Quantifying the Impact of Stratigraphic and Sedimentologic Heterogeneities on Flow in Carbonate Reservoirs through Integrated Flow Simulation Experiments*

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Abstract

We present the results of an investigation into how stratigraphic heterogeneities impact on flow in carbonate ramp reservoirs. Although stratigraphic, sedimentologic, and diagenetic heterogeneities in carbonates reservoirs are well documented, the relative influence of different heterogeneities on recovery is poorly understood.

A hierarchy of heterogeneity in carbonate reservoirs (presented separately by Hampson et al.) was used to catalogue the wide range of heterogeneities documented from outcrop and subsurface examples at progressively decreasing length-scales of observation. Using the hierarchy as a framework, surface-based models were constructed at progressively increasing levels of geologic detail, and an analysis of the impact of heterogeneities on flow is completed at each level. This top-down modeling approach, combined with the use of efficient, surface-based grids, avoids the problem of spending too much time constructing a very high-resolution model, which is not appropriate for direct flow simulation. Additionally, as increasing levels of detail are included into the models, simulated production behavior changes so that an understanding is generated of the interpretational details required to capture fluid flow patterns and of which heterogeneities are key in controlling flow. Well placements, fluid properties, and / or relative permeability and capillary pressure models may alter how geologic heterogeneities impact on flow. Additional simulations, incorporating different production schemes and rock type models, were used to identify and understand these effects.

Experiment Design and Model Set-Up

Our modeling experiments use fractional factorial experimental design as a tool to investigate the relative impact of different heterogeneities on a number of flow-based performance criteria. A selection of heterogeneities relevant to hydrocarbon production was chosen from the hierarchy for inclusion in our geologic models. Each heterogeneity is assigned two end-member settings, which are chosen to be representative of a range of documented reservoirs and outcrop analogues (Figure 1 shows the six stratigraphic heterogeneities modeled here, at levels 1-3 of the hierarchy). The experimental design is used to define the combination of heterogeneity settings that are incorporated into the resulting models. This approach allows efficient exploration of the parameter space defined by the end-member settings of the various heterogeneities, and establishes the rank order of heterogeneities that influence the simulated reservoir performance. The results serve as a screening study that can be used to direct effort in subsequent case-specific modeling studies.

Discussion

Surface-based geologic models of an entire carbonate ramp are produced (depositional dip extent of 32 km, depositional strike extent of 8 km, thickness of 230 m) in order to constrain the stratigraphic context of smaller, reservoir-scale models taken from different locations on the ramp (depositional dip and strike extents of 4 km, thickness of 66 m) and used for flow simulation. No structural dip is added to the stratigraphic models.

Petrophysical properties are assigned so that each cell for a given environment of deposition (EOD) belt has a uniform porosity, horizontal permeability and vertical permeability. These properties are obtained from a propriety dataset of standardized values, based on a comprehensive catalogue of rock property measurements from core plugs tied to detailed sedimentologic description.

Recovery is simulated in the reservoir-scale models over 20 years with a waterflood using (a) a single line drive with 4 km well spacing, (b) a repeat line drive with 1 km well spacing, and (c) a five spot pattern with 500 m well spacing for injection and production wells. All three simulated production schemes use vertical wells that are completed over the whole reservoir interval, but the number of wells, well spacing and well positions vary between the schemes. Bottom hole pressure limits for the injection and production wells are used to maintain water injection rate to yield a pressure gradient of 0.5 to 2.0 psi/ft. Though we are aware that the 4 km line drive is unrealistic, requiring large bottom hole pressures to maintain the pressure gradient, it was included as an extreme example of the effect of well placement on production. To investigate the effect of fluid properties and relative permeability/capillary pressure models on the impact of the geologic heterogeneities we ran additional simulations for comparison: (1) a single set of imbibition curves (relative permeability and capillary pressure data) applied to the whole model, or multiple imbibition curves assigned to three permeability classes in the model; and (2) a favorable or an unfavorable mobility ratio, based on increasing the oil viscosity. Total oil and water production, recovery factor and breakthrough time (water cut at 1 %) were used as performance criteria to analyze the impact of individual heterogeneities on production behavior in our experiments.

Simulation Results and Heterogeneity Ranking

The simulation results for the modeled scenarios show a wide range of production behavior over time. Typically, models with large volumes of original oil-in-place are associated with higher oil production. Water production and time to breakthrough are highly variable across the suite of simulated models. The production data alone suggest that the different combinations of heterogeneities represented in the models have a significant impact on flow in carbonate reservoirs.

Results from this analysis show the impact of changing heterogeneity character from one end-member setting to the other (Figure 1). Figure 2 presents the ranking of the six stratigraphic heterogeneities in a homoclinal ramp system as an example.

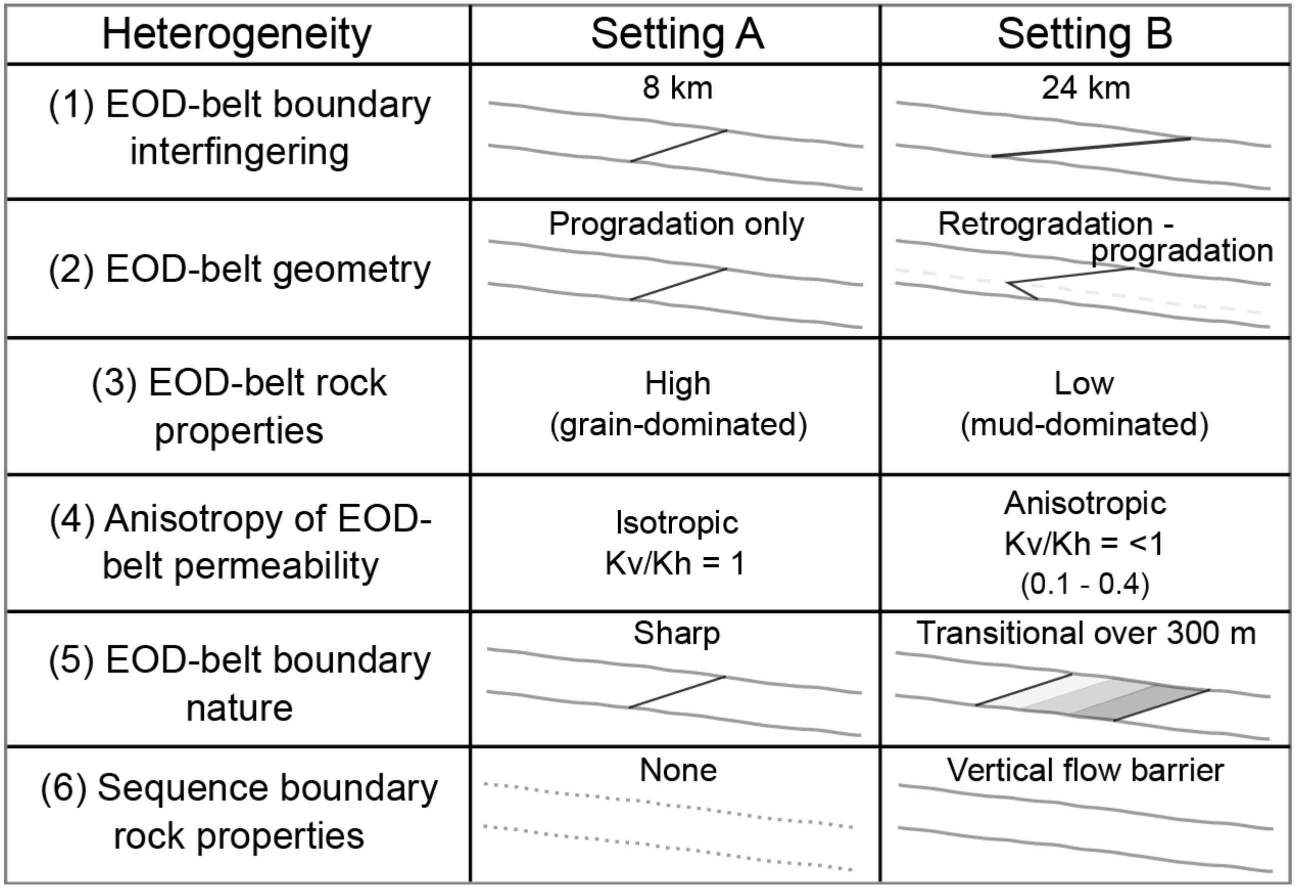
Key findings for stratigraphic heterogeneities are listed below:

- EOD-belt rock properties are consistently the most important heterogeneity influencing flow across all performance criteria. Changing from high to low poro-perm values (Heterogeneity 3; Figure 1) reduces the volume of oil produced and increases the recovery factor (Figure 2), because decreasing EOD-belt rock properties decreases the volume of original oil-in-place by a greater percentage change than the volume of oil produced.
- EOD-belt geometry and interfingering length (Heterogeneities 2 & 1 respectively; Figure 1) have the next most significant impact. Both of these heterogeneities change the stratigraphic architecture of the whole ramp model, resulting in changes to the volume and lateral continuity of the high porosity and high-permeability mid-ramp EOD belt at the reservoir-scale.
- Stratigraphic heterogeneities that influence vertical flow (Heterogeneities 4 – 6; Figure 1) have limited impact on these simulation results, because horizontal flow dominates because of the high lateral pressure gradient imposed by the production scheme.
- Changing the way that relative permeability and capillary pressure are included in simulations, the fluid properties or simulated production scheme has no effect on the rank order of heterogeneities, although slight alterations to the values of the responses are observed.

These results motivate extension of the study to consider sedimentologic heterogeneities at smaller scales (e.g. level 4 of the hierarchy of heterogeneity), and provide a framework within which the impact of these heterogeneities can be quantified. We anticipate that the importance of EOD-belt rock properties and permeability anisotropy will change as detailed depofacies distributions within EODs introduce more tortuous flow paths to the simulation models. Modifying the production scheme to reduce the pressure gradient between injection and production wells and / or to incorporate deviated and horizontal wells is expected to increase the potential for vertical flow within the models. The relative ranking of stratigraphic heterogeneities may change as a result.

Conclusions

Integrating our current investigation of stratigraphic and sedimentologic heterogeneities with research into the impact of diagenetic and structural heterogeneities on flow in carbonate reservoirs will produce a catalogue of what heterogeneities control flow and why. Such a catalogue will provide insights into where efforts should be focused to ensure representative geologic models are constructed and simulated with appropriate production scenarios. Expanding this integrated study, to include enhanced oil recovery (EOR) techniques, carbon dioxide sequestration, and the application of novel gridding and adaptive meshing approaches to geologic and flow simulation models will produce a comprehensive guide for future hydrocarbon production developments.



Heterogeneity	Setting A	Setting B
(1) EOD-belt boundary interfingering	8 km	24 km
(2) EOD-belt geometry	Progradation only	Retrogradation - progradation
(3) EOD-belt rock properties	High (grain-dominated)	Low (mud-dominated)
(4) Anisotropy of EOD-belt permeability	Isotropic Kv/Kh = 1	Anisotropic Kv/Kh = <1 (0.1 - 0.4)
(5) EOD-belt boundary nature	Sharp	Transitional over 300 m
(6) Sequence boundary rock properties	None	Vertical flow barrier

Figure 1. Summary of six stratigraphic heterogeneities selected for inclusion in the geologic models investigated using experimental design methods. EOD = environment of deposition.

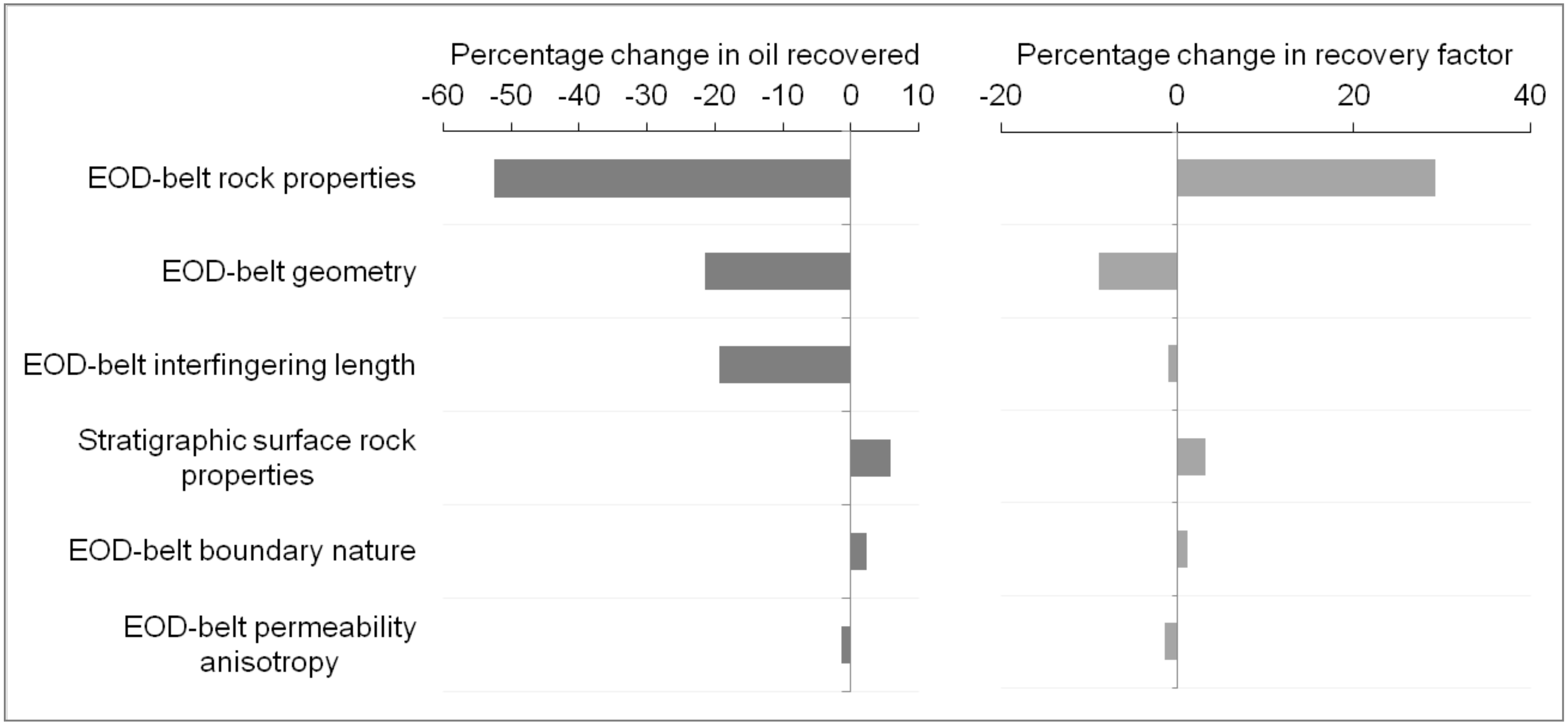


Figure 2. Tornado charts illustrating the impact of changing the six stratigraphic heterogeneities from setting A to B (Figure 1) on (a) total oil production and (b) recovery factor; if an impact is positive then changing the heterogeneity to setting B increases the response (for example more oil is produced).