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FAST SCREENING ASSESSMENTS OF THE IMPACT OF SEDIMENTOLOGICAL HETEROGENEITY ON CO2 MIGRATION AND STORAGE

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Summary

We use a method combining experimental design, sketch-based reservoir modelling, and flow diagnostics to rapidly screen the impact of sedimentological heterogeneities on CO2 migration and storage by stratigraphic trapping. Experimental design allows efficient exploration of a wide parameter space, sketch-based modelling enables rapid construction of deterministic models of interpreted geological scenarios, and flow diagnostics provide computationally cheap approximations of full-physics, multiphase simulations that are reasonable for many subsurface-flow conditions. Integrated sketch-based reservoir modelling and flow diagnostics are implemented in open source research code (Rapid Reservoir Modelling, RRM). The method is applied to two case studies: (1) the Triassic Sherwood Sandstone Group and Bunter Sandstone Formation, UK, which comprise fluvial-aeolian sandstones, floodplain and sabkha heteroliths, and lacustrine mudstones; and (2) the Jurassic Johansen and Cook formations, offshore western Norway, which record progradation of a wave-dominated delta system. Results for the two case studies are compared using effective permeability (kx, ky, kz) and pore volume injected at breakthrough time (a measure of how much injected fluid is stored in the model volume as a result of stratigraphic trapping).

Fast Screening Assessments of the Impact of Sedimentological Heterogeneity on CO_2 Migration and Storage

Introduction

Sedimentological heterogeneity that reduces permeability in CO_2 storage units can be important in two ways: (1) it disperses CO_2 and thus decreases the rate at which the CO_2 plume reaches the limits of the storage site, and (2) it creates small-scale stratigraphic trapping configurations that increase storage efficiency. Sedimentological heterogeneity occurs across multiple length scales and is sparsely sampled in the subsurface, resulting in uncertainty in the types, distribution and effects of such heterogeneity. In this paper, we use a method for fast screening of static and dynamic reservoir parameters to assess the impact of sedimentological heterogeneity on CO_2 migration and storage.

Method

The screening method combines three key elements: (1) experimental design, which allows efficient exploration of a wide parameter space; (2) sketch-based reservoir modelling, which enables rapid construction of deterministic models of interpreted geological scenarios, and (3) flow diagnostics, which provide computationally cheap approximations of full-physics, multiphase simulations that are reasonable for many subsurface-flow conditions. The method allows a large number of geological scenarios to be explored in a fast, efficient manner prior to more detailed follow-up studies.

In the two case studies outlined below, we used a two-level fractional-factorial design (2_{IV}^{8-3}), in which each factor (heterogeneity) is assigned either a low or high setting. Settings are chosen to represent contrasting, but realistic, values for each heterogeneity, based on outcrop-analogue and subsurface data. This experimental design requires only 32 models to be constructed for each case study. The hierarchical spatial arrangement of the studied heterogeneities is conceptualised in cross-sections, maps and/or 3D block diagrams (e.g. Figure 1), which are then used to guide sketch-based model construction (e.g. Figure 2). Sketch-based modelling and integrated flow diagnostics are implemented in user-friendly, open-source research code (Rapid Reservoir Modelling, RRM; Jacquemyn et al. 2021). Geological architectures and heterogeneities (e.g. stratigraphic surfaces, facies-association boundaries, sandbody boundaries) are represented by surfaces that define and bound geological domains. Models are generated without reference to an underlying grid, although a grid is created to visualise them or to perform numerical calculations (e.g. flow diagnostics). Models lack faults and tectonic dip in order to isolate the effects of sedimentological heterogeneity. Flow was simulated in south-to-north and west-to-east orientations between a single injection and a single offtake well (e.g. Fig. 2B). Volumetric and flow-diagnostic calculations for different models are compared using: (1) total pore volume, which describes the maximum potential for fluid storage; (2) effective permeability, computed for the model volume in three major directions (x, y, z) using flow-based upscaling with no-flow boundaries; (3) dynamic Lorenz coefficient; and (4) pore volume injected at breakthrough time, which provides a measure of how much injected fluid is stored in the model volume as a result of stratigraphic trapping (e.g. Figure 3).

Example 1: Sherwood and Bunter Sandstones, UK

The Triassic Sherwood Sandstone Group and lithostratigraphically equivalent Bunter Sandstone Formation are under appraisal for CO_2 storage in depleted hydrocarbon reservoirs of the Liverpool Bay area, East Irish Sea and in the saline aquifer of the Endurance storage site, southern North Sea. These storage units consist of fluvial sandstones with subordinate aeolian sandstones, floodplain and sabkha heteroliths, and lacustrine mudstones. Eight heterogeneities were investigated: (1) thickness of facies-association layers; lateral continuity of (2) aeolian and (3) lacustrine facies-association bodies; (4) proportion and (5) connectivity of channelised fluvial sandbodies, and (6) lateral continuity of sheetflood sandbodies in floodplain-and-sabkha facies-association layers; and (7) mean vertical spacing and (8) mean lateral extent of carbonate-cemented basal channel lags in fluvial facies-association layers (Figure 1). The low and high settings of investigated sedimentological heterogeneities are summarised in Table 1. Each model represents a small, characteristic part of a storage unit (Figure 2).

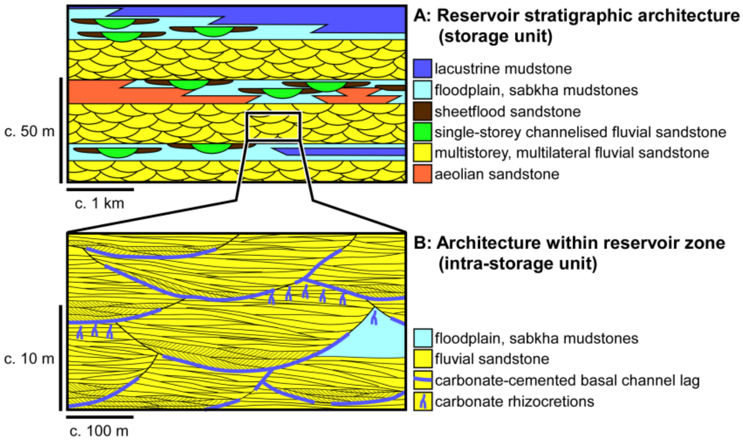

Figure 1. *Interpreted hierarchy of heterogeneities across a range of length scales for the Sherwood Sandstone Group and Bunter Sandstone Formation.*

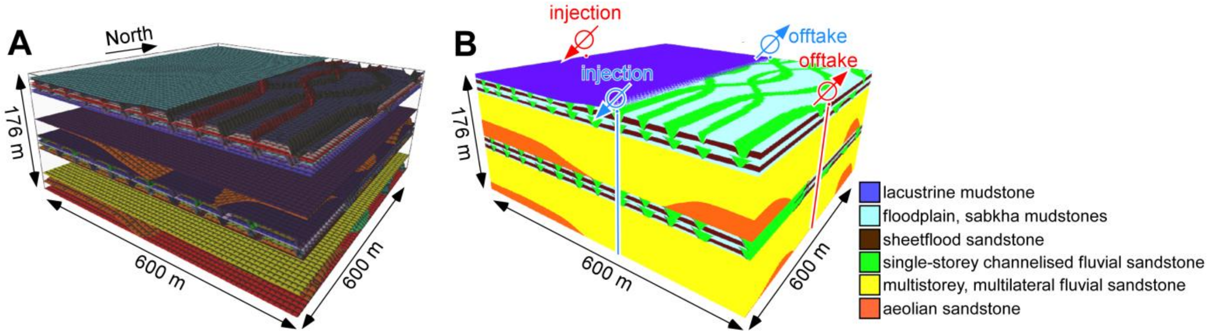

Figure 2. *3D perspective views of a representative model showing: (**A**) sketch-generated surfaces; (**B**) surface-bounded geological domains and well placements for south-to-north (blue) and west-to-east (red) tracer flow.*

Sedimentological heterogeneity (factor)	**Low setting**	**High setting**
thickness of facies-association layers	thin (fluvial: 10 m, aeolian: 5 m, floodplain/sabkha: 5 m, lacustrine: 2 m)	thick (fluvial: 40 m, aeolian: 25 m, floodplain/sabkha: 20 m, lacustrine: 5 m)
lateral continuity of aeolian facies-association bodies	discontinuous lense	continuous sheet
lateral continuity of lacustrine facies-association bodies	discontinuous sheet	continuous sheet
proportion of channelised fluvial sandbodies in floodplain/sabkha facies-association layers	low (c. 17%)	high (c. 33%)
lateral connectivity of channelised fluvial sandbodies in floodplain/sabkha facies-association layers	isolated clusters of channelised sandbodies	connected network of channelised sandbodies
lateral continuity of sheetflood sandbodies in floodplain/sabkha facies-association layers	continuous sheet	discontinuous lense
mean vertical spacing of carbonate-cemented basal channel lags in fluvial facies-association layers	2 m	10 m
mean lateral extent of carbonate-cemented basal channel lags in fluvial facies-association layers	8 m	20 m

Table 1. *Investigated sedimentological heterogeneities (factors) and their low and high settings.*

The predominant control on effective horizontal permeability is the lateral continuity of high-permeability aeolian-sandstone intervals (Figure 3A). Effective vertical permeability is controlled by the lateral extent, thickness and abundance of lacustrine-mudstone layers and aeolian-sandstone layers, and the mean lateral extent and mean vertical spacing of carbonate-cemented basal channel lags in fluvial facies-association layers. Pore volume injected at breakthrough time is controlled largely by three heterogeneities, in order of decreasing impact: (1) the lateral continuity of aeolian-sandstone intervals; (2) the lateral extent of lacustrine-mudstone layers, and (3) the thickness and abundance of fluvial-sandstone, aeolian-sandstone, floodplain-and-sabkha-heterolith and lacustrine-mudstone layers (Figure 3B).

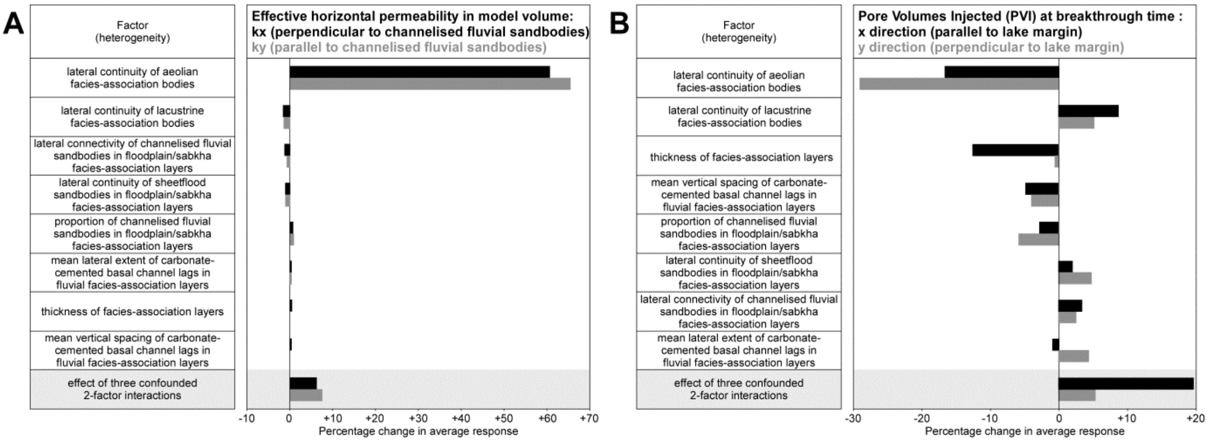

Figure 3. *Tornado charts showing the average percentage changes in (**A**) effective horizontal permeability in west-east (k_x) and north-south (k_y) orientations, and (**B**) pore volume injected at breakthrough time that result from varying each factor from its low to high settings (Table 2).*

Example 2: Johansen and Cook Formations, Northern Lights Project, Offshore Norway

The saline aquifers of the Jurassic Johansen and Cook formations constitute the main CO_2 storage unit in the Northern Lights storage site, offshore western Norway. The Johansen-Cook storage unit records westward progradation of a wave-dominated delta system that at times developed a contiguous southward-accreting spit (Sundal et al. 2016) or southward-deflected subaqueous delta-front clinoforms (e.g. in overlying Sognefjord Formation, Troll Field) (Patruno et al. 2015). Eight heterogeneities were investigated: (1) delta planform geometry; (2) clinoform dip; (3) interfingering extent of facies associations down clinoforms; (4) lateral continuity, (5) lateral extent and (6) vertical spacing of carbonate-cemented concretions; (7) mudstone-drape continuity and extent in cross-bedded, proximal delta-front sandstones; and (8) bioturbation intensity. The low and high settings of investigated sedimentological heterogeneities are summarised in Table 2. Each model represents part of the storage unit (Figure 4).

Sedimentological heterogeneity (factor)	**Low setting**	**High setting**
planform geometry	westward-prograding, arcuate delta	southward-deflected, elongate delta
clinoform dip	gentle (1˚)	steep (3˚)
lateral continuity of carbonate-cemented concretions along transgressive surfaces and maximum flooding surfaces	c. 100 m	c. 1000 m
dip extent of facies interfingering down clinoforms	small (10-150 m)	large (100-250 m)
mean vertical spacing of carbonate-cemented concretions in between transgressive surfaces	1 m	6 m
mean lateral extent of carbonate-cemented concretions in between transgressive surfaces	5.1 m (Frewens Sandstone outcrop analogue)	32.7 m (Bridport Sand Formation outcrop analogue)
mudstone drape continuity and extent in heterolithic cross-bedded sandstones (FA4, FA5)	sandstone proportion = 1.00, k_v/k_h ratio = 1.0	sandstone proportion = 0.97, k_v/k_h ratio = 0.1
bioturbation intensity	less bioturbated; k_h = arithmetic mean	more bioturbated; $k_h = k_v$ = geometric mean

Table 2. *Investigated sedimentological heterogeneities (factors) and their low and high settings.*

Most of the investigated heterogeneities influence the flow-diagnostics results (Figure 5). Heterogeneities that control the distribution and connectivity of high-permeability medial and proximal delta-front sandstones (i.e. delta planform geometry, clinoform dip, and facies-interfingering extent along clinoforms) significantly impact effective horizontal and vertical permeability (Figure 5A) and pore volumes injected at breakthrough time (Figure 5B). In addition, the lateral continuity of carbonate-cemented concretionary layers along transgressive surfaces strongly influences effective vertical permeability, and bioturbation intensity significantly impacts effective horizontal and vertical permeability. Heterogeneities acting in combination are also influential (Figure 5).

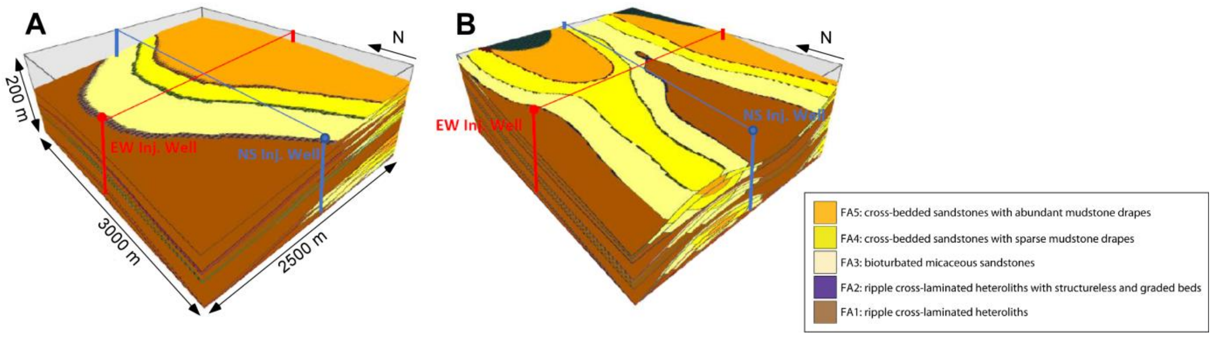

Figure 4. *3D perspective views of models with stratigraphic architectures characterised by: (**A**) an arcuate planform geometry, gentle clinoform dip, and large interfingering extent (Table 4); and (**B**) an elongate planform geometry, steep clinoform dip, and small interfingering extent (Table 4).*

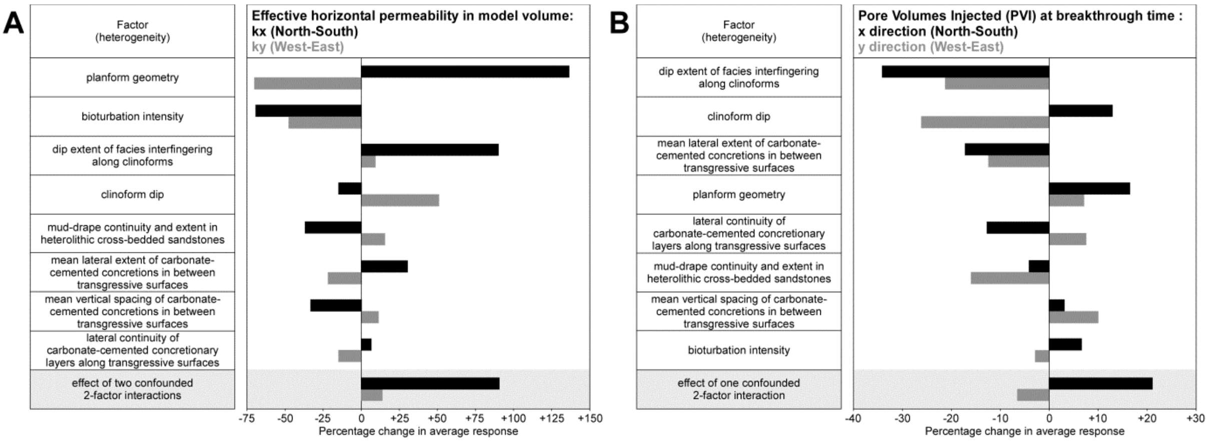

Figure 5. *Tornado charts showing the average percentage changes in (**A**) effective horizontal permeability in north-south (k_x) and west-east (k_y) orientations, and (**B**) pore volume injected at breakthrough time that result from varying each factor from its low to high settings (Table 4).*

Conclusions

The two case studies demonstrate that the screening method presented here is effective in rapidly identifying and ranking key sedimentological heterogeneities that influence CO_2 migration and stratigraphic-trapping potential. The effects of sedimentological heterogeneity vary according to depositional environment and architecture, which are readily incorporated in sketch-based models.

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