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ABSTRACT

In this sensitivity analysis on a 3D model of a heterogeneous fluvial reservoir, two scenario orders have been considered. The first one focuses on the *first-order heterogeneity* (i.e. a fluvial belt with a 100% sand content), and the other one on the *second-order heterogeneity* accounting for the internal sedimentary fill within the fluvial belt (oxbow lakes). CO_2 injections were simulated using THOUGH2, and the dynamic simulations show large variations of reservoir performances. The first-order heterogeneity generates a large spectrum of storage capacities ranging from 30 to 50 Mt, to be related to the natural connectivity variability between fluvial belts induced by the avulsion process. Considering second-order heterogeneity reduces the storage capacities by 30%, highlighting the importance of representing such objects in complex heterogeneous systems. Moreover, it increases the dissolution process, increasing by the way the storage efficiency. The CO_2 plume extension and geometry is also estimated to be strongly dependent on the level of heterogeneity. Finally, trapping into poorly connected fluvial point bars affects strongly the storage capacity of the mobile CO_2 as well as the pressure field.

1. Introduction

Whatever its nature (sedimentary, fracture, diagenetic…) or the considered scale (from pore to basin), the heterogeneity of the rock is a major uncertainty in reservoir production and management, especially with the exploitation of complex reservoirs such as tight, fluvial or fractured reservoirs. While the oil industry has been working on the subject for decades with detailed studies (Journel et al., 1998; Larue and Friedmann, 2005; Larue and Hovadik, 2008; Pranter et al., 2007; Xiangyun et al., 2007), some other disciplines such as Carbon Capture Storage (CCS) only start to look after sedimentary heterogeneity and their impact on flow performances. Flett et al. (2007) have demonstrated the impact of varying quantities of sand and shale on the migration of CO_2 and the effectiveness of certain storage mechanisms. Pilot and commercial-scale sites like Ketzin in Germany and Snøhvit in the North Sea (Norway) have shown the difficulties encountered when predicting CO_2 injectivity and gas migration in highly heterogeneous reservoirs, such as fluvial-deltaic ones (Kempka et al., 2010; Wiese et al., 2010).

One may think to apply the geostatistics-based workflows used in petroleum reservoir characterization for assessing the risk on CO_2 injectivity and migration facing heterogeneities. However, geostatistical approaches are dedicated to reproduce 3D geological models that are conditioned to subsurface data. Since data sets are very

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limited in CCS, their use may be less relevant as uncertainties are huge. Moreover, these techniques hardly reproduce accurate heterogeneities. In this context (i.e. very few data), reservoir analogue models are used to fill the gap and to build the parameter sets required for applying geostatistical techniques. However, even in this case, difficulties still exist with the reproduction of continuous bodies and accurate connectivity from very sparse conditioning data.

Issautier et al. (2014) proposed a model-driven algorithm (SCSS) whose goal is to stochastically reproduce highly heterogeneous reservoir models stemming from outcrop data. In this approach, the stochastic simulations are conditioned on a stratigraphic conceptual model rather than data. The study was devoted to the analysis of the impact of the sedimentary heterogeneity on the reservoir performances, and it demonstrated:

- the impact of the heterogeneity on the reservoir performances at two different scales (first-order: connectivity of the reservoir bodies; and second-order: impact of the sedimentary fill);
- the impact of the geostatistical (SIS, SCSS) methods on the storage capacity.

In this paper, we propose to develop a similar protocol using dynamic simulations with as final objective to assess the impact of first- and second-order heterogeneities on storage capacities, overpressure, CO_2 dissolution, and migration.

For the sake of understanding, the conceptual model and the SCSS technique will be recalled in a first section. Then, the protocol used to model CO_2 injection will be presented. The results and their analysis will be then described and discussed.

2. Conceptual deposition models

In the SCSS algorithm, the geological rules and scenario are included in what is called the "conceptual geological model". In the present study, the concept is directly derived from the outcrop study carried out in central Saudi Arabia on the Minjur Sandstone combined to literature data, especially for object dimensions and stacking pattern (Gibling, 2006; Issautier et al., 2014; Jordan and Pryor, 1992; Miall, 2002). We chose to integrate an outcrop study to better constrain the connectivity parameter. Moreover, the Minjur Sandstone (Issautier et al., 2012a,b) is an analogue of the Triassic European reservoirs in terms of depositional environments, climate and geodynamic contexts, and this study might provide answers about the reservoir performances of such deep saline aquifers in CCS, geothermal and energy storage contexts.

The concept illustrates a depositional sequence and it involves three different sedimentary bodies:

- sheetlike sandstone (i.e. braided type deposits);
- multi-story meander belt;
- single-story meander belt.

To stochastically reproduce this conceptual model, an algorithm was specifically developed using python© interacting with gOcad functions. The code allowed generating two series of 3D numerical models that account for the conceptual geological model. Each pair of models from the two series shares the same architecture and only differs in their internal channel body infill (Fig. 1):

- first-order: the reservoir bodies, i.e. the fluvial belts consist of "homogeneous" stacked point bar sand bodies embedded in a shaly floodplain;
- second-order: the point bar bodies contain internal sedimentary heterogeneity (shaly oxbow lakes) which compartmentalizes the reservoir.

CO_2 injection modeling: the grid covers an area of 25 km × 25 km with a thickness of 60 m. With a resolution of 80 m × 80 m × 2 m, the grid contains 2,500,000 cells. A finer gridding would be suitable to ensure the heterogeneity integrity; yet, it would involve a much larger grid. Consequently, we assume this resolution to be the most adapted to flow simulations in this study. Two facies are considered with constant petrophysical values within each, so that porosity and permeability cannot "mask" the first- and second-heterogeneity signals on the reservoir performances (Table 1).

Flow simulations are performed with TOUGH2-MP (Zhang et al., 2008). The injection is set up in the center of the model, only in sand cells. Because the models are stochastic, none of them has the same amount of available "injection cells". Injections are simulated over 50 years and are pressure-controlled with a maximum injection pressure of 1.5 times the initial hydrostatic reservoir pressure to prevent a probable caprock failure. Consequently, the flow rates vary and evolve with time, depending on the

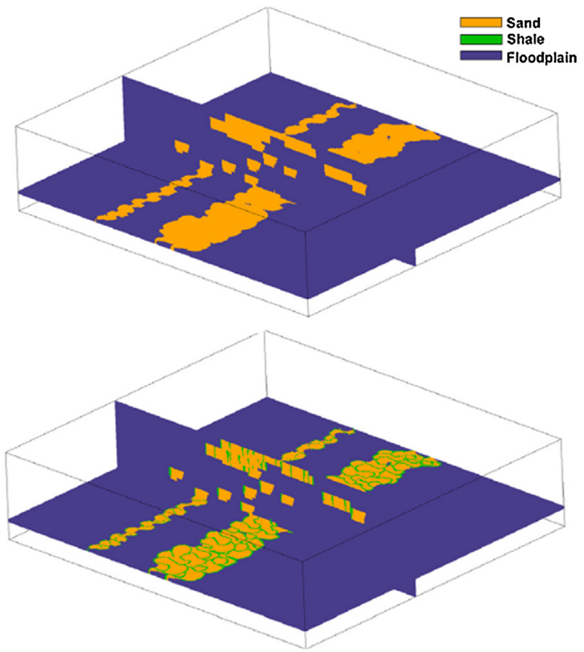

Fig. 1. (Color online.) Example of one scenario with two levels of heterogeneities: point bar only (up) and presence of oxbow lakes (right). Two bodies might be seen: the single-story meander belt on the left of the models and the multi-story meander belt on the center of the models.

Table 1
Petrophysical parameters of the study.

	Permeability (kh)	Permeability (kv)	Porosity (efficient)	Temperature	Pore compressibility
Sand	2.0e−13 m^2	2.0e−14 m^2	20%	45 °C	4.5e−10 Pa−1
Shale	1.0e−18 m^2	1.0e−19 m^2	5%	45 °C	9e−10 Pa−1

well's surrounding pressure due to the injected gas migration and brine displacement. Boundary conditions allow the fluid to exit all lateral faces of the grid, mainly along the longitudinal axe of the model aligned with the point bar large-scale geometry.

Because of CPU time constrains, the model was upgraded, keeping a fine resolution in the center and a coarser grid size elsewhere in order to reduce the number of elements to 850,000 cells. Nevertheless, with such resolution, a reduced number of scenarios could be simulated in a reasonable amount of time and for this, eight scenarios have been selected (from criteria of connectivity) to be representative of the possible range of storage capacity value obtained in Issautier et al. (2014). The eight scenarios are illustrated on Fig. 2.

In the next paragraph, we compare within each scenario, the impact of oxbow lakes, and of the fluvial belts connectivity on:

- the storage capacity;
- the pressure field;
- the dissolution process;
- the plume geometry and extension at the end of the injection.

3. Results

3.1. Storage capacity

In this study, the storage capacity refers to the amount of CO_2 injected across the time. After the 50 years of injection, it consists of the gaseous and dissolved CO_2.

In both model types, the capacity evolution follows a linear trend (Fig. 3) representative of an open system, which allows the fluid to exit the model, and therefore prevents from any rapid overpressure. Issautier et al. (2013) showed that using closed boundary conditions, the maximum allowed pressure (= 1.5 P-hydrostatic) tends to reduce the injection rate after 20 years and so the capacity.

The final capacity values range between 32 and 51 Mt with a mean of about 40 Mt for the first-order of heterogeneity, while it is strongly reduces by 30% when introducing the presence of oxbow lakes in the system. The values range between 12 Mt and 35 Mt (Fig. 3, right). The mean capacity becomes around 29 Mt, with a standard deviation of 7 Mt.

Issautier et al. (2013) showed that the storage capacity does not depend on the number of sand and reservoir bodies perforated by the injection wells. Indeed, a unique injection cell connected to a widespread porous volume is much more efficient than *n* isolated small volumes. Thus, the figures are only related to the available porous volume around the well.

3.2. Pressure field

To understand the impact of the heterogeneity on the pressure field, we plotted the pressure field along *X* (perpendicular to the main drainage azimuth) and *Y* axes for three different depths: Z_{top} at 0 m, Z_{base} at 60 m and Z_{med} at 30 m (Fig. 4). At the base of the reservoir (sheetlike sedimentary bodies), the pressure field appears relatively smooth, with a maximum overpressure that reached at 12 km around the injection well.

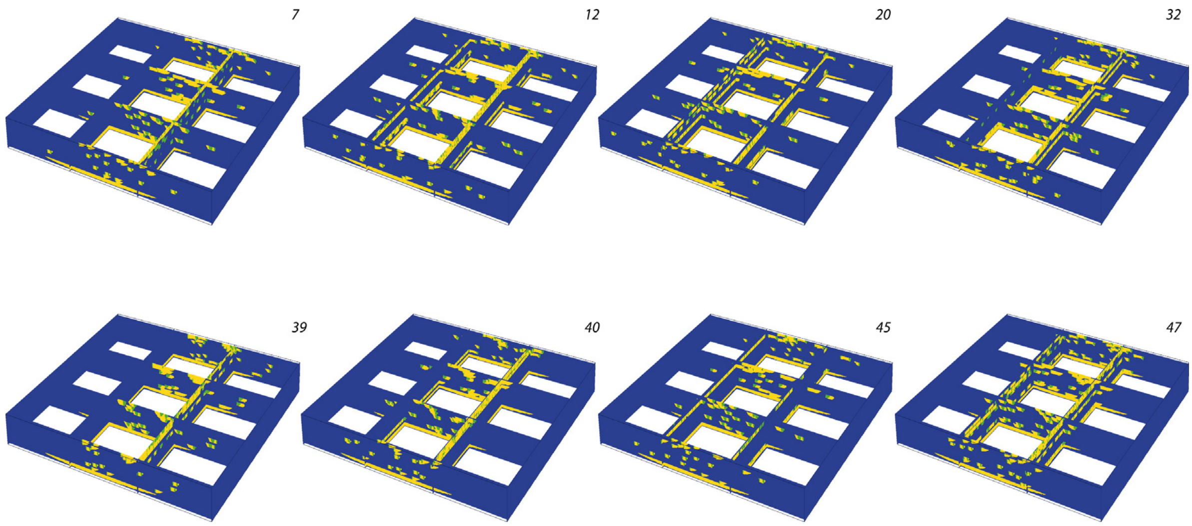

Fig. 2. (Color online.) Representation of eight second-order heterogeneity models selected for the flow simulations with TOUGH2-MP. The connectivity of the reservoir bodies sharply differs from one model to another and it results from the stochastic pattern of the algorithm (Issautier et al., 2014).

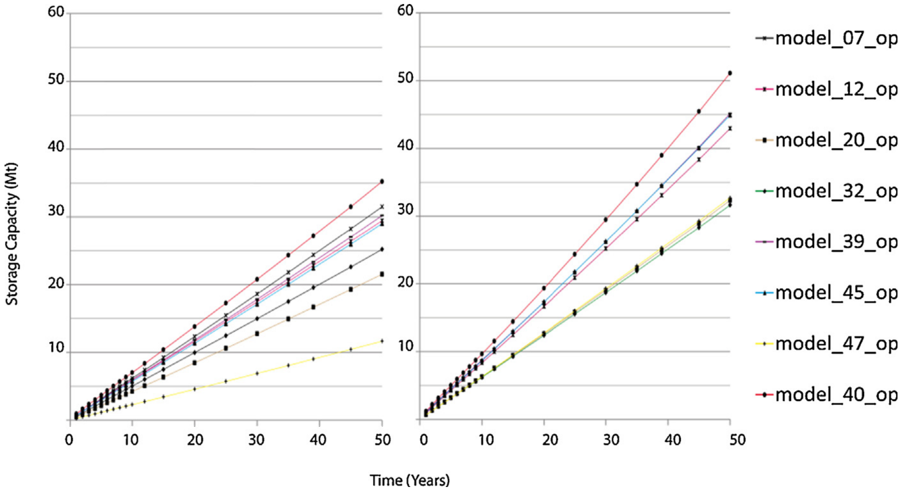

Fig. 3. (Color online.) Impact of oxbow lakes (right) on CO_2 storage capacity of fluvial deposit reservoirs.

While going upward and near the median depth of the model (30 m), the pressure field becomes more "chaotic", especially along the *X* axis, with several pressure drops corresponding to the presence of sand fluvial belts. The uppermost reservoir is materialized by a lateral stack of large meander belts, and it shows a minor effect of the heterogeneity on the pressure field. When considering the first-order of heterogeneity only, very little effect of the heterogeneity on the pressure field is observable along the *Y* axis, which might be explained by an easier drainage of the brine following the injection of CO_2 due to the absence of oxbow lakes.

On the opposite, when considering the second-order of heterogeneity, the pressure field is affected, whatever the depth, by heterogeneity with a marked impact in the middle of the reservoir (Z_{med}), where the sedimentary bodies are poorly connected and where the point bars are well isolated. The effects of heterogeneity seem to be maximal along the *X* axis while the pressure field along the *Y* directions is smoother.

3.2.1. Dissolution process

The dissolution (or solubility) phenomenon is a key criterion in the CO_2 storage context, since it reduces the

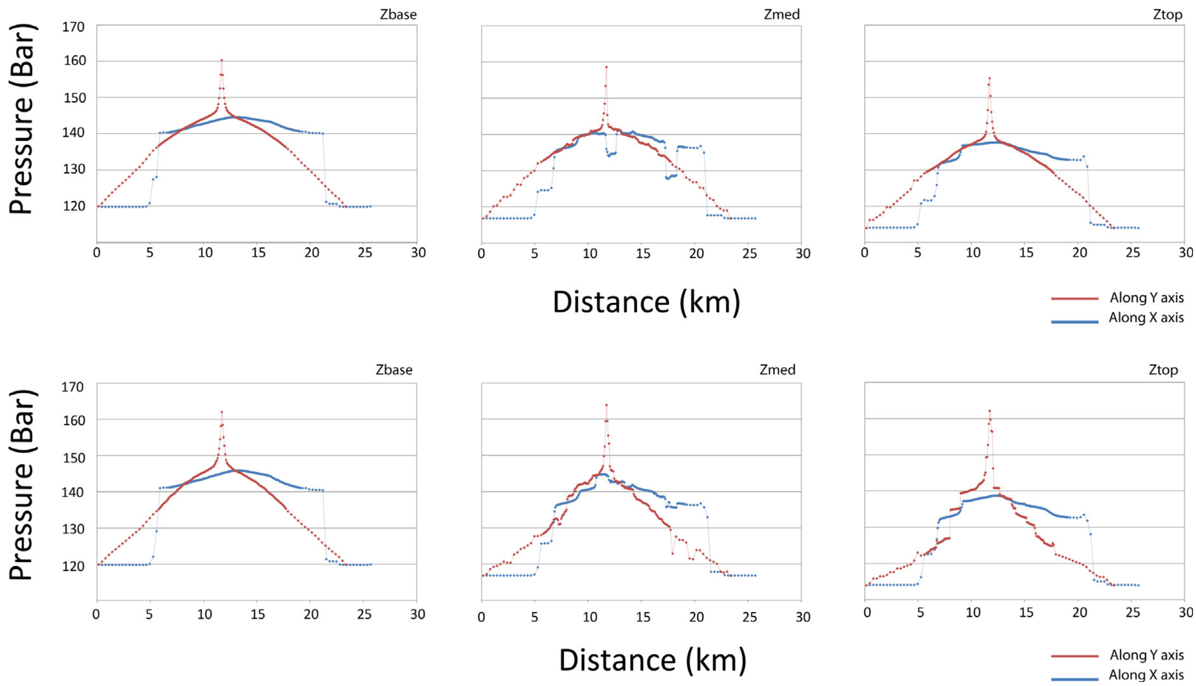

Fig. 4. (Color online.) Impact of the first- (top) and second- (bottom) order heterogeneities on the pressure field at three different depths (top = 0, bottom = 60 m and medium = 30 m). The effects are maximum in the middle of the reservoir (Z_{med}, 30 m), especially along the *X* axis (perpendicular to the fluvial belts), with pressure drops located into the sand bodies.

mobile fraction and increases the integrity of the storage. After 50 years of injection, between 11.5 and 12.2% of the injected CO_2 was dissolved in the brine-saturated pore network, considering first-order heterogeneity only. When including the oxbow lakes, the values increase between 12.8 and 13.7%. Fig. 5 illustrates the ratio of dissolution between models with and without oxbow lakes for each scenario. It shows a global reduction of 10%, indicating a strong role of the oxbow lakes on the CO_2 dissolution on short terms (50 years).

The figures strongly depend on the grid resolution that controls the heterogeneity representation, and finally its ability to increase and deform the CO_2 plume and consequently, the dissolution efficiency.

3.2.2. Plume migration

Due to the difference of injection rate, CO_2 migration according to the eight models differs drastically with (Fig. 6) and without oxbow lakes (Fig. 7). Some plumes are

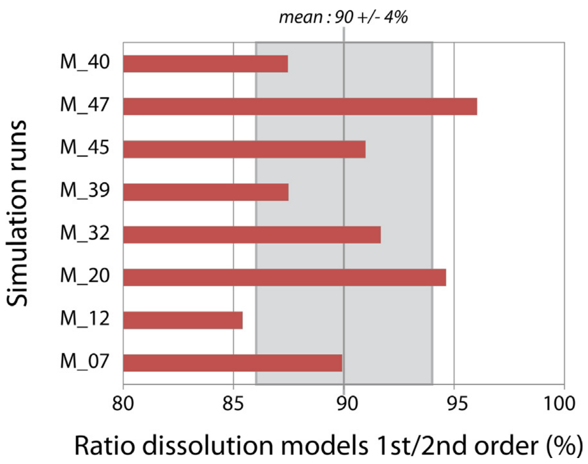

Fig. 5. (Color online.) Ratio between models with and without second-order heterogeneity of dissolved CO_2 for each simulation after 50 years of injection.

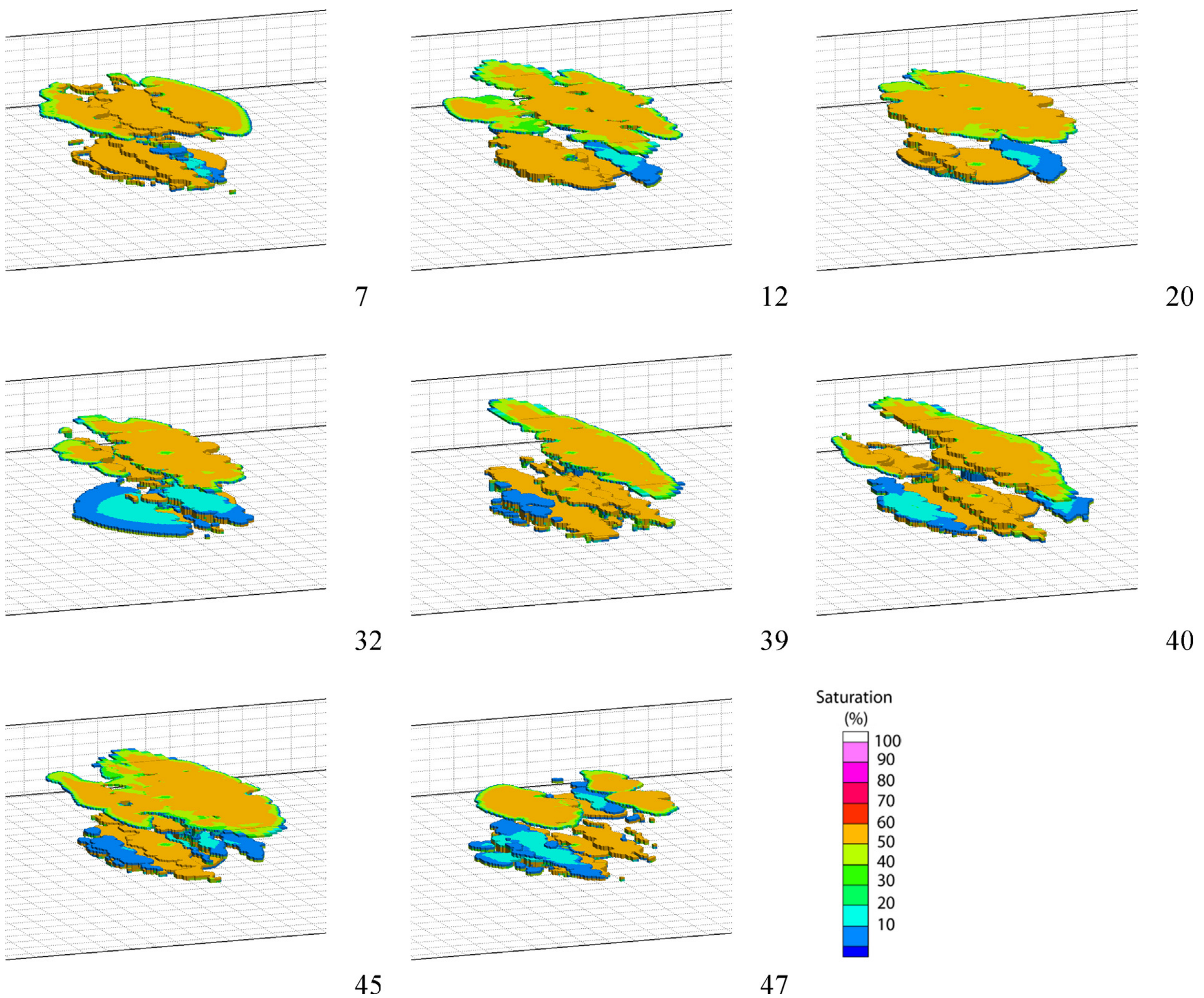

Fig. 6. (Color online.) Migration of the plume in the first-order models. The shapes only depend on the connectivity of the fluvial belts. Some models show a massive stack of CO_2 on the top of the reservoir (models 45, 12, 20).

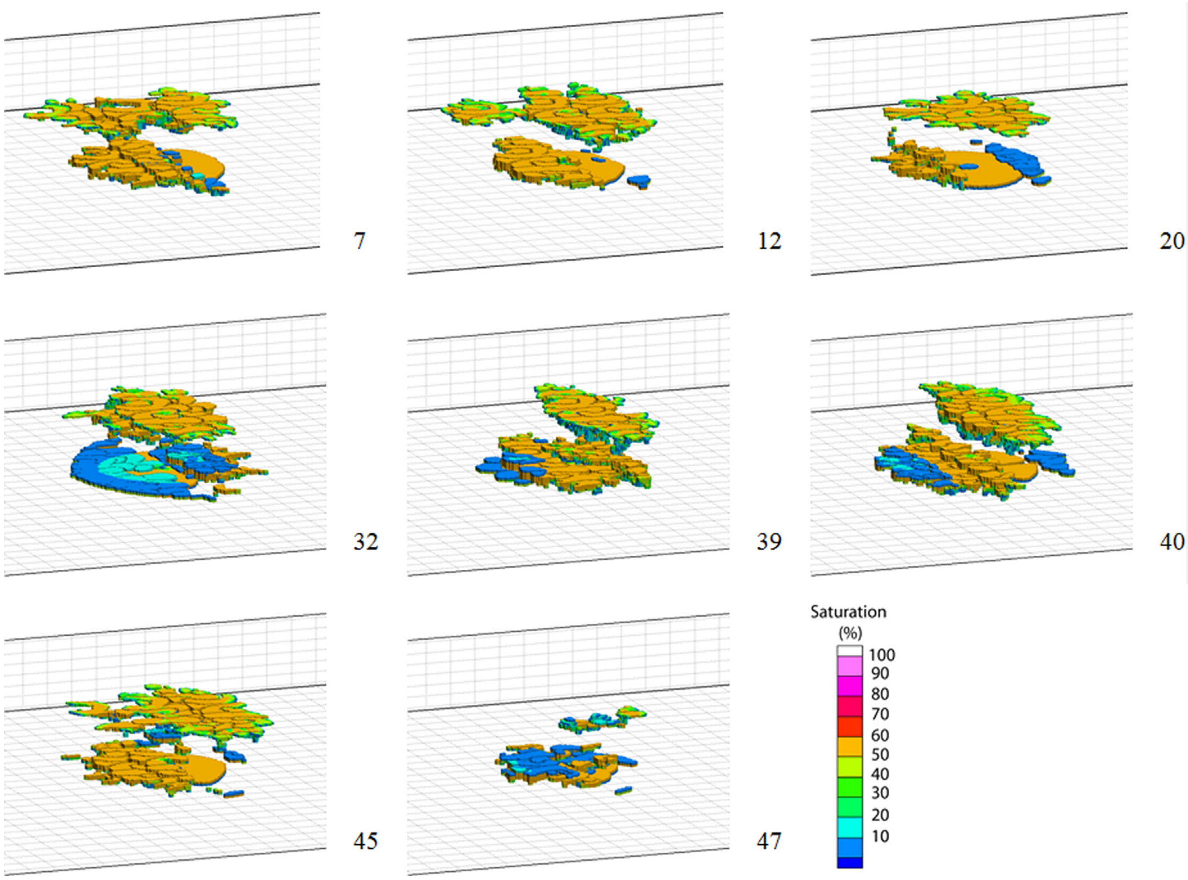

Fig. 7. (Color online.) Migration of the plume in the second-order models. The shapes show varying amount of CO_2 reaching the uppermost reservoir. The impact of the oxbow lakes is clearly visible, isolating CO_2 pockets.

more circular (models 20 and 45), meaning that the injection well hits large volumes of interconnected sand bodies, while some others reveal some anisotropy with elongated geometries. Some models show multiple CO_2-bearing due to poor vertical connection (model 32): the low-saturated plateau is due to the disconnection of the braided bodies and the meandering bodies. Consequently, the CO_2 stacks on top of the sheetlike reservoir body and spreads laterally.

When adding the internal oxbow lakes, the differences strengthen with massive trapping in poorly connected point bars (Fig. 7). Consequently, the amount of CO_2 to reach the uppermost reservoir is much less. The plateau shape at the base of the reservoir, previously described is still visible in several models expressing a poor vertical connection. Model 47 shows a small plume, related to the small volume of CO_2 injected (Fig. 3).

4. Discussion

This type of simulation corresponds to a commercial-scale pilot envisaged for the deployment of CCS worldwide.

When analyzing the impact of the simple connectivity of the sedimentary/reservoir bodies on the storage capacity (first-order heterogeneity models), we demonstrate after 50 years of simulation that the amount of injected CO_2 varies of 40 ± 10 Mt. It corresponds to a standard deviation of 25%, which means that the connectivity of reservoir bodies is a key parameter to control the corresponding storage capacity. The need to integrate this parameter in stochastic simulation becomes crucial. Indeed, using "Poisson process" in simulations does not consider any relation between the simulated bodies that may strongly impact the prediction of storage capacity in CCS, especially because poor conditioning data might be available (wells, vertical proportion curves, etc.). Calculated storage capacities become even lower when considering second-order heterogeneity (oxbow lake), with a mean value of 29 ± 7 Mt, which indicates also the importance of simulating correctly compartmentalization through abandoned meanders. The impact of oxbow lakes on storage capacity induced by the presence of oxbow lakes for each simulated model varies between 7 and 21 Mt, which is massive for a commercial-scale project as that considered in this study (Fig. 8).

This difference results from the existence of oxbow lakes in the second-order models, which in first-order models consist in sandy facies only (increase of capacity). Yet, the volume difference cannot alone explain the storage capacity. The Net to gross in the second-order models varies from 14 to 17% (15.2 ± 0.7), and these three points represent a difference of capacity of roughly 2.9 Mt (far from the mean loss of 12% Mt in Fig. 8). Thus, it implies a strong

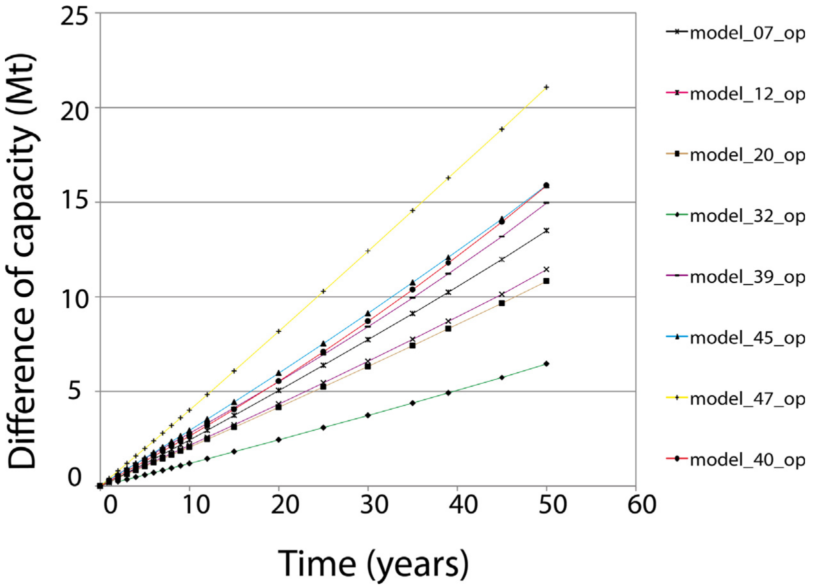

Fig. 8. (Color online.) Difference of storage capacities (first-order capacity – second-order capacity) for each couple of models induced by the presence of oxbow lakes.

role of compartmentalization with two impacts: a pressure increase (decreasing the injectivity) and a faster saturation of the point bars.

The comparison with static capacity estimates (Issautier et al., 2014) shows important differences both in ranking and magnitude values (Fig. 9). For instance, the model with the largest capacity in the dynamic model (N°40) shows a value of 35.2 Mt, while the storage capacity calculated in static mode is 14.6 Mt, which means that static capacity is underestimated by 41.3% (Fig. 9). Though our study is not exhaustive and would need further development, notably in terms of the limited number of models that could be run in a dynamic mode, the actual results highlight the inability of static estimates to match with dynamic results, and so the importance to consider full physics for predicting the storage capacity of geological formations.

Nevertheless, the storage capacities obtained in this study are dependent on several parameters:

- the dimension and geometry of the sedimentary bodies that form the whole reservoir;
- the boundary conditions;
- the injection strategy.

Adding injection wells gives access to porous bodies not necessarily connected to each other, and models with a poor effective capacity could have much better storage capacity in this case.

The figures presented here provide estimates, but should not be considered as generic figures for Triassic-aged reservoirs.

Both first- and second-order heterogeneities do affect the pressure field. Indeed, in an ideal isotropic

DYNAMIC ESTIMATES	
Model ID	Capacity (Mt)
40	35,2
7	31,5
39	30,2
12	29,4
45	29,0
32	25,2
20	21,5
47	11,6

STATIC ESTIMATES	
Model ID	Capacity (Mt)
47	16,8
12	15,2
32	15,1
45	14,8
7	14,6
40	14,6
20	14,4
39	13,6

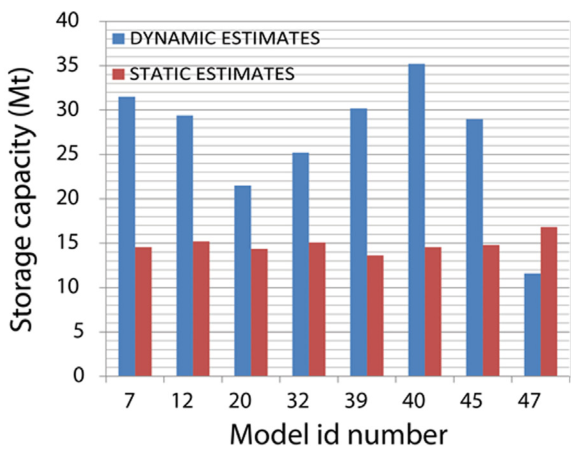

Fig. 9. (Color online.) Storage capacity of each model obtained with a static approach (red plot) and a dynamic one (blue plot). The difference is significant, since the static approach estimate values are roughly 50% less than what is obtained with dynamic simulations.

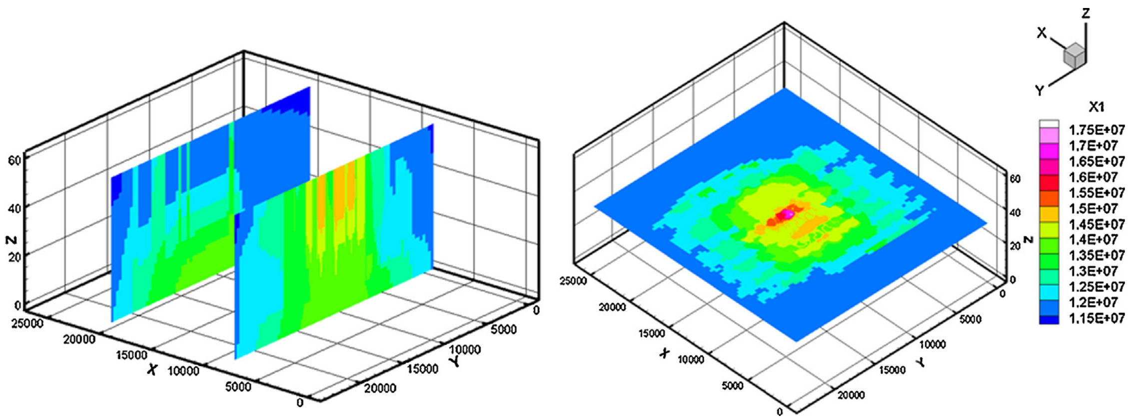

Fig. 10. (Color online.) Pressure field in a second-order heterogeneity model. The heterogeneity strongly disrupts the pressure field as it can be seen along the *Y* axis (left) and the *Z* axis (right). It is materialized by a chaotic pressure field that might affect the hydrodynamics of the aquifer.

reservoir, the overpressure is materialized by a bell-shaped envelop, while when integrating the heterogeneity, the overpressure envelop appears much more disrupted.

Considering homogeneous sand bodies is responsible for pressure drop, and we might interpret these bodies as drains that allow an easier displacement of the brine, locally reducing the overpressure. This pattern disappears when oxbow lakes are added; yet, these models show a lower increase of the overpressure extent, which might be explained by a lower injectivity due to the oxbow lakes along the *Y* axis. It can be noticed that the geometry of the fluvial belt seems to be "printed" on the pressure field and we might interrogate on the impact of such a disrupted pressure field on the aquifer dynamic and convection following CO_2 migration and dissolution with density variation (Fig. 10).

The plume migration, as assumed, is sharply influenced by both levels of heterogeneity. Indeed, the tortuosity is much more important in second-order heterogeneity models, as we can see the geometrical features of the oxbow lakes on the migrating plume extension. Moreover, the trapping in poorly connected point bar decreases the amount of CO_2 that may react with the caprock, which reduces chemical reactivity and enhances storage integrity.

The impact of a higher degree of heterogeneity resolution is minor for the dissolution process (from 12 to 13.3%). Yet, we might assume a greater impact on long-term storage when the plume migrates freely without following a path induced by an overpressure. The main factor that controls the dissolution kinetics is the tortuosity of the CO_2 plume, which implies a larger surface with freshwater.

5. Conclusion

This study has proposed the simulation of CO_2 injection into a fluvial heterogeneous reservoir to evaluate the role of connectivity, as well as the presence of oxbow lakes within meander belts. To better assess the importance of such complex geological geometry, we based our simulation strategy on using a new algorithm allowing us to build a sound fluvial architecture and generate a large number of 50 realizations calibrated on the fieldwork.

For each realization, two levels of heterogeneity are integrated: sand bodies (point bar) repartition, and the presence of oxbow lakes (sedimentary infill).

Using dynamic simulation with a full compositional CO_2-water phase models TOUGH2, we could improve our calculation of the storage capacity variation and compare them with a previous study based on a static method for calculating the capacity of reservoir formations. On the other hand, the number of realizations was limited to eight models due to large computational time.

We demonstrated that each scale of heterogeneity sharply impacts the reservoir's performances. Storage capacity shows a large variance for models with point bars only (from 32 to 51 Mt) due to the connectivity of the fluvial belts materializing the natural variability of the system (avulsion process). The addition of oxbow lakes reduces the capacities drop between 12 and 32 Mt.

This difference is linked to the existence of oxbow lakes that compartmentalize the reservoir, reducing the porous volume and disrupting the injectivity due to the location of surrounding barriers. Indeed, in our models, the injection rate is limited by a maximum pressure injection equal to 1.5 times the hydrostatic pressure of the reservoir. Furthermore, well injectivity is not active when penetrating grid blocks with shale facies. Therefore, only the sand body and connectivity will control CO_2 injection.

When comparing these figures with a previous study based on a static mode calculation of capacity, we obtain a significantly larger storage capacity with the dynamic approach with values roughly 50% larger than when using static calculations. Moreover, the ranking in terms of capacity storage differs also strongly. Though our approach is limited by the small number of realizations studied (only 8 over 50), it stresses the importance of using dynamic simulations with physical laws to better assess the capacity storage estimates and the viability of a project and consequently of the reservoir.

We demonstrated that oxbow lakes play a major role in storage safety because they trap CO_2 in isolated reservoir pools. This reduces the amount of gas able to reach the caprock and thus reduces the risk of alteration due to geochemical reactions, as well as gas leakages through more permeable facies within the caprock.

This paper demonstrates clearly the importance of integrating such complex geological features in 3D earth models to assess better reservoir potential for underground exploitation and storage.

Acknowledgments

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