Surface-Based Reservoir Modelling: Concepts and Application to Carbonate Reservoirs*

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Abstract

We present a surface-based approach to constructing models of carbonate reservoirs. In this approach, all geologic heterogeneity, whether structural, stratigraphic, sedimentologic or diagenetic, that impacts on the spatial distribution of petrophysical properties is modelled as one or more discrete volumes bounded by surfaces. The modelled surfaces can be deterministically interpolated between control lines or points, or incorporate a stochastic element where control data are sparse. Models constructed from surfaces are not constrained by an underlying grid; indeed, the model is generated without reference to a grid. The only difference between 'geologic' and 'simulation' models is that the latter incorporates a grid (or mesh) to allow numerical solution of the governing flow equations, with the grid architecture driven by the architecture of the modelled surfaces. The construction of a grid around surfaces that describe geologic heterogeneity results in more accurate and efficient capture of complex heteroegenity geometries and distributions, relative to current modelling practice of representing most geologic heterogeneity on a pre-defined grid. The surface-based approach to gridding (or meshing) is directly compatible with the next generation of unstructured-mesh simulators, and allows the capabilities of the latter to be utilised fully in the modelling of complex reservoir architectures. A surface-based approach to model construction may facilitate a step change in reservoir modelling capabilities, since once the requirement to upscale geologic models to a structured simulation grid is removed, there is no need to build geologic models that are restricted by grid resolution. The application of the surface-based modelling approach to carbonate reservoirs has been carried out as part of the ExxonMobil-sponsored Fundamental Controls on Flow in Carbonates academic alliance.

General Methodology for Surface-Based Modelling

The surface-based modelling methodology is, in principal, simple: numerous surfaces are used to represent key geological heterogeneities prior to generating a grid (or mesh) for flow simulation. Each surface denotes:

1. a fault surface;
2. a stratigraphic surface;
3. a boundary between environments of deposition (EODs), and/or depofacies types within EOD-belts, and/or reservoir rock types (RRTs) within depofacies belts or bodies; or

4. a boundary between different regions of diagenetic modification of rock properties.

The method can be extended to include fractures, but we do not include these in the models described here (e.g. the method is compatible with the discrete fracture network models of Stephan Matthäi, Sebastian Geiger and their respective groups). The surfaces are ranked into a hierarchy based upon relationships that specify which surfaces are truncated by, or conform to, other surfaces. In detail, this hierarchy will depend upon the reservoir being modelled and it should be identified prior to model construction; in general, the hierarchy will be similar to the list order shown in Figure 1. Fault surfaces are at the top of the hierarchy, because these truncate all other surfaces; however, there may be a hierarchy of fault surfaces, that dictates which faults truncate other faults and which are truncated. Stratigraphic surfaces are next in the hierarchy, as these are truncated by faults but truncate EOD and depofacies boundaries. Again, there will be a hierarchy of stratigraphic surfaces. Next are boundaries between EOD belts, then boundaries between depofacies types within EOD belts, then boundaries between RRTs within depofacies belts and bodies. Not all of these subdivisions may be required in a given reservoir model. Each EOD / depofacies / RRT type is modelled sequentially, according to rules that define which surfaces can truncate previously modelled surfaces, and which are truncated by previous surfaces. Similar rules are used in object-based modelling, to define which objects can erode previously modelled objects. Modelling of diagenetic volumes depends upon whether cementation is controlled by structure, stratigraphy, sedimentologic character or a combination of these three factors.

Regardless of the type of heterogeneity they represent, the surfaces can be deterministically interpolated between control lines or points, or incorporate a stochastic element where control data are sparse. Stochastic modelling of fault surfaces is not yet part of the modelling workflow, but is under development. The surfaces used to model stratigraphic, sedimentologic and diagenetic heterogeneity are assumed to be monotonic and close to horizontal, so they can be created and manipulated using standard reservoir modelling formats and software packages. To ensure that these surfaces are suitable for gridding using conventional cornerpoint methods, the following rules must be applied:

1. all surfaces and volumes between surfaces must be continuous across the model;
2. where a volume pinches out, it is still defined but has zero thickness (i.e. the upper and lower bounding surfaces coincide);
3. surfaces cannot cross each other.

Volumes constrained by surfaces constructed in this way can also be meshed using a variety of methods. The resulting surface-based models can capture structural, stratigraphic, sedimentologic and diagenetic heterogeneity, without being limited by the resolution of a grid defined early in the modelling process (e.g. Figure 2). However, prior to flow simulation, they must be gridded or meshed. This step makes use of the modelled surfaces. Each volume bounded by the surfaces is gridded or meshed separately. The simplest approach is to use a standard cornerpoint grid, in which the grid cells are rectangular in plan view, but may deviate from rectangular in cross-section. Such a grid may be suitable for use in conventional flow simulation software if the deviations from orthogonality are not so severe that they introduce numerical artifacts. However, in many models, cornerpoint grids may fail to properly capture the complex surface architecture; moreover, the non-orthogonality in the resulting grid may be severe. In these models, novel meshing approaches will be required for use in the latest flow simulation software (e.g. Figure 2D).

Implicit in this approach is the assumption that upscaling from ‘geologic’ to ‘simulation’ model is not required. The two models are identical except that in the former, no grid or mesh has been defined within the reservoir volume. Upscaling can be avoided in models gridded and simulated using conventional methods only if the use of surface-based modelling and cornerpoint grids allows the modelled heterogeneity to be captured using fewer grid cells than a conventional, grid-based approach. However, even this approach may not yield models that can be directly flow simulated in many cases, and a more sophisticated approach to meshing is called for.

A more efficient use of computational effort is to adapt the mesh in space and time to be refined where necessary, and coarse elsewhere. Our surface-based modelling approach allows adaptive meshing to be used in reservoir simulation without requiring petrophysical properties to be upscaled each time the mesh is changed, so long as the mesh is coarsened or refined only within the volumes defined by the surfaces. Petrophysical properties are constant within these volumes. Initially, the surfaces are meshed as coarsely as possible whilst preserving their architecture to a pre-defined tolerance. Where necessary, the mesh is refined to capture flow and petrophysical properties are simply assigned to new mesh elements based on the volume within which they are located. Once the saturation front or other flow feature of interest has passed, the mesh is coarsened again.

Hierarchy of Surface-Defined Stratigraphic, Sedimentologic and Diagenetic Heterogeneity in Carbonate Reservoirs

Implementation of the surface-based modelling approach requires the definition of a hierarchical arrangement of surfaces that bound discrete rock volumes of uniform petrophysical properties (cf. surfaces 1-11 in Figure 1). Conceptualizing this hierarchy of surfaces and associated heterogeneities is thus a critical first step in model construction. Figure 3 shows a seven-level hierarchy of stratigraphic, sedimentologic and related diagenetic heterogeneities which can be used for developing surface-based geologic and simulation models of carbonate reservoirs, based on a homoclinal ramp for illustrative purposes.

The large-scale levels of the hierarchy (Levels 1-3; Figure 3A-C) describe stacking of transgressive-regressive stratigraphic cycles, and are based on a hierarchical sequence stratigraphic framework. For simplicity, we refer here to three superimposed orders of stratigraphic cycles, but we recognize that in some cases additional orders of cycles may be present. Modelled surfaces include stratigraphic discontinuities (e.g. sequence boundaries, flooding surfaces), which control the distribution of EOD belts, and EOD-belt boundaries. Stratigraphic heterogeneities at these scales are commonly represented deterministically in conventional reservoir-modelling workflows (e.g. based on one or more interpreted scenarios of seismically resolved stratal geometries, combined with well-log correlations).

The intermediate-scale levels of the hierarchy describe the distribution of depofacies belts and bodies within EOD belts (Level 4; Figure 3D), and the distribution of beds within depofacies volumes (Level 5; Figure 3E). Sedimentologic heterogeneity at these scales controls the diagenetic potential of the rocks. Modelled surfaces include depofacies-belt and depofacies-body boundaries (Level 4), bed boundaries, and diagenetic-body boundaries (Level 5). Heterogeneities at the scale of depofacies belts and bodies (Level 4) tend to be portrayed schematically in sequence stratigraphic and facies models (e.g. “shazam lines” representing interfingering of depofacies belts) and are commonly represented using geostatistical tools in conventional reservoir-modelling workflows. However, much heterogeneity at these scales is governed by bed-scale stratigraphic architecture. Reservoir rock types (RRTs) are defined at bed scale (Level 5) according to lithologic composition and diagenesis (including burial history); they correspond to the petrophysical rock types identified using core-plug data.

The small-scale levels of the hierarchy (Levels 6-7; not shown in Figure 3) focus on the distribution of sedimentary structures, grain types, and bioturbation fabrics between bed boundaries (Level 6), and on the microscopic variation of pore types and their connectivity within individual beds and laminae (Level 7). These heterogeneities define relative permeability and capillary effects within RRTs. Such small-scale heterogeneities cannot be explicitly represented in reservoir simulation models, but their effects on flow can be represented using upscaling techniques applied to volumes of a specific RRT.

Challenges in Application

From a conceptual standpoint, the surface-based hierarchy of heterogeneity and surface-based modelling methodology outlined above are both simple. However, there are significant challenges in applying them, particularly to sparse subsurface data:

1. Identification of the appropriate level of the hierarchy to apply to interpretation of a particular dataset or its constituent parts. The number, extent and geometrical arrangement of surfaces will be determined by the level of the hierarchy that is applied;
2. Definition of discrete surfaces within (apparently) continuous geologic data. For example, a gradational boundary between depofacies belts must be represented by a surface(s) across which there is an abrupt change in petrophysical properties. As noted above, many gradational boundaries of this type are in fact governed by surface-defined stratigraphic architectures at spatial scales that are smaller than grid blocks in conventional reservoir modelling methods (and, indeed, smaller than scales considered in conceptual stratigraphic models);
3. Fracture-network and burial-related diagenetic heterogeneities are currently poorly conceptualized in the context of stratigraphic and sedimentologic heterogeneities, although the surface-based modelling approach is sufficiently flexible to integrate all of these heterogeneity types. One way forward may be to develop geomechanical models that integrate stratigraphic, sedimentologic and environment-related diagenetic heterogeneities with burial history, in order to predict fracture-related heterogeneity for reservoir models. Interactions between various heterogeneity types may be important in developing meaningful predictions of heterogeneity architecture for reservoir flow simulation;
4. Rapid construction of reservoir models using the surface-based approach will likely require the selection of templates of surface configuration from a pre-existing library, combined with automated grid (or mesh) construction for flow simulation;
5. Flow-simulation of complex, surface-defined geometries will not be possible with conventional cornerpoint grids, and adaptive gridding approaches must be used instead.

The first three of these challenges are not specific to surface-based modelling, but arise from uncertainty in geologic interpretation and gaps in fundamental geologic understanding; they are common issues for any approach to reservoir modelling.

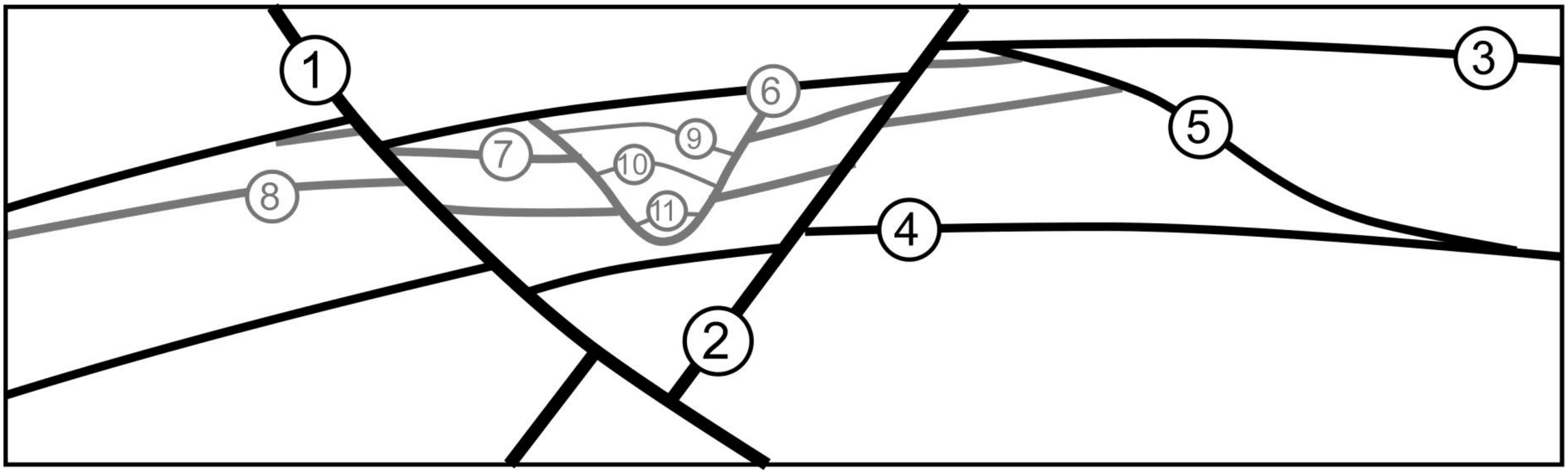

Figure 1. Example surface hierarchy. Fault surfaces (1) and (2) are at the top of the hierarchy; surface (1) is above (truncates) surface (2). Stratigraphic surfaces (3), (4) and (5) are at the next level of the hierarchy; surfaces (3) and (4) are above (truncate) surface (5). EOD-belt boundaries (6), (7) and (8) are at the next level of the hierarchy; surface (6) is above (truncates) surfaces (7) and (8). Depofacies boundaries (9), (10) and (11) are at the lowest level of the hierarchy. RRTs, which are a combination of depofacies and diagenetic overprint, and facture networks, occur at smaller scales than represented in the figure, and are not shown for clarity.

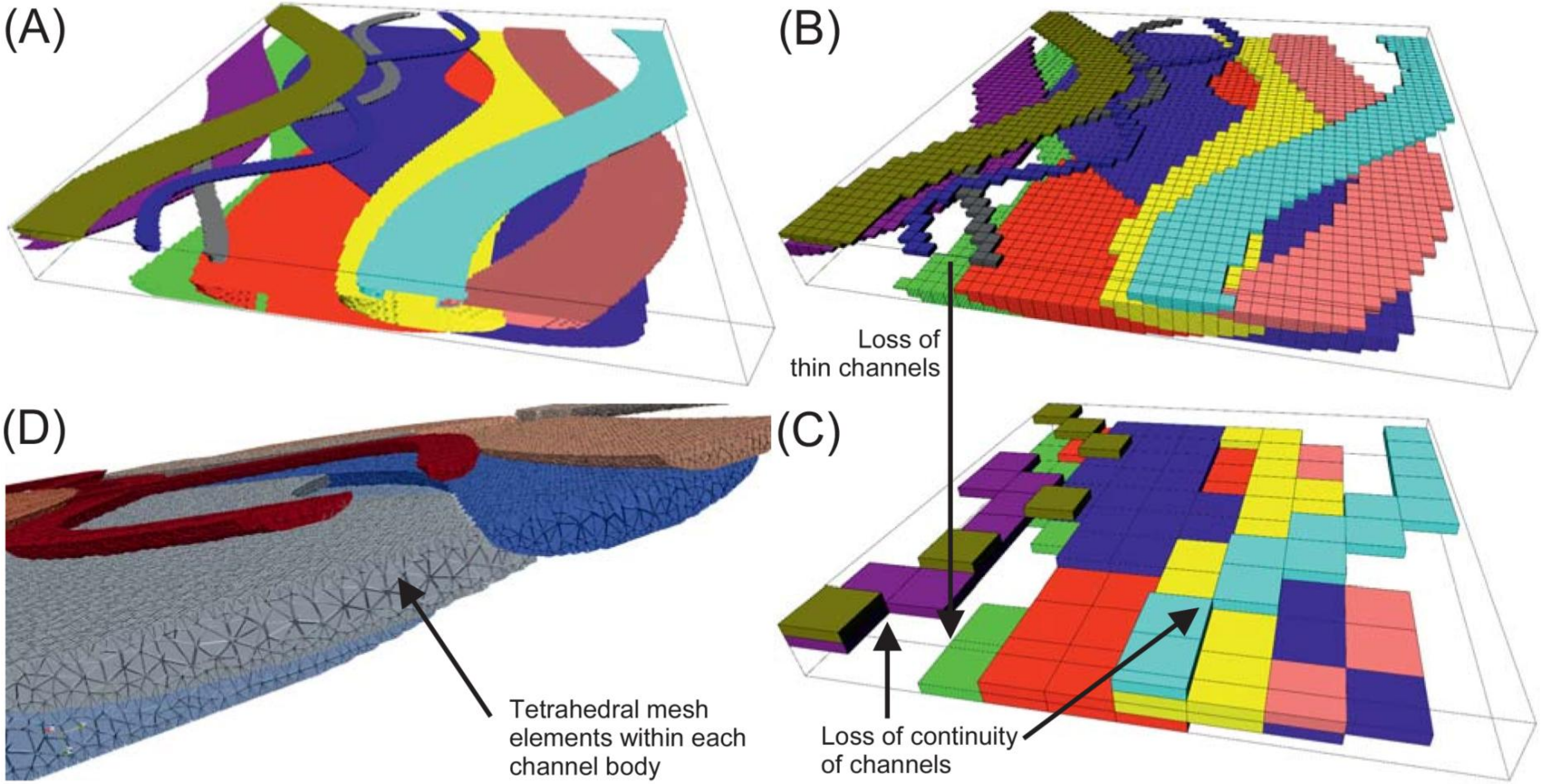

Figure 2. 3D models of channelized geobodies in a non-channelized background. Individual geobodies are colour coded and the background is transparent, for clarity. (A) Surface-based model; each channelized geobody is defined by an upper and lower surface. (B) Grid-based model constructed using an object-based approach on a fine grid; geobodies are reasonably well captured but with a 'stair-step' geometry along their bases. (C) Grid-based model constructed using an object-based approach on a coarser grid; many small geobodies lie below the grid resolution so are not captured in the model, while the connectivity of larger geobodies has not been preserved owing to the lack of 'face-to-face' contacts between grid blocks. This is a typical problem in grid-based reservoir modelling. (D) Close-up view of part of the surface-based model, meshed with tetrahedral elements. The element size and shape is adapted to capture the varying size of the channelized geobodies, and the non-reservoir background is not meshed, as it does not contribute to flow. Thus the complex geobody architecture is well preserved with efficient use of mesh elements.

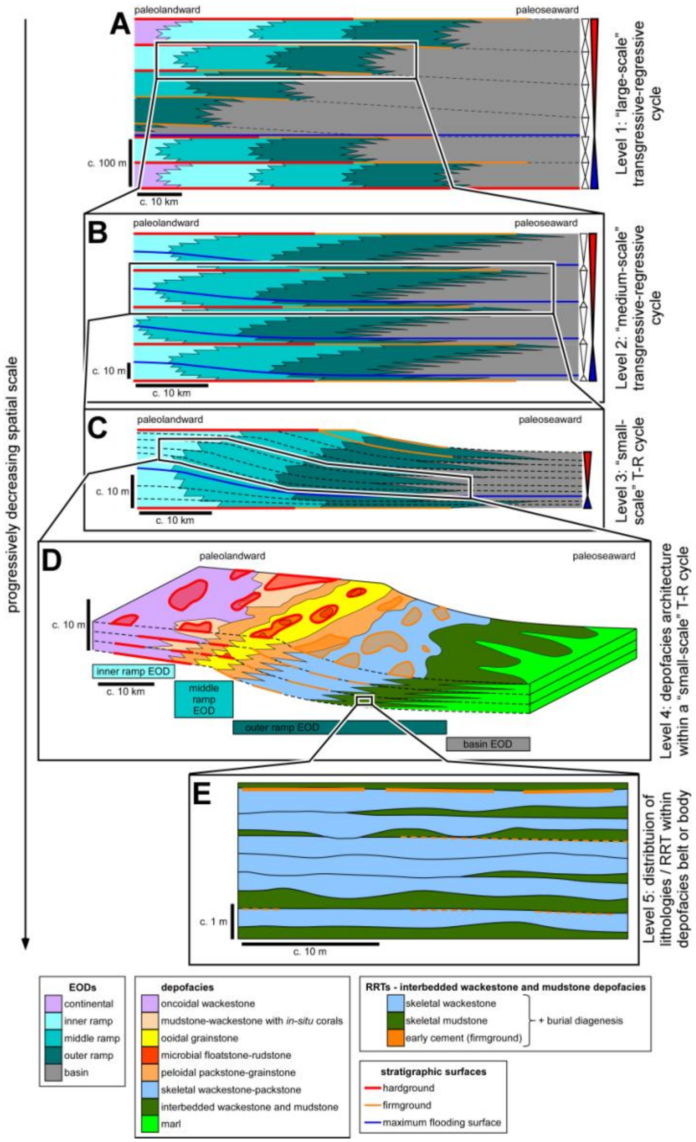

Figure 3. Generic hierarchy of heterogeneities within carbonate reservoirs across a range of length-scales, illustrated using a homoclinal ramp; (A) Level 1: “large-scale” transgressive-regressive stratigraphic cycle, (B) Level 2: “medium-scale” transgressive-regressive stratigraphic cycle, (C) Level 3: “small-scale” transgressive-regressive stratigraphic cycle or parasequence, (D) Level 4: depofacies architecture within a single parasequence, (E) Level 5: bed-scale distribution of RRTs in depofacies belt or body. Levels 6 and 7, respectively intra-bed architecture and pore networks, are not shown here.