H-CUBE Project - Hydrodynamics, Heterogeneity, and Homogeneization in CO2 Storage

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Introduction

The integration of heterogeneity for assessing multiphase flow in porous media is a discipline developed since many years in petroleum reservoir simulation, hydrogeology and subsurface hydrology. The consideration of geological storage of carbon dioxide as a potential mitigation technology to reduce greenhouse gas emission into the atmosphere offers a new context for research developments on this topic. The role of geological heterogeneity distribution will be crucial on the CO2 plume migration and also on the pressure print extension. On one hand, CO2 storage reservoir characterisation should benefit from all scientific results published in the oil/gas engineering context: developed geostatistical tools, proposed strategies for uncertainty analysis, etc. On the other hand, CO2 storage context differs from petroleum as, for instance: a) the involved space and time scales are greater in the CO2-storage domain than in the hydrocarbon industry, b) the amount and availability of data is generally much more limited in CO2 case studies, and c) the use of flow simulation in CO2 storage studies is not for predicting the flow path from an injection well to producing ones, but for estimating the reservoir capacity performance, and safety (overpressure), d) the supercritical CO2 fluid properties differ from hydrocarbon one. As a consequence, new challenges arise and specific developments are still required for correctly assessing the hydrodynamic of CO2 geological storage. The main goal of the project H-CUBE is to provide appropriate theoretical and numerical models for accurate evaluation of the hydrodynamic behaviour of a CO2 storage complex and surrounding area. Particular emphasis will be placed on the determination of the CO2- brine flow with buoyancy forces and dissolution effect in saline aquifers with a methodology for assessing heterogeneity of the geological formations at several scales. This will consist in performing deeper studies on the impact of heterogeneities onto CO2 flow behaviours from near well injection zone (meter scale) to basin scale (~100km), in developing new techniques for optimizing the flow behaviour simulation (up-scaling and homogenisation techniques) and characterisation (proposal of appropriate reservoir descriptors), and in proposing suitable modelling and statistical workflows for assessing uncertainty analysis in function of the envisaged geological contexts. The project is decomposed in four main work packages that are described in this paper.

Upscaling processes

Multiphase flow simulations of CO2 reservoir storage are computationally very intensive. This implies to incorporate the detailed geological information into a coarser model by means of some up-scaling technique which require for a heterogeneous porous medium modifications of constitutive functions at the grid-block scale. We propose to assess the buoyant forces on the CO2 and brine vertical migration into a heterogeneous system. The approach is proposed in a two folds fashion by using both analytical and numerical up-scaling methods. Analytical up-scaling techniques are attractive options because they are computationally efficient and convenient to implement in coarse grid models. We propose to derive an analytical expression for effective multiphase flow properties in a laminar heterogeneous porous media generated with three level of complexity (Fig 1 and “Laminar system” in Fig. 4). Such fine-scale sedimentary bed structures give rise to high permeability contrasts over different length scales (See the seismic of the CO2 plume spreading ate Sleipner for instance). When the intra-facies variability is randomly distributed investigations are principally conducted by means of numerical simulation and a strategy is proposed for assessing specifically the gravity segregation induced by random anisotropic heterogeneous media.

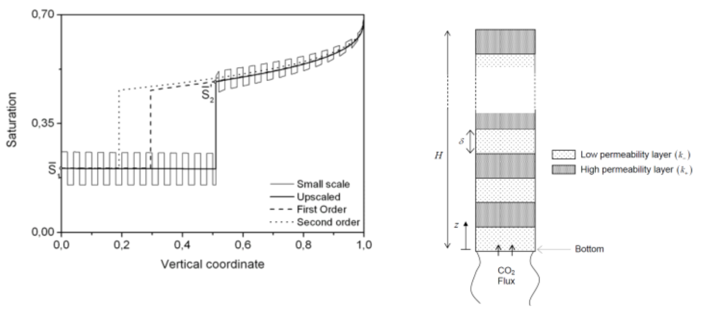


***Figure 1:** Example of a 1D gas saturation profile and up-scaled approximation in perfectly stratified system (Ngo and Mouche, 2013)*

If the migration, governed by buoyancy alone or capillarity alone, is now well understood, this is not the case when the two mechanisms are of equal importance (Mouche et al., 2010). Indeed the capillary pressure and the flux must be continuous at the interface. This leads to a saturation discontinuity which is not easy to capture with a classical numerical code (Hoteit and Firoozabadi 2008). Moreover, a variety of hydrodynamic regimes and fluid partitioning at the interface may be expected. When the layers are discontinuous the CO2 plume may move upwards through the discontinuities. If we assume that the lateral spreading is dispersive the up-scaled migration of CO2 equation should account for lateral dispersion and the up-scaled brine migration should account for a recirculation process. Finally, for a random distribution of the intra-facies variability we propose to investigate the hydrodynamics principally by means of numerical simulation and analysing results with the moment analysis, well known in hydrology for the analysis of the migration of a tracer plume and also recently used in a 2D vertical system for CO2 storage.

Heterogeneity classification and model ranking

When dealing with multiple realization of heterogeneity field distribution on the same 3D static earth model appropriate ranking measures of the static realizations should be defined to select the limited number of geological realizations that will serve as inputs for flow simulations. We propose to define different geometrical and topological descriptors of the porous rock network to characterize a priori reservoir dynamic behaviour. Such descriptors are proposed in (Larue et al., 2008) but concern the petroleum context and are not wholly applicable to CO2 storage as it does not concern flow between injectors and producers and supercritical CO2 has different physical properties than hydrocarbon.
Among the possible envisaged descriptors those related to the geometry of the reservoir volume (anisotropy, tortuosity, etc.) and its connectivity (topological indices, coordinence, etc.) with regard to the well injection location will be under consideration.

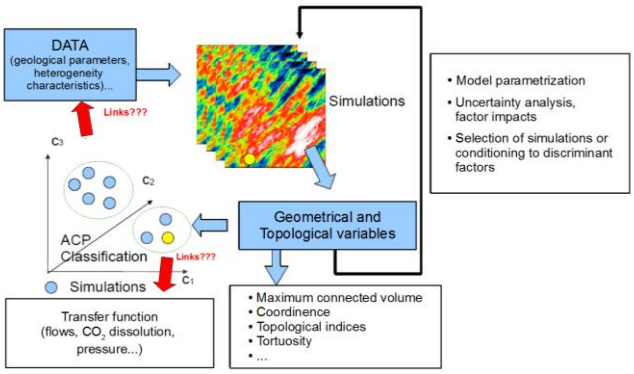


Figure 2 *Global scheme of the proposed approach to ranking the different static models*

Stochastic simulation allows generating multiple reservoir models that can be used to characterize reservoir uncertainty. In many practical situations, the large computation time needed for flow simulation does not allow an evaluation of flow on all reservoir models.
To identify a subset of reservoir models that will be evaluated by flow simulation to compute the statistics (P10, P50, P90) of the response of interest we propose to use the distance kernel method (DKM), as proposed by Scheidt and Caers (2009) which is based on the definition of a dissimilarity distance between reservoir models, which indicates how similar any two reservoir models are in terms of their associated response of interest. The distance can be calculated in any manner such as the Hausdorff distance (Suzuki and Caers 2006), time-of-flight-based distances (Park and Caers 2007), or flow-based distance using fast flow simulators (Scheidt and Caers 2007). The distance matrix is then used to map all realizations into a Euclidean space. Each point represents a reservoir model (Fig. 2); the points are arranged in a way that their Euclidean distances correspond as much as possible to the dissimilarity distance of the realizations. Then, one could group the points in Euclidean space R using principal component analysis or clustering algorithms and select representative points (realizations) for each cluster. The representative reservoir model associated with each cluster is defined as the reservoir model that is closest to the cluster centroids.

Dual Mesh method

Detailed geological models typically contain many more cells than can be accommodated by reservoir simulation due to computer time and memory constraints. However, predictions performed on a coarser up-scaled mesh are inevitably less accurate than those performed on the initial fine mesh. An alternative approach is to retain fine scale information while avoiding the most time consuming feature of the simulations, solving for the flow field on this fine grid. This can be achieved through solving the pressure equation at the coarse scale using appropriately up-scaled properties. Heterogeneity at the fine scale can be introduced during the saturation update by using either a pressure or a flux refinement. In this case, the precision in fluid recovery is considerably improved and the CPU time and memory are much lower than for a full fine scale simulation (Guérillot and Verdière 1996; Audigane and Blunt, 2004). This method has been improved by using vorticity field as a measure of heterogeneity to improve the coarse grid generation (Firoozabadi et al., 2009), and more recently by introducing analytical solution during the up-scaling procedure to speed up the time of calculation.

The different steps of the algorithm of the dual mesh method are for each time step (Fig. 3): **1**. Initiate fine mesh grid properties using initial geological static earth model **2**. Generate the coarse mesh with upscaled properties **3**. Solve of the pressure equation over the low resolution grid **4**. Reconstruction of the velocity fluid on the high resolution mesh **5**. Update of the saturation field on the fine mesh.

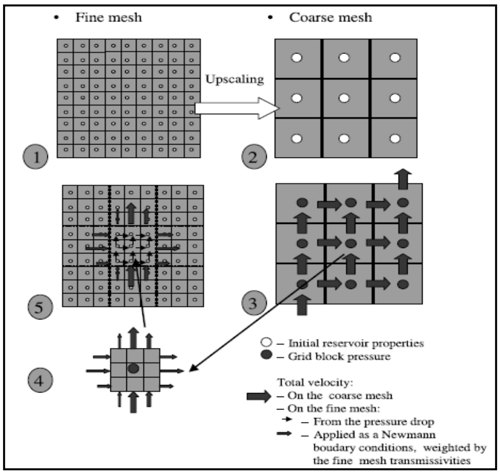
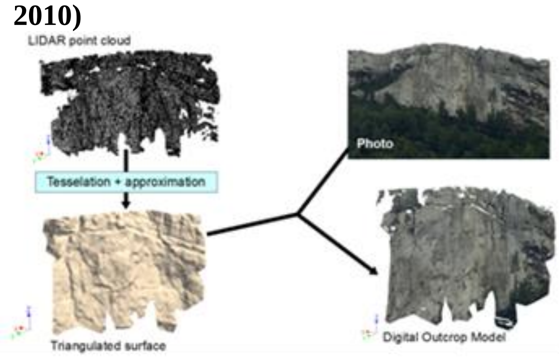
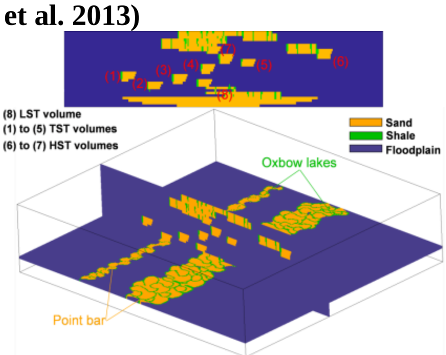
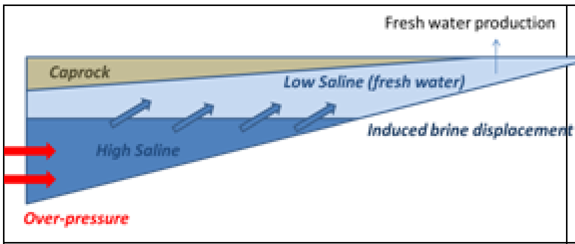


Figure 3: *schematic view of the dual mesh method from Audigane and Blunt, (2004)*

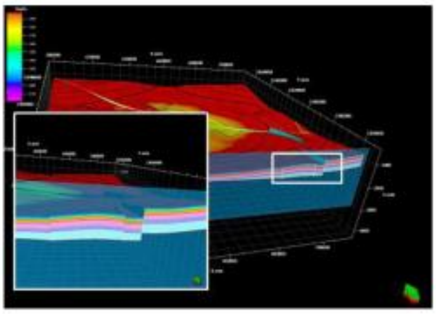
Application to case studies

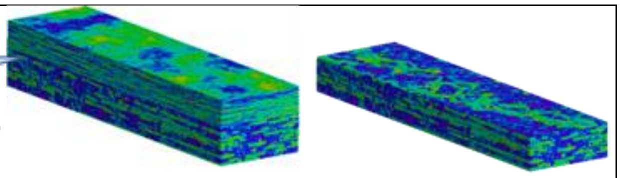
In order to validate the methods previously described, a number of real case studies is envisaged for a direct application of the different methods developed above, and of the integration of the simulation results to a comprehensive analysis. The objective is (i) to manage six case studies of static earth reservoir models with different geological contexts (see Fig.4), (ii) to confront the methods developed in other Tasks to the "geological reality"; (iii) provide a comparative analysis of the up-scaling technique and code performance based on the case studies model predictions of hydrodynamic impacts (pressure, CO2saturation and brine velocity fields) and site performance (capacity estimate)including heterogeneity effects; (iv) to provide a guideline of recommendations to answer some aspect of the CO2 storage directive by identifying best practice on numerical modeling of CO2 storage behavior.

CASE STUDIES	
2D/3D Digital Outcrops Models (Viseur 2010) 	**Fluvial sedimentary heterogeneities (Issautier et al. 2013)** 
Sloping aquifer	**SPE10th Comparative project**

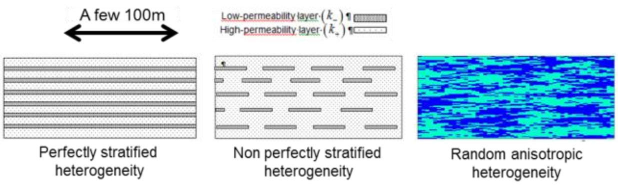


Dogger aquifer in the Paris Basin





Laminar system



Conclusions

The expected outputs of the project will be:

- To give new insights on the understanding of the role of the heterogeneities of various geological types on the performance (capacity) and safety (pressure print, CO2 and brine displacement) assessments of CO2 storage sites. In particular, these results will help operators to optimize the characterization and the monitoring plan according to the encountered geological context;
- To provide recommendations (best practices) for the modeling and proper integration of the reservoir heterogeneities at multiple scales (homogeneization), hence providing further details in combination with the recently published guidance documents for the implementation of the European Directive 2009/31/EC (European Commission, 2011).
- To improve confidence in the numerical simulations predictions by using innovative and powerful techniques (without extra cost) hence eventually participating, to some extent, to the acceptance of the public of the CO2 storage project.

Acknowledgements

This project is funded by the French Agency of National Research (ANR) under the contract SEED 2012 - ANR-12-SEED-0006.

References

Audigane P., M.J. Blunt M.J., 2004, Dual mesh method in upscaling in waterflooding simulation transport in porous media, vol. 55, 71-89.

Mouche, E., Ngo, T. and Audigane, P., 2013, Co2 vertical migration through a piecewise homogeneous porous medium; presented at the SIAM conf. Padova Italy, June 17-20, 2013.

Mouche E., Hayek M., Mügler C., Upscaling of CO2 vertical migration through a periodic layered porous medium: the capillary-free and capillary dominant cases, Advances in Water Resources, 33, pp 1164-1178, 2010.

Guérillot D.R., Verdière S. Different pressure grids for reservoir simulation in heterogeneous reservoirs. SPE29148, 1995.

Firoozabadi, B., Mahani, H., Ashjari, M., Audigane, P., 2009. Improved upscaling of reservoir flow using combination of dual mesh method and vorticity-based gridding, Computational Geosciences, 57-78, vol. 13 (1).

Viseur, S., 2010, Automated methods for fully exploring and interpreting LIDAR data points. 72nd EAGE Conference & Exhibition incorporating SPE EUROPEC 2010, Barcelona, Spain.

Issautier, B., Viseur, S., Audigane, P., Le-Nindre Y-M., 2013, Impacts of fluvial reservoir heterogeneity on connectivity: implications in estimating geological storage capacity for CO2, International Journal of Greenhouse Gas Control, In Press.