15th International Conference on Greenhouse Gas Control Technologies, GHGT-15

15th 18th March 2021 Abu Dhabi, UAE

Assessment of trans-boundary effects at LBr-1 CO_2 storage pilot site and regulatory solutions

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Abstract

The paper evaluates possible trans-boundary issues related to planned CO_2 injection and storage at LBr-1, a candidate structure for a future geological storage pilot. LBr-1 is an abandoned hydrocarbon field situated in the Czech part of the Vienna Basin, close to the Czech-Slovak border. At first, currently valid national legislations relevant to CO_2 geological storage in the Czech Republic and Slovakia were examined. 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 trans-boundary 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 trans-boundary 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 trans-boundary 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. 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. This is a significant complicating factor for possible injection of CO_2 at LBr-1. Despite of this, the realization 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.

Keywords: EU CCS Directive; CO_2 storage; CO_2-EOR; trans-boundary issues; regulatory barriers; CO_2 plume; pressure built-up

1. Introduction

The national transpositions of the EU CCS Directive [1] do not fully address trans-boundary issues of CO_2 storage, 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, a study was carried out using the practical example of the

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LBr-1 potential CO_2 storage pilot site in the Czech Republic [2]. LBr-1 – one of the research sites of the ENOS European H2020 project [3] – is an abandoned hydrocarbon field situated in the Czech part of the Vienna Basin, close to the Czech-Slovak border (Fig. 1). Because of this, it represents a very suitable case for studying various trans-boundary issues related to geological storage of CO_2. LBr-1 is now the subject of continued detailed site assessment, with the ambition to turn the field into a research CO_2 storage pilot site with or without CO_2-EOR.

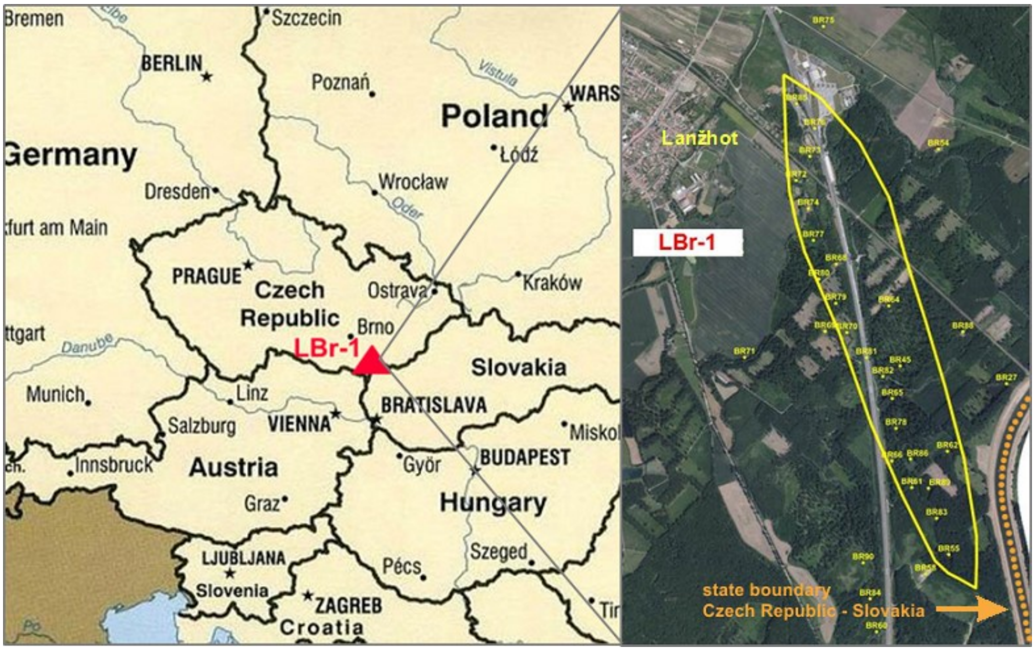

Fig. 1. Location of the LBr-1 site (left) and satellite image of the site (right) with outline of the reservoir area (yellow polygon), Czech-Slovak boundary (orange dotted line) and legacy wells (yellow dots). The reservoir is ca. 3 km long and max. 600 m wide.

The main objective of the study was to evaluate any trans-boundary issues that might arise from geological storage of CO_2 in the LBr-1 field, identify aspects that are difficult to handle, including those where existing legislation and regulations are unclear or lacking, and suggest solutions.

2. Brief geological description of the storage complex

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. The main volumes of oil and gas were produced from LBr-1 in 1959-1969, but sporadic production continued until 2000. Nowadays the field is closed and abandoned.

The reservoir is a combination of a lithological and tectonic trap. The targeted reservoir structure 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 in some places, while the faults of the Brodsky fault system confine the field in the South and partly in the South-East (Fig. 2). The main targeted reservoir horizon of the complex (originally hydrocarbon-bearing) comprises the Middle-Badenian (Serravallian/Langhian - Middle Miocene) 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.

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.

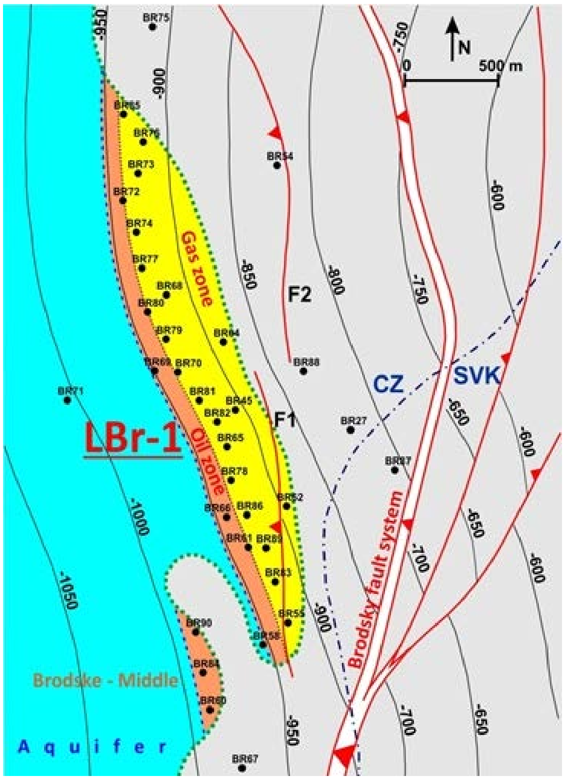

Fig. 2. LBr-1 - generalized structural contour map of the top of the reservoir (the Lab horizon) with wells, faults, initial positions of the oil and gas zones and the pinch-out line of the uppermost L1 partial sand layer (dark-green dotted line).

3. Comparison of national legislations

3.1. Overall assessment

As a first step, present 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 decarbonization strategies: this position is currently weak and the technology is not considered a priority for the use of the subsurface. As a consequence, the relevant legislation and regulations create barriers and obstacles, rather than supporting CCUS deployment. This needs to be changed if the potential of the technology to decarbonize the national economies is to be utilized.

In the Czech Republic, the identified barriers (especially the 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 adaptations of current legislation.

In Slovakia, however, the overall regulatory approach is rather hostile to CO_2 storage, and needs to be changed to enable CO_2 storage in its territory. In particular, the priorities for subsurface use and the approach to the solution of conflicts of interest would need to be addressed (see chapter 3.2).

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

3.2. Implication for the LBr-1 site

The main identified regulatory barrier connected with trans-boundary issues at LBr-1 lies in the limitations of the location of a possible storage site and the determination of regions where CO_2 storage site exploration is enabled in Slovakia. These are defined by the Slovak CO_2 storage Act No 258/2011 [4]. In both cases, a CO_2 storage site has the lowest priority in the whole ranking of priorities. All structures preferred for exploration, production and storage of hydrocarbons, for geothermal use, for radioactive and other waste storage, any other utilization of the subsurface space for energy purpose or structures containing significant groundwater reserves have higher precedence.

Taking this provision into account, the Ministry of Environment of the Slovak Republic determines regions where geological exploration for permanent carbon dioxide storage is enabled (Fig. 3). 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. In the concrete, the area adjacent to the LBr-1 site across the Czech-Slovak border, is part of the excluded area. This means that constructing and operating LBr-1 as a trans-boundary storage site is currently legally impossible, and even performance of possible additional site exploration on the Slovak side of the borderline would not be allowed.

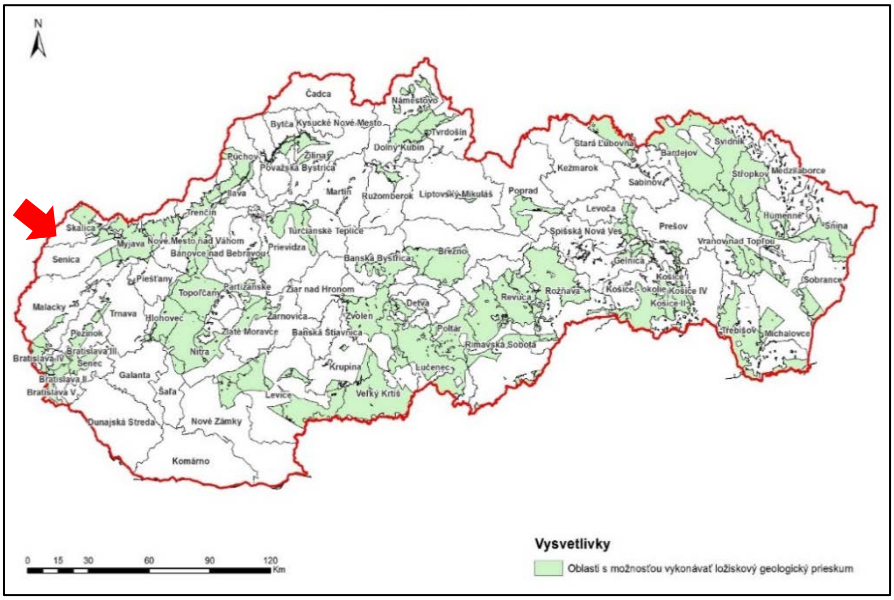

Fig. 3. Map of the Slovak Republic with areas where geological exploration for permanent carbon dioxide storage is enabled marked in green. Status on 1 January 2019. The red arrow depicts the area neighbouring with the LBr-1 site. Source: Ministry of Environment of the Slovak Republic, https://www.minzp.sk/files/sekcia-geologie-prirodnych-zdrojov/ukladanie-CO2_map_2019.jpg

4. Definition of storage complex

4.1. General definitions

The storage complex is defined by the EU CCS Directive [1] 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.

According to the Guidance Document 2 on the EU CCS Directive [5], 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.

Using the definition above, the lateral extent of the storage complex is generally defined by the extent of the CO_2 plume, while the vertical extent is defined by the position of the reservoir and the secondary seal. This is further discussed in chapters 4.2 and 4.3.

4.2. Vertical extent of the storage complex

The vertical extent of the complex is outlined in Fig. 4. 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.

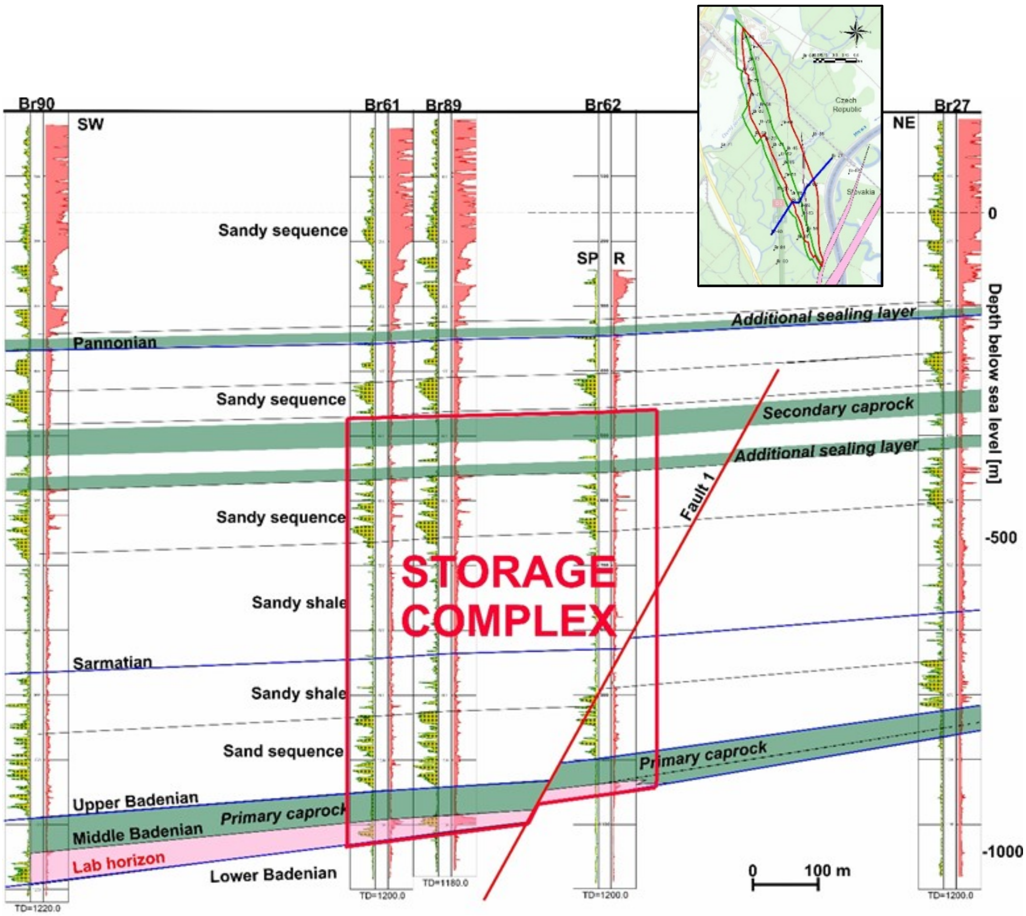

Fig. 1. Schematic outline of vertical extent of the storage complex in a SW-NE cross-section through the southern part of LBr-1. The small map in the top right corner shows the position of the cross-section.

4.3. 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 density of the CO_2 fluid under LBr-1 reservoir temperature (43°C), before eventually mixing with water and remaining oil, will be in the range from roughly 300 to 700 kg/m^3. This means that it is less dense than the reservoir oil in situ (estimated to be around 850 kg/m^3), and denser than the reservoir gas (50 – 100 kg/m^3).

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.

If injected into the oil zone, for instance through any of the existing producers, the CO_2 plume is therefore 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.

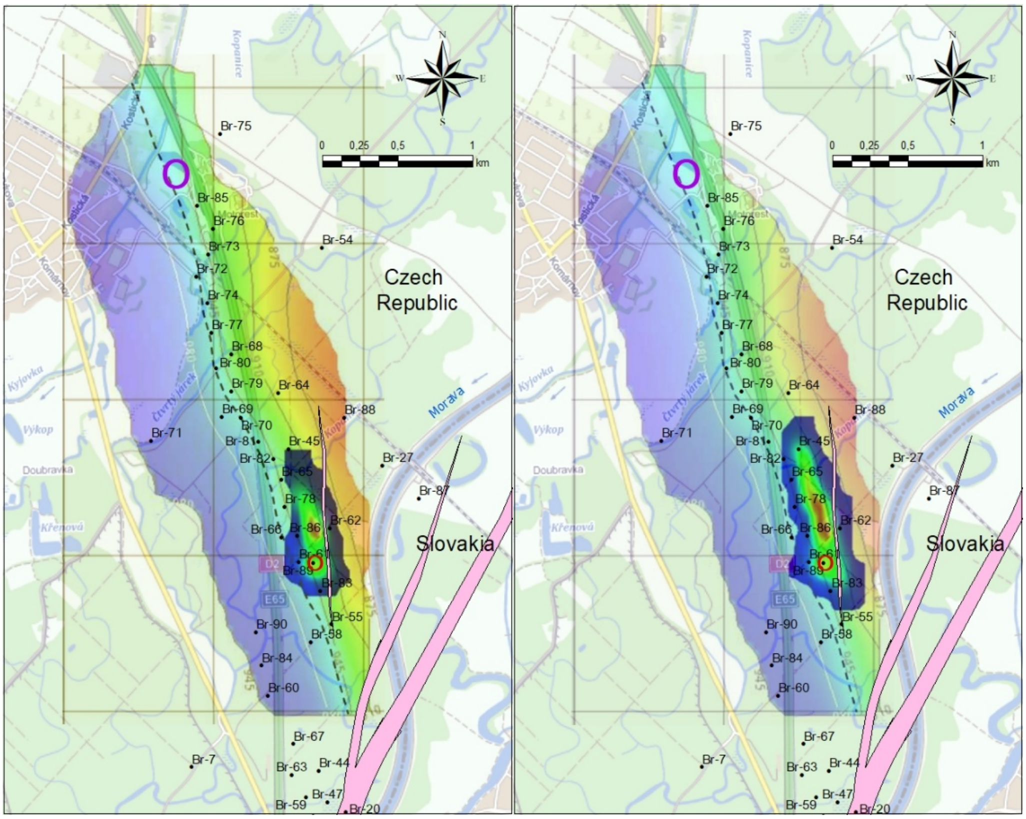

Fig. 5. Maps showing CO_2 plume extension for the base case storage pilot scenario after injection of 11,500 t in year 1 (left) and 23,000 t at the end of year 2 (right) of CO_2. Warmer (more reddish) colours indicate thicker plume and higher CO_2 concentration. Structural maps of the top of the Lab 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.

Fig. 5 and Fig. 6 show the modelled distribution of the CO_2 plume in the base case storage pilot scenario [6]. 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.

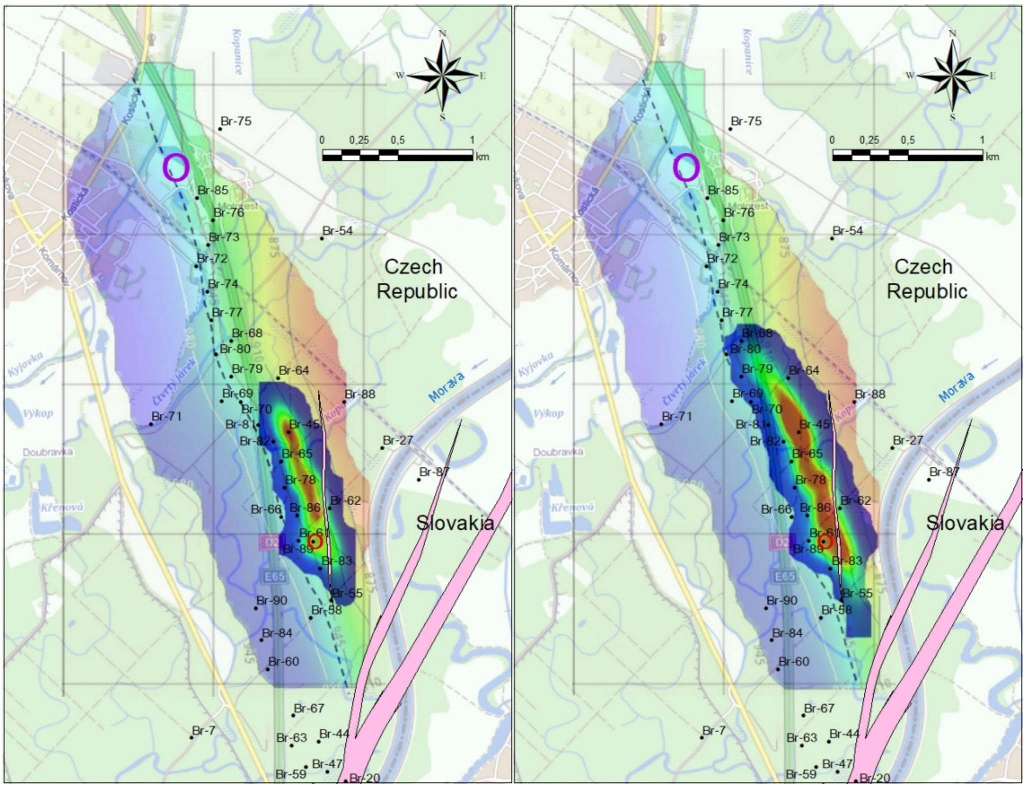

Fig. 6. Maps showing CO_2 plume extension for the base case storage pilot scenario after injection of 35,000 t at the end of year 3 (left) and 70,000 t after 6 years of injection (right) of CO_2. Warmer (more reddish) colours indicate thicker plume and higher CO_2 concentration. Structural maps of the 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.

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 Brodsky 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.

Fig. 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 Brodsky fault system in the south end of the reservoir where possible leakage through the fault plane cannot be excluded (see Chapter 5.2 for details).

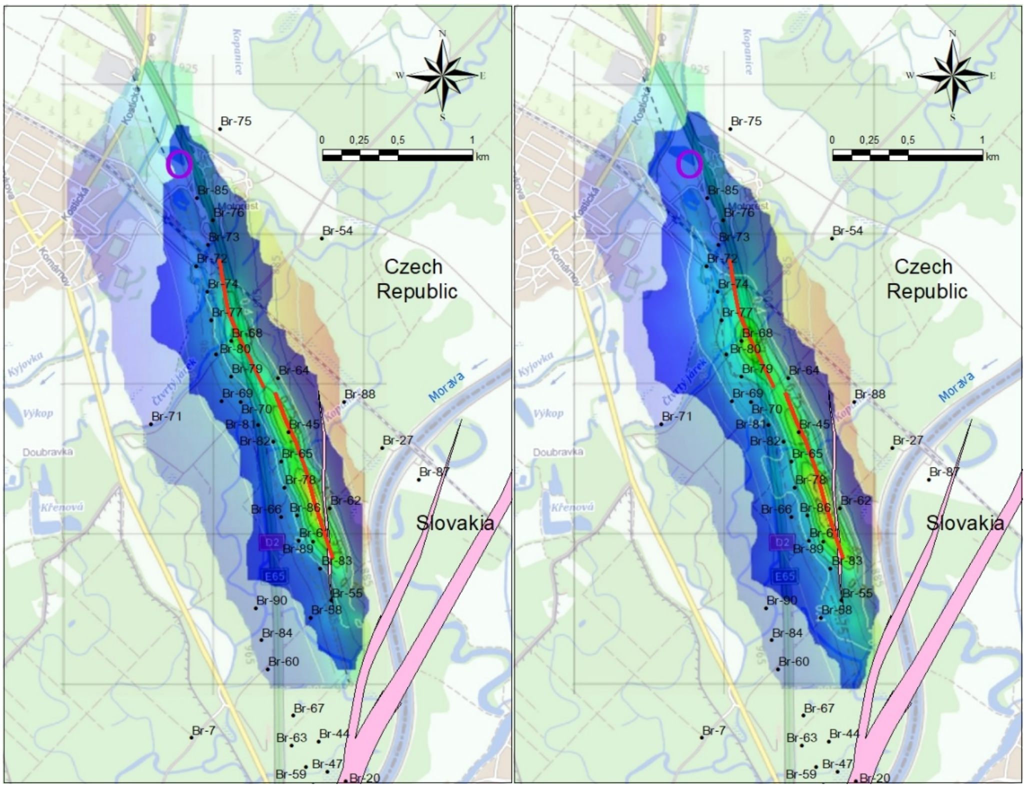

Fig. 7. Maps showing CO_2 plume extension for the "full-scale" storage scenario, following 6 years of moderate injection, after injection of 160,000 t at the end of year 7 (left) and 260,000 t at the end of year 8 (right) of CO_2. In this case, horizontal injectors were used (positions indicated by red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

As shown in Fig. 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.

Fig. 8 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 another part of the ENOS project [7] where various CO_2-EOR scenarios were simulated and co-optimization of enhanced oil recovery and CO_2 storage based on economic criteria (maximizing Net Present Value) was performed. 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 Fig. 8 and Fig. 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 Fig. 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.

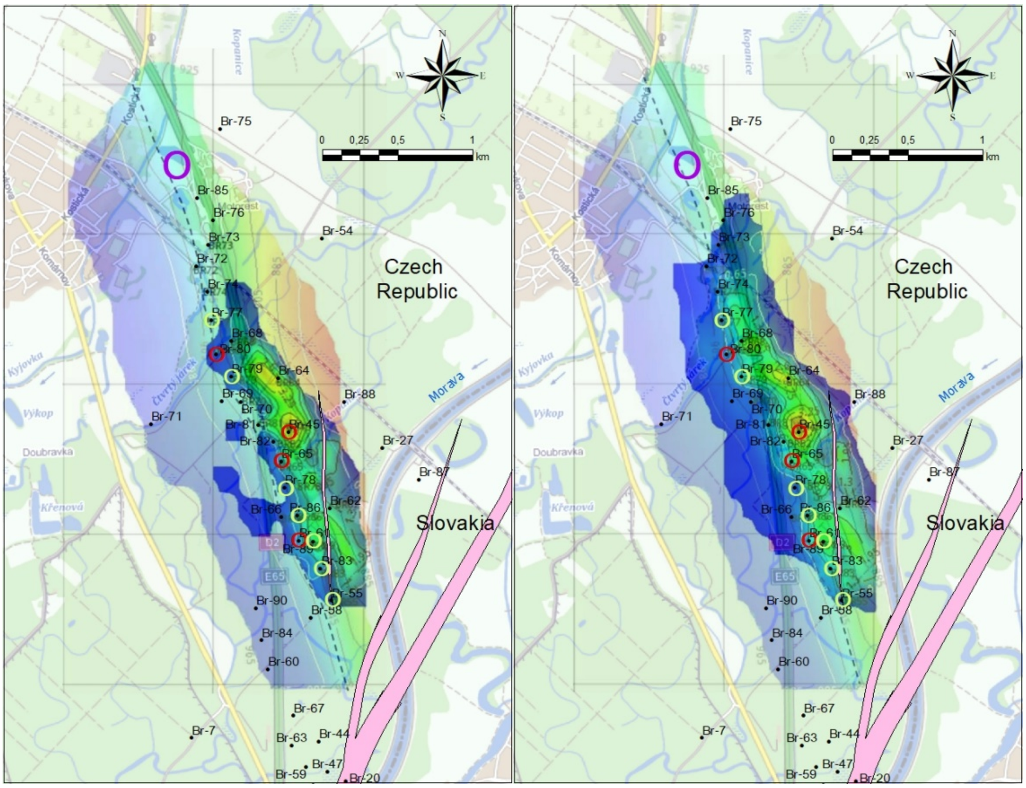

Fig. 8. Maps showing the CO_2 plume extension for the CO_2-EOR case after storing of 60,000 t (left) and 140,000 t (right) of CO_2. The red circles represent injectors, the yellow circles producers.

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 5.2 in detail.

From the trans-boundary 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 trans-boundary issues are thus not connected with the location of the storage complex itself but rather with other phenomena that are discussed in Chapter 5 below.

5. Possible trans-boundary issues

Four possible types of trans-boundary 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 did not appear to cause trans-boundary issues [8], the other two phenomena were identified to deserve serious consideration and are discussed below.

5.1. 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. When assessing the risk represented by abandoned wells at LBr-1, it needs to be considered that the majority of oil and gas exploration and production activities on the site 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. These facts underline the importance of careful assessment of the status of abandoned wells penetrating the planned CO_2 storage reservoir.

In total, 31 exploration and production wells were drilled on the LBr-1 area, 25 of which directly penetrate the reservoir horizon. All wells are currently abandoned. The dates of abandonment of the wells 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.

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 at LBr-1 were subject of a thorough assessment in the previous REPP-CO_2 and ENOS projects [9]. 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 Fig. 9.

Green circles in the map 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. Fig. 10 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. Only for 56 % of the wells the abandonment status is compliant with current regulation, 4 % have minor deficiencies and 40 % are showing more significant deficiencies, especially missing perforation plugging (12 %), insufficient length of plugs (20 %), or even a combination of these (8 %). 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.

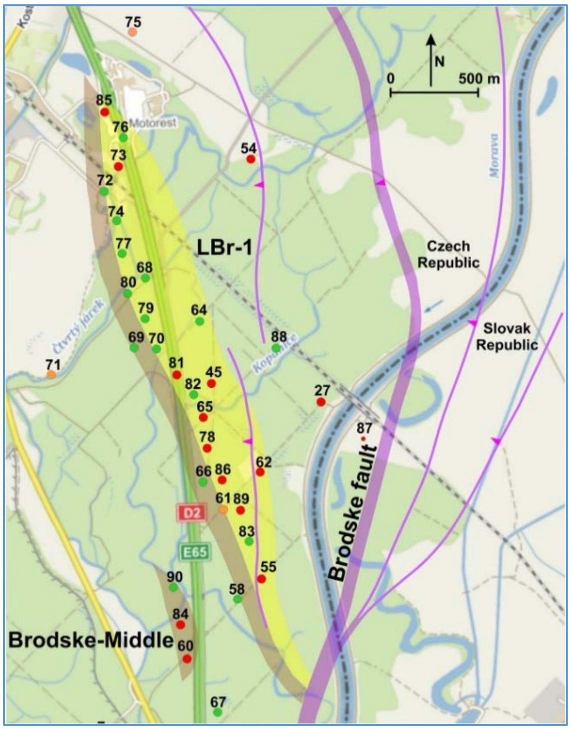

Fig. 9. “Traffic-light” map of wells at the LBr-1 site. Green circles indicate wells for which the current status of abandonment meets the requirement of valid legislation. Abandonment status of wells indicated by red circles does not meet these requirements. Orange circles indicate only marginal deviations 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.

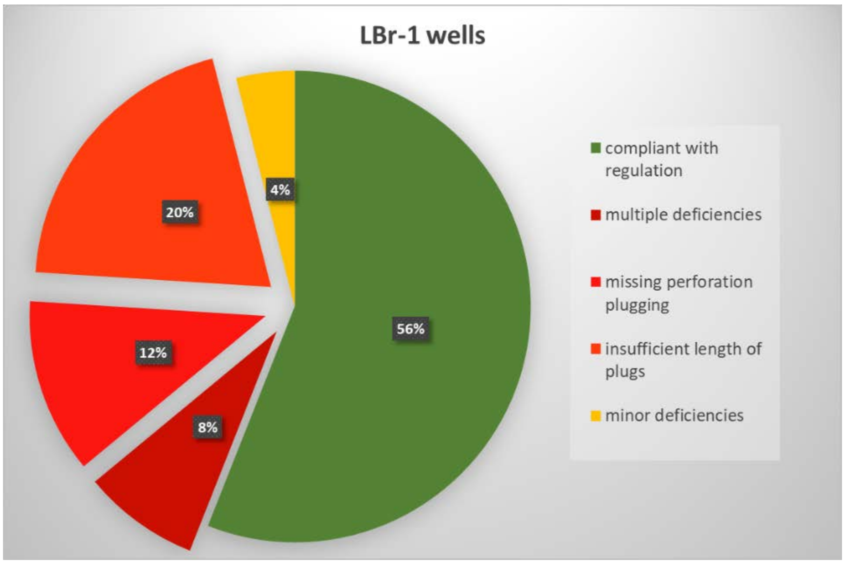

Fig. 10. Summary of well abandonment status for wells penetrating the LBr-1 reservoir.

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 Fig. 11. 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.

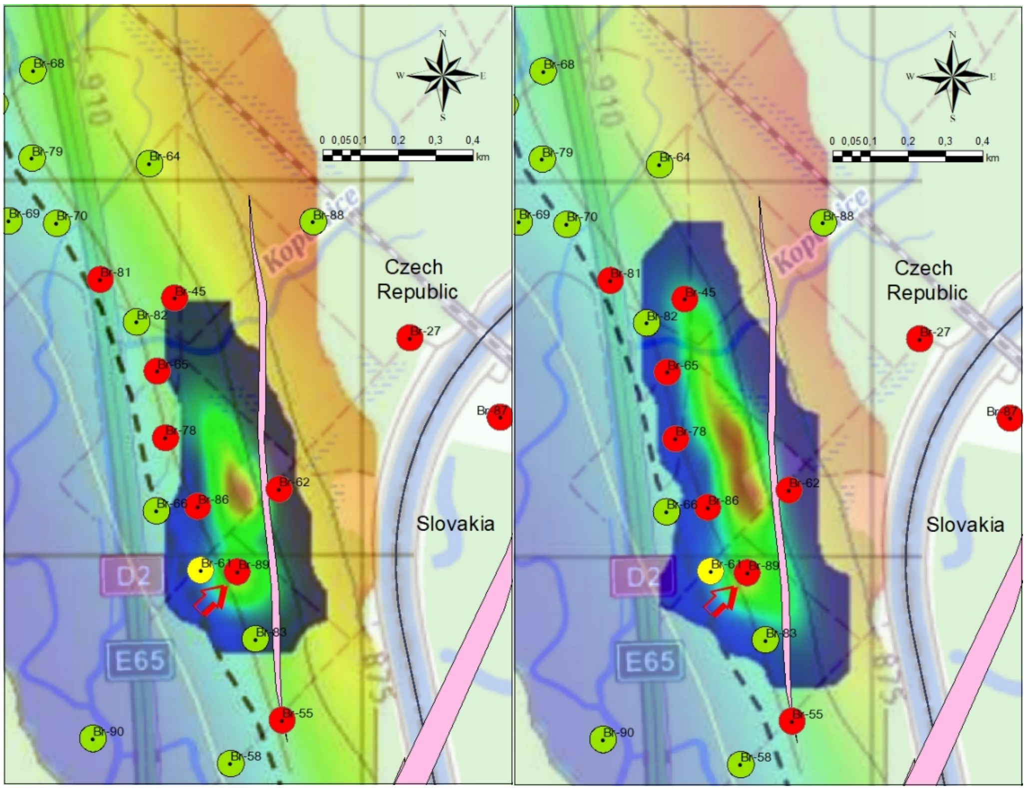

Fig. 11. Maps of LBr-1 showing the simulated extent of CO_2 plume in the basic pilot project scenario, superimposed on the "traffic-lights" map of the wells from Fig. 9. Left – plume extent after injection of 11,500 t CO_2; right – plume extent after injection of 23,000 t CO_2. Injection well (Br-89) is marked by red arrow.

The maps 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. In addition to 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 "heritage" of an eruption encountered during drilling. This is one of the reasons while the Br-62 well has been chosen for a further modelling study.

The map in Fig. 11 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.

Fig. 12 displays the current 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.

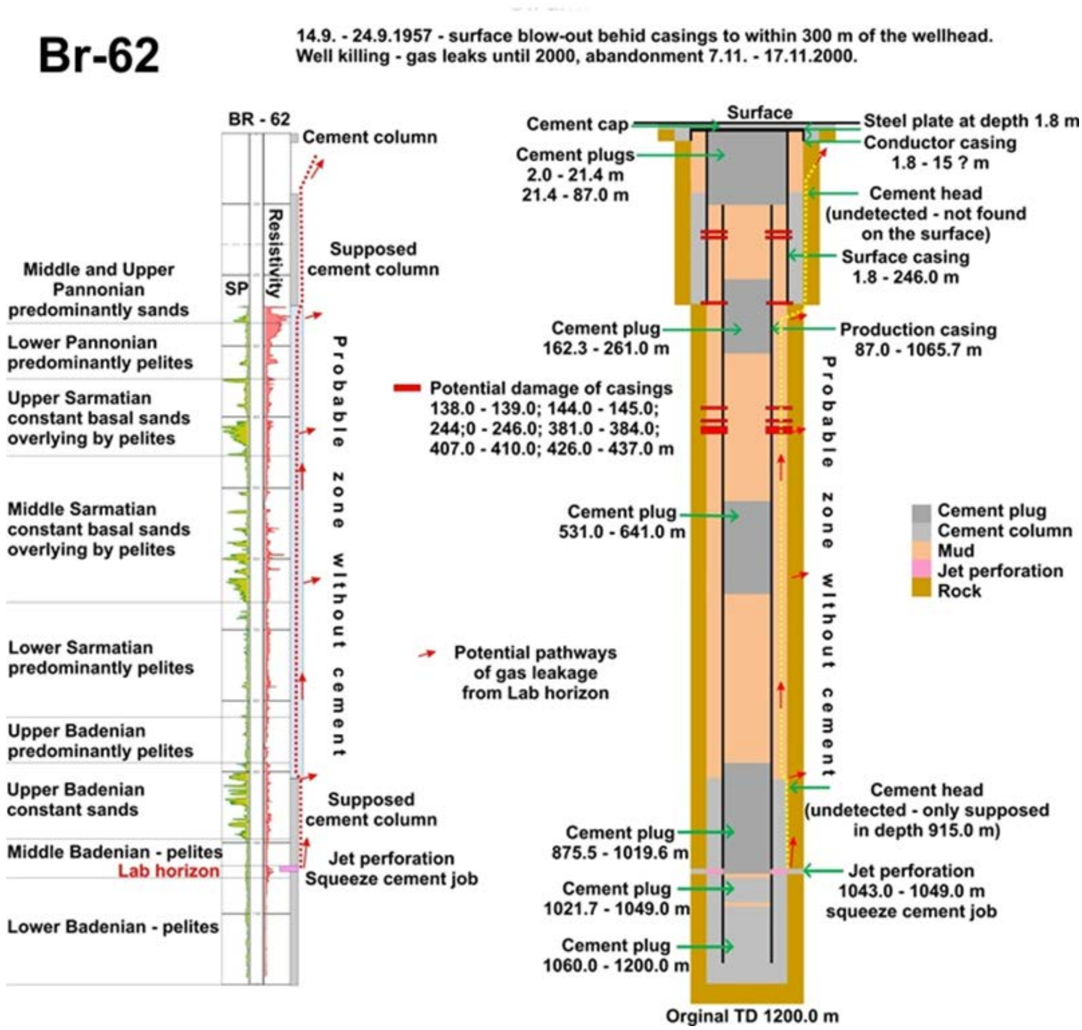

Fig. 12. Well design for Br-62 (right) and well logs with basic stratigraphy (left). Possible leakage pathways (red arrows) correspond to the situation when plugging and abandonment procedures did not result in isolation of the reservoir from other horizons and the surface. Probable zone without cement 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 Fig. 13. 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 Fig. 13) 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. 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.

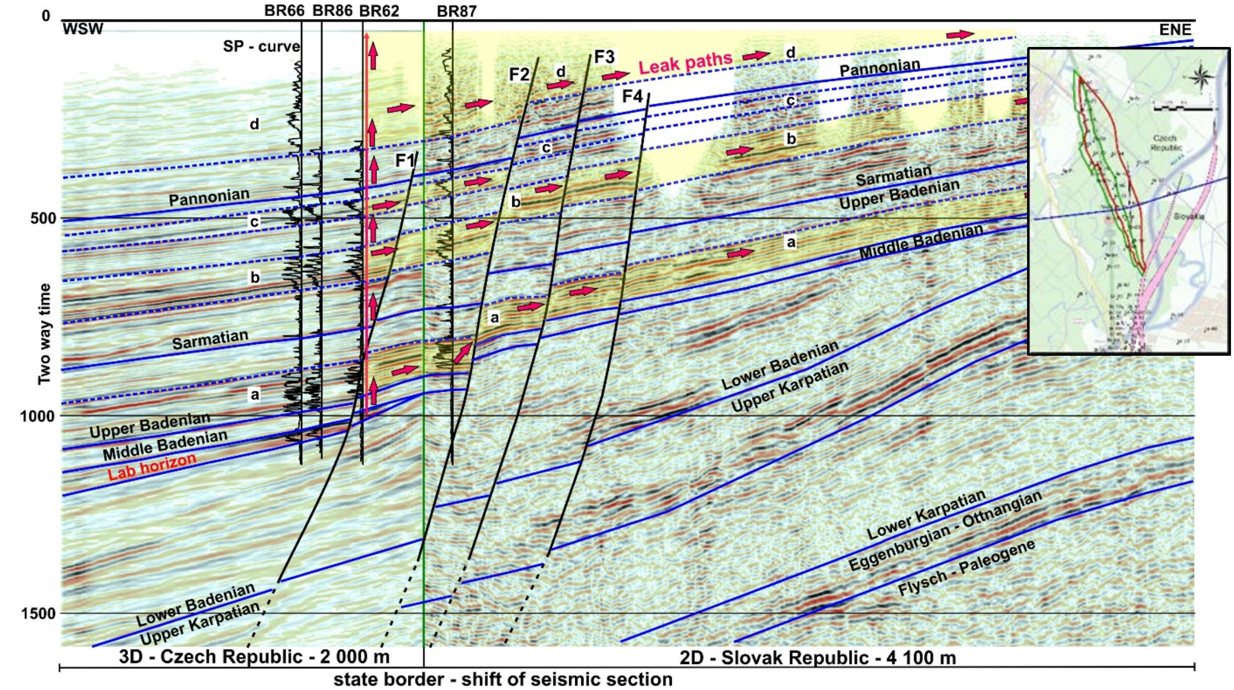

Fig. 13. Composite 3D–2D seismic section across LBr-1 in approximately WSW-ENE direction from the Czech Republic (left) towards the Slovak Republic (right) with indications of undesirable potential leakage pathways of CO_2 or hydrocarbons. Potential leakage pathways are marked by red arrows and yellowish sequence of sand layers: a – Upper Badenian, b, c – Sarmatian, d – Pannonian. F1, F2, F3 and F4 are faults of the Brodsky 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 and NAFTA 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.

Even though the simulated leakage rates for CO_2 leakage both through the cement plugs and through micro-annuli are low [9, 10], the performed analysis of possible leakage pathways clearly shows that CO_2 leakage through abandoned wells would in most cases have trans-boundary consequences because the leaked CO_2 would migrate into the territory of Slovakia. This would influence not only the corresponding monitoring requirements, but also the overall process of storage site preparation and permitting.

5.2. 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 Vienna Basin (Czech part) example 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, and also in the phase of field transition into a storage site, is whether the hydrocarbon trap is filled up to its capacity, i.e. up to the spill points. 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 original oil-water contact (OWC), which – according to the static 3D reservoir model – lies at the structural depth of -953 m. The field was 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. 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 of the field, i.e. OWC at -953 m and GOC at -943 m.

The analysis of the northern edge of the reservoir shows that if the CO_2 plume exceeds the northern spill point (position indicated in maps in Fig. 5-8), the gas would most probably (based on 3D seismic interpretation) migrate northwards into the area of the neighbouring Hrusky hydrocarbon field and end up in one of the stratigraphic (hydrocarbon-bearing) traps situated here. It can be, however, excluded, that this migration scenario has any trans-boundary effect [8].

The situation in the southern part of LBr-1 (Fig. 14) is more complicated. The upper part of the Lab horizon is obviously bound by the pinch-out boundary, which is sufficiently confirmed by well data. The lowermost horizon is, however, terminated here by the Brodske fault at least in its deeper, aquifer part. The fault plays here a significant structural role with its 200 m vertical movement. On the other side of the fault, 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 neighbouring Brodske-South field can be used as an example of the structural development. The Lab 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 by wells). 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 interpreted spill point. The results document inflow of fluids from various thin horizons in Lower Badenian.

This means that the Lower Badenian complex, even though predominantly pelitic, does not work as a sealing in some places. This needs to be taken into account when assessing possible fluid flow through the Brodske fault.

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 trans-boundary 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 Fig. 7). The basic CO_2 storage pilot scenario is excluded from this category.

6. Conclusions

The presented study evaluated possible trans-boundary 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 the Czech Republic, the identified barriers (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.

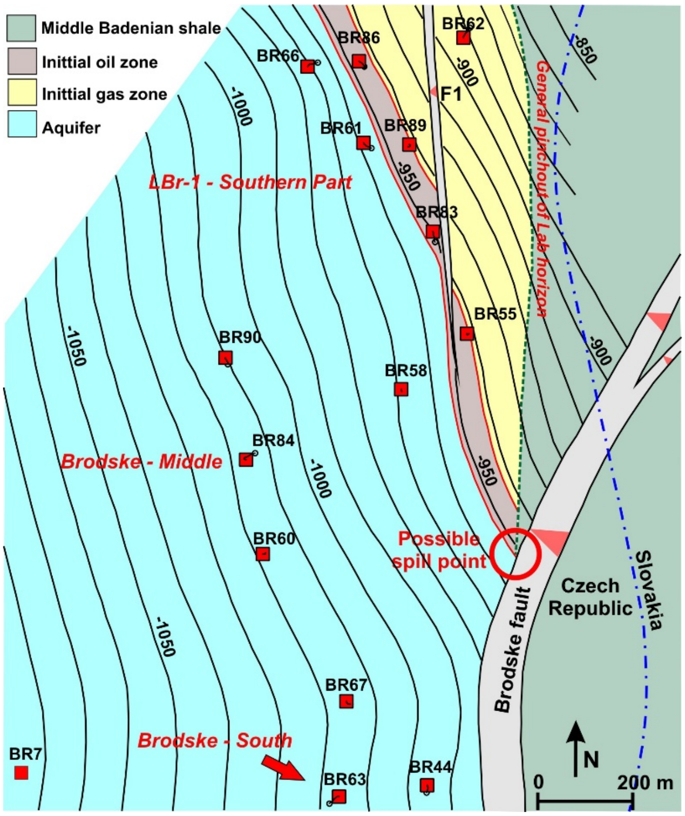

Fig. 14. Southern edge of LBr-1 - generalized structural contour map of the top of the lowermost L4 partial sand of the Lab horizon with faults, initial positions of the oil and gas zones, L4 pinch-out line and the interpreted position of the southern spill point

In the second step, implications of the current legislation and regulatory regimes on the LBr-1 site itself were studied. According to the currently valid regulations in Slovakia, the area adjacent to the LBr-1 site across the Czech-Slovak border does not belong to the part of Slovak territory where geological exploration for permanent carbon dioxide storage is enabled. This means that constructing and operating LBr-1 as a trans-boundary storage site is currently legally impossible, and even performance of possible additional site exploration on the Slovak side of the borderline would not be allowed.

Detailed analysis of the extent of the storage complex at LBr-1 revealed that the storage site and storage complex are located entirely on the territory of the Czech Republic. However, several trans-boundary 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 trans-boundary 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 trans-boundary 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 trans-boundary, 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.

Acknowledgements

The presented results were achieved within the REPP-CO_2 and ENOS projects. The REPP-CO_2 project was supported by a grant from Norway within the CZ08 Programme of Norway Grants 2009-2014. ENOS has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 653718. The results were prepared for publication within the CO_2-SPICER project that benefits from a € 2.32 mil. grant from Norway and Technology Agency of the Czech Republic.

MND a.s., Palivový kombinát Ústí, s.p. and NAFTA a.s. are gratefully acknowledged for provision of site data for the purposes of this study.

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