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Roadmap for Modelling and Quantitative Understanding

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Multiscale Stratigraphic Reservoir Characterization for Flow and Storage of CO2: Roadmap for Modelling and Quantitative Understanding

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Summary

This poster outlines a hierarchical, multiscale modelling approach that is adapted from proven hydrocarbon reservoir characterization workflows to determine which 3D sedimentological and stratigraphic heterogeneity types at which temporal and spatial scales and in which configurations are most important for successful long-term CO2 storage. The approach is particularly in saline aquifers that are data-poor but have the potential to store large CO2 volumes. It uses the Representative Element Volume (REV) concept and associated upscaling methodology to characterise sedimentological heterogeneity types , and it leverages novel modelling tools that facilitate rapid model construction and prototyping, geometrically accurate representation of key geological heterogeneities in models, and computationally efficient simulation of all CO2 trapping mechanisms over relevant spatial and temporal scales.

Multiscale Stratigraphic Reservoir Characterization for Flow and Storage of CO_2: Roadmap for Modelling and Quantitative Understanding

Introduction

Numerous studies have quantified the key geological heterogeneities that impact on flow and hydrocarbon recovery, using nested, high-resolution models that span the core- to reservoir-scale. These studies have calculated effective (upscaled) properties relevant to hydrocarbon production that can be used to represent the impact on flow of smaller-scale heterogeneities in larger-scale models. An equivalent level of detailed, multiscale modelling for CO_2 storage is required to extend our understanding to storage, different fluid properties, and trapping mechanisms such as dissolution and precipitation unique to CO_2 storage. In addition, both imbibition and drainage processes are relevant at the leading and trailing edges of the CO_2 plume and the timescales of interest are much longer. The principal challenge in a dedicated CO_2 reservoir characterization process is thus to determine which 3D sedimentological and stratigraphic heterogeneity types at which temporal and spatial scales and in which configurations are most important for successful long-term CO_2 storage.

Here we outline a hierarchical, multiscale modelling approach that is adapted from proven hydrocarbon reservoir characterization workflows to address these challenges, particularly in saline aquifers that are data-poor but have the potential to store large CO_2 volumes. The approach uses the Representative Element Volume (REV) concept and associated upscaling methodology to characterise sedimentological heterogeneity types (Fig. 1), and it leverages novel modelling tools that facilitate rapid model construction and prototyping, geometrically accurate representation of key geological heterogeneities in models, and computationally efficient simulation of all CO_2 trapping mechanisms over relevant spatial and temporal scales.

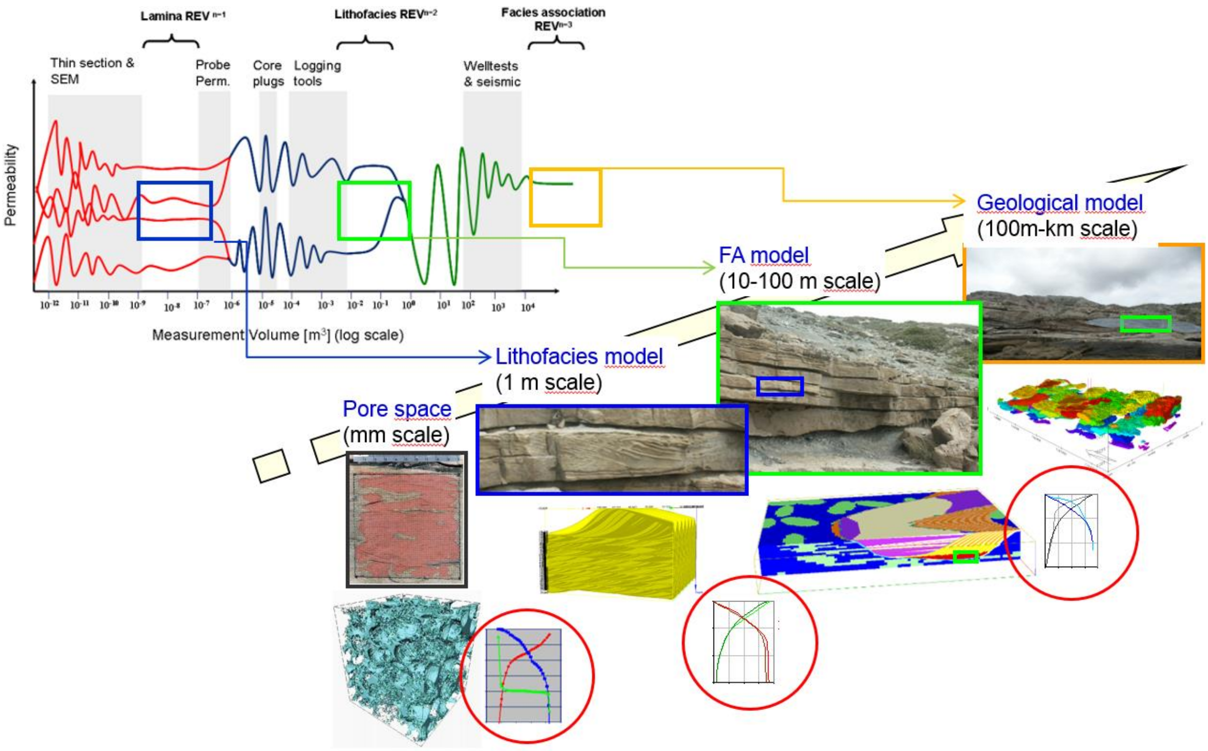

Figure 1. *Conceptual sketch of different scales of REV related to sedimentological heterogeneities and scales of measurement (top left). This example shows four different lamination types that combine into two lithofacies, which are combined in a facies association. Distinct scales of permeability heterogeneity require dedicated models that honour scale-related data. The end product for upscaling is a simplified type curve. After Nordahl & Ringrose (2008).*

Method and Modelling Tools

The first step in our approach is to synthesise a hierarchy of sedimentological heterogeneity for the CO_2 storage complex (e.g. Jackson et al. 2022). This hierarchy provides a framework to identify, organise and model heterogeneities. Although the hierarchy honours all available subsurface data, it also incorporates concepts and data derived from outcrop, subsurface and computational analogues that bridge gaps in the scales, resolution and sampling distribution of subsurface data. Computational analogues are derived from 3D forward stratigraphic models of hydrodynamics, sediment transport, morphology and stratigraphy (Fig. 2) that can investigate the range of boundary conditions and large parameter space implicit in geological interpretations (e.g. Van Der Vegt et al., 2018). Forward stratigraphic models provide a full 3D representation of stratigraphic and sedimentological heterogeneity at the spatial scale of the depositional system.

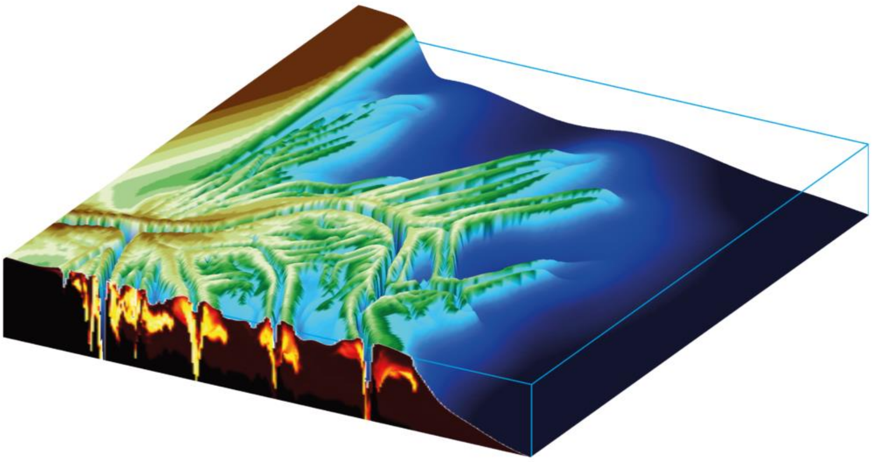

Figure 2. *3D view of forward stratigraphic model of sand-poor, fluvial-dominated delta and deltaic deposits constructed using Delft 3D software (https://oss.deltares.nl/web/delft3d). The model illustrates delta morphology, deltaic stratal architecture and grain size distribution.*

Nested, hierarchical models are constructed using a surface-based approach, in which all heterogeneity is modelled as discrete volumes bounded by surfaces (e.g. sequence stratigraphic surfaces, facies boundaries, bedding surfaces, diagenetic contacts). This approach is geometrically accurate and computationally efficient, because surfaces are created without reference to a pre-defined grid, and it honours the underlying geological interpretations (Fig. 3; Jackson et al. 2014, Jacquemyn et al. 2019). Surfaces can be taken directly from seismic mapping and well correlations, or indirectly from stratigraphic forward model outputs and outcrop analogue data. Using geological surfaces aids model consistency across spatial scales, because surfaces at large hierarchical scales define the framework for distributing surfaces at successively smaller hierarchical scales. The resulting models can be exported to commercial flow simulation software or to complementary surface-based, adaptive-mesh flow simulators that optimise simulation to the numerical problem at hand (Jackson et al. 2015; https://www.imperial.ac.uk/earth-science/research/research-groups/norms/software/ic-ferst/).

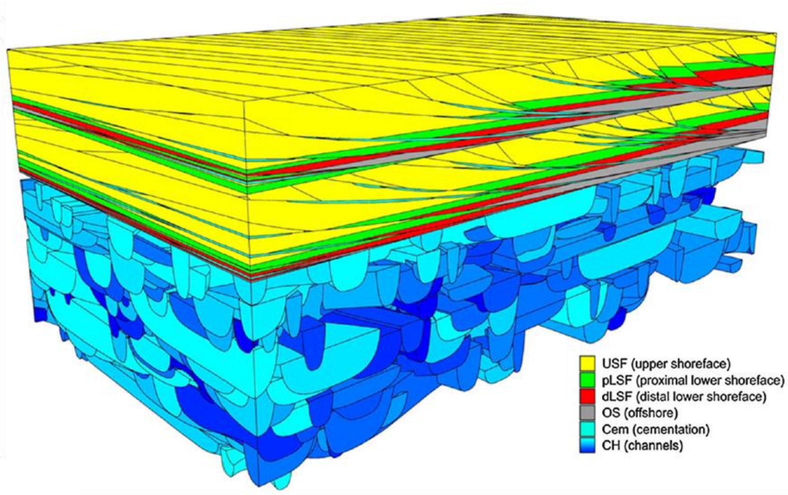

Figure 3. *Surface-based reservoir model of channelised fluvial sandbodies overlain by two vertically stacked shoreface parasequences (x5 vertical exaggeration), constructed using IC-SURF software (Jacquemyn et al. 2019; https://www.imperial.ac.uk/earth-science/research/research-groups/norms/software/ic-surf/).*

Hierarchical, multiscale modelling requires rapid construction of models, in order to capture all heterogeneities of interest and multiple geological scenarios. Prototyping of reservoir models constructed using sketched surfaces facilitates this process. Sketch-based modelling is geologically intuitive and allows fast screening and ranking of geological models prior to more detailed investigation (Fig. 4; Jacquemyn et al. 2021, Jackson et al. 2022), particularly when combined with flow diagnostics that allow rapid, quantitative assessment of flow properties using a single pressure solution (Petrovskyy et al. 2023).

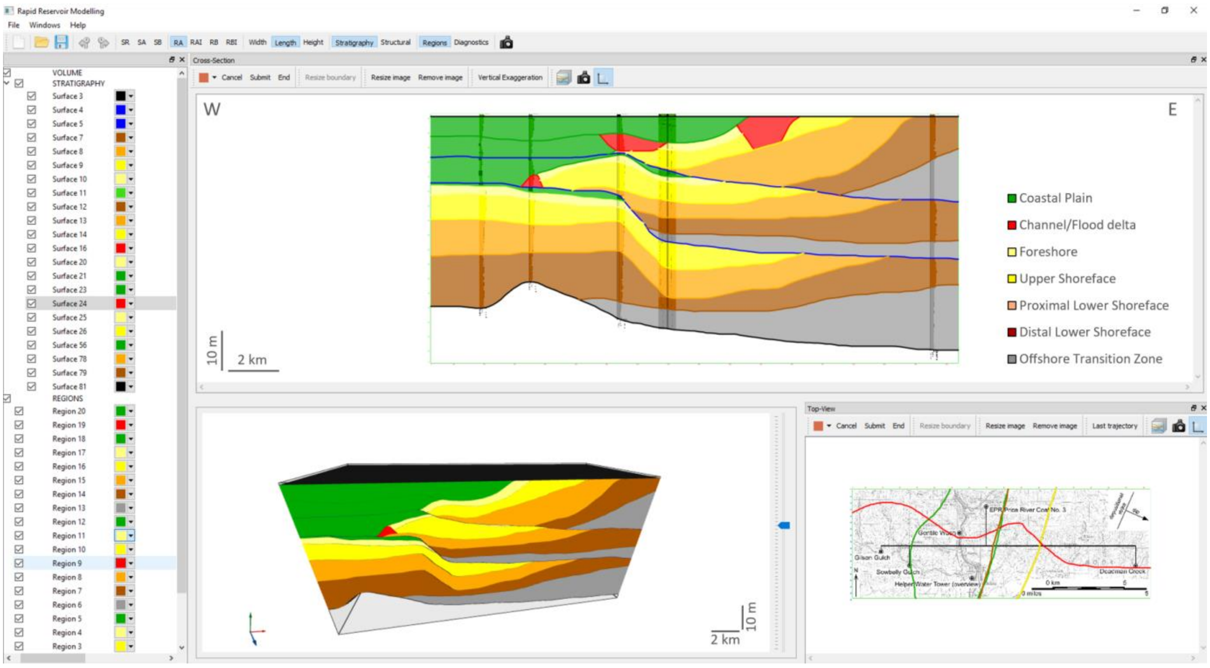

Figure 4. *Sketched 3D model of three progradationally stacked shoreface parasequences, based on correlation of five measured outcrop sections (Jacquemyn et al. 2021). The 3D model was sketched in less than 10 minutes using Rapid Reservoir Modelling (RRM) software (https://rapidreservoir.org/).*

Dynamic behaviour of the CO_2 plume involves injection and buoyancy-driven migration, dissolution of CO_2 into brine, and chemical rock alteration. Acccurate prediction of CO_2 plume migration therefore requires numerical modelling of general multiphase flow, chemical precipitation and dissolution, based on the thermodynamic and chemical interaction of CO_2 with 3D geological heterogeneity over various timescales. We extend an existing framework for modelling complex physical systems, in order to investigate CO_2 sequestration processes including chemical reactions of calcite precipitation (Kala & Voskov 2020) and enhanced CO_2 dissolution (Lyu et al. 2021) (Fig. 5).

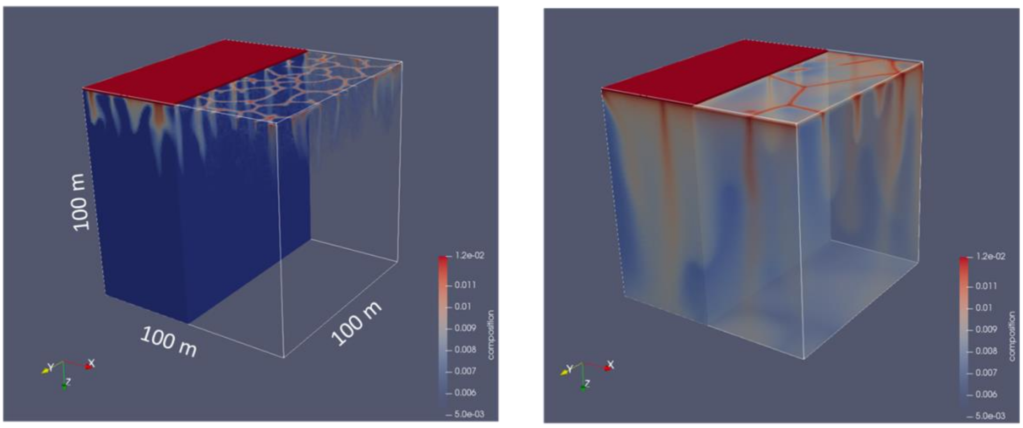

Figure 5. *Full-physics simulation of enhanced CO_2 dissolution and related gravity fingering, showing CO2 concentration after 50 years (left) and 1000 years (right) using the Delft Advanced Research Terra Simulator (DARTS) framework (https://darts.citg.tudelft.nl/).*

Future work

We have the capability to undertake multiscale characterisation and modelling for flow and storage of CO_2, by integrating novel modelling tools into, and adapting, existing reservoir modelling workflows. Our approach will: (1) leverage understanding of stratigraphic processes and products to represent key heterogeneities in reservoir models; (2) embed prototyping and gains in computational efficiency to rapidly construct and interrogate reservoir models; and (3) integrate simulation of CO_2-specific trapping mechanisms over relevant spatial and time scales. Watch this space!

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