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First field example of remediation of unwanted migration from a natural CO_2 reservoir: the Bečej field, Serbia

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Abstract

The Bečej field, discovered in 1951 by the Petroleum Industry of Serbia (NIS), is one of the largest natural CO_2 fields in Europe. Uncontrolled migration of CO_2 out of the main reservoir, leading to subsurface seepage and surface leakage, was caused by the Bč-5 well blowout in 1968. Remediation measures were deployed in 2007 to reduce and prevent further leakage of CO_2 from the Bečej natural CO_2 field. To the best of our knowledge, this is the first field application of remediation measures deployed to remedy leakage from a natural CO_2 reservoir – a natural analogue for an engineered geological storage site. Experiences and lessons learned from the Bečej field case are studied within the MiReCOL project (Mitigation and Remediation of CO_2 Leakage). The project aims at developing a handbook of corrective measures, which can be considered in the event of significant irregularities and leakage from a CO_2 storage site. We performed a comprehensive geological characterization of the Bečej field and interpreted the most recently collected monitoring data to assess the effectiveness of the remediation measures taken in 2007. A static model was constructed that comprises the main CO_2 reservoir (Upper Cretaceous and Badennian) and several aquifers in the overburden (Pontian and Pliocene). Eight small hydrocarbon reservoirs are defined above the main CO_2 pool at depths ranging from 450 to 900 m, suggesting that the Bečej CO_2 field is a natural leaking system. The monitoring data indicate that the remediation measures were effective and have practically stopped the decline of reservoir pressure.

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Keywords: CO_2 *storage;* CO_2 *leakage; leakage remediation; leakage mitigation; Bečej* CO_2 *field.*

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1. Introduction

The Bečej field is located in the southeastern part of Pannonian basin, in the northern part of Serbia, partly below the city of Bečej (Fig. 1). It is one of the largest natural CO_2 fields in Europe. The field was discovered in 1951 by the Petroleum Industry of Serbia (NIS).

Fig. 1. Location of Bečej CO_2 field

A blowout occurred on 10 November 1968 during drilling of well Bc-5[1]. Uncontrolled leakage lasted 209 days, till 6 June 1969, when the borehole collapse killed the well [1]. Vertical gas migration from the main CO_2 pool into the overlying aquifers in the overburden however continued. The gas migration was closely monitored because of the populated area in the vicinity, and the use of confined aquifers and the uppermost unconfined aquifer for water supply. The monitoring network comprised: (i) more than 30 wells with depths in the range of 10 to 300 m, within a radius of 1000 m around well Bc-5, and (ii) 2 deep wells (Bc-X-1 and Bc-X-2) for formation pressure measurements at depths from 740 to 850 m.

In the next 39 years after the well accident, the reservoir pressure was steadily declining at a rate of about 1 bar/year despite the fact that CO_2 was not produced until after 1986 and the volumes of CO_2 produced since 1986 were small (~$35x10^6$ m^3/year). Analyses of the production and pressure monitoring data clearly indicated that the drop of formation pressure could largely be attributed to the vertical migration of CO_2 in the collapsed well. The estimated amount of gas that migrated from the main CO_2 pool into the shallow aquifers in the overburden was possibly ten times higher than the volume of CO_2 produced from the main reservoir. This led to the conclusion that the problem of unwanted gas migration could not be solved by conventional well treatment or workover techniques. In order to control and stop the CO_2 migration, a series of activities were undertaken by NIS that finally led to remediation operations in 2007 [2,3].

Experiences and lessons learned from the Bečej field case are currently studied within the MiReCOL project (Mitigation and Remediation of CO_2 Leakage). The project aims at developing a handbook of corrective measures, which can be considered in the event of significant irregularities and leakage from a CO_2 storage site. The Bečej field case is particularly interesting and relevant because it represents, to the best of our knowledge, the first field

[1] Names of Bečej wells will be written as “Bc” instead of “Bč”.

application of remediation measures deployed to remedy leakage from a natural CO_2 reservoir - a natural analogue for a large-scale engineered geological CO_2 storage site.

The objective of our work was to perform a comprehensive geological characterization of the Bečej field and construct an accurate static Petrel model of the reservoir and the overburden. The static model is a starting point for further research on CO_2 mitigation and remediation actions applied to the Bečej field. Further, we describe remediation of the well leak and present the most recently collected monitoring data, which show that the remediation measures taken in 2007 were successful.

2. Geological overview of the Bečej CO_2 field

2.1. Geological setting and stratigraphy

The geological structure of the Bečej field is complex [4]. The main CO_2 pool is formed in the massive heterogeneous reservoir of Upper Cretaceous flysch and Badennian sand and limestone deposits. The reservoir is situated along a regional fault zone, and its structure was formed by a felsic igneous rock intrusion. This intrusion has, according to the current hypothesis, become a source of carbon-dioxide through the processes of metamorphism.

The following stratigraphic units are determined (in order from youngest to oldest; Fig. 2):

- Quaternary and Pliocene (Q + Pl).
- Pontian (M_3^2) Upper Miocene.
- Badennian (M_2^1) Middle Miocene.
- Upper Cretaceous (K_2).
- Felsic igneous rock of undefined Paleozoic age.

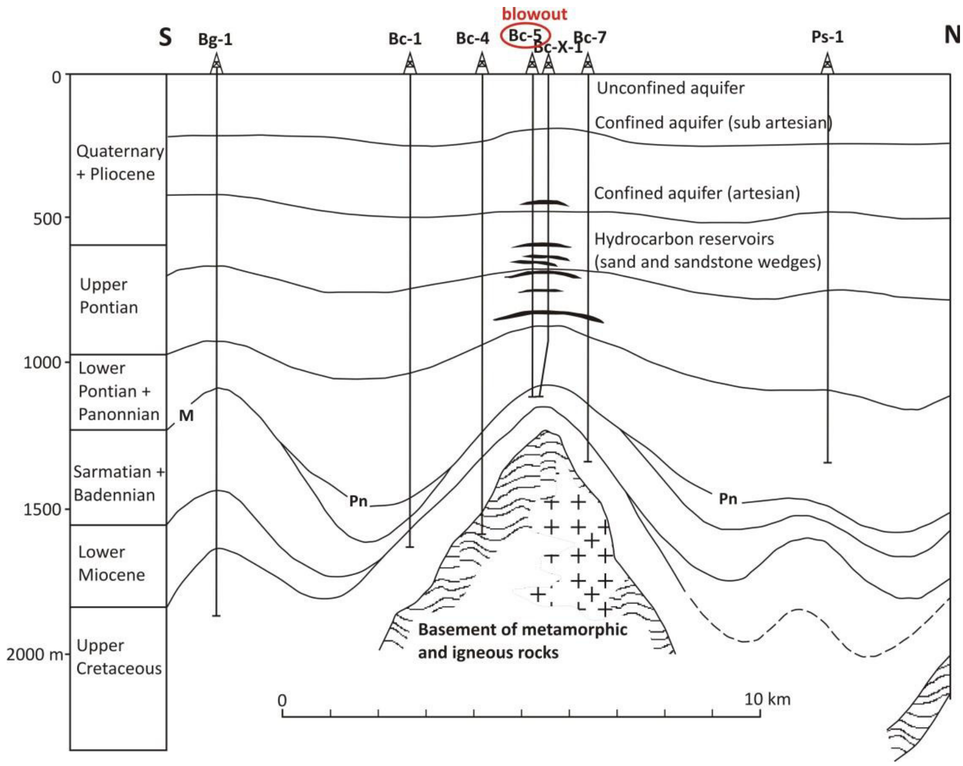

Fig. 2. South-north regional geological cross-section of the Bečej field (Bačko Gradište-Bečej-Banatsko Petrovo Selo) [5].

2.2. Reservoir

The Upper Cretaceous (K_2) siltstones, marlstones and very fine grained sandstones form the lower part of the reservoir. These sediments transgressively overlay the basement of metamorphic and igneous rocks of the Paleozoic age.

The upper part of the reservoir consists of different shallow marine facies of the Badennian age such as fine- to medium-grained sandstones composed of mineral, rare rock or organic detritus with calcite cement and organic limestone.

The uppermost part of the reservoir is represented by a very thin sandstone layer whose stratigraphic affiliation was not determined due to lack of petrological-stratigraphic analysis. According to the genesis it is assumed that those are the shallow clastic beach sediments.

The top of the main Badennian CO_2 reservoir is at a depth of about 1100 m TVD. The initial reservoir pressure was 151 bar and the reservoir temperature is 87 °C.

2.3. Overburden

The overburden comprises multiple shale and sandy layers acting as seals, semi-permeable layers and saline and fresh water aquifers. Accumulations of methane are occasionally found in the shallow overburden when drilling water wells, as was the case before and after the 1968 Bečej well incident.

Sediments above the reservoir consist of marlstones, clayey and marly sandstones and clays of Lower Pontian age deposited in caspi-brackish conditions. These 300m-thick sediments unconformably cover Badennian sediments. During the Upper Pontian caspi-brackish depositional environment gradually changed into lacustrine. The sediments of Upper Pontian are represented by poorly cemented sandstones alternating with clayey sandstones and marlstones in the lower part of the unit, while sands and clays dominate in the upper part. The occurrences of laminae of coal and coaly clays are very frequent.

Over the course of the Pliocene and Quaternary the depositional environment changed from lacustrine to lacustrine-fluvial, fluvial and aeolian environments. During these periods layers of alternating sands, clays and their varieties were deposited.

The Upper Pontian and Pliocene sandstones and sands have great significance as very porous and permeable rocks saturated with hydrocarbon gasses and geothermal groundwater. To explore small reservoirs of methane several wells were drilled giving positive results, but all the wells were abandoned after detection of increased content of CO_2 in gas composition. In the municipality of Bečej, the accumulations of gases were registered during exploration in layers above the main CO_2 reservoir even before the 1968 well incident. On the basis of seismic interpretation, a total of eight small hydrocarbon reservoirs are defined at depths ranging from 450 to 900 m.

Beside hydrocarbon reservoirs, an important mineral resource is geothermal groundwater since the history of using thermal waters in Bečej is long. All the geothermal wells are artesian flowing wells because they are tapping confined aquifers saturated with water and gas, dominantly methane. Water from aquifers at a depth of 400 m has a temperature of 35 °C and it has been used for drinking and bathing in Bečej spa more than hundred years. The deep wells provide waters of 60 to 65 °C for space heating of the hotel and sport center in Bečej.

2.4. Structural setting

The Bečej field is confined within a four-way dip closure on top of a regional fault zone. The structure was formed by a felsic igneous rock intrusion, which generated hydrocarbons and CO_2 in the processes of metamorphism. The basement and the overlying sediments are intersected by a few generations of faults and fractures extending near to, or up to, ground surface level. The presence of faults and fractures, and several accumulations of methane and possibly CO_2 in the shallow overburden, suggest that the Bečej CO_2 field is a naturally leaking CO_2 system.

During the Paleogene, Upper Cretaceous flysch deposits were exposed to subaerial erosion processes. The Bečej horst structure was shaped by strong extension during the early Miocene. The position of faults, characteristics and areal distribution were determined on the basis of seismic interpretation.

During the Badennian transgression, basal rudaceous sediments were deposited in the peripheral parts of the structure. During slow deepening of the basin, organic limestones carbonate reef complexes were deposited covering the whole structure except in the southern part.

In the Sarmatian and Pannonian sedimentation ceased due to marine regression and was continued in the Lower Pontian when the progradational clastic deposition was active in the broader area.

The older faults, created in the early Miocene, were reactivated during the late Pliocene and early Quaternary compressional tectonic phase of Pannonian basin evolution [6]. During this phase of tectonic evolution, next to reactivation of existing faults, new faults and fractures were formed which cut across the Pontian, Pliocene and Quaternary sedimentary complex.

3. Static model

3.1. Available data

Available data from different sources are used to construct a static model of the Bečej field. The static model contains a reservoir model of the main CO_2 pool within the Badennian and the most important aquifers in the overburden of the Pontian and Pliocene.

Input data available for modelling included: twenty seven interpreted 2D seismic profiles, well logging data from 18 wells, petrophysical interpretation of well logging data, data from cores and cuttings, and well test results.

3.2. Structural modelling

Seismic horizons interpreted on 2D profiles comprise the top of the main Badennian reservoir, top of the sandstone formations of Pontian age and the aquifers of Pliocene age.

Synthetic seismograms were derived from well Bcj-2, located in the southern part of the field, which had an appropriate suite of well logs for synthetic modelling. Unfortunately, neither check-shot velocity survey nor vertical seismic profiling were acquired from the wells on the Bečej CO_2 field. Therefore we used a synthetic seismogram from a check-shot velocity survey from well Bg-3 located in the area of Bačko Gradište (Fig.2) about 11.5 km away from Bcj-2. The Bg-3 synthetic seismogram gave a better match with the seismic data compared to the Bcj-2 seismogram; hence, the Bg-3 check-shot velocity data were used for time-depth conversion of the interpreted seismic horizons.

Detailed well correlation was carried out. A key well for correlation is Bcj-1, as it has the most complete suite of well logs and laboratory measurements, and intersects all the interpreted horizons. Seismic interpretation of horizons and depth markers picked from ten wells that penetrate the main Badennian reservoir were used to create the structural contour map of the reservoir top at 50-m resolution (Fig. 3a). Kriging method was applied for surface interpolation. Thicknesses of the stratigraphic intervals derived from well data were used to create structural surfaces of major aquifers in the overburden (Fig. 3b).

Fault data from seismic interpretation combined with mapped fault polygons from previous studies were used to construct 3 major faults. The faults were incorporated into the model as zigzags. The structural surfaces were adjusted taking into account those faults.

At the final stage of structural modelling, a 3D reservoir simulation grid of the main Badennian reservoir was created. Grid resolution is 100 x 100 m with an average grid block thickness of 1 m.

3.3. Reservoir properties

The petrophysical interpretation of well logging measurements is performed to derive the rock properties for the main Badennian reservoir and the aquifers in the overburden. The key properties derived are the net thickness, shaliness, porosity, permeability and water saturation.

Two lithotypes are differentiated from the well data: clay and reservoir rock. The vertical proportion curve is determined to characterize the correlation between the two lithologies and their distribution pattern. The lithological model of the reservoir is then populated by two lithotypes using the sequential indicator simulation method, while preserving the trend of the vertical proportion curve. The range of porosity values is from 12 to 26 % and permeability values from 2 to 50 mD.

The spatial distribution of porosity and permeability are modelled using the sequential Gaussian simulation algorithm. The co-kriging was used with porosity as a secondary variable to maintain the porosity-permeability relation. The gas-water contact within the Badennian and partially in the Cretaceous is assumed at a depth of 1225 m TVD.

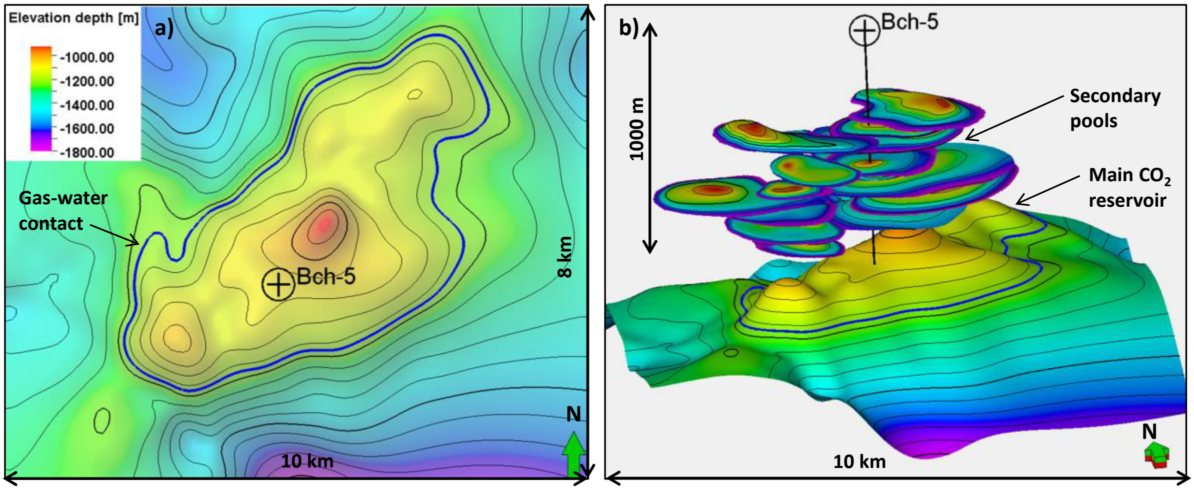

Fig. 3. a) Top of the main Badennian CO_2 reservoir and b) and secondary pools formed in the shallow aquifers incorporated in the structural model.

4. Remediation measures

The remediation measures were deployed by NIS in 2007 in an attempt to slow down or stop the leak of CO_2 from the Bečej natural CO_2 field. Here we briefly describe the remediation measures that were partially published earlier [2,3,7]. The evidence for continuous leak of CO_2 from the main pool since the 1968 well accident was a continuous drop in formation pressure in the main CO_2 reservoir, and the elevated pressures and concentrations of CO_2 in the aquifers above the main pool. Increased concentrations of CO_2 measured in wells Bcj-1 and Bcj-2 are attributed to the uncontrolled migration of CO_2 into the overburden after the well blowout (Table 1). The presence of methane is however unrelated to the well incident as accumulations of methane are commonly found above the main CO_2 reservoir before the well incident.

Table 1. Measured concentrations of methane and carbon-dioxide in the overburden before the remediation in 2007.

Well	Year of measurement	Sampling depth (*m*)	CH_4 (*mol %*)	CO_2 (*mol %*)
Bcj-1	1996	893-911	15.1	79.8
Bcj-2	2002	658-672	44.4	51.3

The remediation strategy adopted to counter the CO_2 leak comprised drilling a new well (Bc-9) to reach the bottom of the collapsed well Bc-5 and inject a gel-forming material to plug the leakage pathway in situ (Fig. 4). Directional well Bc-9 was drilled in 2006 and completed with minor kicks and fluid loss. The well penetrates the upper section of the main CO_2 reservoir, and its liner casing is completely cemented and perforated in the interval of

1131 to 1133 m. The bottom of Bc-9 is believed to be 11 m away from the bottom of the collapsed well Bc-5 (Fig. 5).

Another directional well Bc-X-1, which was drilled as a part of remediation activities already in 1969 but not used, served as observation well and back-up injection well. The bottom of Bc-X-1 is believed to be within a 15 m distance from the bottom of Bc-5 (Fig. 5).

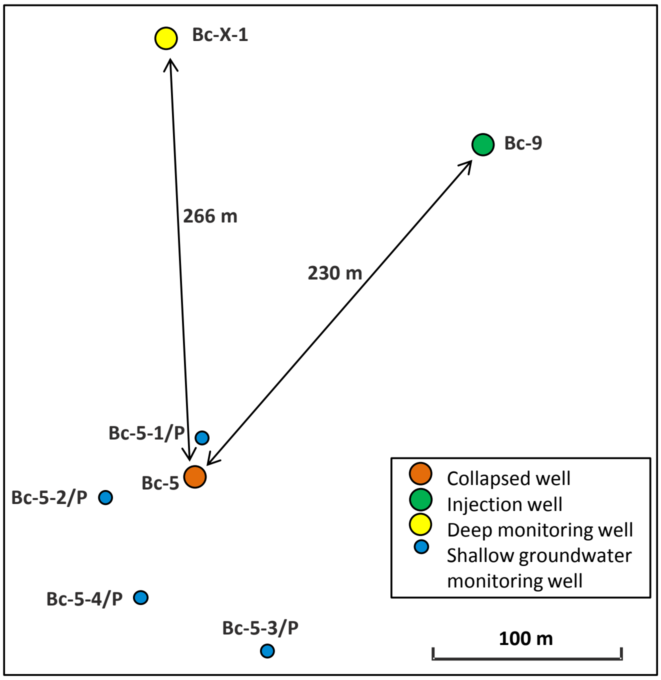

Fig. 4. Position of wells used for remediation and monitoring of the collapsed well Bc-5.

The remediation was performed by NIS in 2007 in two phases: the preparatory phase and the main treatment.

The preparatory phase included the injectivity test, acidizing job and flush treatment to clean the well. During this phase 150 m^3 of water was injected.

The main treatment included the injection of 1700 m^3 of environmentally-friendly chemicals in well Bc-9. The treatment was designed in such a way that it could be repeated if not successful the first time. Injection lasted one month and consisted of the following steps:

- injection of pure silicate solution to fill the collapsed zone of well Bc-5;
- injection of silicate solution containing polymer and urea that cause polymerization of silicates, coagulate and gel forming a solid void-filling material;
- injection of polymer-silicate solution containing urea and formaldehyde;
- alternating injection of polymer-silicate solution and cross-linking solution;
- injection of 2000 m^3 of water to flush the chemicals off the bottom-hole.

A moderate increase of pressure and the inflow of fluid that were observed in the monitoring well Bc-X-1 from the early phase of operations, were the first signs that the damaged well Bc-5 and the bottom of the well Bc-X-1 were filled up with the chemicals injected through well Bc-9.

The long-term monitoring program over the subsequent years comprised groundwater quality monitoring and formation pressure measurements.

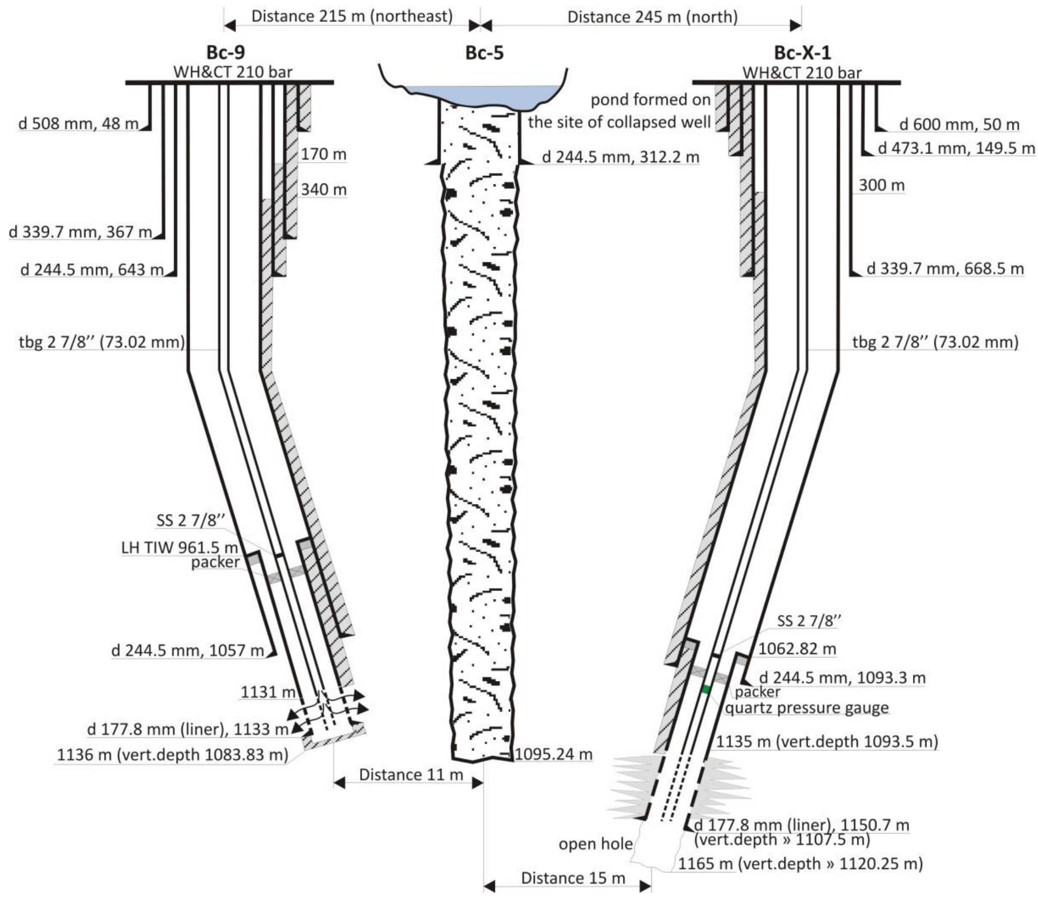

Fig. 5. Designs of injection well Bc-9, monitoring well Bc-X-1 and collapsed well Bc-5.

5. Monitoring the effects of remediation

Monitoring of groundwater quality started in 2006, one year before the remediation operations, to establish baseline conditions. Four shallow wells were drilled in the vicinity of the collapsed well Bc-5 to sample groundwater to a depth of 60 m (Fig. 4). The monitoring lasted for six years (2006-2012) and the sampling frequency was one sample per month. The parameters that were measured in water include CO_2 concentration, pH, carbonate and bicarbonate content, hardness, dry residue and potassium permanganate.

During the six years of monitoring, the measured concentrations of CO_2 in three wells did not exceed values of a few tens of mg/l, which are within the range of natural concentrations of CO_2 in shallow aquifers (Fig. 6). Remarkable deviations were recorded in monitoring well Bc-5-1/P, which is the closest to the collapsed well Bc-5. The CO_2 concentrations in Bc-5-1/P were 4-5 times higher than the concentrations in Bc-5-4/P, although both wells monitor the shallow unconfined aquifer at the 13-19 m depth range. High concentrations in Bc-5-1/P are attributed to uncontrolled migration of CO_2 caused by the well blowout in 1968. CO_2 concentrations in all wells reached the maximum values in 2010, three years after the remediation. Since 2010, a steady decline in CO_2 concentrations is observed in all wells (Fig. 6).

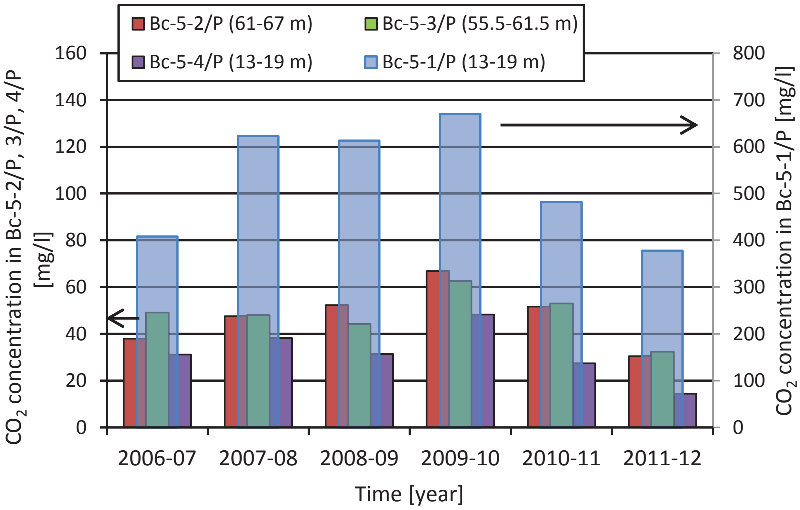

Fig. 6. Measured CO_2 concentrations in the groundwater on site of Bc-5.

Measured formation pressures clearly indicate that the remediation measures performed in 2007 were effective. The decline of reservoir pressure, noticeable within the period from 1968 to 2007, was practically stopped after the remediation (Fig. 7). This implies that the unwanted migration of CO_2 from the main pool into the overlying aquifers via the collapsed well was significantly reduced, if not completely stopped, and that the remediation measures were successfully conducted.

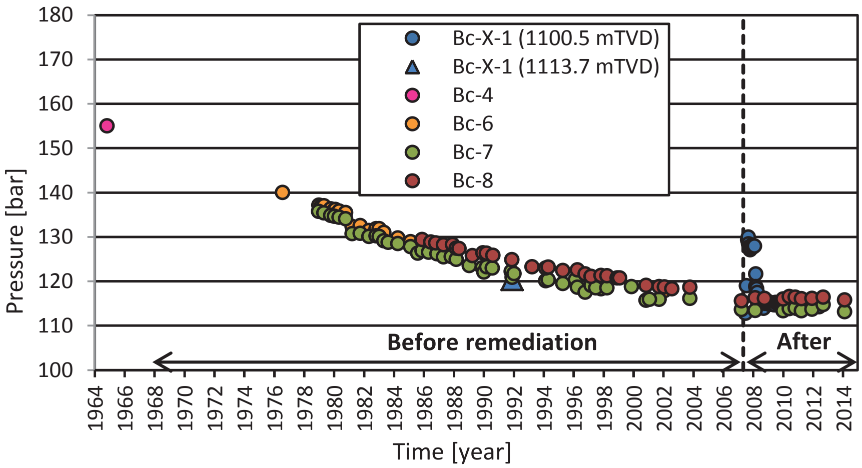

Fig. 7. Measured formation pressures in the main CO_2 reservoir.

6. Conclusions

Corrective measures need to be taken in the event of unwanted migration and leakage of CO_2 from an engineered geological storage site. The remediation performed on the Bečej CO_2 field in Serbia to stop the leak caused by a well blowout in 1968 is, to the best of our knowledge, the first field-scale application of an in situ remediation performed on a natural CO_2 reservoir – an analogue for an engineered geological storage site. The Bečej field case is therefore an excellent case to study in the MiReCOL project (Mitigation and Remediation of CO_2 Leakage), which aims at developing a handbook of corrective measures that can be considered in the event of significant irregularities and leakage from a CO_2 storage site.

This study describes the results of a detailed geological characterization and static modelling of the Bečej field. The main conclusions from this study are as follows:

- The main CO_2 reservoir is formed in the Upper Cretaceous heterogeneous massive flysch and Badennian sand and limestone deposits.
- The overburden comprises multiple shale and sandy layers acting as seals, semi-permeable layers, saline and fresh water aquifers.
- Eight small hydrocarbon reservoirs are identified above the main CO_2 pool at depths ranging from 450 to 900 m.
- Accumulations of methane, and possibly CO_2, that were occasionally found in the shallow overburden when drilling water wells before and after the 1968 Bečej well blowout, suggest that the Bečej CO_2 field is a naturally leaking system.
- The most recently collected monitoring data indicate that the remediation measures conducted in 2007 to counter the leak by injecting gel-forming chemicals were effective and have practically stopped further decline of reservoir pressure.

Follow-up work will consider dynamic modelling of CO_2 migration to quantify leakage in the Bečej field. The effectiveness of various remediation scenarios will be assessed on the model of the Bečej field and generic models inspired by this model.

Acknowledgements

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