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Efficient Multiscale Reservoir Characterisation and Effective Property Estimation using Sketch-Based Modelling and Flow Diagnostics

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Summary

We describe an efficient and novel method to characterise multiscale geological heterogeneity and its effects on fluid flow using an open-source, sketch-based modelling and flow diagnostics tool (Rapid Reservoir Modelling. RRM). The method has three aims: (1) to generate a nested hierarchy of geologically accurate models of sedimentological heterogeneity at different scales; (2) to determine the representative elementary volume (REV) for each heterogeneity style, in order to calculate effective properties for larger scale models; and (3) to evaluate the impact of sedimentological heterogeneity on fluid flow and trapping in the hierarchy of geological models. The sketch-based modelling approach enables the construction of multiple geometrically accurate geological models and allows us to analyse them quickly using flow diagnostics and simulation tools. We illustrate this approach using examples from Triassic fluvial sandstones of the UK (Bunter Sandstone and Sherwood Sandstone), which host groundwater and geothermal resources and are targets for carbon capture and storage (CCS).

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Introduction

Subsurface geoenergy applications (e.g. carbon capture and storage, CCS; H_2 and gas storage; geothermal; hydrocarbon production) use geomodels to estimate resource volumes, to plan for production and/or injection of fluids, and to minimise and mitigate risk due to geological uncertainty. In many cases, these tasks require understanding and prediction of how geological heterogeneity affects fluid flow across multiple spatial scales. Best practice is to construct a nested hierarchy of geological models that encapsulate the geological heterogeneity at appropriate scales, and to derive effective properties that capture the effects of heterogeneities that characterise each hierarchical scale (Nordahl & Ringrose 2008). However, this approach is too time-consuming and computationally expensive to be practical using conventional modelling tools and workflows. Here we use an open-source, sketch-based modelling and flow diagnostics tool (Rapid Reservoir Modelling. RRM) (Jacquemyn et al. 2021; Petrovskyy et al. 2023) to address three aims: (1) to generate a nested hierarchy of geologically accurate models of sedimentological heterogeneity at different scales; (2) to determine the representative elementary volume (REV) for each heterogeneity style, in order to calculate effective properties for larger scale models; and (3) to evaluate the impact of sedimentological heterogeneity on fluid flow and trapping in the hierarchy of geological models. The sketch-based modelling approach enables the construction of multiple geometrically accurate geological models and allows us to analyse them quickly using flow diagnostics and simulation tools. We illustrate this approach using examples from Triassic fluvial sandstones of the UK (Bunter Sandstone and Sherwood Sandstone), which host groundwater and geothermal resources and are targets for CCS (Hossain et al. 2024a, 2024b).

Method

Rapid Reservoir Modelling (RRM) integrates intuitive, sketch-based interface and modelling, with geological operators and a flow diagnostics module. Sketches drawn on one or more 2D vertical cross sections and horizontal slices are combined into 3D surfaces (Jacquemyn et al. 2021) (Figure 1). Geological operators ensure correct truncation relationships between these 3D surfaces by the modelling engine. The flow diagnostics module allows users to assign petrophysical properties to geological domains and then computes metrics (e.g. volumes, time-of-flight, breakthrough times, flow-based effective permeability) to assess how the sketched geological heterogeneity impacts flow patterns (Petrovskyy et al. 2023). Flow diagnostics rely on a reduced-physics, single-phase pressure solution to calculate key flow properties in a rapid, computationally efficient manner.

After constructing a model, the lowest model resolution that captures the continuity and connectivity of laminae and beds of contrasting permeability is determined. Effective permeability is calculated in three orthogonal directions in the model, corresponding to depositional dip (k_d), depositional strike (k_s), and vertical (k_v) directions. The number of grid cells is increased (thus increasing model resolution) until values of k_d, k_s, and k_v converge to a stable value at the minimum grid resolution required to capture the heterogeneity that is characteristic of a particular model (Figure 2A).

The initial sketch-based model of a particular facies is large relative to the heterogeneities that are characteristic of that facies (e.g. foreset-lamina extent in a planar cross-bed set; Figure 1D). To find the REV dimensions in the depositional dip, depositional strike, and vertical directions, the sides of the initial model that are perpendicular to the direction of interest are progressively cropped, to generate a sub-volume of the model, and the effective permeability in all three directions is calculated for the model sub-volume. Effective permeability was then plotted against the model dimension in the direction of interest (Figure 2B-D). At small volumes, effective permeability shows oscillations due to non-representative sampling of heterogeneities. At progressively larger volumes, the oscillations in effective permeability decrease in amplitude, and measurements of effective permeability stabilize. The model sub-volume at which values of effective permeability stabilize is identified as the REV, which is sufficiently large to characterise the heterogeneity of the facies (Figure 2B-D).

Construction and REV analysis of a typical, sketch-based model is completed within several hours, illustrating the practical viability of our multiscale modelling approach.

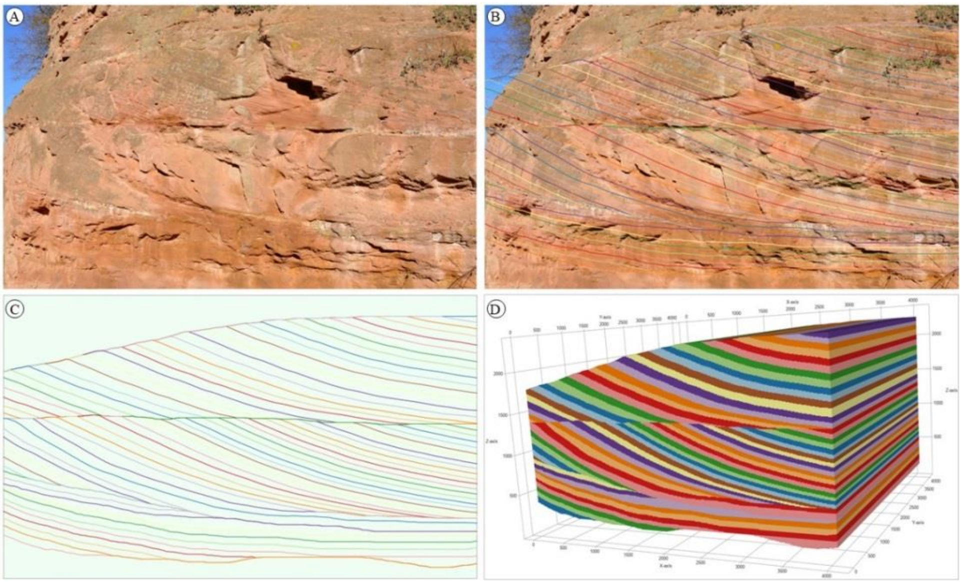

Figure 1. *Construction of sketch-based 3D model, using the example of planar cross-bedded sandstone facies (after Hossain et al. 2024b).* ***A****) Outcrop photo of planar cross-bedded sandstone facies in outcrop analogue;* ***B****) lines sketched over cross-set bounding surfaces and foresets in photo, and* ***C****) with photo removed; and* ***D****) 3D model with sketched surfaces extrapolated perpendicular to the plane of the photo.*

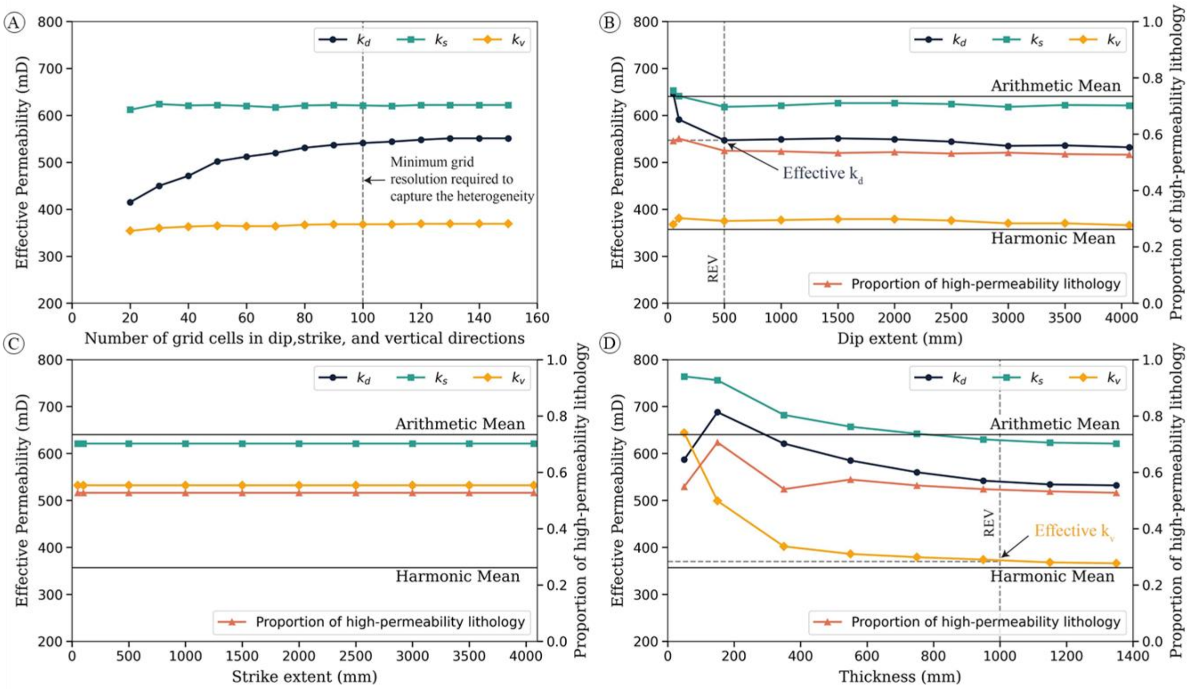

Figure 2. *Plots illustrating how appropriate model resolution and REV dimensions are determined, exemplified by the model of planar cross-bedded sandstone facies (Figure 1) (after Hossain et al. 2024b).* ***A****) Effective permeability in the depositional dip (k_d), depositional strike (k_s) and vertical (k_v) directions plotted against the number of grid cells in the dip, strike and vertical directions, to establish the minimum grid resolution that captures characteristic heterogeneity. Vertical dashed line shows the minimum resolution required to capture the heterogeneity related to this facies.* ***B-D****) Effective permeability (k_d, k_s, k_v) plotted against increasing model dimensions:* ***B****) along depositional dip,* ***C****) along depositional strike, and* ***D****) vertically, to establish REV dimensions. Values of arithmetic*

and harmonic means, and the proportion of high-permeability lithology (clay-poor sandstone in this facies) in each model sub-volume are shown for comparison. Vertical and horizontal dashed lines show the REV dimension and the effective permeability, respectively, along the depositional dip and vertical directions.

Results

Sketch-based models of 12 facies characterised in core and outcrop analogues (Hossain et al. 2024a) were generated (Figure 3) in order to determine their effective permeability in three dimensions (Hossain et al. 2024b). REV analysis shows that the sample volumes required to obtain effective permeability are significantly larger than that of core plugs for most facies (Figure 4). Hence, permeability values obtained from core plugs are not appropriate for most facies.

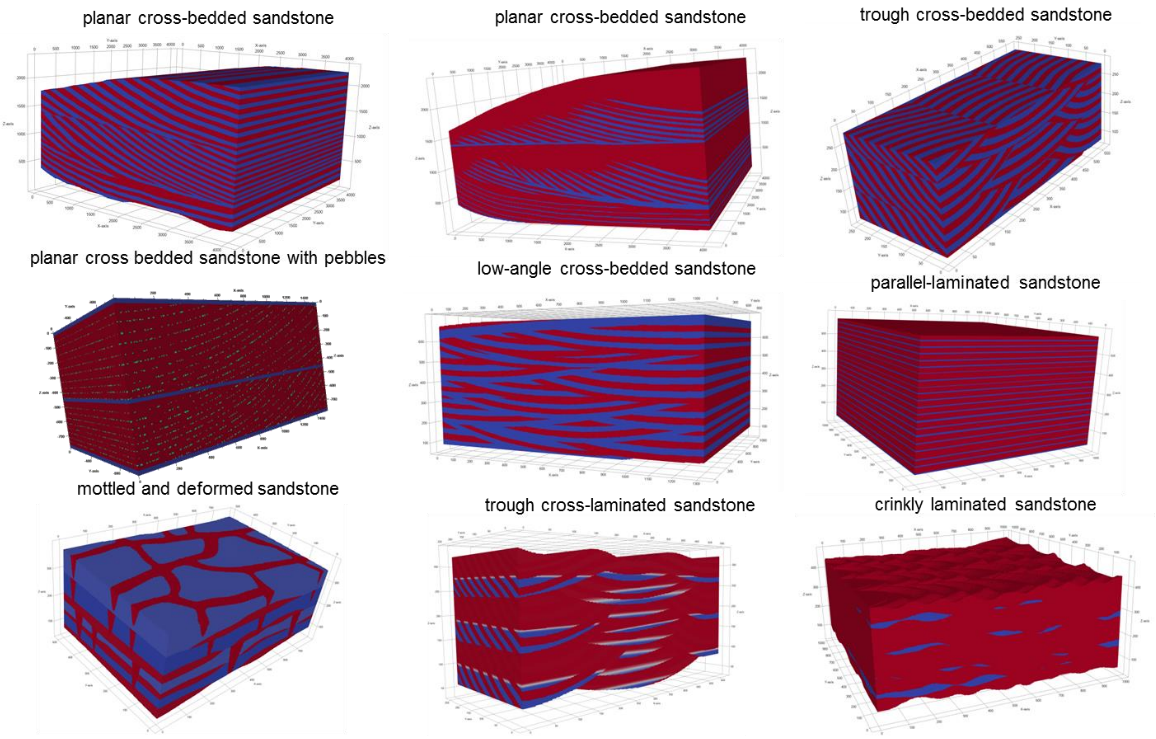

Figure 3. *Perspective views of sketch-based 3D models of selected facies in the Bunter Sandstone and Sherwood Sandstone (after Hossain et al. 2024b). High-permeability (e.g. clay-poor sandstones) and low-permeability (e.g. clay-rich sandstones) are shown in red and blue, respectively.*

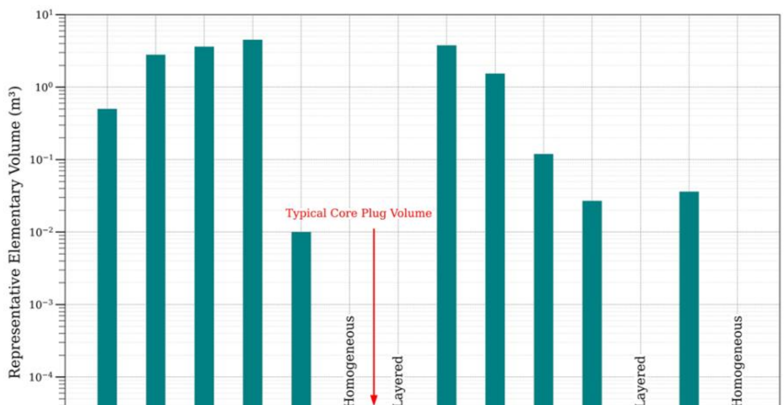

Figure 4. *REV volumes of different facies (e.g. Figure 3). The red line shows the volume of a typical core plug.*

Ongoing Work

The effective permeability values derived for facies REVs are being used in larger-scale models of facies associations and architectural elements. It is likely that multiscale variations in effective permeability, from facies to reservoir scales, create significant baffles to flow that may influence groundwater movement and heat transport, and aid stratigraphic baffling and trapping of CO_2 in storage reservoirs. Preliminary results indicate that facies can be grouped into two or three categories in models of facies associations and architectural elements, thus helping to guide future data collection and reservoir characterisation effort.

CO_2 trapping is being further investigated by extending flow diagnostics to calculate effective permeability and capillary pressure for two-phase immiscible flow assuming capillary equilibrium. This assumption is reasonable at small scales (e.g. facies, facies associations) in regions that are not close to injection or offtake wells. Under such conditions, phase saturation is controlled by local capillary pressure, and can thus be very rapidly calculated.

Conclusions

Sketch-based modelling is an approach to generate 3D geological models quickly and intuitively, sketched over data or based on concepts. Models can be sketched at multiple spatial scales, and effective properties of small-scale models can be robustly estimated using flow diagnostics and used to populate larger scale models. Fast model construction and analysis enables the effects of geological heterogeneity to be investigated in a nested hierarchy of geological models at timescales that are practical for reservoir modelling projects, as in the examples shown for the Bunter Sandstone and Sherwood Sandstone.

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