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Energy Procedia 4 (2011) 3574–3581

Energy Procedia

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GHGT-10

In Salah CO_2 injection modeling: a preliminary approach to predict short term reservoir behavior

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Abstract

A short term performance assessment methodology under development and validation at the In Salah CO_2 storage site is presented. The progressive approach first concludes of the necessity to consider a dual media reservoir system at Krechba to fit with gas reservoir production, CO_2 injection and CO_2 breakthrough at an old appraisal well (Kb-5). To improve gas migration prediction while also considering the geomechanical behavior of the site, an extended geomodel has been developed. Fluid pressure simulation results representative of the dual media reservoir model and of the simple medium upper layer ones (up to the water table) are used to initiate the geomechanical modeling. Comparison of the preliminary geomechanical simulation results assuming a poro-elastic behavior and InSAR satellite surface displacement data are coherent and in the same order of magnitude (~20 millimeters at maximum displacement).

Keywords: CO_2 storage, fluid flow modelling, geomechanics, performance assessment, In Salah

1. Introduction

The Carbon Capture and Storage (CCS) option relies on the exploitation of an appropriate underground structure to efficiently and safely store significant amount of CO_2. Two types of reservoirs are targeted: deep saline aquifers or depleted oil and gas reservoirs, combining or not an EOR/EGR phase before CO_2 storage in this last case. Nowadays, oil & gas operators are testing how to manage in situ gas field CO_2 production by re-injecting this gas into deep saline aquifers (such as in the Sleipner and Snøhvit projects offshore Norway) or directly into the aquifer of the producing reservoir (as done by BP, Statoil and Sonatrach in the case of the In Salah project).

In the CO2ReMoVe European project, partners work on developing tools and methods to model and monitor the CO_2 injection and the corresponding plume migration at both short and long terms. The aim is to be able to predict and verify how CO_2 can migrate and interact in the formation while considering the different geomechanical and physico-chemical phenomena. The challenge is to understand the reservoir and storage complex behaviors on the basis of the initial database complemented with an comprehensive monitoring program operated on a series of sites. Site characterization is the key step prior developing the reservoir model and a complete earth model of the storage complex.

A progressive approach is applied considering: at first, the injection feasibility in the reservoir in order to confirm storage capacities and then, the impact of injecting and storing CO_2 on the site behavior. As soon as effects become

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doi:10.1016/j.egypro.2011.02.286

observable, prediction and monitored data are compared. During the injection phase (a few tens of years), feedback from the field monitoring program helps to better understand how the site effectively behaves.

This is an important learning period during which site modeling is improved and validated by applying an adapted monitoring program. The final step consists in predicting and monitoring site abandonment for the long term after injection has ceased. At any time, the challenge is to assess if the storage complex maintains its integrity. It means that any discrepancy between prediction and observation has to be explained. If it remains after model and methodology updating or improvement then it has to be managed and remediation is required. To anticipate such a situation, general and site dependent risk scenarios are run during the site selection and validation phases.

CCS deployment main steps	**Available data and knowledge for Krechba (key data related to applied approach – non exhaustive list)**	**Applied approach involving tools and methods at Krechba for CO_2 migration modeling**
Site selection	Conventional field gas data	Performance assessment risk scenario analysis (at short and long terms)
Site characterization field measurements laboratory measurements	Reference baseline for a series of monitoring techniques Storage reservoir petrophysical properties	Data mining **Scenario #1:** non faulted, non fractured single medium 3D reservoir modeling (model #1)
Test and validation phase (a few years) Remediation when necessary	CO_2 injection data and natural gas production ones (2008) Breakthrough at Kb-5 and associated tracer response (2008) FMI analysis (2008) InSAR satellite data (2008) Interpreted 4D seismic data (1997 & 2009 3D seismic acquisitions)	--> Evaluation of Scenario #1 **Scenario #2:** faulted single medium 3D reservoir modeling (model #2) --> Evaluation of Scenario #2 **Scenario #3a:** "faulted / fractured" dual media 3D reservoir modeling (model #3) --> Evaluation of Scenario #3a **Scenario #3b:** "faulted / fractured" dual media 3D reservoir and geomechanical modeling on an extended geomodel version (model #4) --> Evaluation of Scenario #3b
Storage exploitation (a few tens of years)	Production monitoring Geomechanical monitoring Fluid migration mapping techniques	Scenario and model to be confirmed, improved or modified for both short and long term performance assessment and risk management
Storage closure and abandonment • closure phase under operator liability (~ 20 / 30 years) • post-closure phase under government liability (no time limit)	Adapted monitoring programme for each phase to be defined on the basis of experience and knowledge acquisition for the Krechba site.	Long term performance assessment and risk management on the basis of the best short term results

Table 1: Short term CO_2 migration modeling approach in a simplified CCS context presentation. The data availability in column (2) does not reflect all the monitoring techniques that are deployed at Krechba but just the key ones for the modeling approach here applied.

This paper presents the approach developed by IFP Energies Nouvelles in the scope of the CO2ReMoVe project to study short term CO_2 migration into the Krechba reservoir at In Salah. The study presented here has been achieved prior to the 4D seismic processing and interpretation. It illustrates the chronology of the short term prediction approach (Table 1) when monitoring feedback is delivered in parallel.

In this approach, 3D fluid flow modeling is run using our in-house software COORES[TM1] V1.3 where the following phenomena are managed: structural trapping, capillary trapping and CO_2 dissolution. In the short term, the mineral trapping has not been considered but it has to be for long term prediction. The fluid flow modeling results (reservoir pressure) are used as input for the geomechanical of the site behavior which is achieved by using the ABAQUS™[2] software.

2. CO_2 storage at In Salah

The In Salah project concerns a series of gas fields located in central South Algeria (Figure 1) and containing ~1-10 % of CO_2. To export the natural gas, it is necessary for operators to reduce the CO_2 concentration to the sales gas export concentration threshold (0.3%). It was decided in the In Salah project to re-inject the captured CO_2 into the Krechba reservoir aquifer to study the CCS concept at an industrial scale avoiding in the same time the emission of ~17 millions tonnes of CO_2 (Figure 2). Gas is now produced with five wells and the CO_2 is injected in the northern part of the structure through three horizontal wells (Figure 3). CO_2 is injected up to 1900 m depth in a 20-m thick Carboniferous sandstone of ~10 mD permeability and ~15 % porosity (Figure 4).

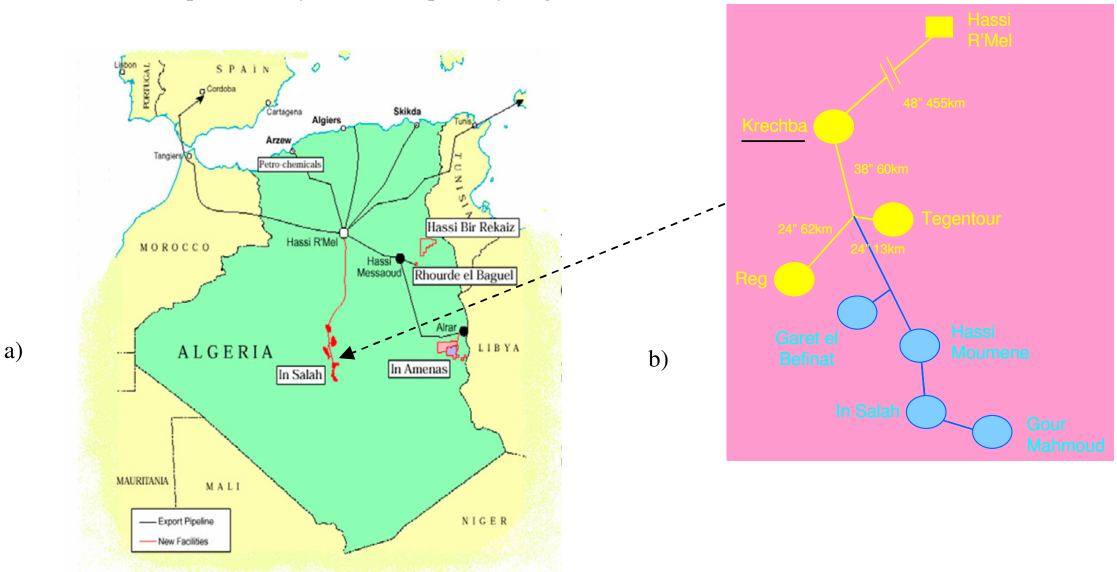

Figure 1: In Salah gas project location (a) and field network (b) - source In Salah JV.

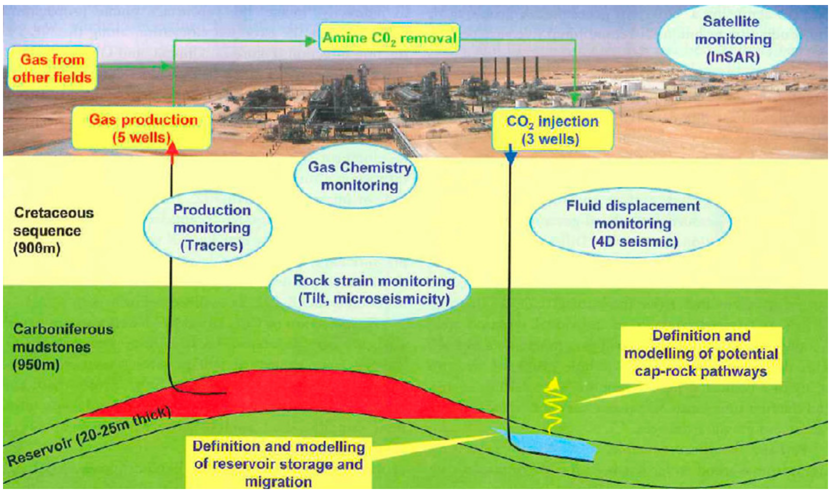

Figure 2: Krechba field (Ringrose et al. 2009).

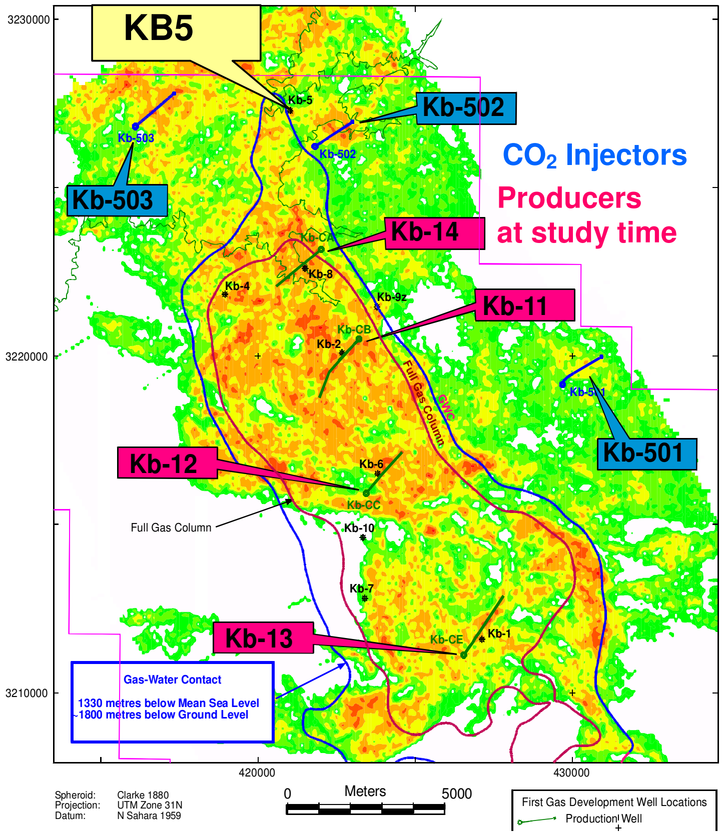

Figure 3: Location of production and injection wells (at time of the study), source In Salah JV.

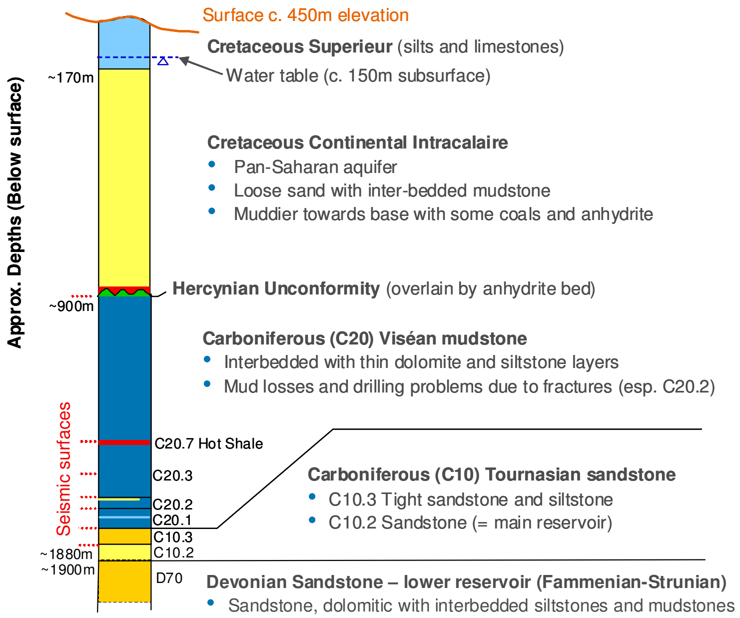

Figure 4: Krechba stratigraphic structure, source In Salah JV.

At reservoir conditions (90°C and 175 bar at 1800 m depth), CO_2 is supercritical. The first results relative to the initial plume development after an injection of 2.5 million tons of CO_2 (at end of 2008) suggest a NW migration (Ringrose et al., 2009). These results agree with satellite InSAR data interpretation (ground surface deformation - Vasco et al. 2008) and the CO_2 breakthrough at an old appraisal well (Kb-5) located 1.3 km from the Kb-502 injector. Tracer analysis confirms the Kb-502 origin of the CO_2. Surface deformation measurements (up to 20 mm near Kb-502) are coherent with both injection of CO_2 and gas production. They may reflect on first approximation the reservoir permeability distribution. The breakthrough at Kb-5 occurred between two well-head inspections (August 2006 and June 2007). At least, the CO_2 migration trend is fully consistent with major faults and fracture network orientations. A 3D seismic acquired in August 2009 is under interpretation and will make it possible to image the CO_2 migration at the reservoir level.

3. Short term performance assessment approach for the 3D flow modeling

The preliminary work consisted in the numerical simulation of the CO_2 injection in the northern part of the Krechba reservoir. This short-term storage performance study had mainly consisted in better characterizing the field and in understanding its behavior taking into account two main monitoring results. In practice, using reservoir gas production and CO_2 injection volume rates, different approaches have been investigated to correctly map the pressure evolution at wells and the observed CO_2 breakthrough at the old appraisal well (Kb-5) which was being used as an observation well but is now fully decommissioned.

In the initial study (scenario #1), the media have been assumed to be neither fractured nor faulted (model #1). But, the modeling results of this single medium model immediately showed it would not be possible to inject targeted volumes in time. When considering field injection and production data, history matching was unsuccessful because of the injector pressure or the CO2 breakthrough at Kb-5 (no possible breakthrough before March 2008 with such a model representation). Then we concluded that this simple model cannot be representative of the Krechba geology. The occurrence of the breakthrough before June 2007 requires a significant permeability increase between Kb-502 and Kb-5.

So, in a second study (scenario #2), the previous model was enriched by faults in the Kb-502 area using a corridor fault to explain the early CO2 breakthrough at Kb-5 (model #2). Despite the good fit with this event, the simulated Kb-502 pressure did not match with the measured pressures. Moreover, at that time new data were interpreted by project partners: FMI analysis from C10.2 to C20.7 formations (no data above) highlighted the existence of numerous fractures oriented North-West and South-East. An updated reservoir model integrating these measurements was then selected.

Then we focused (scenario #3a) on a dual media reservoir model (#3) of 120,000 cells with six pseudo-components (CO_2, N_2-C1, C2, C3-C4, C5 and C6+). In the dual media concept (Bourbiaux et al., 2005), the fractured reservoir is assumed to consist of two media (the fracture or/and fault network and the rock matrix), that exchange fluids together. In this approach, a simplified geometrical representation of the reservoir is proposed in order to facilitate the formulation of matrix-fracture transfers. It consists of an array of identical matrix blocks delimited by an orthogonal set of equidistant fractures oriented along the main directions of flow within the reservoir. The reservoir model has been achieved through calibrating per well zone the matrix's permeability, the fracture's porosity and permeability and the matrix's block size to match the bottom hole pressures (BHPs).

This model satisfied both the BHPs history matching and the CO_2 breakthrough time period at Kb-5 at both the C10-2 and C10-3 formations. Breakthrough occurs in November 2006 in this scenario. The matrix block size (1-2 km) of the dual media model shows the main conductive fracture network to be low in density and field wide. In other words a main fracture characteristic spacing of 1 to 2 km is optimal to fit with monitoring data. The analysis of the simulation results shows a vertical CO_2 migration through the fractures up to the C10-2 top first, then to the C10-3 (Figure 5). Prediction runs with this dual media model shows CO_2 reaching Kb-14, in the northern part of the field, after ~5 years of production and Kb-11 after ~10 years. Such results will be improved / updated when the results of the 4D seismic monitoring of the plume extension will be available and by considering associated earth model updates.

So we concluded that scenario #3a is quite satisfactory when considering our knowledge of the site behavior and monitoring feedback at that time (mid 2009). But such results also show that it is necessary to extend the geomodel vertically and in the northern part to avoid artifacts associated with unsuitable modeling boundary conditions for both geomechanical and fluid flow modeling considerations. In addition, the InSAR satellite surface deformation monitoring results (Vasco et al., 2008) clearly indicate the importance of CO_2 injection on the reservoir geomechanical behavior with local significant uplifts coincident with injection areas. Advanced interpretation of such observations suggest that it is useful to invert the surface deformation in term of reservoir pressure distribution and at least in term of reservoir permeability heterogeneity. So it appears necessary to consider such effects in the reservoir modeling approach to better quantify pressure distribution in the reservoir and as a consequence to have a more reliable fluid migration modeling.

In zone A (upper right side in Figure 5), one has to notice that the presence of methane results from the gas water contact (GWC) assumption and may be not representative of real pore fluid content.

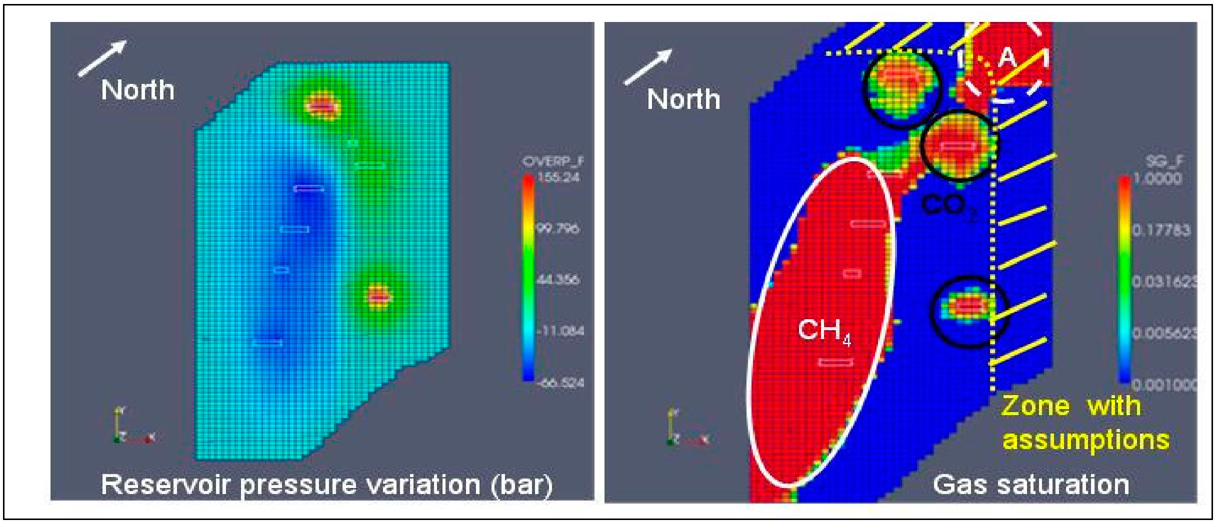

Figure 5: Results (December 2007) of the flow simulation using COORES^{TM1}

4. 3D geomechanical and fluid flow modeling for the short term performance assessment

Scenario #3b corresponds to scenario #3a applied on an extended geomodel (#4) and with 3D geomechanical and fluid flow modeling. The initial geomodel (#3) has been extended in the North direction and the upper layers are considered up to the surface. This new geomodel has benefited from the last available improvements especially some feedback from the re-processing of the baseline survey 3D seismic acquired in 1997. It does not take into account the time lapse (4D) seismic interpretation which is currently on-going. The geological model (Figure 6) has been developed under GOCAD^{TM3} and populated from the reservoir C10.2 layer up to the surface with petrophysical properties using statistical data furnished by Statoil. A complementary impermeable and non porous layer subdivided into fifteen numerical layers have been introduced below the reservoir to be able to properly manage the geomechanical boundary conditions. Mechanical properties have been chosen homogeneous per layer (assessed from well data such as logs and cores). For overburden, the lack of geomechanical and petrophysical information is a limitation for the models.

The fluid flow model is solved in the C10.2 and C10.3 dual media reservoir model (200,000 cells of model #4) with six pseudo-components (CO_2, N_2-C1, C2, C3-C4, C5 and C6+), which is equivalent to a single medium model of 1.2 million cells with one component in terms of CPU time. Prior to simulate the geomechanical behavior, it was necessary to perform history matching (Figure 7) of this updated reservoir model (#4) with the same matching data set as used for scenario #3a. To that purpose, the history matching process software Condor$^{Flow\ TM4}$ was used (Feraille et al., 2004). An objective function is defined to measure the mismatch between the data and the simulation results. The optimization algorithm based on gradients is finally applied to obtain the values of the matching parameters that minimize the objective function.

The coupling between fluid flow and geomechanical models is external and weak. It is also sometimes called a one–way coupling. In practice, we evaluate the geomechanical behavior computing effective stresses, strains and porosity variations.

The geomechanical simulation is achieved assuming a poroelastic behavior (so it is not necessary to achieve geostatic equilibrium). The input data consist of the two pressure datasets delivered by the fluid flow simulation: the matrix fluid pressure for layers from the reservoir level (composed of C10.2 and C10.3) up to the water table and the fracture network fluid pressure limited to the C10.2 and C10.3 formations. First simulation results after 6 years of injection (Figure 8) are coherent with satellite displacement data and are of same order of magnitude (~20 millimeters maximum). At least, we target to benefit from all available data that may be used to constrain or validate our simulations. In this study, we have only considered the surface deformation for validation. Later it would be interesting to also integrate qualitative information from tiltmeter and passive seismic monitoring when the faults can be considered in the model.

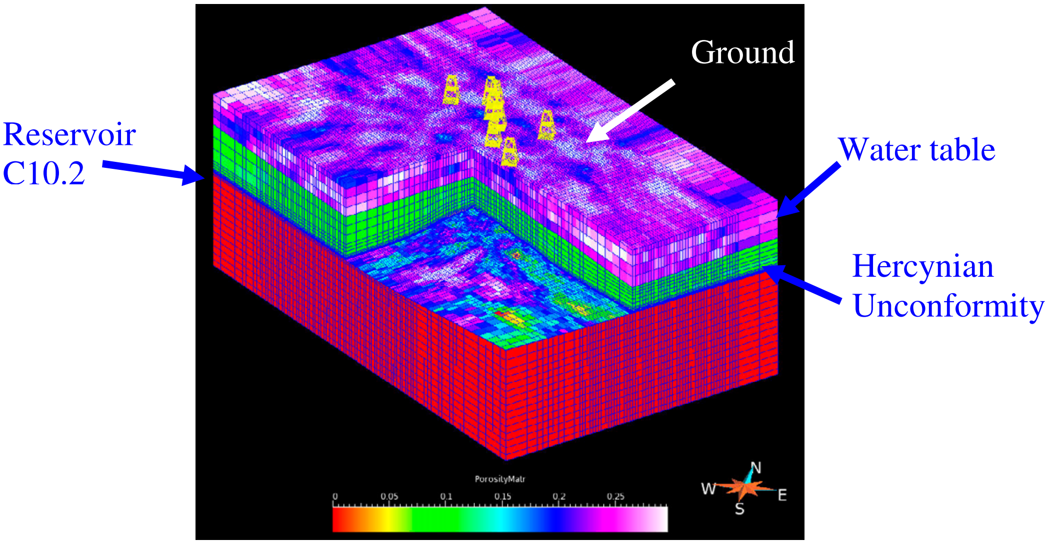

Figure 6: 35-layer extended geomodel (#4) for Krechba (300,000 cells) with following dimensions 41 km – 64 km – 4.8 km (with a vertical factor of 5 on the plot).

This work must be considered as a first step of a progressive and pragmatic approach to address short term performance assessment at Krechba while developing a general methodology for this kind of study. Improvements are ongoing for the history matching and it would be interesting to transform the pressure grids issued from reservoir modeling in a more adapted one for the geomechanical modeling using finite elements. From case to case, it could be interesting to apply a true 3D coupling (explicit if possible with adequate time intervals) between geomechanical and fluid flow simulations and to also integrate fault behavior in the geomechanical modeling. 3D seismic stratigraphic inversion would also be useful to improve the geomodel.

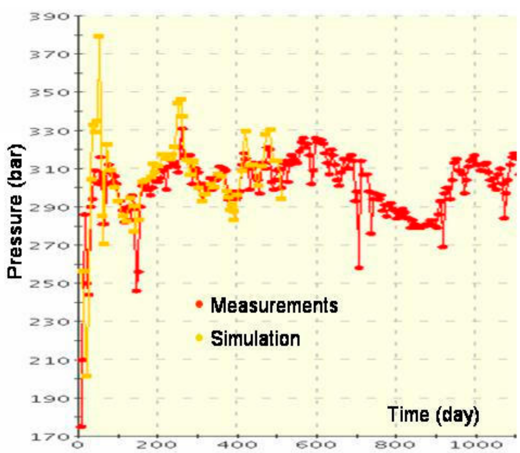

Figure 7: Preliminary history matching results for reservoir model #4 at Kb-501 injector.

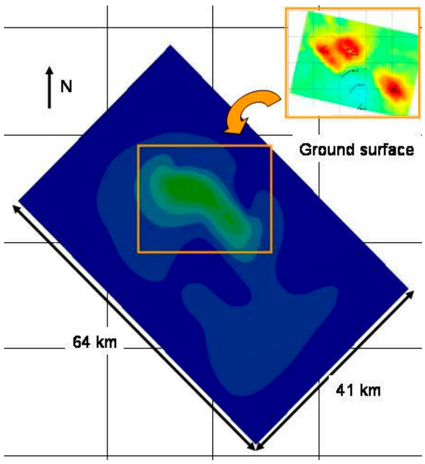

Figure 8: Simulated surface displacement results (January 2009) and InSAR data (source In Salah JV).

5. Conclusions

The 3D fluid flow modeling methodology developed here for CO_2 migration modeling at Krechba is a long time and progressive approach where site representation is permanently improved over time on the basis of monitoring feedback. The initial lack of knowledge on reservoir description (facies distribution, mechanical and petrophysical properties distribution) is more or less compensated over time by the monitoring feedback, which help reducing the scenarios spectrum and uncertainties. The assumptions we made and geomodel we used remain acceptable until interpretation of new data becomes available. The role of fault / fracture networks is confirmed as dominant in the flow system.

For Krechba, satellite imaging of surface deformation highlighted the geomechanical associated effect at very short term too. Modeling such coupled phenomena has required updating and extending the geomodels. The extended reservoir model is still under validation for production/injection history matching and it will contribute to improve the reliability of this preliminary geomechanical simulation results. These last ones are already coherent with InSAR satellite surface deformation data.

A complementary study would be to include faults in the geomechanical modeling assuming they could be better described on the basis of 4D seismic interpretation (on-going by In Salah JIP), but modeling their behavior would remain a strong challenge. Finally, it is important to consider that field data are essential to allow model validation by history matching and so to improve short term and *a fortiori* long term prediction.

Acknowledgements

The authors thank the CO2ReMoVe European project (Contract n° SES6 518350 funded by the EU 6th framework programme and industry partners BP, ConocoPhillips, ExxonMobil, Statoil, Schlumberger, Total, Vattenfall and Wintershall) and the In Salah JV constituted of BP, Sonatrach and Statoil to allow the publication of this work. They are also grateful to Allan Mathieson from BP for reviewing the document and to all partners for fruitful technical comments during project discussion. The success of the CO2ReMoVe project depends to a large degree on the accessibility of the storage sites and associated data, we thank BP and Statoil for their strong collaboration.

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