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Assessment of a mature hydrocarbon field in SE Czech Republic for a CO_2 storage pilot

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Abstract

Preparation and execution of a CO_2 storage pilot project is one of the first logical steps in the effort to kick-start CCS in the region of Central & Eastern Europe, utilizing onshore geological structures for permanent CO_2 storage. The main aims of this activity are to test the suitability of local geological structures and demonstrate the feasibility and safety of the technology to local stakeholders. The Czech-Norwegian CO2-SPICER project is an example of such developments. The target structure of CO2-SPICER – Zar−3 – is a hydrocarbon field situated in an erosional relict of fractured carbonates of Jurassic age on the SE slopes of the Bohemian Massif, covered by Paleogene deposits and Carpathian flysch nappes. The first stage of site assessment has been completed, and the article provides an overview of its results. Construction of a 3D geological model of the storage complex was the first important step on the route, preparing input for subsequent reservoir simulations of the field history and planned CO_2 injection. Reservoir assessment is also focusing on specific features of the fractured-vuggy reservoir and accounting for the effects associated with CO_2 injection, including geochemistry and geomechanics. Geochemical studies focus on fluid-rock interactions, and geomechanical ones on formation integrity and fracture mechanics under reservoir pressure build-up and cooling of the formation by injected CO_2. Risk assessment is another component of the project, aiming at identifying potential leakage pathways and assessing consequences for the area of interest. Preparatory work for the site monitoring plan includes applicability analysis of various monitoring methods, supported by execution of baseline monitoring of selected phenomena, in particular composition of soil gas, natural and induced seismicity and properties of shallow groundwater. The project also includes evaluation of advanced reservoir containment monitoring technologies including time-lapse pressure transient analysis. While the key actions are directed towards the piloting activities, the project also looks beyond to full-field implementation and potential to establish a regional CCS cluster.

Keywords: CO_2 storage; Czech Republic; hydrocarbon field; carbonates; 3D geological model; baseline monitoring; risk assessment; injection scenarios

1. Introduction

The region of Central & Eastern Europe, including the Czech Republic, is lagging behind other parts of Europe (especially countries surrounding the North Sea region) in development of CCS; hence, also the practical experience

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with CO_2 geological storage is limited. On the other hand, the recently confirmed EU decarbonisation goals and the rising prices of emission allowances have caused increased interest of industrial companies in the CCS technology as possible solution for handling their CO_2 emissions. These are the main reasons for the ongoing efforts to kick-start CCS in the region and prepare first CO_2 storage sites. A first logical step on this road is execution of a CO_2 storage pilot to test the suitability of local geological structures and demonstrate the feasibility and safety of the technology to local stakeholders. The Czech-Norwegian CO2-SPICER project, launched in 2020, is an example of such developments [1].

The target geological structure of CO2-SPICER project – Zar-3 – is a hydrocarbon field situated in an erosional relict of fractured carbonates of Jurassic age on the SE slopes of the Bohemian Massif, covered by Paleogene deposits and Carpathian flysch nappes (Fig. 1). The field was discovered in 2001 and is now in the final production phase. This relatively "young age" of the field, together with the ongoing hydrocarbon production provide many advantages. These include direct access to the reservoir, availability of field monitoring data, generally good condition of well completions, well-preserved core material and detailed reservoir description available. However, the geology of naturally fractured carbonates brings specific research challenges. The first stage of site assessment has been completed, and selected results are presented in the following chapters.

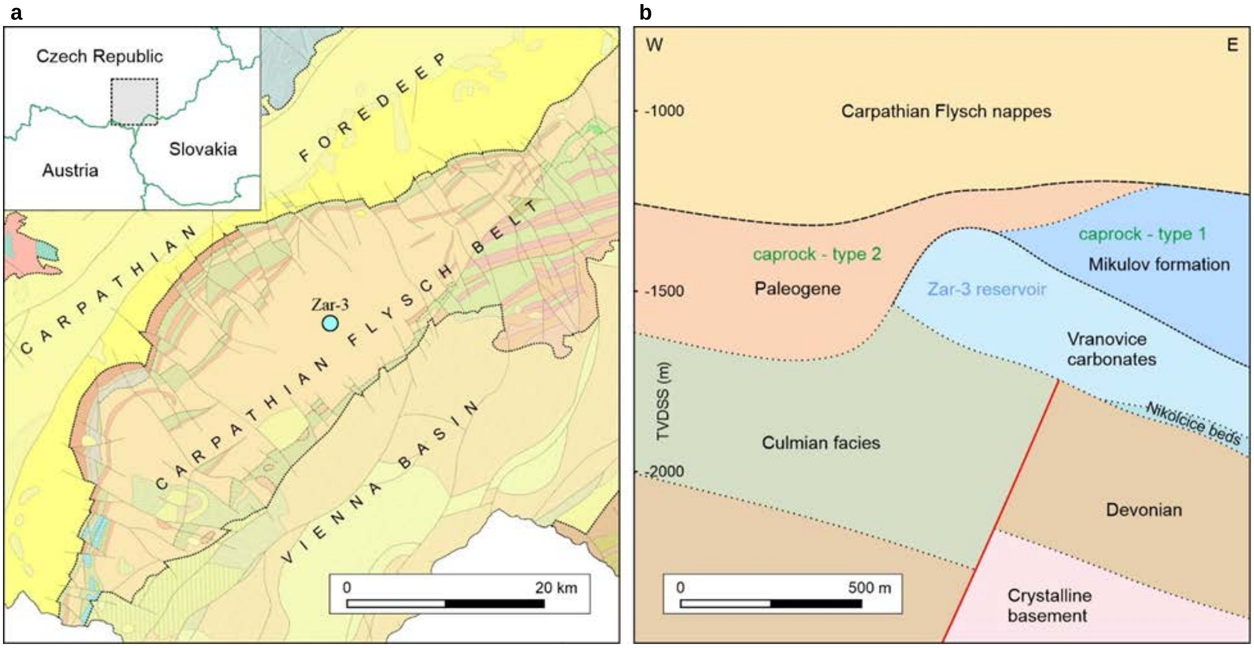

Fig. 1. (a) Location of the Zar-3 site on geological map of the SE part of Czech Republic. Source: CGS ArcGIS server map services (http://www.geology.cz/extranet/mapy/mapy-online/esri). (b) Schematic geological cross-section of W-E direction through the Zar-3 structure.

2. 3D geological model

Construction of a 3D geological model of the storage complex is the first important step on the route. A detailed well data analysis was done including well logs evaluation, correlation with core data and calibration of well data to seismic. Then regional and local seismic interpretations of key horizons using the most recent seismic data processing were done. Resulting time interpretation grids and surfaces were migrated to depth domain using several iterations of the velocity model. Finally, fault modelling and pillar gridding followed by construction of horizons and vertical layering were finished, resulting in first iteration of a geometrical geological model of the field (Fig. 2).

In the following step, petrophysical properties were calculated from the well logs results and core measurements. Resulting porosity and permeability values were upscaled to the wells within the area of interest. The 3D distribution for both key reservoir properties – porosity and permeability - was done in tens of iterations using different statistic parameters and finally two working results were chosen for tests of dynamic modelling (Fig. 3)

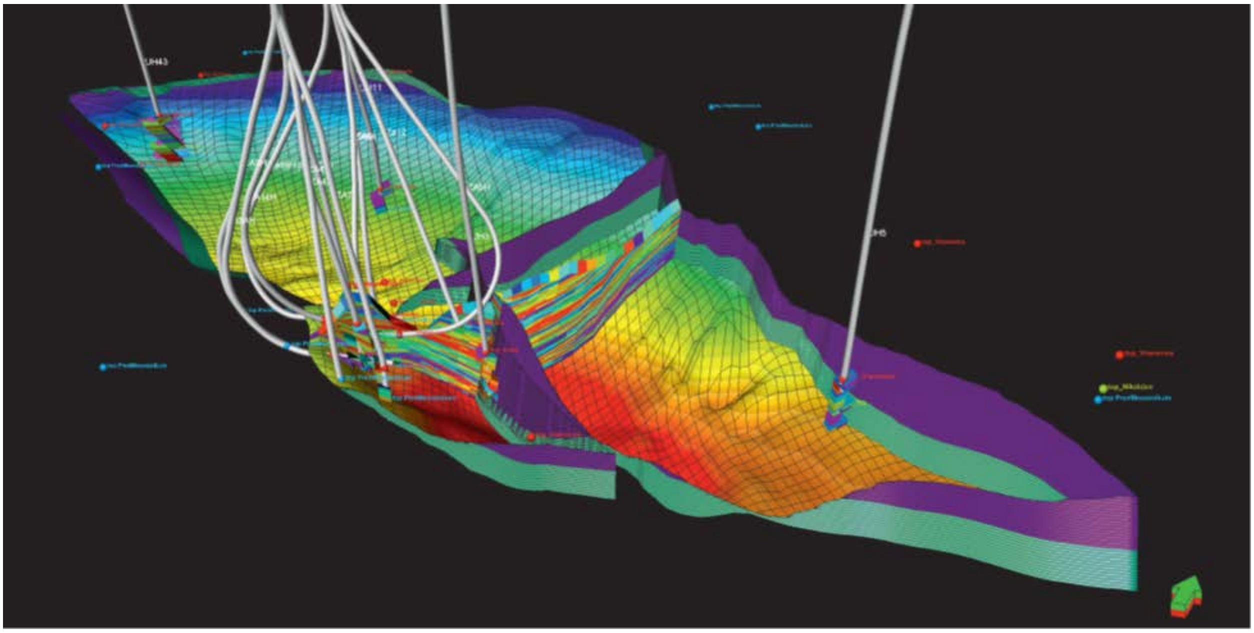

Fig. 2. 3D geological model of the Zar-3 storage complex.

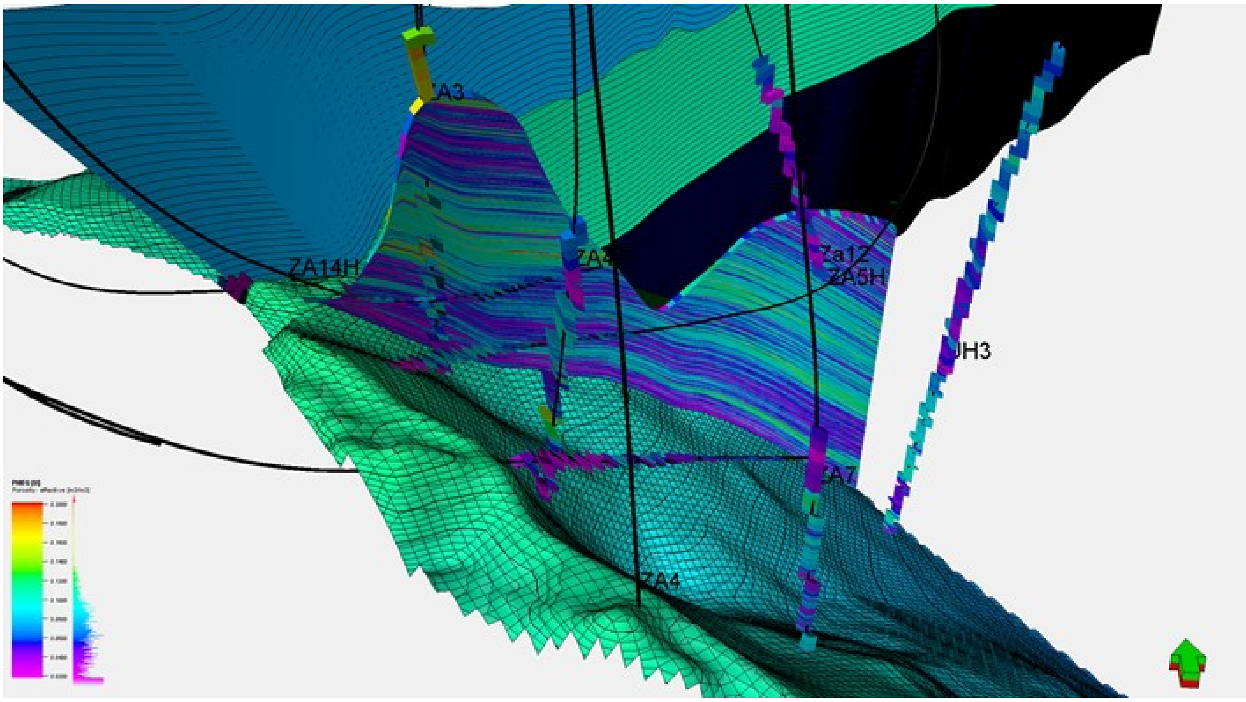

Fig. 3. Porosity distribution in the Zar-3 core reservoir body shown in a W-E oriented cross-section. (PHIE = porosity).

Reservoir assessment is also focusing on specific features of the fractured-vuggy reservoir and accounting for the effects associated with CO_2 injection, including geochemistry and geomechanics. Geochemical studies focus on fluid-rock interactions, and geomechanical ones on formation integrity and fracture mechanics under reservoir pressure build-up and cooling of the formation by injected CO_2. Specific well tests were designed in the project to evaluate well injectivity and hydraulic reservoir properties under pressure build-up caused by CO_2 injection to be carried out and interpreted within the project duration.

3. Geomechanical evaluations

Geomechanical evaluations were performed to ensure stability of the field and surrounding rocks during CO_2 injection. A database of field rock samples was assembled, and core samples of intact rock fragments have been acquired. Depending upon the size of intact core samples, and availability of the samples from the different relevant formations in the field, a test matrix was developed to determine elastic (stiffness) and plastic (strength) properties. All sampled experiments were described in a master table with well name, core-interval, depth, picture of the core, and main lithological description included. Rock samples were acquired from the seal (Paleogene, Lower Carboniferous, and Upper Jurassic Mikulov marls), and reservoir rocks (mainly carbonates /dolomites/ of Vranovice Fm. and partly clastics and dolomites of Nikolčice Fm.). In all, 66 core samples for mechanical experiments were available.

Key data on size, weight, density, porosity, Darcian and Klinkenberg permeabilities were acquired before the samples were exposed to ultrasonic sound velocity determination that were used to estimate dynamic Poisson's ratio and Young's modulus. The sound velocity determination is non-destructive, so each rock sample was further used in destructive rock-mechanical tests: Brazilian tests for tensile strength estimation, unconfined compressive strength (UCS) tests, and tri-axial tests for evaluating Mohr-Coulomb failure. This was done with pristine core material, and the material that was exposed to CO_2 at elevated pressure and temperature over time. Then, sound velocity was tested again to identify any stiffness changes.

Suitably sized samples were placed in a COREVAL 700 porosimeter and permeameter by Vinci technologies enabling porosity and permeability estimations (both Darcian and Klinkenberg, using nitrogen) at a range of hydrostatic stresses. Samples used here were hydrostatically loaded from zero to 31.7 MPa in five steps, and porosity and permeability were determined at each step. This enabled us to evaluate pore volume compressibility and how permeability changes with pore pressure (assuming the effective stress principle, i.e. equivalence of varying confining pressure and pore pressure in stress-strain determination). During injection of cold CO_2, the reservoir cools down, so thermal contraction leads to side stress relaxation (assuming uniaxial strain, i.e. the lateral size of the reservoir remains constant). Thermal expansion experiments were conducted at 20 and 100°C to quantify this effect.

All experimental data were collected in a database shared with the project partners, as one of the primary deliveries of the project. During the execution of the test programme, the database was continuously populated, and the results of the experiments will be used to complete the geomechanical analysis, and then for injection planning and risk assessments further in the project.

As an example, the experimental results on strength tests of unaltered, pristine core material from Vranovice carbonates (dolomites) reservoir rock from the ZA4A well are presented. Petrophysical properties of five samples are displayed in Table 1, together with Brazilian test results for tensile strength, unconfined compressive strength and triaxial tests.

Strengths obtained in triaxial and UCS tests were combined in Mohr circles (Fig. 4). The tangent to the two Mohr circles represents the failure line with parameters: cohesion 12.3 MPa, internal friction of 0.39, and angle 21.3°. The vertical orange line represents tensile strength.

When the failure envelope obtained from sample experiments is displayed together with principal effective stresses, stability may be evaluated. The in-situ field stresses are uncertain, as formation integrity tests and leak-off well tests have not been performed. Thus, estimates were required. Based on assumptions that the largest principal stress is vertical and given by the weight of the overburden rocks a value of $S_1 = \rho g h = 39.0$ MPa was obtained, using average overburden density of 2.3 gcm^{-3} and 1724 m depth.

Table 1. Mechanical tests of elastic stiffness and strength of Vranovice carbonates (dolomites) reservoir rocks in the depth interval 1722-1750 m below surface in well ZA4A. The effective failure stresses S1 and S3 of the triaxial and UCS tests were used to determine the Mohr-Coulomb failure envelope via the first and second invariants, p=(S1+2S3)/3 and q=S1-S3. The Brazilian tests were used to determine tensile strength. Porosity and Klinkenberg nitrogen permeability were determined by the permeameter. Poisson's ratio and Young's modulus were estimated from ultrasonic measurements of pressure and shear wave velocity.
* The three Brazilian samples were too small to be placed in the permeameter, although from sample size, dry weight and mineral density of 68 g/cm3, their porosity of 1.5, 6.0 and 2.3%, respectively, could be determined.

Test type	Sample	Lithology	Depth, m	Porosity, %	Perm., mD	Poisson ratio (dyn)	Youngs mod. (dyn), GPa	Failure stresses:	
								S1, MPa	S3, MPa
Triaxial	ZA4A c3_b3	Upper Jurassic Vranovice Dolomite	1750	3.8	12.9	0.38	10.5	51.0	7.0
Brazil	ZA4A c1_b3		1724	n.a. (*)		0.39	45.2	0.0	-2.55
						0.36	104.0	0.0	-1.91
						0.39	29.1	0.0	-1.97
UCS	ZA4A c1_b5		1722	1.30	0.93	0.44	22.6	36.0	0.0

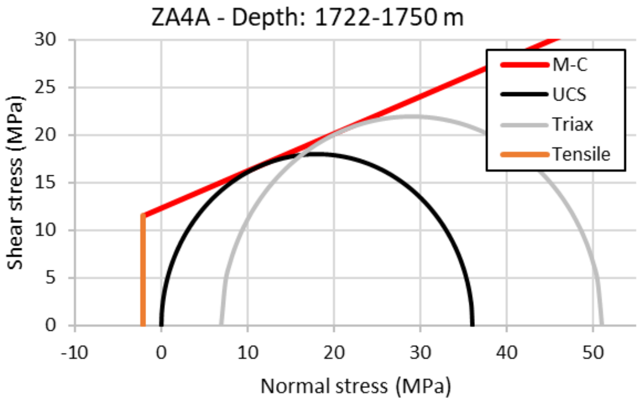

Fig. 4. Mohr-Coulomb failure line fitted to the tangent of the Mohr circles of UCS and triaxial test results

The principal stresses were estimated in three ways:

- Extrapolation of shallow field data to depths of 1724 m, measured in distant fields (see Figure 5a) provides: $S_1 = 42.2$ MPa, and $S_3 = 22.9$ MPa.
- Uni-axial strain assumption where the least effective stress is related to the weight: $S_3 = S_1\,\nu/(1-\nu) = 25.0$ MPa, where $\nu = 0.38$ is Poisson's ratio estimated from the dynamic sound velocity tests.
- Break-out analysis of in-situ stresses in boreholes, where wells are either with or without breakouts, in a normal faulting or strike-slip setting [2] provides: S1 of 39.0 MPa and S3 ranged within 22 to 33 MPa (giving rise two Mohr circles with minimum and maximum value of least principle stress).

Figure 5a displays the extrapolation of the stresses from the literature and the estimated stresses using two techniques described above to the field depth of 1.72 km. When plotting, all four obtained effective stress Mohr circles together with the Mohr-Coulomb failure envelope (Figure 5b) evaluated using pore pressure of 17 MPa (hydrostatic pressure) argue that no failure is expected for chosen pore pressure.

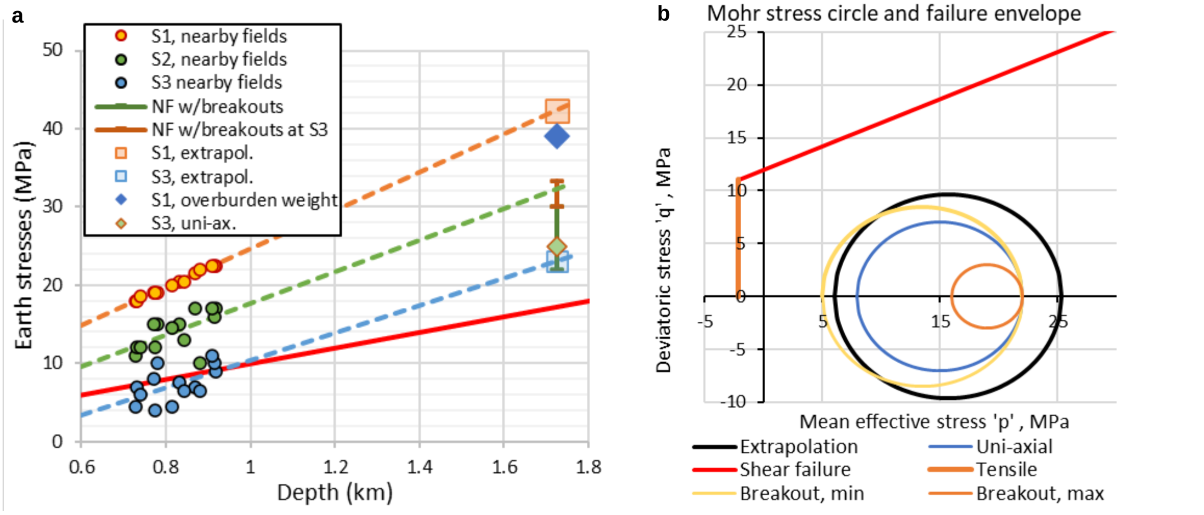

Fig. 5. (a) Earth stresses in field: Circles display measured field stresses from four fields (around 160 km away from the field in focus). Stresses extrapolated to 1.72 km depth from surface is displayed by squares. The blue diamond displays integrated weight of the overburden, while the green diamond displays side stress estimated via Poisson's ratio ($\nu = 0.38$) and uni-axial strain assumption. The brown and green vertical lines represent output of the analysis performed based on the method suggested by Zoback et al. [2]. (b) Mohr Coulomb failure line and tensile strength (red and brown lines), compared with four Mohr circles of effective stresses with pore pressure of 17 MPa, based on breakout-analysis, uniaxial strain assumption and extrapolation.

Survival bias in the sampling, i.e. that only the strongest core samples survived coring and handling, suggest that both stiffness and strength estimates may over-estimate the field scale data. Further, porosity and permeability of the samples are low compared to field values reported. We argue the importance of performing well tests to reduce the uncertainty prior pilot injection. At the current stage, the uncertainty will be used further in scenario simulations planned in the project.

4. Risk assessment

Risk assessment is another important component of the project, aiming at identifying potential leakage pathways and assessing consequences for the area of interest. Leakage scenarios have a particular focus on abandoned wellbores, while also covering caprock integrity and fault reactivation. The risk of leakage from abandoned wells is performed as a well-specific quantitative assessment, where design and well barriers of each well are accounted for, in addition to its proximity to various risk receptors. Reference well cases have been established based on collected field data, for which leakage simulations have been performed to be used as a baseline for assessments of effects and exposure.

The initial key task was to identify data requirements necessary for subsequent analyses of risk and defining the boundaries for the assessment, both in terms of scope as well as geographical boundaries, i.e. an area of interest. An initial kick-off meeting was held early in the project to outline the risk assessment requirements and desired results, and define what data would be relevant to that end. This included geographical maps of the area of interest, geological information including the 3D geological model of the reservoir and well data. The abandoned wells are of particular interest, and data on location of these wells, along with well-logs, well reports and plug and abandonment (P&A) schematics were studied in detail. The main purpose of this data collection at an early screening stage was to establish where leakage could likely occur, who or what would likely be affected, and in what way.

While assessments of caprock integrity and flow potential along faults rely heavily on the geological modelling, and thus are contingent on the progression of this work, emphasis was initially placed on establishing an appropriate model for leakage from abandoned wellbores. An adapted version of a framework and software tool developed by

NORCE for risk assessment of plugged and abandoned oil & gas wells [3, 4] was selected for this purpose. Focusing on CO_2 instead of hydrocarbon gases, the tool combined well-specific P&A barrier properties, geological data and fluid properties to create a leakage risk assessment per well. Adapting a Monte Carlo approach, the tool allowed for incorporating uncertainties in both well integrity and underlying models and propagate these uncertainties to the resulting leakage rate assessments. While there are multiple possible ways in which P&A barrier systems may fail and result in a leak, this analysis focused only on the forming of microannulus as a migration path through the wellbore. Other assumptions and simplifications were also necessary for modelling purposes. Preliminary simulations of leakage potential from all abandoned wellbores located within the area of interest allowed for an outset risk ranking, and a reasonable idea of most likely location of a leak and its possible magnitude. This was in turn used as a basis for assessing how leaked substance (CO_2 or CH_4) would disperse from its initial location.

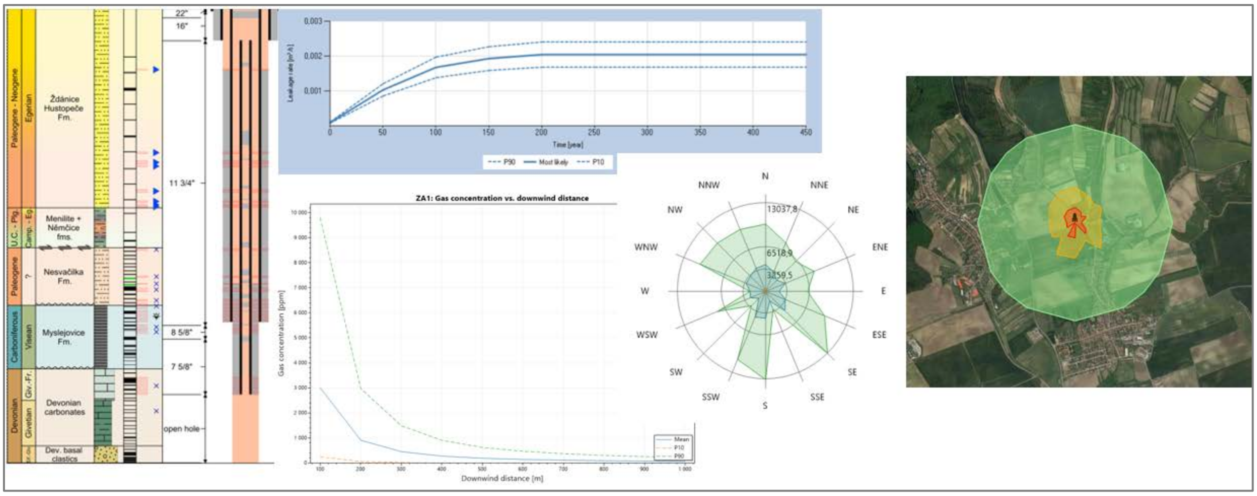

Fig.6: Examples of source data used for assessment of risk of leakage from abandoned wellbores, here showing lithology and plug & abandonment schematic, and examples of simulated results, such as potential leakage rates vs time, released gas concentration vs distance from release point, wind direction map and risk level gas concentration at possible release locations.

Figure 6 is only a conceptual schematic and is for illustration only, but it does show at a general level the use of well barrier data, leakage rate simulations over time, possible dispersion of released gas, and how this could possibly be risked when superimposed on a map originating at the wellbore location.
Once finalized, these simulations, together with assessments of caprock integrity and fault leakage potential, will form the basis for determining overall risk for humans, environment and infrastructure, which in turn will inform overall decisions concerning site storage integrity. This could include preventive and mitigating measures as well as operating parameters or monitoring measures.

5. Monitoring

Preparatory work for the site monitoring plan included an applicability analysis of various monitoring methods, supported by execution of baseline monitoring of selected phenomena, in particular soil gas composition, natural and induced seismicity, and properties of shallow groundwater.

The atmogeochemical monitoring is carried out in two ways – periodically and continuously. The former is performed three times a year using the Ecoprobe-5^{TM} portable instrument based on 95 monitoring points (Fig. 7). Contents of methane, total petroleum, carbon dioxide and oxygen in soil gas is evaluated. The latter is based on five permanent IGS probes (manufactured by Sapienza University of Rome) deployed to enable continuous monitoring of CO_2 content in soil gas. The main aim of the continuous monitoring is to detect trends of seasonal variations in greater detail.

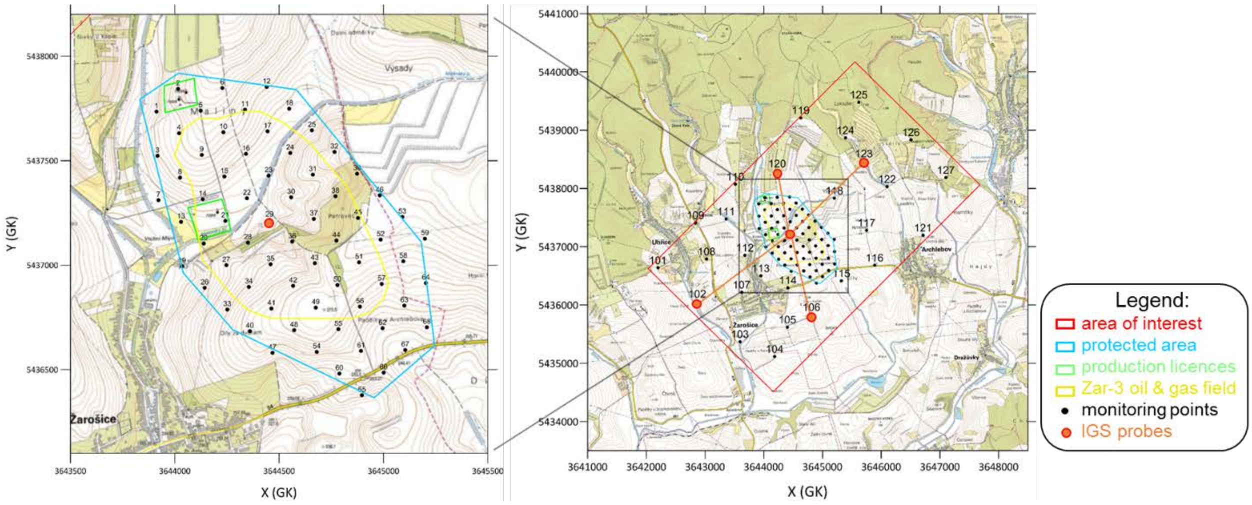

Fig.7. Atmogeochemical monitoring network at Zar-3 composed of 95 monitoring points. Left: 68 points in a grid of 150x150 m directly above the Zar-3 field; right: the broader area of interest with locations of the 27 additional monitoring points and the positions of permanent IGS probes for continuous CO_2 monitoring.

The periodical monitoring indicates that the CO_2 content in soil gas varies widely depending on the season of the year (Fig. 8, Tab. 2). This is mainly related to the vegetation growth and land use. The average content of CO_2 in soil gas was nearly 1.5 $\%_{vol.}$ during the spring campaign (June 2021), rising to 2.5 $\%_{vol.}$ in the summer-autumn season (September 2021), but dropped significantly to 0.4 $\%_{vol.}$ in winter (February 2022). The highest content of CO_2 in soil gas was measured during the summer-autumn campaign on the grasslands (19 monitoring points; average CO_2 content 3.20 $\%_{vol.}$), followed by groves (7 monitoring points; average CO_2 content 2.35 $\%_{vol.}$) and cultivated fields (69 monitoring points; average CO_2 content 2.24 $\%_{vol.}$). The CO_2 content variations between the spring and summer-autumn campaigns are significant (average value 110% higher in summer-autumn) on cultivated fields, but shows relatively stable values on grasslands (18% higher) and in groves (12% higher). However, the soil CO_2 content was surprisingly low and concentrated in a narrow interval (0.35 – 0.48 $\%_{vol}$) regardless of the land use in winter (Tab. 2, Fig. 8 right).

Table 2: The CO_2 content ($\%_{vol.}$) in soil gas during the different season of 2021 and 2022. Range of measured values is given in numerator (number of monitoring points in parenthesis); mean values (averages) in denominator.

Campaign / Land use	Spring June 2021	Summer-autumn September 2021	Winter February 2022
All monitoring points (regardless of land use)	0.07 – 9.09 (95) / 1.51	0.06 – 9.67 (95) / 2.47	0.07 – 2.33 (95) / 0.38
Cultivated fields	0.07 – 6.14 (69) / 1.07	0.06 – 9.67 (69) / 2.24	0.07 – 2.33 (69) / 0.35
Grassland	0.08 – 9.09 (19) / 2.70	0.26 – 6.93 (19) / 3.20	0.09 – 0.85 (19) / 0.44
Groves (forests)	0.50 – 3.69 (7) / 2.10	0.46 – 5.00 (7) / 2.35	0.07 – 1.29 (7) / 0.48

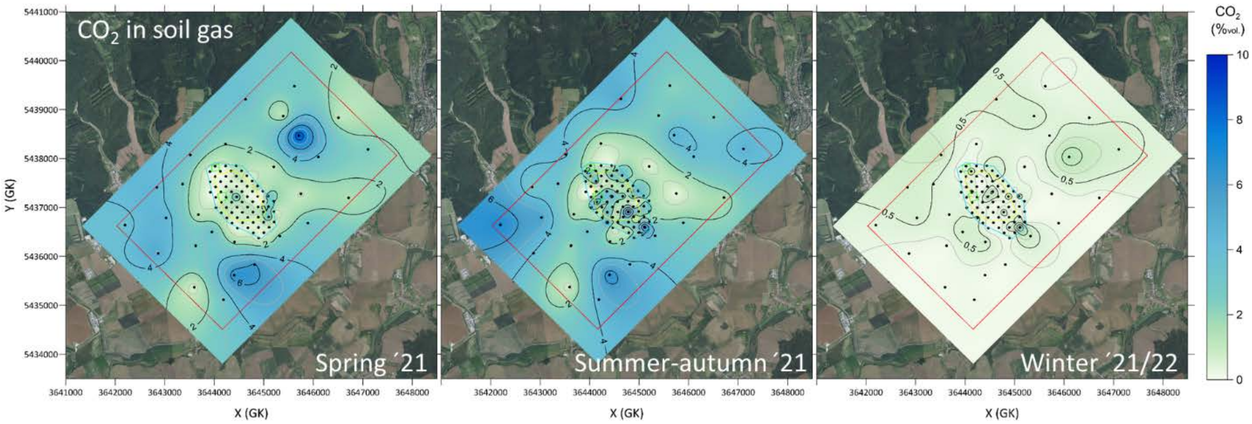

Fig. 8. Average CO_2 content in soil gas (in $\%_{vol.}$) during different monitoring campaigns – seasons of the year. The highest values were measured during the summer-autumn season due to the vegetation growth (middle). The lowest CO_2 content, regardless of the land use, was measured in winter season (right).

The continuous monitoring of CO_2 content in soil gas using the permanent probes confirms the strong variations depending on the season of the year, mainly caused by the vegetation growth – the CO_2 summer maximum, autumn decrease, winter minimum and spring increase are clearly visible (Fig. 9). High values of CO_2 content in soil gas of up to 9 $\%_{vol.}$ were measured in one of the monitoring sites for several weeks in summer 2021. This was higher than maximum values of up to $6\%_{vol.}$ measured in summer 2022. As the monitoring probe is permanently located in the same place, the difference between summer of 2021 and 2022 must be related to weather conditions and vegetation fitness. Differences between the values measured by individual probes are mainly caused by different soil properties, water table level and vegetation in situ. All the probes are placed in grasslands.

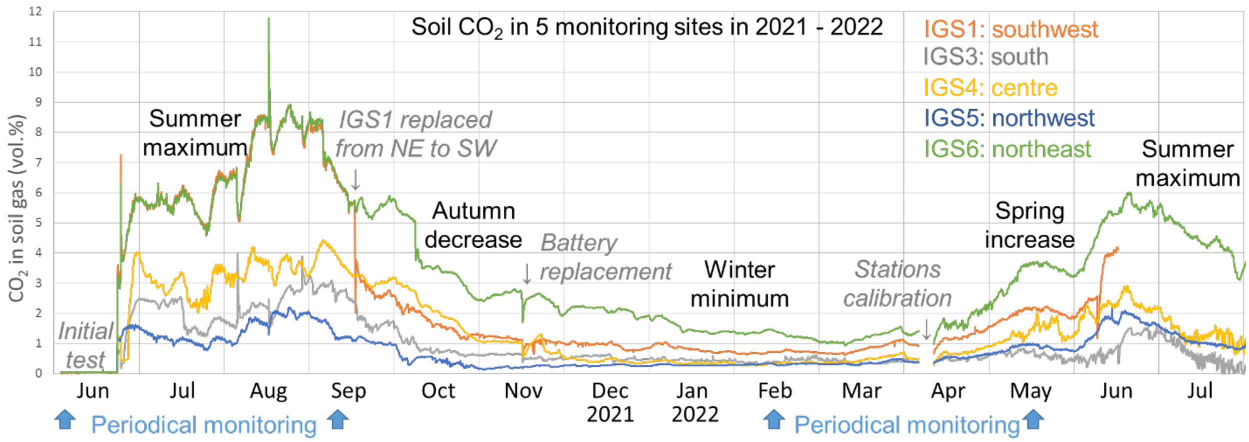

Fig. 9. Variations of CO_2 content in soil gas measured by 5 permanent monitoring stations (IGS, Sapienza University of Rome). The maximum contents were measured in summer seasons related to the vegetation activity. A strong decrease in CO_2 content was observed in the autumn, while the lowest values were measured in winter.

The project also includes evaluation of advanced reservoir containment monitoring technologies including time-lapse pressure transient analysis progressed in the ENOS project [5]. The evaluation consists of deployment of pressure gauges in observation and active wells, including permanent downhole gauges (PDG), to test capabilities of the technology for the specific conditions of the field, followed by design of the permanent well monitoring system.

The evaluation addresses capabilities of such systems for real-time monitoring of well performance in combination with reservoir containment. Based on the geomechanical evaluations and the risk assessment described above, a possibility to detect and monitor potential leakage (e.g. via abandoned wells) will be studied on the reservoir model. The study will further use simulated pressure responses in gauges, located in different wells at different depths (downhole and wellhead) to evaluate capabilities of the well monitoring system in combination with consideration of costs and technical limitations associated with deployment of such monitoring system.

6. Site development scenarios

While the key actions are directed towards the piloting activities, the project also looks beyond to full-field implementation and potential to establish a regional CCS cluster. The reservoir simulations will be combined with a regional evaluation tool developed in the Strategy CCUS project [6] to evaluate the capture and storage potential of the region.

The site development scenarios will be created for short (pilot + field implementation) and long (regional) term developments. The short term scenario has two possibilities – either to pair the field with a small-scale emitter and consider the two as a stand-alone cluster or look into Zar-3 as a crystallization point for regional CCUS development with pilot transitioning into a part of a large cluster offering long-term solution for several emitters with several storage sites.

In the first short-term scenario we will pair the Zar-3 field with a matching (CO_2 volume-wise) emitter like a potential blue hydrogen production facility, glass factory located in the vicinity or direct air capture facility. The site is then expected to hold at least 10 years of emissions.

In the second short-term scenario emissions will come from larger scale facility like cement or energy production (CHP, WtE). The pilot will confirm the feasibility of the CCS in the area and will then connect various emitters shown in Fig. 10 on the left with available storage sites, shown in Fig. 10 on the right.

Following the methodology developed in Strategy CCUS project [7] we will perform a value chain analysis of potential southeastern cluster in Czech Republic using the same method and baseline data as done for the Strategy CCUS project. Therefore, the scenario will be directly comparable with other 8 promising regions analyzed in Strategy CCUS.

7. Conclusions

Results of the first stage of CO2-SPICER – a Czech-Norwegian research project aiming at preparation of the first CO_2 storage pilot in the Czech Republic – have not revealed any significant obstacles for using the investigated Zar-3 structure for CO_2 storage purposes. As expected, the complex geological settings of the area and the storage site geology, especially the fractured and vuggy carbonates as reservoir rocks, proved to be challenging. However, the related uncertainties, i.e. in distribution of reservoir properties, are manageable and can be handled in future stages of the work. In general, the work has brought additional knowledge in the area of CO_2 storage in carbonates that is very different from the more often used clastic reservoirs.

The extensive geomechanical and geochemical assessments provided sufficient information for evaluation of possible geomechanical and geochemical effects on storage complex behaviour during and after CO_2 injection. The study also identified remaining uncertainties associated with the reservoir assessment, e.g. the in-situ stress field, and additional field surveys such as well tests have been suggested to reduce these uncertainties. Main hazards related to CO_2 injection on the site were identified within the risk assessment part of the project and work is ongoing to characterise individual hazards in detail, including possible exposure and effects. Main focus is on possible leakage pathways related to abandoned wells. On-site baseline monitoring using selected techniques has provided valuable results for future precise specification of site monitoring methodology in the prepared site monitoring plan. For example, the atmogeochemical monitoring combining extensive seasonal campaigns of repeated surveys with deployment of permanent monitoring stations brought a good understanding of seasonal variations in CO_2 soil gas content, as well as of the influence of land use types on measured values.

The site development scenarios, currently under preparation, will look beyond the pilot-scale injection scenario, to full-field implementation and potential to establish a regional CCS cluster.

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