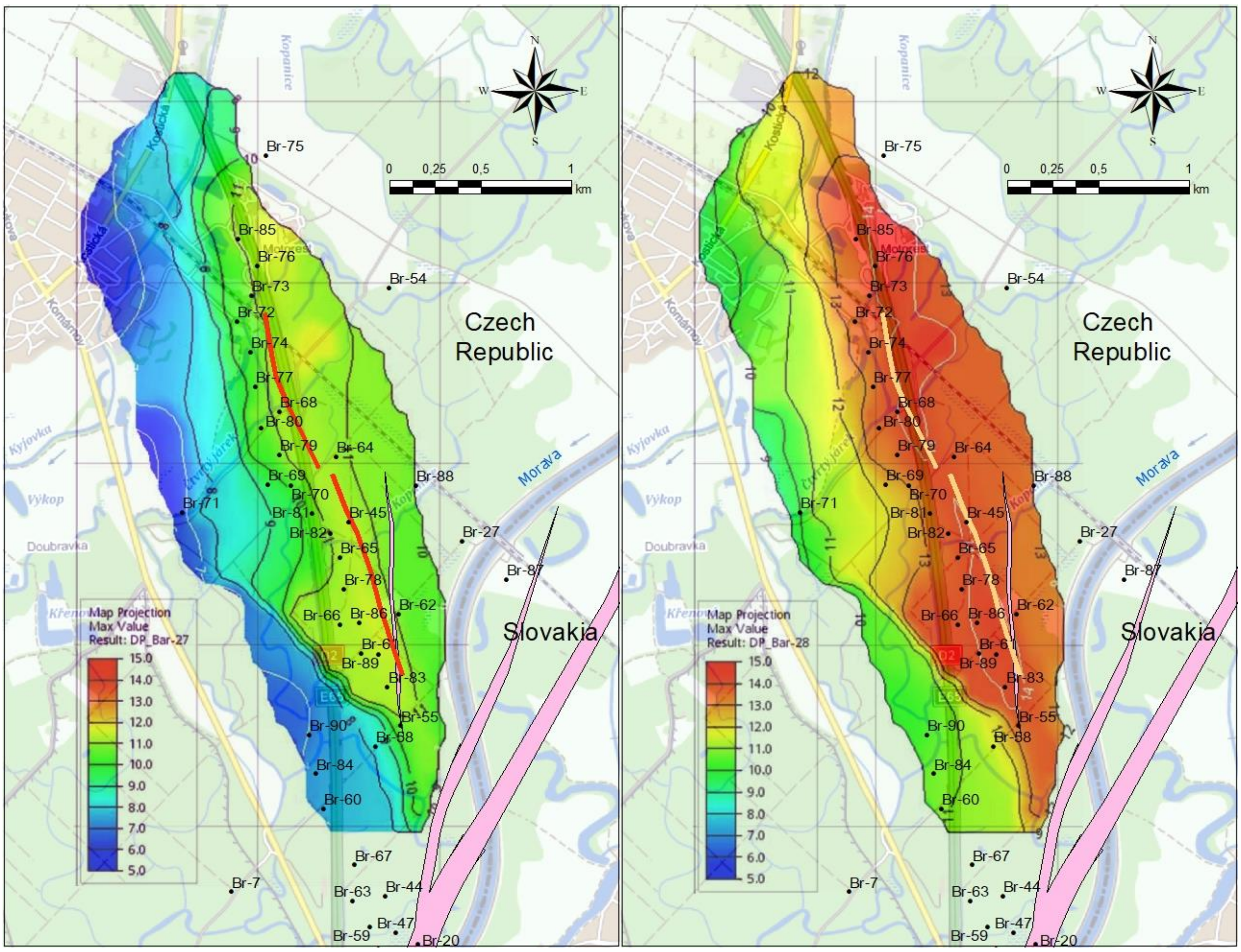

Figure 13 Distribution of pressure changes (bars) for the “full-scale” storage scenario after injection of 160,000 t (left) and 260,000 t (right) of CO_2. Positions of horizontal injection wells are indicated by red/orange lines.

In the “full-scale” storage scenario (Figure 13), the whole reservoir is affected and larger pressure differences can be observed: 5 – 12 bars after injection of 160 kt and 9 -15 bars after injection of 300 kt of CO_2.

Figure 14 portrays the pressure in the reservoir for the CO_2-EOR scenario. Since oil is produced along with an important amount of water (and also a great deal of hydrocarbon gas), the overall reservoir pressure does not increase as CO_2 is stored. The pressure distribution appears however to be slightly more variable in this case, even though it is a matter of only a few bars. The reason could be a slightly reduced general fluid mobility due to more co-flow of oil and CO_2. The pressure footprint in this particular case is negligible.

In line with our understanding of the geological setting and interpretation of the initial pressure conditions in the LBr-1 reservoir, we do not expect any spreading of pressure increase into surrounding rock environment, with the exception of the connected aquifer toward the west of the field.

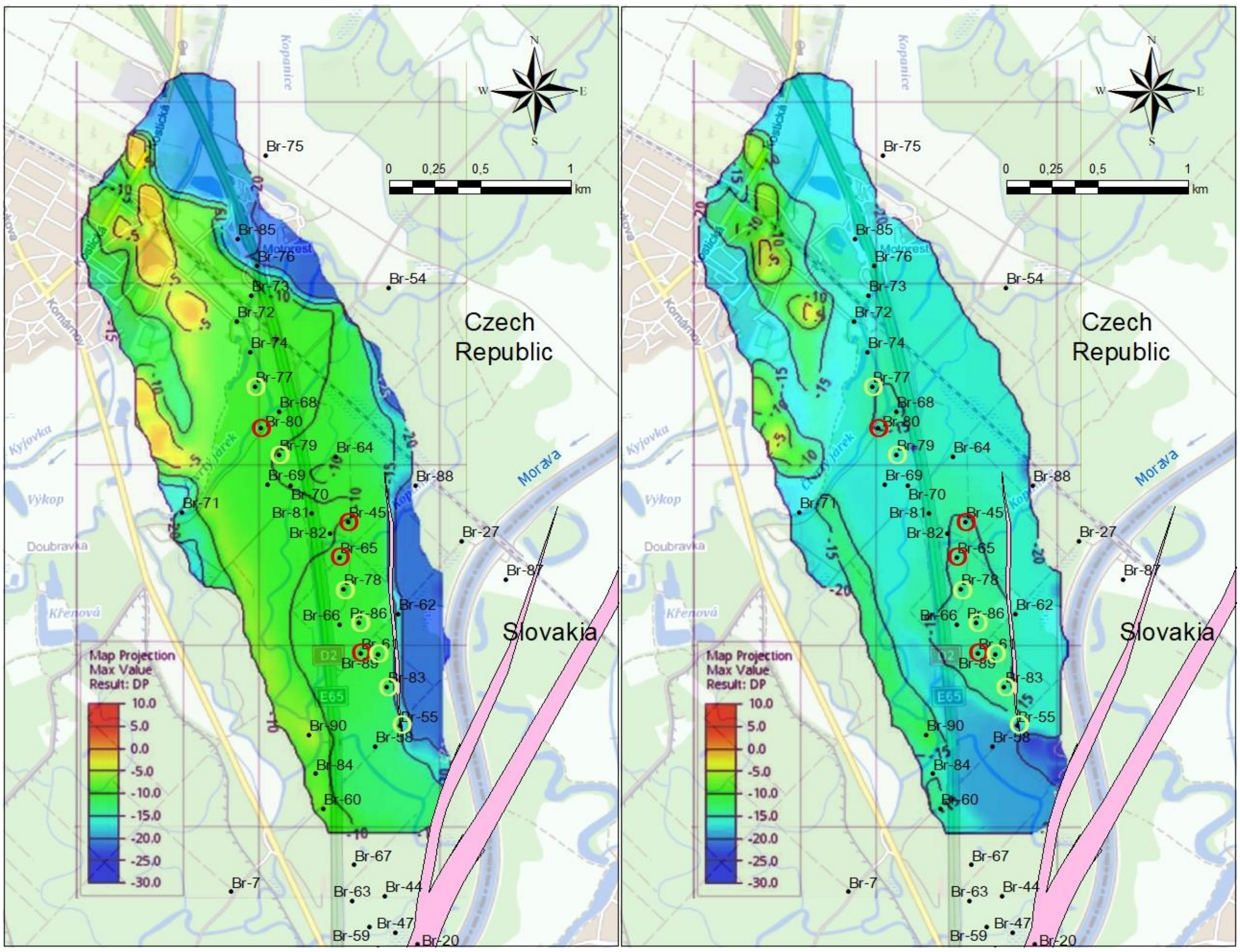

Figure 14 Distribution of pressure changes (bars) for the CO_2-EOR scenario after injection of 60,000 t (left) and 140,000 t (right) of CO_2.

The best possible interpretations of early measurement indicate an original reservoir pressure of about 12 MPa (120 bars) at the oil zone depth of around 950 m below mean sea level (approximately 1150 m below local terrain), indicating a moderately over-pressured reservoir, i.e. pressure higher than hydrostatic. These interpretations also appear to be in line with the general geological understanding and other observations in the Vienna Basin.

Initial overpressure strongly suggests that the hydrocarbon reservoir, together with its connected aquifer form a sealed chamber, able to confine pressure over geological time. This assumption has also been the foundation for the reservoir modelling and history matching, forming the basis for the simulations of CO_2 storage and EOR in the LBr-1 reservoir. If this is the case, there should be no pressure changes beyond the Lab horizon formations containing the LBr-1 reservoir and its connected aquifer.

Based on the above, we can state that the pressure footprint of CO_2 injection at LBr-1 is limited to the storage site in all considered scenarios. This means that that no transboundary effects related to pressure build-up are expected.

The assumption of a limited aquifer as discussed above is, however, partly based on pressure measurements taken during production start-up in the late 1950s, and subject to the quality and precision of recording technology at the time. The possibility of initial hydrostatic, rather than over pressured conditions and thus a potential for an open-ended aquifer may therefore need consideration. A plan for realization of a CO_2-EOR/storage project in the LBr-1 reservoir should hence include an earliest possible reservoir pressure measurement in order to exclude the possibility that the aquifer is not confined.

4.2 Possible leakage through boreholes

Leakage of the stored CO_2 out of the storage complex is considered to be one of the main risks associated with a CO_2 storage site. The qualitative assessment of leakage risk for the LBr-1 site (including that connected with the existence of legacy boreholes on the site) was first initiated as a work package in the REPP-CO2 project (Hladik et al., 2017), covering identification, analysis and evaluation of leakage risk in accordance with ISO 31000 (ISO, 2018). The risk identification phase was performed using a combined FEP (Features, Events, Processes) and barrier analysis approach to identify various leakage scenarios, their causes, preventive barriers and mitigating measures, and possible consequences of leaks (Arild et. al., 2017). A summarizing bow-tie diagram with the most important findings is shown in Figure 15.

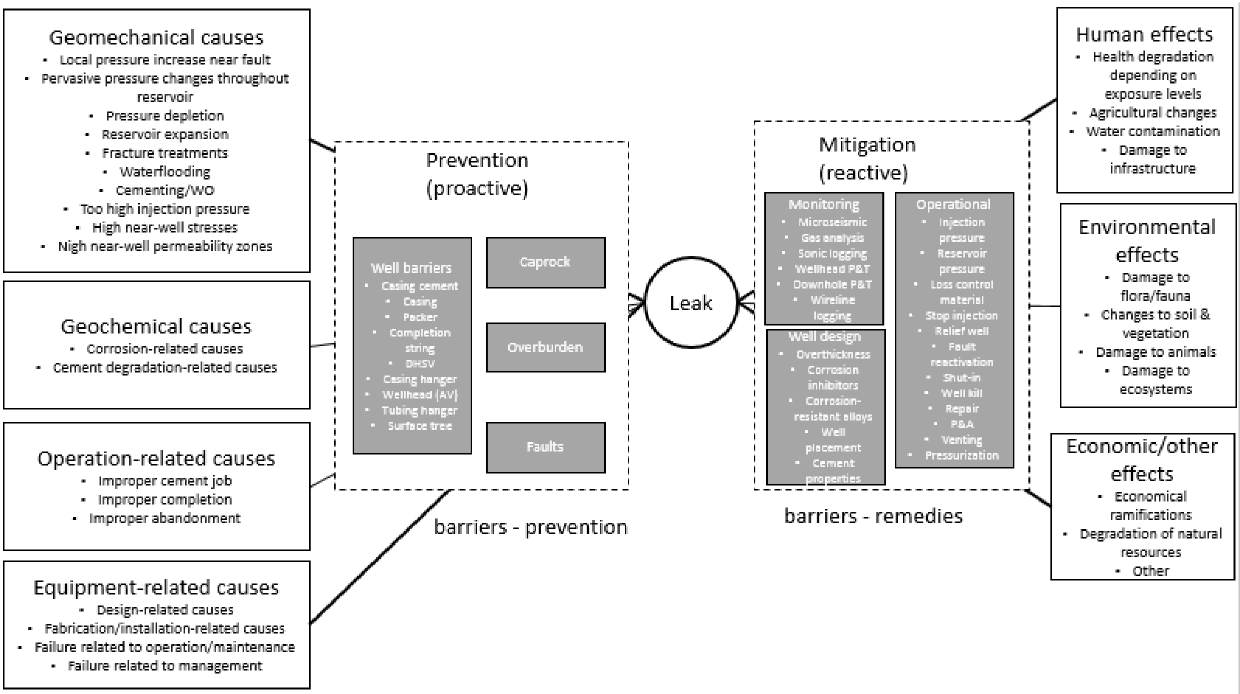

Figure 15 Bow-tie diagram illustrating specific components (causes, barriers, effects) of risk assessment of a CO_2 leak event (links between causes/barriers and barriers/effects have been simplified). Adopted from Ford et al. (2016).

The bow-tie diagram was used as a basis for narrowing the scope to focus on the most important leakage scenarios. Based on published frequencies of leakage in literature for comparable storages sites, the frequency of CO_2 leakage occurrence (per year) from an abandoned well was estimated to be in the interval <$4.5*10^{-3}$, $4.4*10^{-2}$>, while equivalent leakage from an injection well, or blowout during drilling of an exploration well was estimated to be roughly two orders of magnitude lower. Scenarios covering leakage through the caprock, through faults or through spill points were all estimated to 10^{-6}. Thus, leakage from abandoned wells was concluded to be the most likely leakage scenario and was therefore the main point of focus in the subsequent analyses.

When assessing the risk represented by abandoned wells, it needs to be taken into account that the majority of oil and gas exploration and production activities at LBr-1 were performed during the 1950s and 1960s. Drilling procedures, requirements for well design quality, relevant safety regulations and well abandonment methods depended on the equipment and technology available by that time.

Typical problems (at that time) were associated with preparation of the appropriate cement mix and execution of the cement job behind the well casing. In numerous cases, getting the cement mix up to the planned or required level of at least 50 – 100 m above the casing shoe was not successfully achieved. In a number of LBr-1 production wells the cement head is located even several hundred meters below the foot of the preceding column. Such cases usually happened, when the annular volume and behind-casing volume, i.e. the space between the casing and rock wall, were poorly estimated. Cement job problems were also associated with occurrence of caverns in the rock wall, which formed during the drilling, or with inappropriate cement mix preparation, which resulted in cement loss to the porous horizons.

As a result, the height of the behind-casing cement column was in many cases not sufficient to isolate horizons saturated with hydrocarbons from the above horizon filled with water, in spite of the fact that there was a clay horizon between them. In such cases, further drilling into horizons filled with gas or even overpressured gas (above-hydrostatic pressure) resulted in gas leakages behind the casing into the overlying aquifers with lower formation pressure. In exceptional cases, such as at the Br-62 well, eruptions through the subsurface horizons set in (see below).

These facts underline the importance of careful assessment of the status of abandoned wells penetrating the planned CO_2 storage reservoir.

An overview of the known abandoned wells for the LBr-1 field and the whole Brodske hydrocarbon complex is shown in both Figure 2 and Figure 16. In total, more than 100 wells were drilled in the area of the Brodske complex. Regarding their location, they can be divided as follows:

- LBr-1 – reservoir area – 25 wells
- Dry wells outside LBr-1 – 6 wells
- Brodske–Middle (independent production lens) – 3 wells
- Brodske-South – Czech part – reservoir area – 15 wells
- Dry wells outside Brodske-South – Czech territory – 3 wells
- Brodske-South – Slovak part – reservoir area – 27 wells
- Brodske-Upper Block area - more than 20 wells

All wells are currently abandoned. The dates of abandonment of the wells on the Czech territory vary from 1957 to 2004, and there is not a clear dependence of the abandonment dates on the termination of production.

During the 1950s-1960s, the well abandonment procedures were different from now and can be considered problematic from today's point of view. Major deficiencies can be summarized as follows:

- Pressurized cement job was omitted in some of the perforated horizons.
- Not always was the squeeze cement job in the perforated interval of the reservoir horizon accomplished successfully.
- Usual abandonment included isolation cement plug in the production casing above the perforated horizon, then the so-called "liquidation cement plug" in the surface column. Finally, the well head was cut off at 1-2 m below the surface and (not always) a steel plate was welded on the conductor casing. Such procedure is generally not in accordance with the currently valid abandonment regulations.

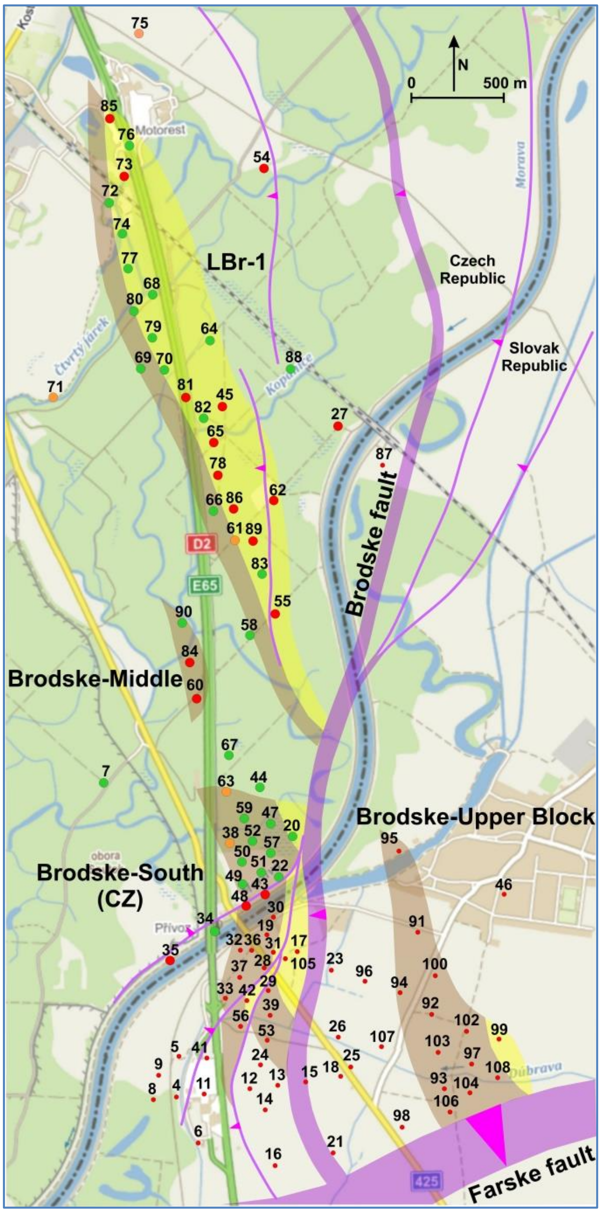

Figure 16 “Traffic-light” map of wells in the Czech part of the Brodske hydrocarbon complex. Green circles indicate wells for which the current status of abandonment meets the requirement of valid legislation. Abandonment status of wells indicated by red circles does not meet these requirements. Orange circles indicate only marginal deviations from the prescribed status. Coloured polygons indicate the position of original hydrocarbon-bearing zones. Main faults are drawn in violet. The Morava river represents the Czech-Slovak state boundary.

Due to the above-mentioned problems, selected wells were re-abandoned within a national project devoted to remediation of old environmental damage carried out in 2012–2015. The wells were re-opened and the cement plugs were drilled through inside the production casing. 22 wells in the Czech part of the complex were selected for re-abandonment within this project; six of these wells (Br-58, Br-66, Br-68, Br-69, Br-72, Br-74) penetrate the LBr-1 reservoir.

All the abandoned wells in the Czech part of the Brodske complex (plus six selected wells in the Slovak part for comparison) were subject of a thorough assessment, partly in the previous REPP-CO2 project and partly in ENOS Task 3.2.4 (Ford et al., 2018b). The focus was on comparison of the well abandonment status (based on archive data) with the currently valid Czech legislation. A traffic-light system was used to assess the status of individual wells. The results of the assessment are shown in the map in Figure 21.

Green circles indicate that the abandonment status is compliant with the current regulations, while red colour indicates clear discrepancy. Orange colour indicates only marginal deviations from the prescribed status. If we take the set of all wells in the Czech part of the Brodske complex, only for 57 % of the wells the abandonment status is compliant with current regulation, 10 % have deficiencies and 33 % are showing more significant deficiencies, especially missing perforation plugging (8 %), insufficient length of plugs (12 %), or even a combination of these (13 %). It should be noted here that all the original abandonments were performed before the validity of the amendment of the regulatory decree (June 2011) when no exact rules for cement plug length were in place. Only the re-abandonment campaign in 2012–2015 was regulated by the new rules.

Concerning the situation in Slovakia, it needs to be stated that there is not any regulation available in the Slovak Republic that would concretely define the well abandonment requirements as comparable to the Czech decree No 52/2011. The currently valid Slovak decree No 7/1981 (amended by decree No 88/1985) provides only some general guidelines. For this reason, the status of the selected wells from the Slovak part of the Brodske complex was compared with the requirements set by the Czech legislation, which enabled the same basis for comparison.

All six wells from the Slovak territory selected for assessment were found not compliant with the requirements valid in the Czech Republic. This reflects the general situation: the status of well abandonment in the Slovak part of the Brodske complex is worse than that in the Czech part. This is an important finding that needs to be taken into account when assessing possible leakage pathways of CO_2 migrating out of the LBr-1 storage complex into the territory of Slovakia, as well as when considering the possibility of upscaling the LBr-1 storage pilot project to a larger, transboundary storage site.

Figure 17 shows the abandonment status of the 25 wells penetrating the LBr-1 reservoir. These wells are the most relevant for studying possible leakage through wells from the reservoir, especially if their toe section comes into contact with the CO_2 plume.

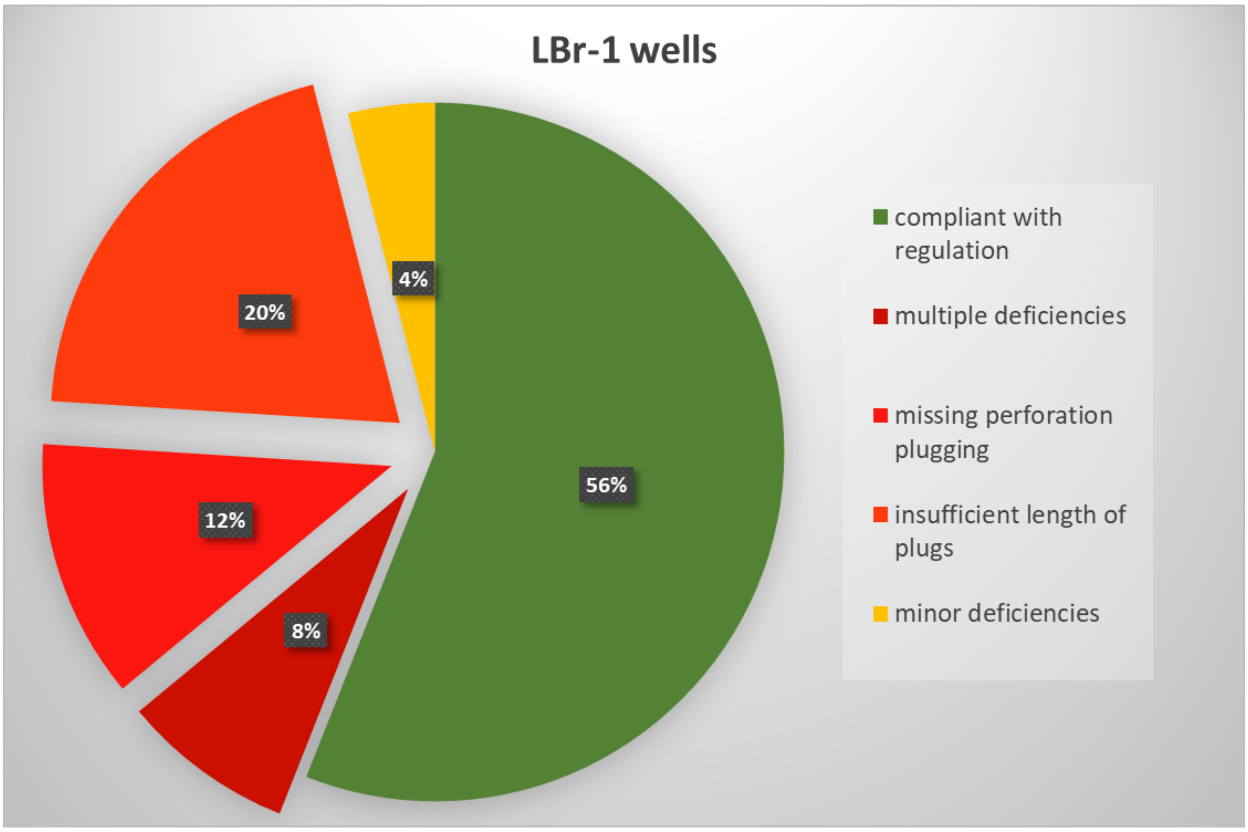

Figure 17 Summary of well abandonment status for wells penetrating the LBr-1 reservoir. Adopted from Ford et al. (2018b).

The situation regarding the quality of abandonment of wells at LBr-1 is similar to the overall status of wells in the whole Brodske complex area: 56% of the wells were abandoned in a way that complies with current legislation while 40% demonstrate various kinds of serious deficiencies.

From the risk assessment point of view, interesting information can be drawn from the comparison of the simulated extent of the CO_2 plume in the LBr-1 reservoir with the position of individual wells and their status, as shown in maps in Figure 18. The maps clearly indicate which wells are likely to contact the plume of stored CO_2 and – in case of bad condition – may represent leakage pathways for the CO_2 stored in the reservoir.

The maps in Figure 18 show simulation results of CO_2 injection for early phases of the basic storage pilot scenario, which assumes a total injection of 70,000 t of CO_2 over six years. The map on the left depicts the extent of CO_2 plume after injection of 11,500 t CO_2. Except Br-89 (injection well), four other wells are clearly situated in the CO_2 plume area: Br-61, Br-62, Br-83 and Br-86. For Br-83 (green circle) the status of abandonment satisfies the regulation criteria; well Br-61 (yellow circle) shows only minor deficiencies. The other two wells (red circles), however, do not comply with current regulations. In Br-86 the perforations have not been sufficiently plugged, and Br-62 has insufficient lengths of plugs above perforations. In addition, Br-62 bears the eruption "heritage". This is one of the reasons while the Br-62 well has been chosen for a further modelling and simulation study, partly performed in ENOS WP3 (Ford et al., 2018b) and finalised by a study of possible leakage pathways in WP4 (see below).

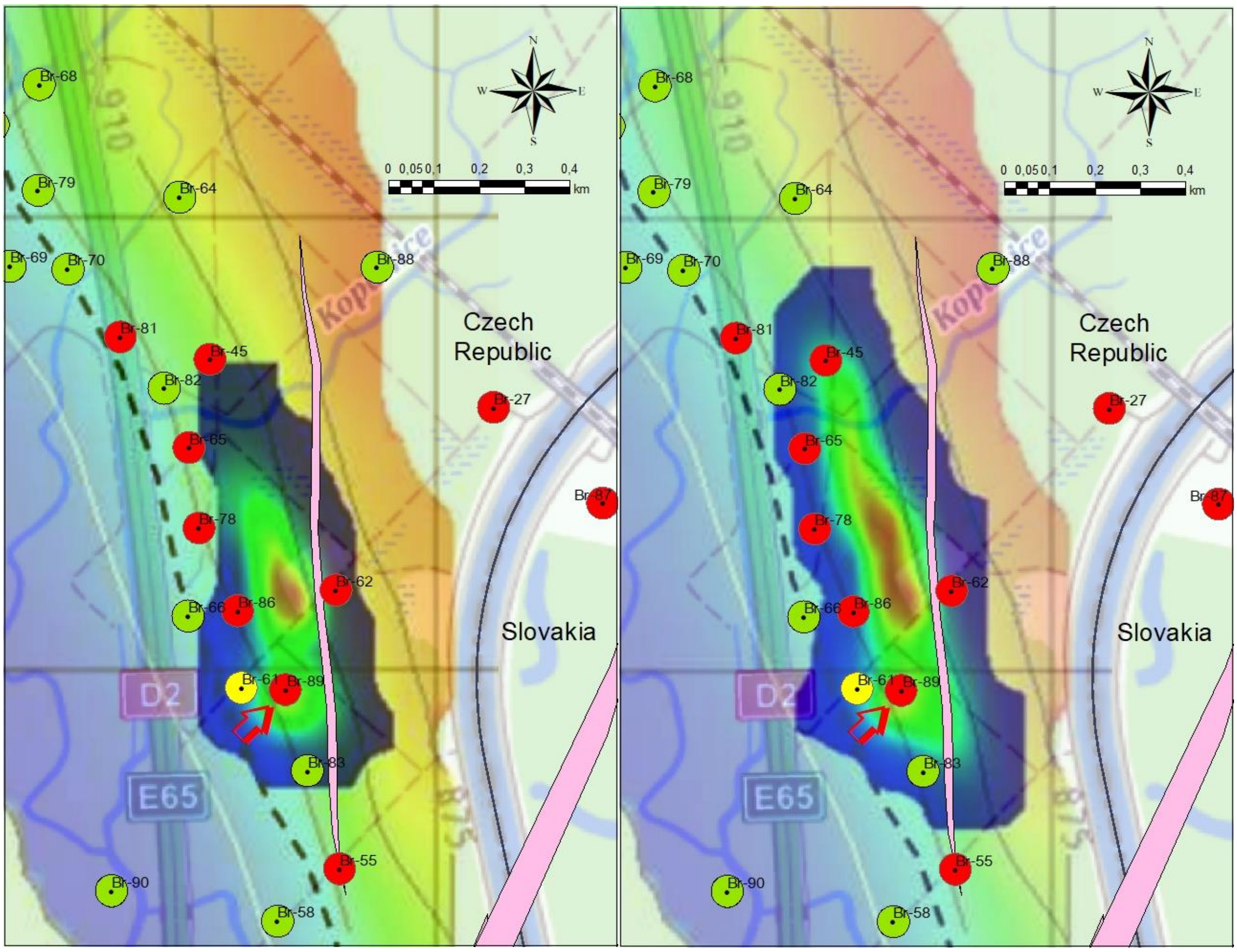

Figure 18 Maps of LBr-1 showing the simulated extent of CO_2 plume in the basic pilot project scenario, superimposed on the "traffic-lights" map from Figure 16. Left – plume extent after injection of 11,500 t CO_2; right – plume extent after injection of 23,000 t CO_2. Injection well (Br-89) is marked by red arrow.

The map in Figure 18 on the right shows the situation after injection of 23,000 t CO_2. Four more wells are affected by the CO_2 plume – Br-82 (the only one with abandonment status compliant with current regulations), Br-45, Br-65 and Br- 78 (all three with significant deficiencies in comparison with the regulation requirements).

For the purposes of studying possible leakage pathways, the Br-62 well was selected as the model source of leakage. It is close to the suggested injection well, its plugs are thinner than required by regulation, the behind-casing cementation is considered to be poor, and it suffered from an eruption in the exploration phase.

Figure 19 displays the status of well Br-62 and indicates possible CO_2 leakage pathways that should be considered in case the quality of the cementation of casing perforations at the Lab horizon depth and the behind-casing cementation is insufficient. The long interval (several hundreds of metres) where most probably cement is missing behind the casing makes upward fluid migration in this part of the well very easy. If the CO_2 (and possibly other fluids) overcomes the barrier represented by the ca. 120-130 m long cementation behind the casing, it can use this pathway and migrate into porous layers in the overburden.

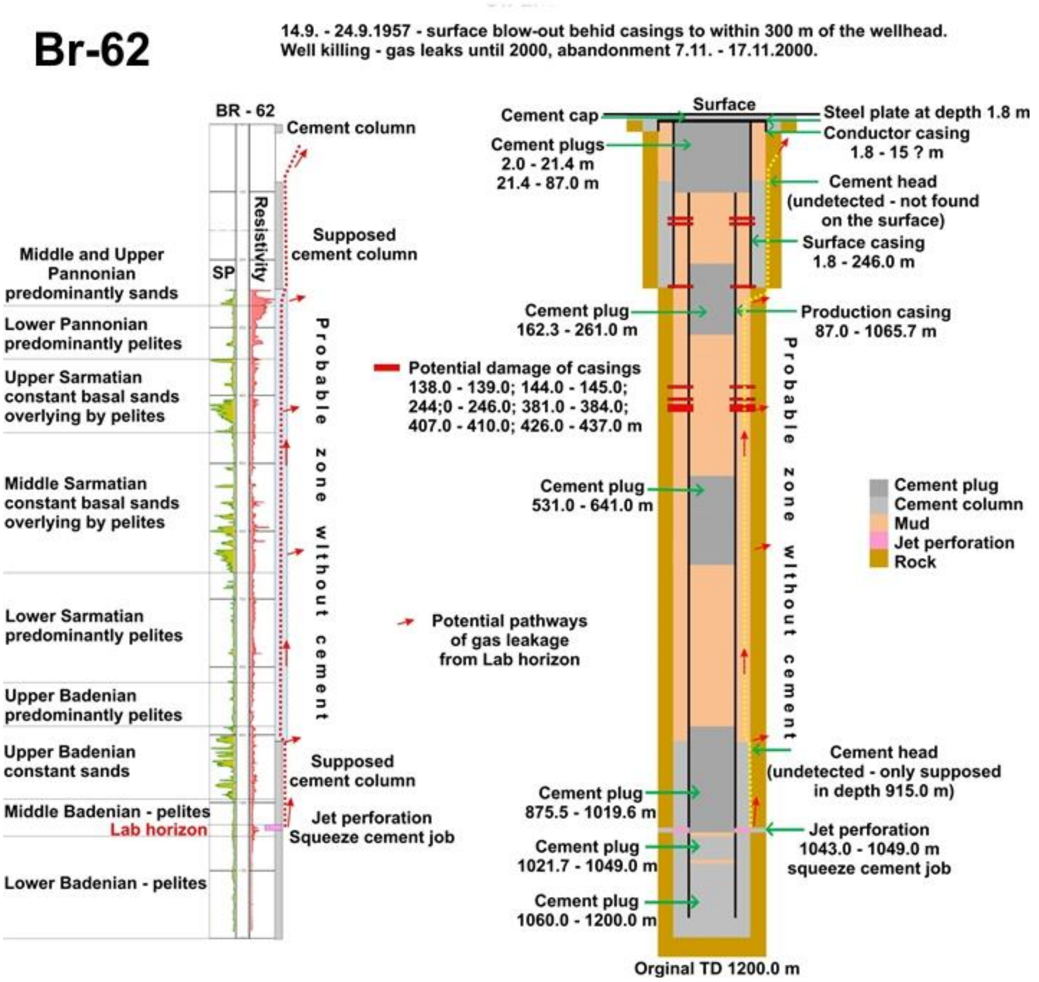

Figure 19 Well design for Br-62 (right) and well logs with basic stratigraphy (left). Possible leakage pathways (red arrows) correspond to the situation when plugging and abandonment procedures did not result in isolation of the reservoir from other horizons and the surface. Probable zone without cement is behind casing, where the cement head was undetected, but believed to be at 915 m.

Possible CO_2 migration pathways that need to be considered in case CO_2 leakage occurs in well Br-62 are shown in Figure 20. The Lab horizon reservoir is encountered by wells Br-66, Br-86 and Br-62 and pinches out close to the Czech-Slovak border. It does not appear any more in well Br-87 that is situated to the west from the pinch-out line.

Possible leakage scenario would be very similar to the situation after the Br-62 well accident in September 1957. When the Br-62 well was drilled, the overpressured Lab horizon was penetrated. The pressurized gas escaped through the well and behind the casing to the above-lying sandy horizons (red arrows in Figure 20) in the Upper Badenian, Middle and Upper Sarmatian and Pannonian and caused both surface and subsurface blowout. Gushes of gas bubbles were reported in the nearby Morava River about 300 m away. The horizontal distance of gas migration depended on the reservoir properties of the overlying sandstones and properties of the faults intersecting these layers. The role of the faults is discussed in Chapter 4.3. In any case, the scenario based on CO_2 leakage through well Br-62 clearly shows that the CO_2 can migrate across the border to the territory of Slovakia.

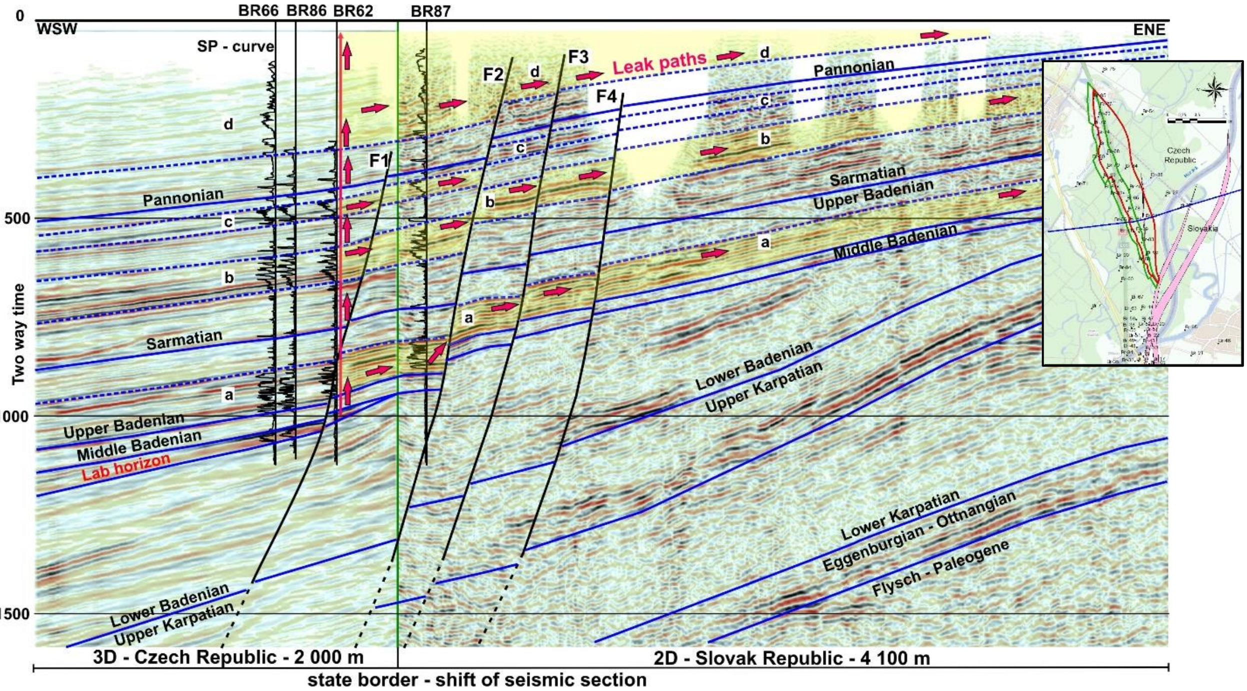

Figure 20 Composite 3D–2D seismic section across LBr-1 in approximately WSW-ENE direction from the Czech Republic (left) towards the Slovak Republic (right) with indications of undesirable potential leakage pathways of CO_2 or hydrocarbons. Potential leakage pathways are marked by red arrows and yellowish sequence of sand layers: a – Upper Badenian, b, c – Sarmatian, d – Pannonian. F1, F2, F3 and F4 are faults of the Brodske fault system (F2 – main fault). Position of the Czech-Slovak state border is marked by green line. The small map in the top right corner shows the position of the cross-section. Seismic data courtesy of MND a.s.

A similar situation would arise in most of the cases of CO_2 leakage through abandoned wells at LBr-1 in case the CO_2 escapes behind the casing. If the buoyant gas flows into a permeable layer, it will always migrate up-dip (i.e. towards Slovakia), following the layering that is generally dipping to the west / west-south-west.

In addition to possible leakage pathways discussed above, it is also important to quantify the amount of CO_2 that can leak through abandoned wells. Studies focused on this topic were performed in both the REPP-CO2 and ENOS projects and their results are briefly summarised below.

The risk analysis in REPP-CO2 (Ford et al., 2016) considered a total of 45 abandoned wells, 16 of which were re-abandoned (as per time of writing). For these wells, information was gathered with respect to P&A (plug and abandonment) design, fluid type, year abandoned (and where relevant, re-abandoned), total depth and depth of perforations. Using the information gathered, some initial leakage simulations were performed. These simulations considered leakage of CO_2 or CH_4 (methane, the expected occurring natural gas substance for the field) *through the cement plug*, using a model as described in CO2CARE (2012). The study did not cover leakage through cracks in the cement nor through micro-annuli, both scenarios expected to yield far greater leakage rates compared to leakage through a bulk material. As a worst case scenario in that study, a blow-out scenario (unrestricted flow) was considered.

Parameters required for leakage simulations, such as plug thickness and permeability, and gas properties (density, viscosity, solubility) were represented as probability distributions to quantify uncertainty, and the simulations were performed using Monte Carlo simulations. The cement type used on the LBr-1 wells was Portland cement, probably grade G or H. It was not possible to extract porosities or permeabilities from reports or cement bond logs, and these parameters were quantified based on expert judgements. Wells that were recently re-abandoned were assumed to have lower permeability compared to wells that were not re-abandoned. The overpressure used in the simulations was conservatively set to 30% above hydrostatic.

Figure 21 shows simulated CO_2 leakage rates as a histogram, when considering flow through all cement plugs of a well. The model used to estimate leakage rates is that of CO2CARE (2012). It is based on Darcy's law for fluid flow through a porous medium, according to:

$$q_v = \frac{\kappa \cdot \kappa_r}{\mu}\left(\frac{\Delta P}{\varepsilon} + \Delta\rho \cdot g\right)$$

where q_v is the volumetric fluid flux, κ the intrinsic permeability of the cement, κr its relative permeability model, μ the fluid viscosity, ΔP the pressure difference due to injection overpressure of the reservoir, ε the plug thickness, Δρ the density difference between the gas and the brine, and g the gravitational acceleration (CO2CARE, 2012).

The simulations are based on sampling a random well for each iteration. The simulated CO_2 leakage rates are regarded as being very small. Considering an injection scenario of ca. 11 500 t/year (basic CO_2 storage pilot scenario), such leakage rates constitute << 1% of this amount. For a leakage to be considered large, it would at least have to be in the order of magnitude > 1000 t/year.

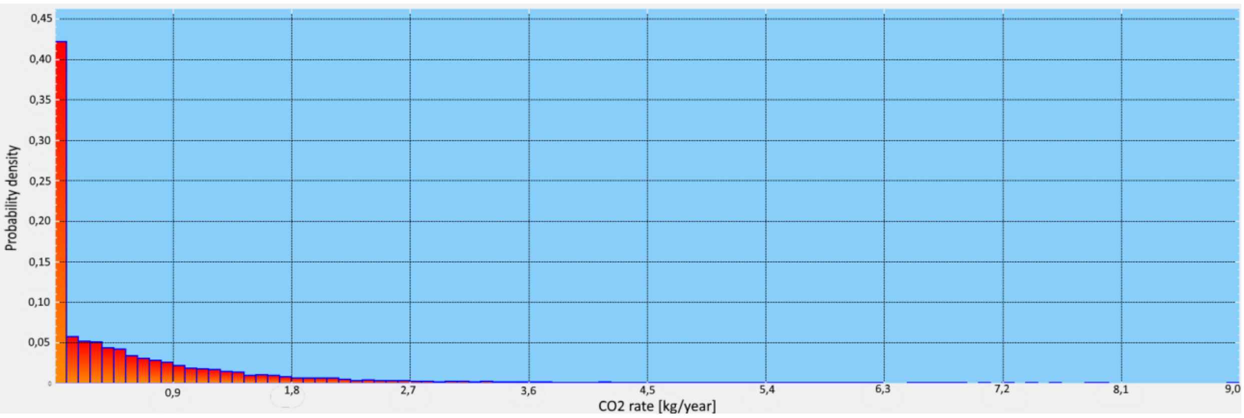

Figure 21 Simulated CO_2 leakage rate through cement plugs represented by probability density (vertical axis) in relation to leakage rate in kg/year (horizontal axis). Adopted from Ford et al. (2016).

The simulations give a mean CO_2 leakage rate of 0.6 kg/year, with a maximum of 10.5 kg/year. Under these conditions, the minimum time before CO_2 leakage occurs is 10 years, but with a mean (expected) value of ca. 293 000 years. Only wells Br-60 and Br-73 have P90 values > 4 kg/year, coinciding with the fact that these wells are the only ones to have a total cement plug thickness < 100 m.

Equivalent CH_4 simulations give a mean CH_4 leakage rate of 0.4 kg/year, with a maximum of 5.6 kg/year. Minimum time before CH_4 leakage is 1.7 years, but with a mean (expected) value of ca. 28 100 years.

For any non-abrupt leakage scenarios to pose a health threat, this would require the trapping of the CO_2 or CH_4 in a closed space, which humans were then exposed to. The risk to humans beyond the proximity of the injection site is very low, as released CO_2 or CH_4 would be dispersed into the atmosphere at low concentrations relative to human thresholds. Dispersion simulations were performed using a Gaussian Plume Equation (see e.g. Abdel-Rahman, 2008). Figure 22 shows how the CO_2 concentration would decrease with distance from the release point, and under different wind speeds, using a pessimistic assumption of a CO_2 leakage rate through the cement plugs of 10.5 kg/year.

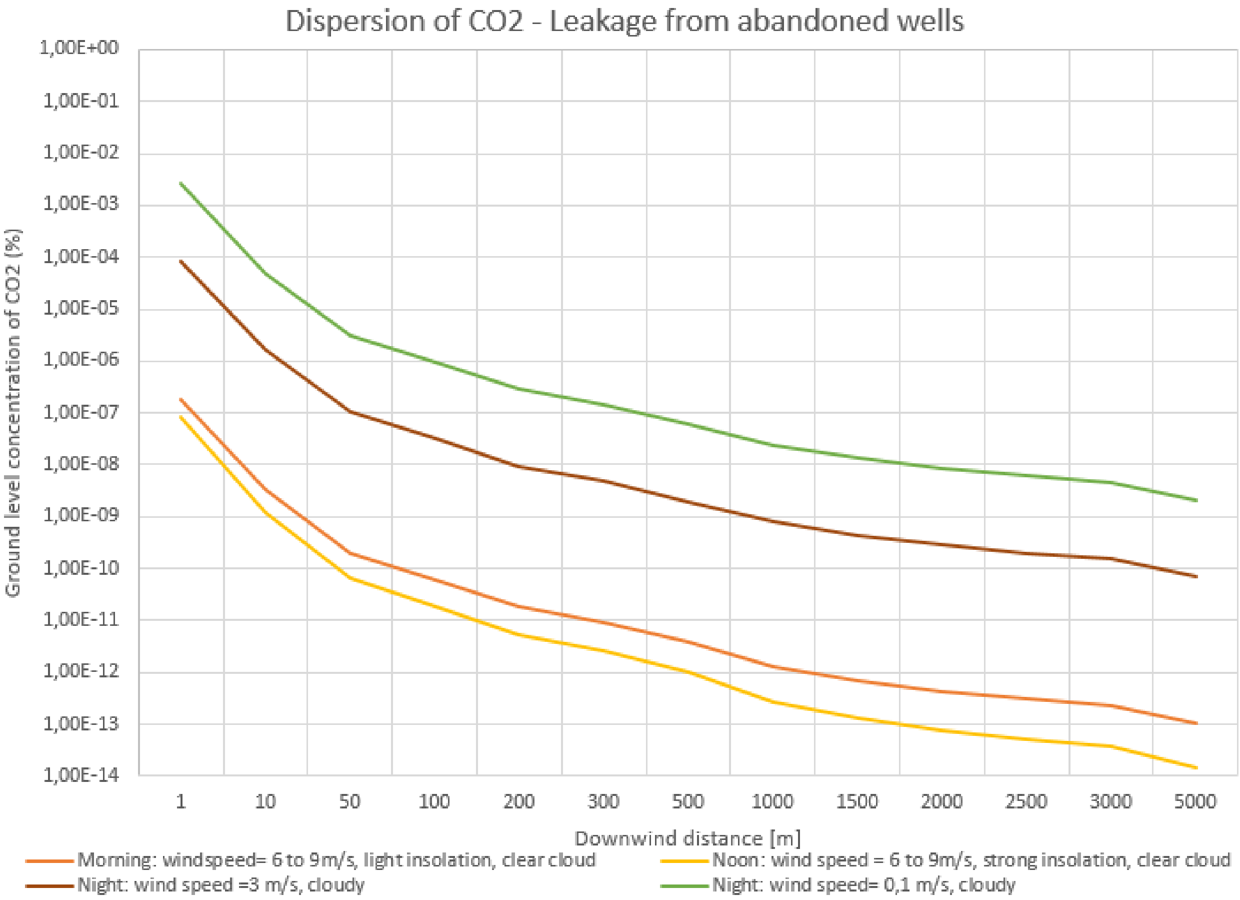

Figure 22: Dispersion of CO_2 in the event of a pessimistic assumption of 10.5 kg/year leakage from abandoned wells, for various wind speeds and insolation/clouds (Ford et al., 2016).

For leakage rates of this magnitude, a release to surface would not yield any effect to human health or the environment, unless exposure occurred directly at the leakage point (max. ca. 5000 ppm). At proximities anywhere away from the point of release, the concentration levels are not detectable (< 1 ppm). Noticeable effect to human health would require CO_2 concentration levels in air in excess of 1.5 % (15 000 ppm). CH_4 dispersion would be of similar magnitudes for equivalent leakage scenarios.

An important limitation of the leakage assessment performed in the REPP-CO2 project is related to the lack of assessment for scenarios including cement cracks or microannuli. This was therefore addressed as part of the ENOS project, WP3 (Ford et al., 2018b).

The framework applied for the updated leakage risk assessment was based on Ford et. al. (2018a); for equations it is referred to this publication and the references therein. The main input parameters consist of deterministic input, such as well and P&A design and reservoir characteristics as well as uncertain inputs that typically relate to the size of fractures, micro-annuli and permeability of cement. Assuming that the uncertain input parameters can somehow be established, the underlying models for leakage rates (bulk, fractures, micro-annuli) are run in a Monte Carlo framework to produce leakage rate distributions. As the pressures evolve over time, so too does the resulting leakage rate. In this framework, parameter uncertainties are represented as probability distributions.

The most important factor however, is the microannuli gap size. The leakage rates are extremely sensitive to the value of this parameter. In practice, this parameter is unknown, and potentially subject to large uncertainty, in particular where there is concern regarding the overall integrity of cement. While cement bond logs (CBL) or Sustained Casing Pressure (SCP) can sometimes be used to make inference on the integrity of cement barriers, these still do not translate into any meaningful expression for microannuli size. However, using a relation between effective wellbore permeability and microannuli size (Stormont et. al., 2018), various scenarios can be established to illustrate how leakage rate will vary with changing microannuli size. Four such scenarios were established, based on different assumptions:

- Scenario 1: The effective wellbore permeability is unknown and could be anywhere in the range $<10^{-20}, 10^{-12}>$ m^2
- Scenario 2: The effective wellbore permeability is more likely to be “average” than either “good” or “bad”, and is represented as a triangle distribution $T(10^{-20}, 10^{-18}, 10^{-14})$ m^2.
- Scenario 3: Information of well integrity exists such that wells can be grouped into either “good” or “degraded” groups. We assume there is a 90% chance that the well integrity is sound, and we use a lognormal distribution with mean = -20 and variance = 2 to represent the case of “good” well integrity, and a lognormal distribution with mean = -15 and variance = 2 to represent the case of “degraded” well integrity. The approach is similar to the approach by NRAP (2017).
- Scenario 4: Similar to Scenario 3, but with three categories (good, medium, bad) and distribution of categories based on isolation compliance with regulations performed in REPP-CO2 for LBr-1 wells. We assume a lognormal distribution with mean = -20 and variance = 1 to represent the case of “good” well integrity, that the “medium” case is represented using a lognormal distribution with mean = -18 and variance = 1 and a lognormal distribution with mean = -16 and variance = 1 to represent the “bad” cases, and where the probability for cases “good”, “medium” and “bad” are 57%, 18% and 25%, respectively.

The simulations of total leakage rate for these four scenarios are summarized in Table 2.

Table 2: Leakage rate simulations for an example case well, for various scenarios with different microannuli size distributions

Scenario	**Estimated CO_2 mass flow rate [t/year]**		
	Mean	**P10**	**P90**
1	77	0.08	230
2	0.5	0.0004	1.5
3	0.4	0.0002	1.2
4	0.0004	$1.8 * 10^{-8}$	0.002

Scenario 1, which could be viewed as a worst-case microannuli scenario, corresponds to sizes ranging from 0 to 70 µm. The rates for this scenario are relatively high, but the assumption here is that the plugs are equally likely to be in a severely degraded state as in an acceptable state, or anywhere in between. Table 2 generally shows the importance of obtaining information pertaining to the state of the well barriers, for example via cement bond logs and other relevant information. Scenario 2, provided that little information exists, represents a more realistic scenario, where the uncertainty in effective wellbore permeability is centred around typical permeability values for cement. If more information was available that would increase confidence on the integrity of the well barriers (Scenario 3 and 4), the leakage rates would likely be lower still.

Both above-discussed studies show that the quantities of CO_2 that can possibly leak from the reservoir through abandoned wells are low. Leakage through bulk cement would yield negligible leakage rates; leakage through microannuli has comparatively higher leakage potential. However, for significant leakage scenarios to occur, this would require severely degraded well barriers or poorly constructed and cemented wells. The information collected from the LBr-1 field does not give indications that this is currently the case. The main risk regarding integrity of abandoned wellbores is related to those wells not in compliance with current abandonment regulations. For investigated leakage rates, the dispersion of CO_2 or CH_4 would pose a very low risk to human health.

On the other hand, the performed analysis of possible leakage pathways clearly shows that a CO_2 leakage behind the casing of an abandoned well would in most cases have transboundary consequences because the leaked CO_2 would migrate into the territory of Slovakia.

4.3 Possible leakage through faults

The geological structure of the Vienna Basin (Figure 23) comprises several main tectonic blocks, bound by major fault systems (e.g., Hamilton et al., 1990). The most significant fault systems in the Czech and Slovak parts of VB area comprise the Schrattenberg, Steinberg, Lanzhot - Hrusky, Farske, and Hodonin - Gbely fault systems. LBr-1 is situated in the Lanzhot block, which forms the SW end of the wedge-shaped Hodonin – Gbely horst bound by the N-S Lanzhot - Hrusky fault on the west and the W-E Farske fault on the SE. The N-S trending Brodske fault system bounds the Lanzhot block on the east.

The partial blocks differ in their lithostratigraphy as well as in the thickness of their sedimentary fill. Prochac et al. (2012) provide a review of tectonic evolution of the northern Vienna basin. In the Early Miocene, the thrust sheets of the Alps and West Carpathians were still moving and approached the Bohemian Massif. By the end of Karpatian, the overthrusting changed, Early Miocene sediments were visibly deformed and eroded, what resulted in an unconformity on top of the Lower Miocene. During the Middle Miocene (Badenian and Sarmatian) the basin geometry was controlled by trans-tensional strike-slip faulting in a thin-skinned pull-apart basin with a rhombic shape (Burchfiel and Royden, 1982; Royden 1985; Ladwein et al., 1991; Fodor, 1995). The fault systems were interpreted from seismic profiles as flower structures. Prochac et al. (2012) emphasize, that this concept has some limitations as in many cases no specific strike-slip offset of geological features, such as submarine channels, has been observed in the seismic on both the footwalls and hanging walls of faults.

Tectonic features played an important role in the formation of the Brodske hydrocarbon complex, which is controlled, among others, by extensional Brodske and Farské fault systems (also called Brodsky and Farsky system – see Figure 24). Both fault systems are interpreted as active during the Middle to Late Miocene.

The WSW-ENE trending Farske fault system limits the Brodske complex from south and separates the Lanzhot Block and the Hodonin – Gbely Horst from the Kuty Depression, the deepest part (5.5 km) of the Vienna Basin in Slovakia. The N-S trending Brodske system intersects the Brodske complex and contributes to its relatively complicated structure. The main Brodske fault plays a major role in the southern part of the complex where it separates the Brodske – South part from the Brodske - High Block, with a fault throw of more than 100 m. It also represents a sealing element of individual Lab sand layers that are separated here by clayey intercalations that are – in places – more than 10 m thick. Here, the Brodske – South field forms several combined-type traps with sealing represented by fault planes of minor branch faults combined with stratigraphic pinch out of the individual sandy layers.

The main Brodske fault also plays an important bounding role at the southern edge of LBr-1 where it limits the extent of the Lab horizon, in particular the deepest L4 partial sand horizon and the adjacent aquifer. The presence of a possible spill point in this area, linked to the properties of the Brodske fault, is discussed in Chapter 4.4.

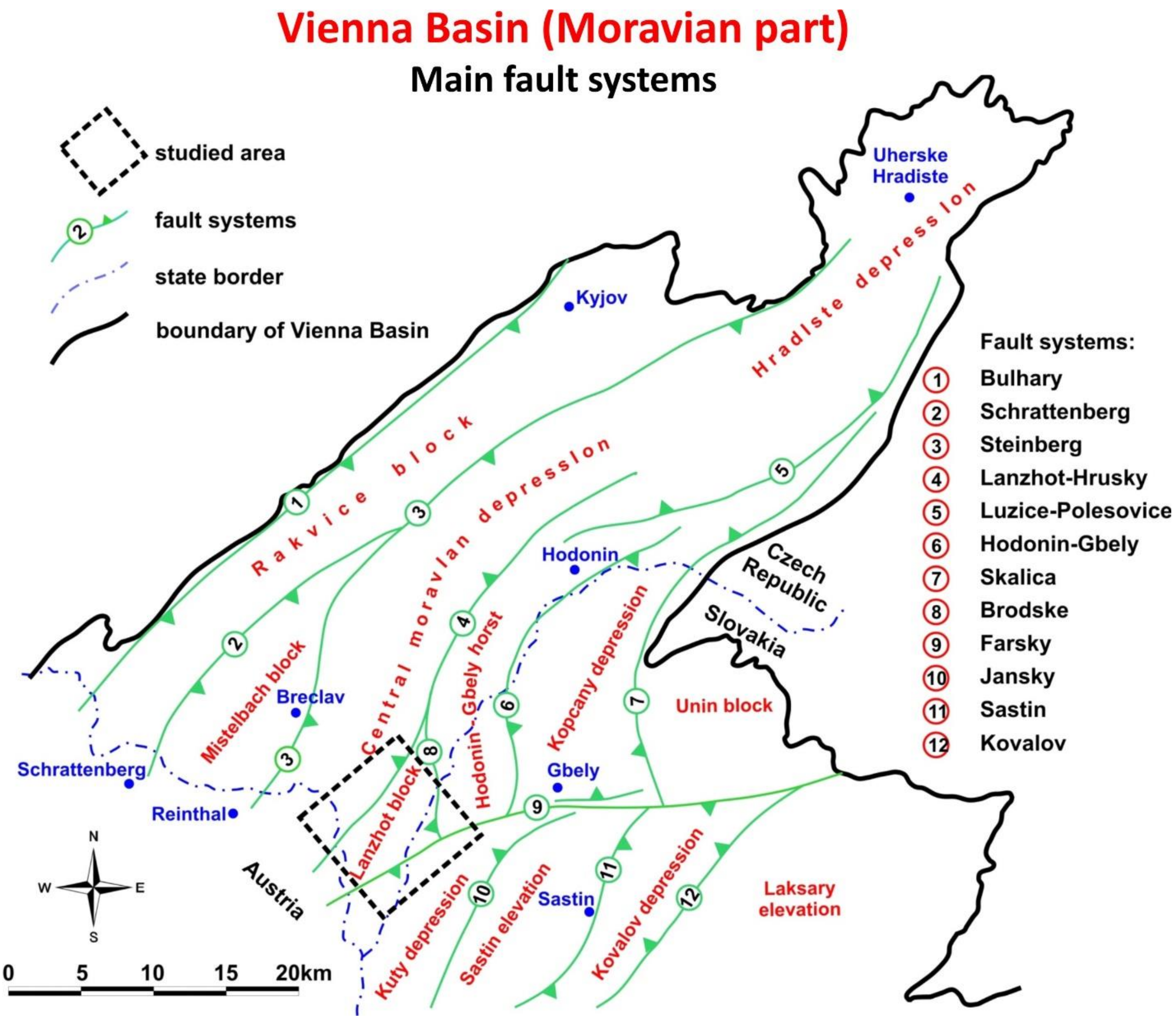

Figure 23: Map of major faults and tectonic blocks in the Czech (Moravian) part of the Vienna Basin. Location of the study area is marked by a dashed rectangle.

The main Brodske fault is accompanied by a series of accompanying minor faults that intersect the Brodske – South part (see above), LBr-1 and its eastern neighbourhood. LBr-1 itself is intersected by one minor fault (F1 in Figure 24), while the main Brodske fault and several accompanying faults can be observed in the eastern neighbourhood of the field. These faults do not influence the reservoir itself but play an important role in assessment of possible leakage pathways in case of a CO_2 leak through abandoned wells (see Chapter 4.2).

The sealing function of the faults confining the hydrocarbon reservoirs (incl. LBr-1) is proven by the existence of the reservoir itself. It is based on either the seal-seal juxtaposition of layers, or sealing properties of the fault zone fill (or a combination of these factors).

Detailed fault mapping at LBr-1 is being carried out as part of ENOS WP3, Task 3.2.1. The main data sources are 3D seismic and well data, especially well logs. From this point of view, the situation is favourable because LBr-1 is fully covered by a 3D seismic data block (kindly provided by MND a.s., the former site operator), and the presence of many legacy wells on the site enables a detailed correlation of well-log diagrams.

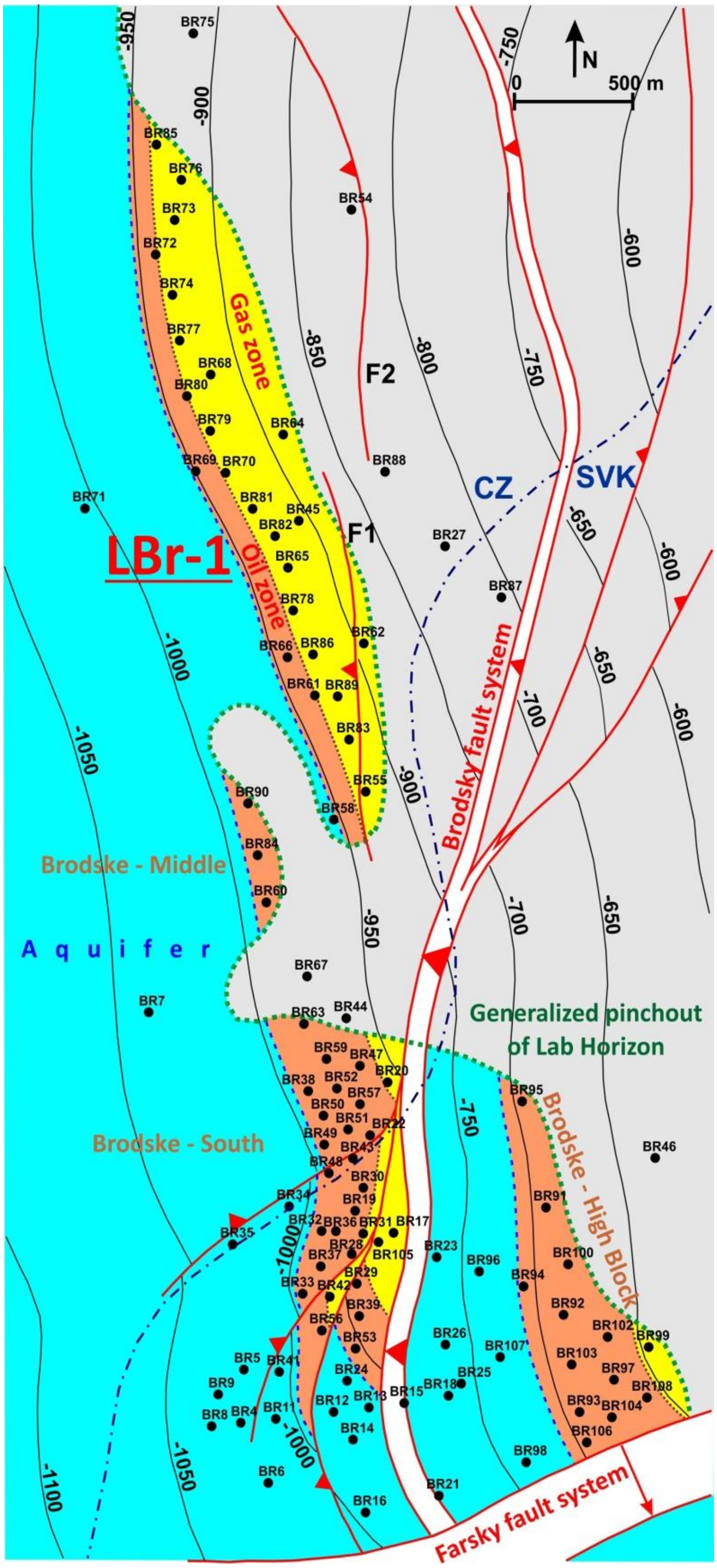

Figure 24: Brodske hydrocarbon complex - generalized structural contour map of the top of Lab horizon (top L1) with wells, faults, initial positions of the oil and gas zones and the Lab horizon pinch-out line

The workflow includes the following steps:

- mapping of fault geometry using 3D seismic data;
- mapping of faults based on correlation of well-diagrams of individual wells;
- assessment of sealing properties of the faults based on presence of hydrocarbon accumulations;
- construction of Allan diagrams examining the juxtaposition of layers at both sides of the fault.

Examples of results of fault mapping at LBr-1 are shown in Figure 25 and Figure 26. Three minor faults can be identified in the area of interest – Fault 1, Fault 2, Fault 3. The fault throw for Faults 1 and 2 is below 20 m; despite of this they can be clearly distinguished in the seismic data. The main Brodske fault is only caught at the SE margin of the seismic data cube and can be mapped only in a short interval, based on sudden termination of continuous seismic reflections.

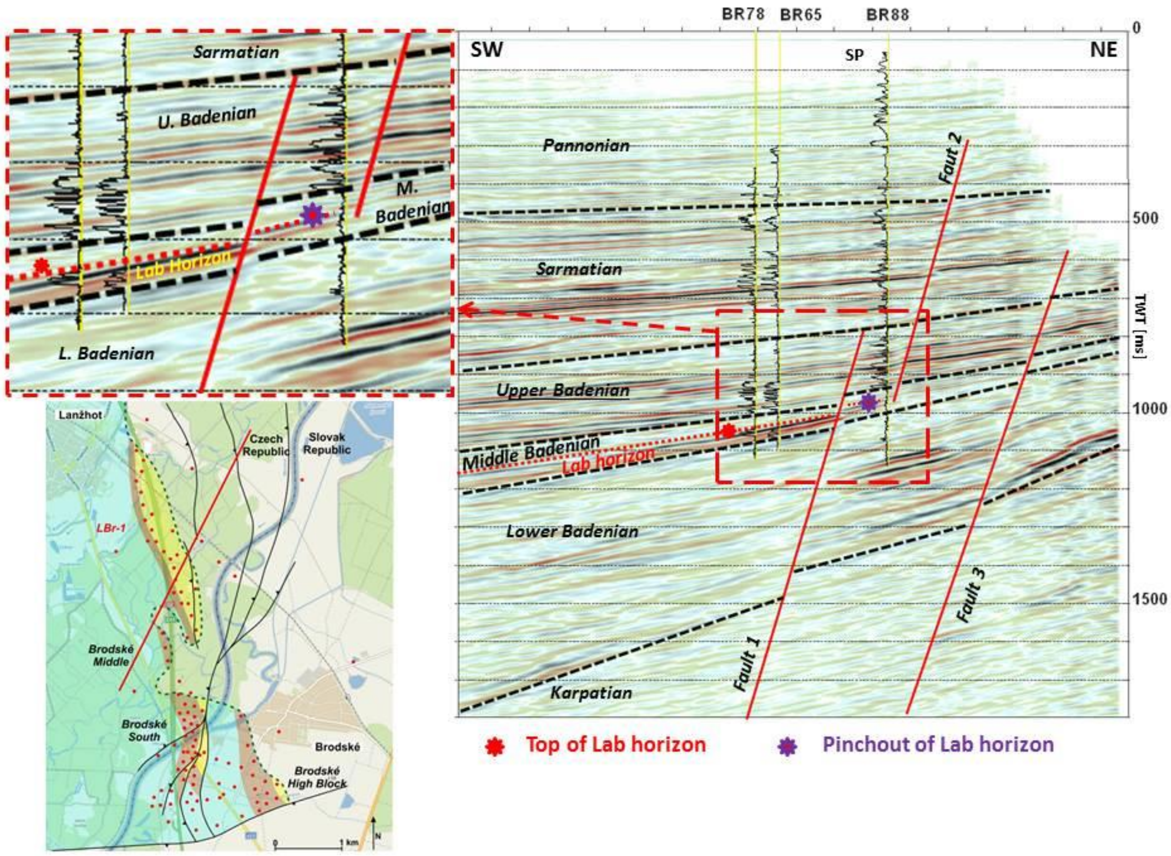

Figure 25: Results of fault mapping using 3D seismic data and well-logs. Migrated seismic time section (crossline 1256) across LBr-1 with well-logs and interpretation is displayed on the right, with magnified detail of the Lab horizon pinch-out area in upper left corner. The map in bottom left corner shows the position of the section. Seismic data courtesy of MND a.s.

Faults 2 and 3 are located outside of the position of the sandy Lab horizon and do not play any role in reservoir sealing or disturbance. Fault 1 is intersecting the reservoir and desires therefore closer attention. Taking the 50 – 60 m thickness of the caprock (Middle Badenian clays) in this area into account, the fault with 10 – 20 m throw does not represent a danger for the sealing properties of the caprock. It can, however, interconnect the individual partial sand layers of the Lab horizon, as shown in the Allan diagram of Fault 1 in Figure 27.

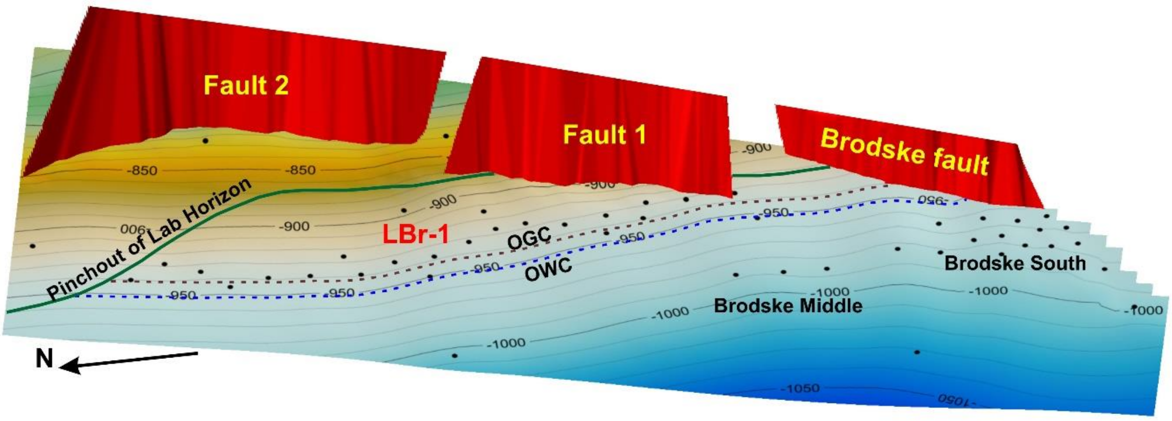

Figure 26: 3D view of the top of the Lab horizon with interpreted faults, initial oil-water and oil-gas contacts and the pinch-out line of Lab horizon

The diagram indicates partial sealing of the fault in its northern and central part, thanks to the reservoir – seal juxtaposition, and its interconnecting function in the southern part caused by the reservoir – reservoir juxtaposition.

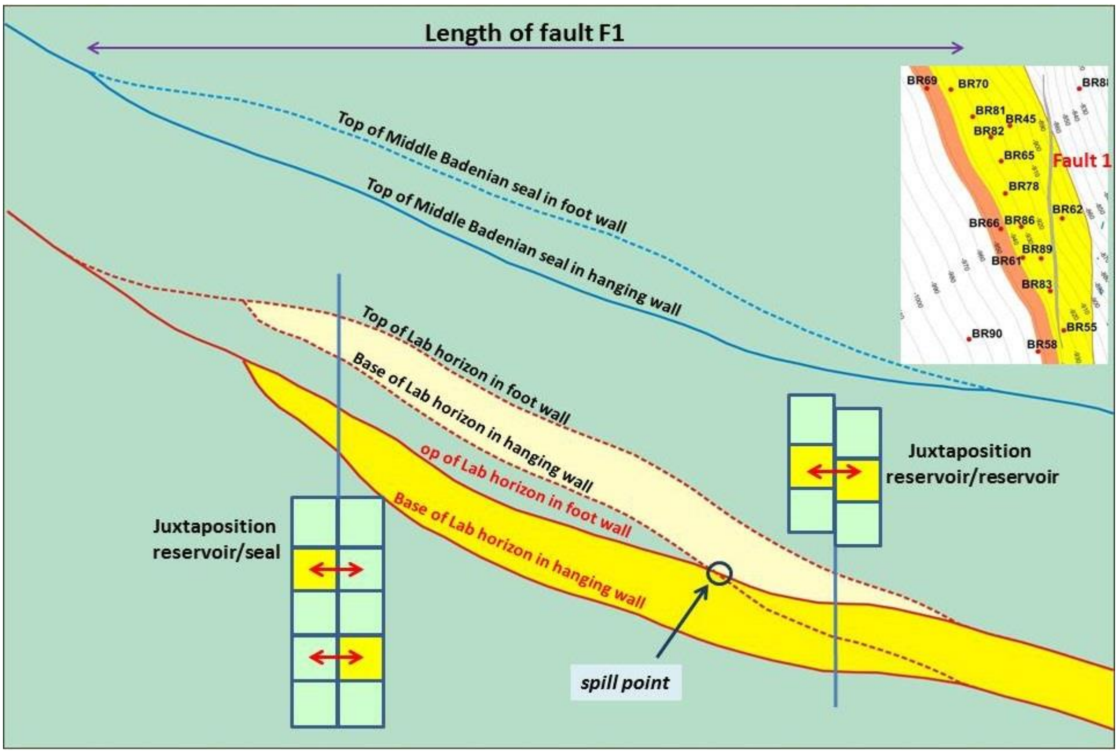

Figure 27: Simplified Allan diagram of Fault 1

A very good example of the function of faults related to possible leakage pathways of CO_2 leaked from the reservoir is shown in Figure 28. The figure shows probable migration pathways for CO_2 leaked through well Br-62 (the leakage scenario is described in detail in Chapter 4.2). The role of the main Brodske fault depends again on the juxtaposition of permeable vs impermeable layers. The fault is interpreted as open in the Upper Badenian, Middle Sarmatian and Pannonian due to sand/sand contact on both sides of the fault (green ellipses), while in the Upper Sarmatian it is considered closed due to the sand/clay interface (red ellipse). This means that the fault would not act as a sealing barrier for several of these migration pathways, indicating that – in the worst case scenario – the CO_2 can migrate up-dip up to the neighbouring Kostice oil and gas field (well Kos-17 on the NNW margin of the cross-section) and possibly further to Slovakia.

In summary it can be stated that the faults intersecting or confining LBr-1 do not represent a risk for the sealing integrity of the reservoir. On the contrary, together with the stratigraphic features (especially the reservoir pinch-out), they represent part of the trapping mechanism that has been proven by the existence of the hydrocarbon field itself. From this point of view, the faults are not expected to cause any transboundary issue at LBr-1. Only in case of leakage along a wellbore, the Brodske fault would allow CO_2 migration to Slovakia at shallower depths, above the primary caprock.

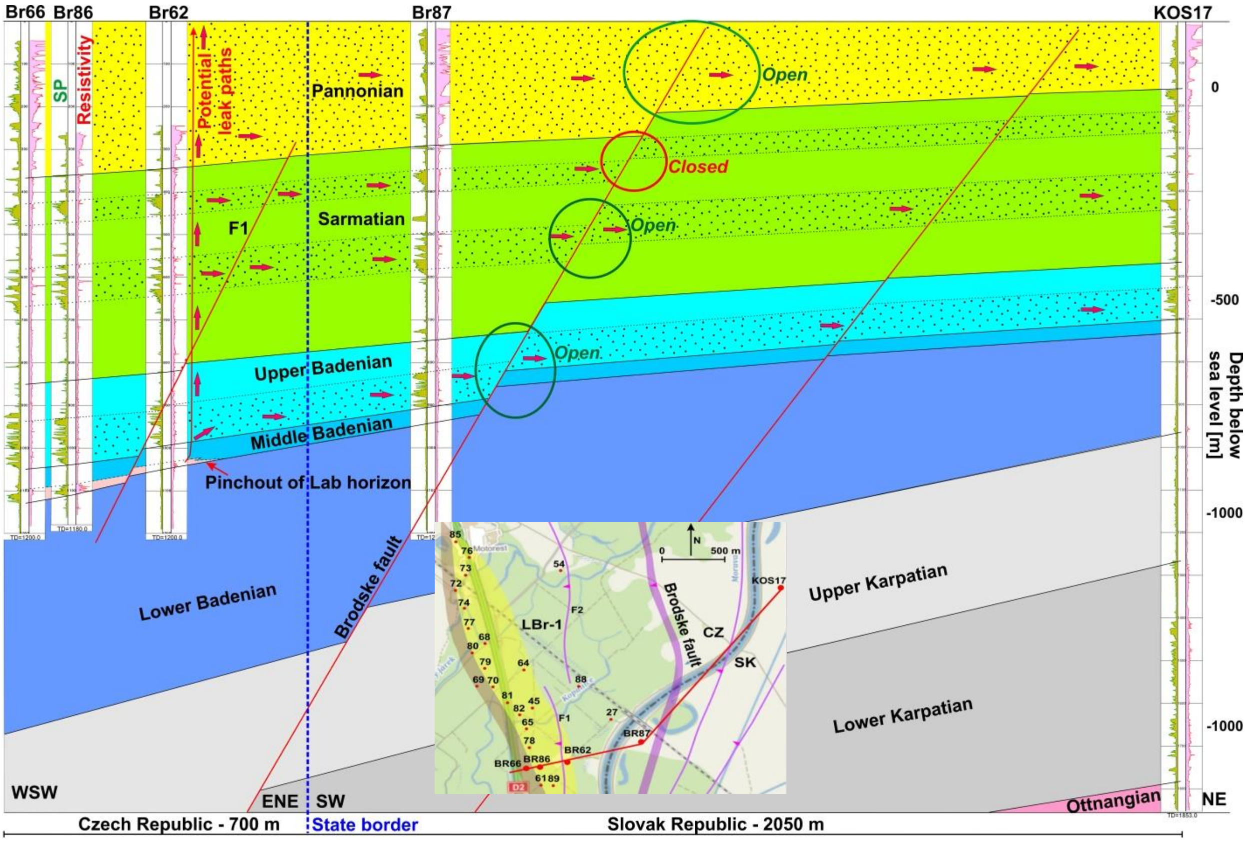

Figure 28: Schematic geological cross section through LBr-1 from the Czech Republic towards the Slovak Republic with wells, well logs and indications of potential CO_2 leakage pathways (red arrows). The small map in the middle bottom part indicates the position of the cross section.

4.4 Spill points and possible fluid migration out of the reservoir

Leakage of CO_2 from the reservoir due to exceeding the spill point is another risk scenario that needs to be considered, especially when the amount of CO_2 to be injected comes near to the reservoir storage capacity. The spill point also represents a “gate” for possible migration of other fluids out of the reservoir, in particular the brine that is pushed out from the pores by the injected CO_2.

Spill points already played an important role in the time when hydrocarbon fields are formed. The migration of hydrocarbons that gradually push brine from structural and stratigraphic traps turns them into petroleum traps. This process occurs both during the primary migration of hydrocarbons from source rock to the reservoir, and during the follow-up secondary migration within the reservoir. Oil normally migrates first. It may (but not always) fill the trap up to the full trap capacity, i.e. up to the spill points. Small-volume traps can be filled entirely while the big ones only partly, depending on the amount of migrating oil.

Natural gas migration usually follows oil. The gas fills the traps and can push oil or its part out of the smaller traps. The oil then migrates further to shallower structures in the area.

As a result, hydrocarbon accumulations form a specific distribution pattern. In the following part, the example of the Vienna Basin (Czech part) is described more in detail. The following types of structures can be found:

- Shallow structures (up to 600 – 1,000 m) contain biodegraded oil accumulations with low gas volumes due to gas escape to the surface. Pure gas fields with no oil usually contain microbial (biogenic) methane;
- At middle depths (1,000 – 3,000 m) combined oil & gas fields occur.
- Structures over 3,000 m deep usually contain gas with gas-condensate.

The principal question during the field exploration phase is whether the hydrocarbon trap is filled up to its capacity, i.e. up to the spill points.

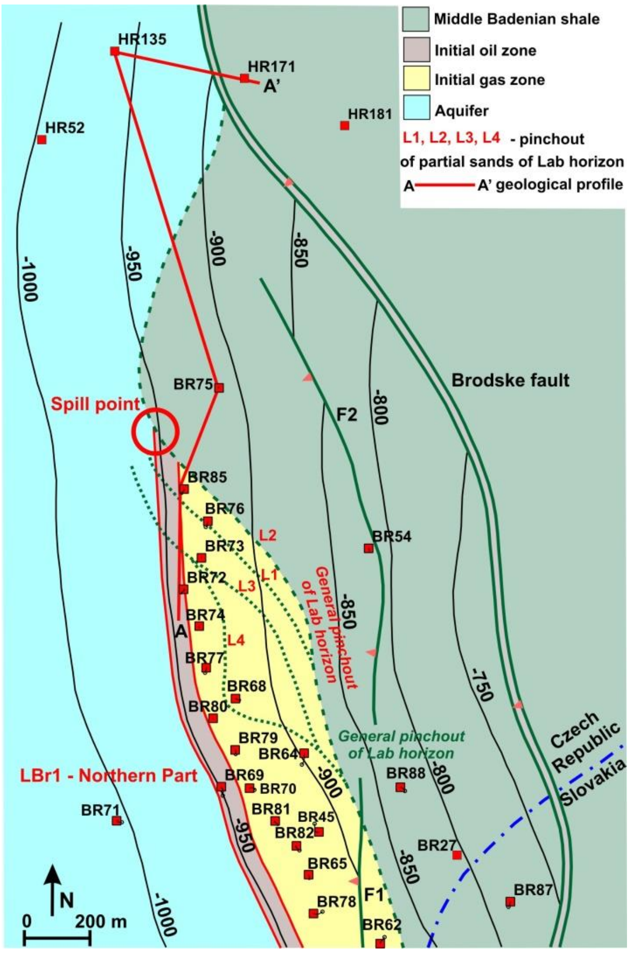

Figure 29: Northern edge of LBr-1 - generalized structural contour map of the top of Lab horizon (top L1) with faults, initial positions of the oil and gas zones, pinch-out lines of Lab horizon partial sand layers and the interpreted position of the northern spill point. The red line shows the position of the cross-section displayed in Figure 30.

According to the current level of understanding, LBr-1 seems to be a hydrocarbon trap that has been filled up to its capacity. From the depth point of view, the expected spill point occurs a few meters below the oil-water contact (OWC), which – according to the static 3D reservoir model – lies at the structural depth of -953 m). The field is formed by a relatively thin oil-and-gas zone along the pinch-out line of the Lab sandy horizon, which indicates possible presence of spill points close to the OWC. The four partial layers (L1 - L4) have their own, independent pinch-out lines. The layers are mostly separated by clay intercalations, but closer to the general pinch-out line they are vertically interconnected in several places. Based on the observations mentioned above and the 3D reservoir model we conclude, that the OWC and the gas-oil contact (GOC) occur at the same structural level in all partial layers, i.e. OWC at -953 m and GOC at -943 m.

In the northern part of LBr-1 (Figure 29), the sealing in all partial layers L1 - L4 is tied to the pinch-out lines. A spill point is assumed to occur in the area of the Br-85 well. The Lab horizon continues here northwards with good-quality sands occurring in Hr-52 and Hr-135 wells (belonging to the neighbouring Hrusky field) in deeper structural position. In Hr-135 its structural depth is -968 m, i.e. ca. 15 m below the OWC at LBr-1 (-953 m). The pinch-out zone is situated between the Hr-135 and Hr-171 wells. Moreover, a fault with vertical movement of ca. 20 m has been identified between these two wells (see also Figure 30). The Lab horizon ascends from Hr-135 to Hr-171 and pinches out gradually at a structural depth of -900 m, i.e. ca. 50 m above the OWC at LBr-1. The horizon is also documented more to the north, in other Hr wells. One can even consider existence of a small HC field similar to LBr-1 in this area.

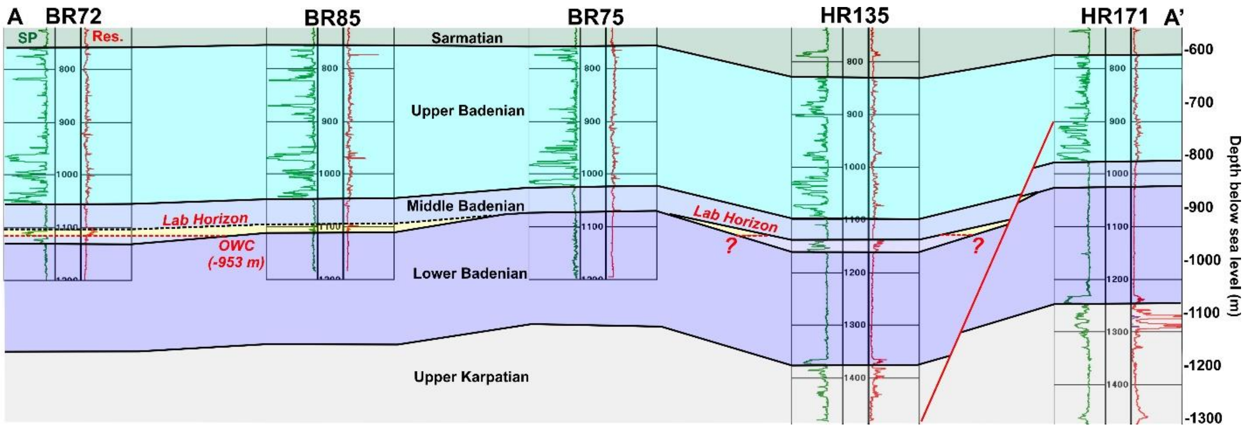

Figure 30: Schematic cross-section across the northern edge of LBr-1 (position shown in Figure 29) with well logs and geological interpretation

Based on these “indirect” pieces of evidence, the assumption of a spill point positioned north of the Br-85 well seems reasonable, especially in the L2 layer.

If the CO_2 exceeds the northern spill point, it would most probably (based on 3D seismic interpretation) migrate northwards into the area of the Hrusky field and end up in one of the stratigraphic (hydrocarbon-bearing) traps situated here. A more detailed assessment of its possible further fate exceeds the framework of this study. It can be, however, excluded, that this migration scenario has any transboundary effect.

The situation in the southern part of LBr-1 (Figure 31) is more complicated. Partial layers L1, L2 and L3 of the Lab horizon are obviously bound by the pinch-out boundary, which is sufficiently confirmed by well data.

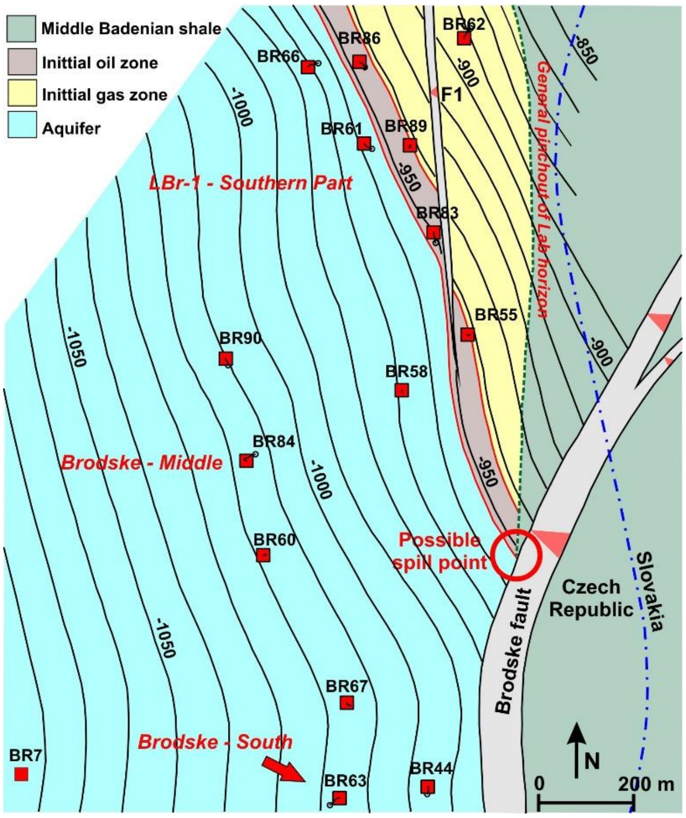

Figure 31: Southern edge of LBr-1 - generalized structural contour map of the top of the L4 partial sand with faults, initial positions of the oil and gas zones, pinch-out line of the Lab horizon and the interpreted position of the southern spill point

The L4 layer is, however, a different case. L4 is the thickest sand complex of the field and occurs not only at LBr-1, but also at Brodske-Middle and Brodske-South. It forms a relatively big hydrocarbon trap at LBr-1, otherwise it represents just an aquifer in the whole area (except a small tectonic interblock at Brodske-South). The Brodske fault plays here a significant role with its 200 m vertical movement. According to Figure 31, the sealing of the hydrocarbon trap is ensured by the pinch-out of the layer (more probable), or it is partially secured by the Brodske fault (less probable but possible). In any case, L4 occurrence is terminated here by the Brodske fault at least in its deeper, aquifer part. On the other side of the fault (so called Brodske-Upper Block or High Block), older rocks of the Lower Badenian complex appear; unfortunately; no well has been drilled in this area to provide more detailed information.

An analogous situation at the Brodske-South field (Figure 32) can be used as an example of the structural development. The L4 horizon on the fault hanging wall is in contact with the Lower Badenian complex that includes tiny sand layers or low-permeable sandy clays (as documented in well Br-20). This means that the fault does not necessarily represent a barrier for possible fluid flow towards NE.

Additional evidence that the Lower Badenian complex is permeable can be found in results of pumping tests focusing on Lower Badenian layers carried out in several wells in the southern part of LBr-1, incl. the Br-55 well that is close to the possible spill point (Figure 33). The results document inflow of fluids from various thin horizons in Lower Badenian.

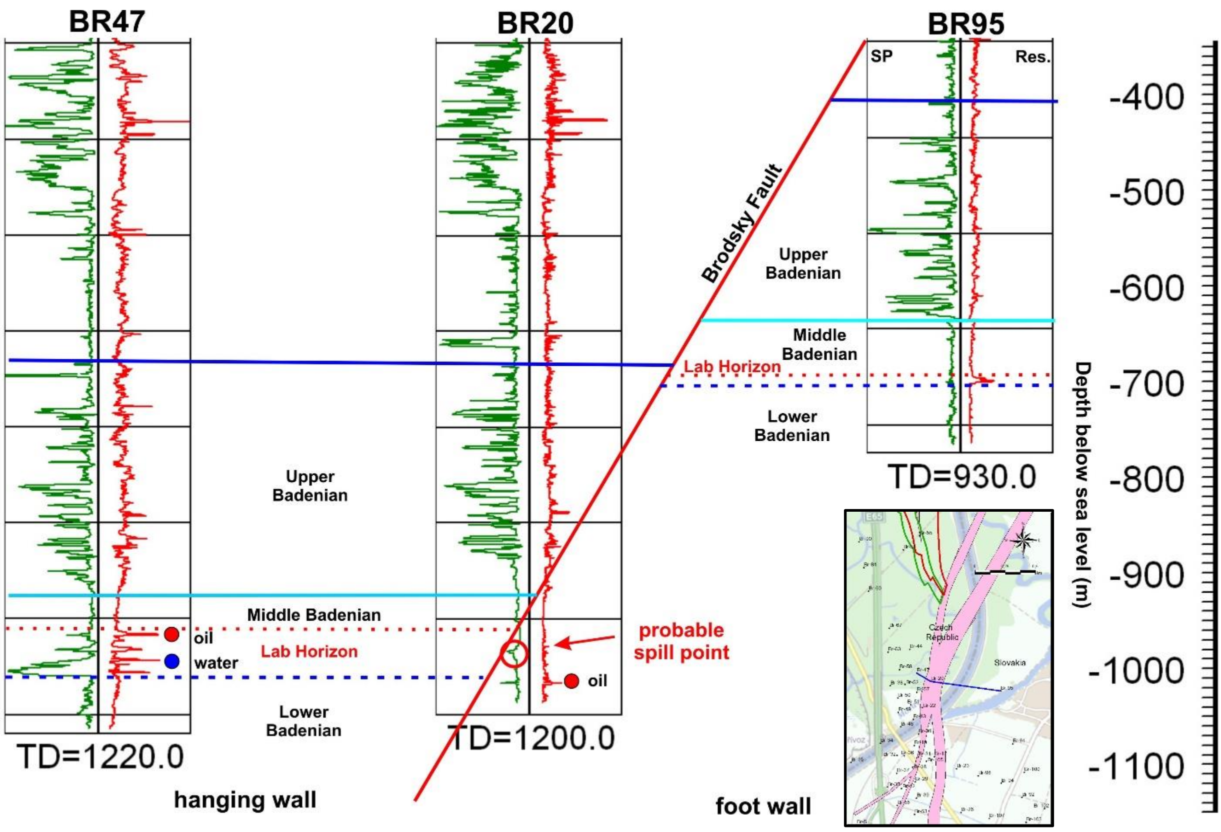

Figure 32: Schematic cross-section through the Brodske fault in the area of Brodske-South (position shown in the small map in the bottom right corner) with wells, well logs and position of the Lab horizon

This means that the Lower Badenian complex, even though predominantly pelitic, does not work as a sealing in some places (its sealing properties are not as good as those of the Middle Badenian clays forming the caprock of the Lab horizon). This needs to be taken into account when assessing possible fluid flow through the Brodske fault. It is difficult to identify the permeable layers due to lack of information – the drilling was stopped after the Lab horizon was penetrated, both on the hanging wall of the fault, and especially on the footwall, in the Brodske-Upper Block area (which means that data for unequivocal verification of the spill point position are lacking). Moreover, the Middle Badenian – Lower Badenian contact is discordant, which makes a sufficiently reliable correlation of the Lower Badenian strata impossible.

In any case, if a CO_2 leakage through the Brodske fault occurs, the general dip of the layers in the Brodske complex (to the west / south-west) would cause the migration of the gas towards east / north-east, i.e. in the territory of Slovakia. This conclusion represents a possible additional transboundary issue linked to CO_2 storage at LBr-1. It should be, however, stressed that this risk is only related to scenarios with larger volumes of injected CO_2 where the CO_2 plume reaches the southern reservoir margin (see Chapter 3.2). The basic CO_2 storage pilot scenario is excluded from this category.

The presence of spill points at LBr-1 as described above is very probable. The uncertainty is connected with their depth position. To be on the safe side, it is necessary to reckon with the possibility that they coincide with the position of the OWC according to the static reservoir model – in this case at -953 m structural depth.

The precise position of the spill points can probably be determined only by real injection of fluids for several years, accompanied by well monitoring and reservoir pressure measurements.

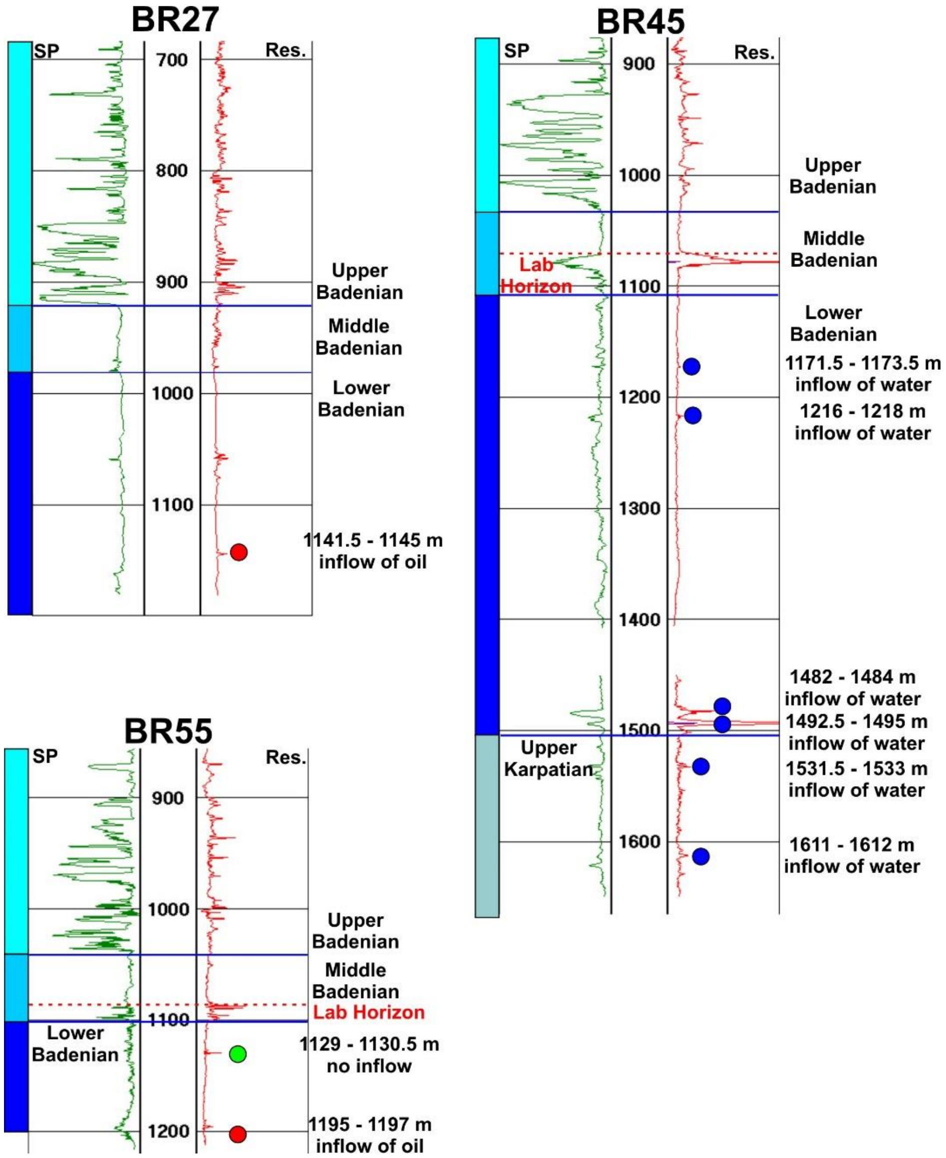

Figure 33: Results of pumping tests carried out in Br-27, Br-45 and Br-55 wells documenting presence of permeable layers in the Lower Badenian complex

5 Identified legislative and regulatory barriers and proposed solutions

Several legislative and regulatory barriers for CCUS were identified in both the Czech Republic and Slovakia. In the Czech Republic, three main barriers can be observed:

- Temporary ban of CO_2 storage exceeding the amount of 100,000 t (§ 24 of the Storage Act). This ban will expire on 01/01/2020 unless the law is changed at the last minute and the ban is prolonged; the barrier will thus disappear.
- Limitation of the amount of stored CO_2 to 1 mill. tonnes per site per year (§ 6 of the Storage Act). This limitation is a needless obstacle that would cause problems to larger-scale CO_2 storage projects and should be removed from the Act.
- Missing provisions for the financial security (§ 15 of the Storage Act). The financial security should be regulated by a special Government decree that, however, has not been approved yet. This represents a significant uncertainty that can only be removed by adoption of the decree. The decree should be written in pro-active way, supporting the storage site developers and setting the financial burden related to the security to a necessary minimum. In case the requirements are exaggerated, e.g. asking for a security equal to the cost of EU-ETS allowances corresponding to the whole amount of injected CO_2 (even though it is technically completely impossible that all CO_2 from the storage site is released back to the atmosphere), they can easily become a show-stopper for any CO_2 storage-related activity in the country.

The situation in Slovakia is different. The main barrier for CO_2 storage is the list of limitations concerning the location of a possible storage site and the determination of regions where CO_2 storage site exploration is enabled. As can be seen below, in both cases the CO_2 storage site has the lowest priority in the whole ranking of priorities.

According to § 3 of the Slovak Act No 258/2011 (Slovak 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 safety of energy supply or development of renewable energy sources
- rock structures containing significant groundwater reserves including natural healing and natural mineral water resources
- water structures (as defined by the Slovak Water Act No 364/2004)

According to § 24 of the Slovak Geological Act, the Ministry of Environment of the Slovak Republic determines regions where geological exploration for permanent carbon dioxide storage is enabled. The Ministry publishes the location of the determined regions on its website annually, including a map. According to the last Ministry´s update of the regions (status on 01/01/2019), the following areas must be excluded:

- valid exploration licences (blocks) for all raw materials - 72 exploration licences were registered on 01/01/2019
- reserved mineral deposits (no matter which raw material is protected and at which depth) - 599 reserved mineral deposits were registered on 01/01/2019
- nature and landscape protected areas including Natura 2000 - 23 large-scale areas (national parks etc.), 1,097 small-scale areas (nature reserves, natural monuments, caves), 14 wetland (Ramsar convention) localities, 14 general nature protected areas and 683 protected areas of Natura 2000 were registered on 01/01/2019

- water protection areas - 12 protected areas of natural water accumulation, 1,350 protected areas of groundwater resources, 120 surface water bodies (rivers, lakes and dam lakes utilized or suitable as drinking water resource, also known as surface water accumulation protected areas), 23 protected areas of the natural healing (water) resources and 21 protected areas of natural mineral (water) resources were registered on 01/01/2019
- geothermal areas - 26 promising geothermal areas were registered on 01/01/2019
- radioactive waste storage areas - 3 promising radioactive waste storage areas were registered on 01/01/2019
- military training areas - 3 military training areas are also excluded.

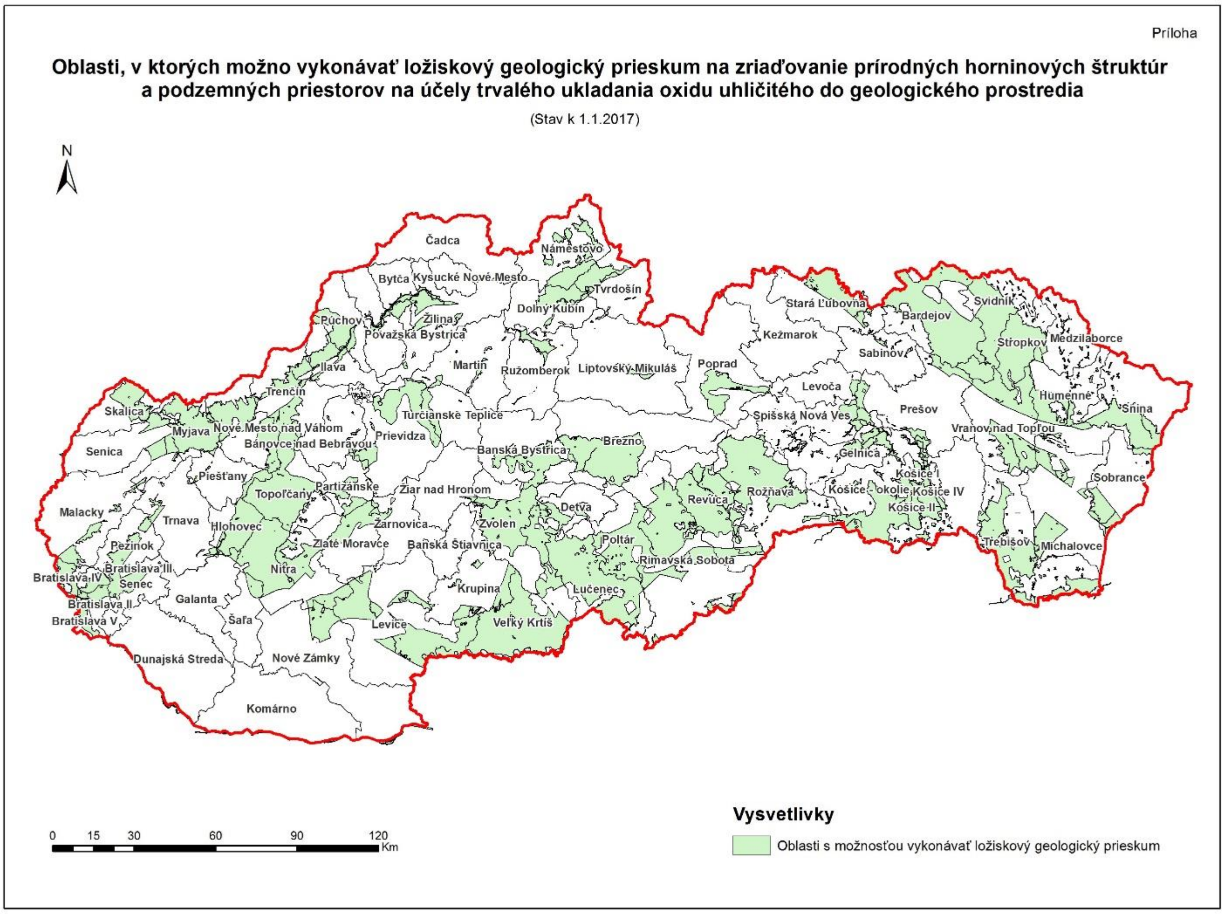

Figure 34 Map of the Slovak Republic with areas where geological exploration for permanent carbon dioxide storage is enabled marked in green. Status on 1 January 2019. Source: Ministry of Environment of the Slovak Republic, https://www.minzp.sk/files/sekcia-geologie-prirodnych-zdrojov/ukladanie-co2_map_2019.jpg

The above-stated list of types of excluded areas represents an unsurmountable barrier for exploration for CO_2 storage in Slovakia while for other types of geological exploration it is a typical list of conflicts of interest that are handled on case by case basis. The case-by-case way of handling of conflicts of interest for CO_2 storage sites exploration is applied in most of the other EU countries, including the Czech Republic.

Current status of areas where geological exploration for permanent carbon dioxide storage is enabled is shown in Figure 34. The map clearly indicates that CO_2 storage is only possible on a small part of the Slovak territory, mainly in areas that are geologically unsuitable. Most of the sedimentary basins with suitable geology are excluded due the above-mentioned limitations.

Another uncertainty is connected with the vague definition of the financial security (Slovak Storage Act No 258/2011, §16). The security amount is set by the District Mining Authority, based on several parameters but without any quantification. The amount can even be changed during the storage site operation.

It is clear that the aim of both the lawmakers and regulators in the process of transposition of the EU CCS Directive into the Slovak law was to make CO_2 storage on the territory of Slovakia as good as impossible, even though a strict ban as in some other national legislations has not been imposed.

To enable CO_2 storage in Slovakia, the overall regulatory approach needs to be completely changed. If CCUS is recognised as an important and needed technology (see below for possible reasons), its position in the ranking of technologies utilising the subsurface needs to improve. Only based on this, the relevant laws and regulations can be modified.

The following recommendations can be inferred in case there are good reasons to support deployment of CO_2 storage in the Slovak Republic by effective regulation:

- re-considering the priorities for subsurface use, taking the climate-change mitigation role of CCUS and CO_2 storage into account
- allowing exploration for CO_2 storage sites in exploration licence areas for hydrocarbons, taking possible development of a hydrocarbon-producing field into a CO_2 storage site into account, both with and without the intermediate step of an enhanced hydrocarbon recovery phase
- allowing exploration for CO_2 storage sites in exploration licence areas for raw materials situated at different depths than those of a possible storage site
- re-considering the solution of conflict of interest between storage site exploration activities with nature protection, water protection or military use; replace a strict ban by a case-by-case approach that would take both nature / environment and climate protection benefits into account, namely in cases where the impact of exploration activities would be negligible or limited.

Such changes would open the door to large volumes of CO_2 storage potential in Slovak sedimentary basins and enable possible deployment of CCUS.

In both countries there are unclear or missing regulations governing the CO_2-EOR activity and possible transfer of the oilfield produced with help of CO_2-EOR into a CO_2 storage site (see Chapter 2 for details). This situation gives in fact an unlimited power to the responsible Mining Authority to decide upon all aspects of site development. Combined with the lack of experience with CO_2-EOR in the region this represents a big uncertainty for possible investors and operators.

In general, the current status of CCUS legislation in both countries under study reflects the position of the technology in their decarbonisation strategies. This position is currently weak and the technology is not considered important. As a reason, the relevant legislation and regulations are rather focusing on creating barriers and obstacles, rather than supporting CCUS deployment. This needs to be changed if the potential of the technology to decarbonise the national economies shall be utilised.

First of all, the importance of CCUS and CO_2 geological storage needs to be re-considered in the light of the new European climate and energy policy. The proposed greenhouse-gas neutrality of the EU by 2050 will most probably mean that the technology will be needed to abate CO_2 emissions from some difficult-to-decarbonise industries like cement, steel and chemicals. In addition, negative CO_2 emissions to be achieved by means of BECCS (bio-energy production with CCS) or DACCS (direct air CO_2 capture with storage) can become inevitable. If the awareness of this CCUS potential is achieved, the increased importance of the technology can be reflected in the improvement of legislation and regulations much more easily.

What are the implications of the current legislation and regulatory regimes on the LBr-1 site itself, when combined with the definition of the storage complex (Chapter 3) and possible transboundary effects (Chapter 4)?

The most important finding is that both the storage site and storage complex are located entirely on the territory of the Czech Republic. Hence, sensu stricto, LBr-1 is not a cross-boundary storage site. However, several transboundary issues were identified (see chapter 4), especially those that are related to possible (even if unlikely) leakage of CO_2 from the storage complex through poorly constructed or abandoned wells or non-sealing faults. This means that a cooperation of regulatory authorities from both Czech and Slovak Republics will be in any case necessary. The main reason is that many parts of the site preparation, injection, closure and post-closure phases will necessarily be transboundary, especially the risk assessment, monitoring (all phases) and possible leakage mitigation measures.

This is a significant complicating factor for possible realisation of the pilot project. It is unclear how such cooperation should be organised; most probably it would require an intergovernmental agreement signed at the highest level. An option might be to declare the storage site transboundary, extending its area (or that of the storage complex) across the border into the area of Slovakia. In such case the authorities in both countries would be in the same position with respect to the regulation and supervision of the storage site while, at the same time, the site would need to meet the regulatory requirements of both legislations. Such a solution is, however, impossible at the moment because the area neighbouring with LBr-1 in the Slovak territory is not among those where geological exploration for permanent carbon dioxide storage is enabled.

Let us now examine the three main scenarios of LBr-1 site development more in detail:

For the **basic storage pilot scenario** that is limited to 70,000 t CO_2 stored, the site falls in the category of '*storage below 100 kilotonnes undertaken for research, development or testing of new products and processes'* (as defined by the EU CCS Directive). This means that the CCS Directive shall not apply to such a storage site and the activities will be regulated by other, more general laws valid in the Czech Republic. These especially include the Geological Act (No 62/1988) for site exploration and the Mining Activity Act (No 61/1988) for drilling of wells. All possible conflicts of interest will need to be handled according to the relevant laws similarly to any activity of this type.

Since CO_2 geological storage is a completely new type of activity in the country, the related permitting also will be new for the competent authorities. The Ministry of Environment, the Czech Mining Authority and the Dept. of Environment of the South Moravian Regional Authority are the main regulatory bodies involved. There are a lot of uncertainties connected with this process, mostly due to lack of experience and absence of any precedents. This means that both the project developer and the relevant authorities will have to do a lot of pioneering work. This process, however, cannot be avoided, simply because both sides need to gain the necessary experience. Possible guidance could be partly obtained from the few onshore CO_2 storage pilot projects that were already carried out in Europe, especially Ketzin in Germany and Lacq in France. Experience can also be taken form the Hontomín pilot site in Spain and the late ROAD project and current commercial scale P18-2 developments in the Netherlands even though the latter two are offshore projects. With regard to Hontomín this should be, however, done with caution because the recent changes in local regulations created new, unexpected hurdles to CO_2 injection at Hontomín that have not been overcome until now. Moreover, the transfer of experience in all above mentioned cases will be limited by differences in the national geological and mining laws that are based on different historical development in various parts of Europe.

The **"full-scale" storage scenario** falls fully under the scope of the EU CCS Directive transposed into the Czech Storage Act (No 85/2012). It can be realised only after 01/01/2020 when the temporary ban implied by the Act expires, provided the law is not changed in the meantime. This scenario assumes the largest extent of the CO_2 plume (see Chapter 3.2), which will require a detailed evaluation of the position of possible spill points both at the northern edge of the reservoir and at the southern, tectonically conditioned margin. To be able to perform this evaluation, a complementary site exploration phase needs to be carried out, in order to clarify some of the last continuing uncertainties related to the site – the real position of the current water-oil contact and the sealing function of the southern confining fault (branch of the Brodske fault), especially in its deeper parts below the original hydrocarbon accumulation. This evaluation will determine the maximum CO_2 storage capacity of the LBr-1 reservoir that can be utilised, keeping the extension of the CO_2 in a safe distance from the spill points.

Similarly to the other two scenarios, also in this case a cross-border cooperation between the Czech Republic and Slovakia will be needed (see above). For the "full-scale" storage scenario this aspect is even more important because the scenario involves the largest amount of CO_2 to be stored and the largest extent of the CO_2 plume.

The **CO_2-EOR scenario** would be regulated by the Czech Ming Act (No 44/1988) and the Mining Activity Act (No 61/1988). After the oil production is stopped, two options can arise. The first one would represent a transition of LBr-1 from an oil production site to a CO_2 storage site. In such case, oil production wells are shut down and abandoned according to the valid regulations, or transformed to injection or monitoring wells. The transition to the CO_2 storage site is subject to approval by the Mining Authority. After this step, the storage site is regulated by the Storage Act; the Mining Authority remains the main competent authority.
The second option is a full abandonment of the site, without any continuation of CO_2 storage activity. Even in this case a significant amount of CO_2 can be stored in the reservoir because it is expected that, in the end, all CO_2 brought to the site is stored in the reservoir. The CO_2 either stays underground thanks to various trapping mechanisms already after it is injected, or it is – if produced back together with the oil – separated from hydrocarbons on the surface and re-injected. Based on currently valid laws, after the oil production is stopped, the site is closed and abandoned, based on valid regulations. No special provisions related to CO_2-EOR are in place. What is, however, completely unclear, is if the Mining Authority uses its power to set additional requirements for abandonment of the site. These might include special provisions for well plugging or some monitoring focused on possible leakage or the CO_2 plume stability.

This uncertainty might represent a barrier for possible larger implementation of CO_2-EOR in the Vienna Basin, especially considering similar situation in the neighbouring countries. A solution might be to declare at least basic principles of CO_2-EOR operations regulation so that possible investors and oil companies have a clear idea of expected requirements. The related costs are, indeed, an important item in the overall economic framework of the whole CO_2-EOR scenario and can significantly influence the strategic decision making.

Assessment of CO_2-EOR potential of the Vienna Basin, covering relevant territories of the Czech Republic, Slovakia and Austria, is subject of research in ENOS Task 6.5. A strategic development plan devoted to this topic will be prepared as deliverable D6.7, due in Q1 2020.

In case a CO_2-EOR project wants to apply for carbon credits under the European Trading System (ETS) a detailed monitoring and accounting procedure needs to be in place to assess the exact amount of CO_2 going in the reservoir and the amount that is being back-produced and re-injected. This topic is covered in detail in ENOS deliverable D4.11.

6 Conclusions

The presented study evaluated possible transboundary issues related to CO_2 injection and storage at LBr-1. At first, currently valid national legislations relevant to CO_2 geological storage in the Czech Republic and Slovakia were examined and several legislative and regulatory barriers for CCUS were identified. In general, the current status of CCUS legislation in both countries reflects the position of the technology in their decarbonisation strategies. This position is currently weak and the technology is not considered important. As a consequence, the relevant legislation and regulations are rather focusing on creating barriers and obstacles, rather than supporting CCUS deployment. This needs to be changed if the potential of the technology to decarbonise the national economies shall be utilised.

In the Czech Republic, the identified barriers (temporary ban of CO_2 storage until 01/01/2020, limitation of the amount of stored CO_2 per site per year and missing provisions for the financial security) can be removed by relatively easy and simple improvements of legislation. In Slovakia, however, the overall regulatory approach needs to be changed to enable CO_2 storage on its territory. This especially concerns re-considering the priorities for subsurface use and the approach to the solution of conflicts of interest.

In both countries there are unclear or missing regulations governing the CO_2-EOR activity and possible transfer of the oilfield produced with help of CO_2-EOR into a CO_2 storage site, which represents a big uncertainty for possible investors and operators.

In the second step, implications of the current legislation and regulatory regimes on the LBr-1 site itself were studied. The most important finding is that both the storage site and storage complex are located entirely on the territory of the Czech Republic. However, several transboundary issues were identified, especially those that are related to possible (even if unlikely) leakage of CO_2 from the storage complex

Four possible types of transboundary issues were examined in detail – pressure build-up, possible leakage through boreholes, possible leakage through faults and possible migration of fluids out of the reservoir due to exceeding spill points, for three scenarios – limited CO_2 storage, full storage and CO_2-EOR scenario. While pressure build-up and leakage through faults do not appear to cause transboundary issues, the other two phenomena need to be carefully considered. In case CO_2 leakage appears either through abandoned wells or due to exceeding the southern spill point, the analysis of possible leakage pathways shows that the CO_2 could migrate into the territory of Slovakia. There are three main factors that limit the level of concern: the probability of large leakage occurrence is low, the amount of possibly leaked CO_2 would be very limited, and the spill point is reached only in case the reservoir is filled up to its limit.

Nevertheless, these findings mean that a cooperation of regulatory authorities from both Czech and Slovak Republics will be necessary to prepare and operate the storage site. The main reason is that many parts of the site preparation, injection, closure and post-closure phases will be transboundary, especially the risk assessment, monitoring (all phases) and possible leakage mitigation measures. This is a significant complicating factor for possible injection of CO_2 at LBr-1.

Despite of this, the realisation of a CO_2 storage project on the site is considered viable, especially in the basic pilot storage scenario. This case avoids the spill-point related concerns (because of the limited extent of CO_2 plume) and involves only a limited number of abandoned wells that need to be taken care of concerning their abandonment status. The lack of experience with CO_2 storage sites and absence of any regulatory precedents in both countries will require a lot of pioneering work do be done by both the project developer and the relevant authorities. This process, however, cannot be avoided, simply because both sides need to gain the necessary experience that can be utilised in future, when preparing, operating and regulating next CO_2 storage projects.

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References

Abdel-Rahman, A. A. (2008): On The Atmospheric Dispersion and Gaussian Plume Model, 2nd International Conference on Waste Management, Water Pollution, Air Pollution, Indoor Climate (WWAI'08), Corfu, Greece, October 26-28, 2008. ISBN: 978-960-474-017-8.

Arild, Ø., Ford, E.P., Lohne, H.P., Mansouri, M., Havlova, V. (2017): A comparison of FEP-analysis and barrier analysis for CO2 leakage risk assessment on an abandoned Czech oilfield. Energy Procedia, Vol. 114, July 2017, pp. 4237-4255.

Association ASPEN (2009): Support to the Introduction of the Enabling Legal Framework on Carbon Dioxide Capture and Storage (CCS). AEA Group, Didcot, 158 pp.

Berenblyum, R., Kollbotn, L., Nair, R., Hladík, V., Franců, J., Pereszlényi, M., Kolejka, V., Sinayuc, C. (2019): Reservoir models of novel CO2-EOR concepts at LBr-1. ENOS deliverable D4.5.

CO2CARE (2012): CO2 Site Closure Assessment Research, Deliverable D2.5: Report on Analytical Computation of Leakage on a Cement Plug, February 2012.

EC (2009): Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006

Fodor, L. (1995): From transpression to transtension: Oligocene–Miocene structural evolution of the Vienna Basin and the East Alpine–Western Carpathian junction. Tectonophysics, 242, pp. 151–182.

Ford, E., Lohne, H.P., Arild, Ø., Havlová, V., Štván, F., Klempa, M., Bujok, P., Hladik, V., Franců, J., Janderková, J., Krejčí, O., Pereszlényi, M., Kolejka, V., Khrulenko, A., Kollbotn, L. (2016): Final risk assessment report. REPP-CO2 Deliverable V4.3.

Ford, E.P., Moeinikia, F., Lohne, H.P., Arild, Ø., Mansouri, M., Fjelde, K.K. (2018a): Leakage Calculator for Plugged-and-Abandoned Wells, SPE Production & Operations (ISSN 1930-1863), Volume 33, Issue 02.

Ford, E.P., Omekeh, A.V., Berenblyum, R., Kollbotn, L., Hladik, V., Francu, J., Pereszlenyi, M., Kolejka, V., Jirman, P. (2018b): Assessing risks presented by boreholes: Recommendations on a risk assessment framework for CO2 storage. ENOS deliverable D3.2.

Hamilton, W., Jiříček, R., Wessely, G. (1990): The Alpine–Carpathian floor of the Vienna Basin in Austria and ČSSR. In: Minaříková, D. and Lobitzer, H. (Eds.) Thirty Years of Geological Cooperation between Austria and Czechoslovakia. Geological Survey, Prague, pp. 46–56.

Hladik, V., Berenblyum, R. Pereszlenyi, M., Krejci, O., Francu, J., Riis, F., Ford, E., Kollbotn, L., Khrulenko, A. (2017): LBr-1 – Research CO2 Storage Pilot in the Czech Republic. Energy Procedia, Vol. 114, July 2017, pp. 5742-5747.

ICF International (2010): Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide - Guidance Document 2 - Site Characterisation, CO2 Stream Composition, Monitoring and Corrective Measures. ICF International, London, 143 pp.

ISO (2018): ISO 31000:2018 – Risk management – Guidelines. Second edition, 2018-02-14.

Kollbotn, L., Berenblyum, R. (2016): Injection scenario analysis and suitable process recommendations. REPP-CO2 Deliverable V3.11.

Ladwein, H.W., Schmidt, F., Seifert, P., Wessely, G. (1991): Geodynamics and generation of hydrocarbons in the region of the Vienna basin, Austria. In: Spencer, A.M. (Ed.) Generation, Accumulation and Production of Europe's Hydrocarbons. Oxford University Press, Oxford, pp. 289–305.

National Risk Assessment Partnership - NRAP (2017): Probability Distributions for Effective Permeability of Potentially Leaking Wells at CO2 Sequestration Sites, NRAP-TRS-III-021-2017, 21 April 2017.

Prochác, R., Pereszlényi, M., Sopková, B. (2012): Tectono-sedimentary features in 3D seismic data from the Moravian part of the Vienna Basin, First Break, 30, pp. 49-56.

Royden, L.H. (1985): Vienna Basin: a thin-skinned pull-apart basin. In: Biddle, K.T. and Christie-Blick, N. (Eds.) Strike-Slip Deformation, Basin Formation and Sedimentation. Society of Economic Paleontologists and Mineralogists, Special Publications, 37, pp. 319–338.

Stormont, J.C., Fernandez, S.G., Taha, M.R., Matteo, E.N. (2018): Gas flow through cement-casing microannuli under varying stress conditions. Geomechanics for Energy and the Environment, Vol. 13, March 2018, pp. 1-13.

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