Fundamental controls on flow in carbonates: an introduction

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BACKGROUND AND RATIONALE

The challenges posed by carbonate reservoirs today have been recognized for decades. ‘Old’ problems include the prediction of heterogeneous carbonate rock properties in the subsurface, the variable wettability of carbonate rocks, and the uneven sweep and early water breakthrough that commonly result from the presence of fractures, karst and/or other heterogeneities providing high-permeability flow paths (Buhnes & Fitting 1945; Craze 1950). While recent shifts in the industry have diverted attention to unconventional resources, conventional carbonate reservoirs remain the largest class of oil resources for the planet. Their recoveries, however, remain relatively low overall (Montaron 2008; Burchette 2012). While new technologies offer a deeper understanding of near-wellbore properties and processes, there remain large uncertainties in the distributions of flow velocities and the nature of flow paths between wells. These uncertainties arise from our inability to delineate geological features over a wide range of length scales, to represent them appropriately in flow simulations, to quantify their impacts on flow, as well as their impacts on evolving multiphase fluid distributions. While we wrestle with suitable proxies for geological heterogeneities that cannot be deterministically resolved in subsurface data or explicitly represented in field-scale reservoir models, many in the industry are forced to rely on long-established simulation technologies that have not kept pace with developments in modelling. In the absence of fully deterministic characterization and representation of the reservoir in our flow-simulation models, we need to mitigate the risks associated with uncertainty. Experiments designed to improve our ability to predict in the subsurface and to explore the range of possible responses can help. Clearly, there is an opportunity to pursue carefully designed subsurface experiments to test hypotheses for flow behaviour. Shallow subsurface experiments have already shown that, even between very closely spaced wells, it can be extremely difficult to define precise flow paths (Nair et al. 2008). Given this flow path uncertainty, we also need to explore a range of possible flow behaviours under reservoir conditions via models that establish a realistic range of scenarios. These scenarios can be derived or ‘inspired’ from both outcrops and the subsurface.

This thematic set brings together a group of papers that capture research advances related to the prediction of carbonate reservoir quality, first-order evaluations of flow behaviours (flow partitioning), and novel methods to evaluate the impact of geological features on flow for one or more scenarios of fluid type and production scheme. Most of these papers grew from outcrop investigations that a range of reasonable scenarios will make for predictions of flow in carbonate reservoirs (Agar 2009). The papers published here and elsewhere represent an unfailing co-operation between multiple university research groups and a major oil company to pursue paradigm shifts and novel research contributions for broad scientific benefit. These exemplary collaborations set high benchmark, and it is the guest editors’ belief that this type of collaboration is critical to the future of the oil and gas industry. With broad industry shifts in ownership of resources, as well as asset type and technological emphasis (Myers Jaffe et al. 2011), there is a clear need for future technologists who are comfortable crossing the geoscience–engineering divide. Both industry and academia have a role to play in realizing this objective and both stand to win, in terms of new commercial insights and novel connections that can re-energise long-established fields of research and academic teaching programmes (e.g. Agar et al. 2013).

OVERVIEW OF PAPERS

The internal organization of many carbonate reservoirs is governed at first order by the development of stratigraphic architectures and associated distributions of environment-of-deposition (EOD) belts. Although these architectures may be substantially modified after deposition, they are present in relict form as the template for diagenetic and structural overprints. Fitch et al. develop a suite of simple models that capture the range of plausible stratigraphic architectures and rock properties at EOD-belt scale for carbonate ramps. They then use these models in conjunction with experimental design techniques to systematically explore the influence of stratigraphic and sedimentological heterogeneities, well placement and completion, fluid properties, and rock types on flow during waterflooding in order to identify and explain which parameters matter for a given scenario. In their experiments, the modelled geology is found to be more important than the simulated fluid properties and production scenarios.

In an effort to develop a predictive understanding of the factors that control the distributions of reservoir rock types and their influence on flow behaviours, Whitaker et al. adopt forward modelling methods combined with streamline simulations. Instead of relying solely on statistics from core plugs and well data, they attempt to ‘fill in’ subsurface stratigraphic architectures and facies distributions using a process-based understanding of the factors influencing porosity and permeability evolution during deposition and early diagenesis. In addition, their study shows how outcrop investigations can be used to ‘inspire’ thinking related to the design and content of reservoir models. In this case, the Triassic Latemar Platform (Dolomites, northern Italy) offered a test for the ability of forward modelling software to reproduce key features of and linkages between stratigraphic architecture, facies distributions, and early diagenetic overprinting. It is emphasized, however, that as for other outcrop-based simulation studies discussed in this issue, the overall aim is not to duplicate every detail of an outcrop but to use the outcrop to guide likely scenarios in the subsurface. Whitaker et al. highlight a novel approach to explore the difference that a range of reasonable scenarios will make for predictions of recovery, and their relationship to diagenetic histories. Their work reinforces the need to consider ways to preserve
extreme high- and low-permeability features that would be otherwise obscured by routine upscaling methods.

A long-lived topic of research, dolomitization, is well known for its potential to impact reservoir properties (Ehrenberg 2004; Gregg 2004; Machel 2004). Yet, the petroleum industry still lacks robust tools to make reliable predictions of the impact of dolomitization on flow paths and overall connectivity between wells. Ideally, one wants to be able to make statements about the size, shape and distribution of dolomitized geobodies, as well as the specific impacts of dolomitization on flow properties. *Corbella et al.* bring together field, laboratory and modelling studies to explore the processes that influenced dolomitization in an outcrop analogue. Exposures of a Late Cretaceous carbonate ramp in NE Spain (Benicàssim) provided an opportunity to compare the style and distribution of stratiform and fault-controlled dolomitization with results of numerical reactive transport models. Corbella *et al.* were able to determine how the original rock-property distributions and likely fluid regimes influenced partially dolomitized sections and, therefore, locally heterogeneous reservoir quality. The study contributes to a currently sparse set of examples that serve to constrain hydrothermal dolomitization processes and the factors impacting the lateral extent of dolomitization. Moreover, their study emphasizes the importance of understanding linked structural-stratigraphic plumbing in such systems (Jones & Xiao 2005). The outlined approach demonstrates how iterations between geological observations and analyses from well data and reactive transport modelling can be used to extend predictions of the distribution and connectivity of dolomitized geobodies away from wells.

Further constraints on the geometry and spatial distribution of dolomite, and its representation in reservoir models, is provided by the paper by *Benson et al.* These authors use a comprehensive dataset compiled from outcrops of a Miocene oolite–microbialite platform (La Molata, SE Spain: Franseen *et al.* 1998). The data support a novel model for low-temperature dolomitization (Li *et al.* 2013) that was used to develop new workflows for incorporating detailed, outcrop-derived geometrical and palaeobathymetric constraints on facies architecture into reservoir models. These workflows were developed and validated using the rich La Molata outcrop dataset, but are sufficiently flexible to guide the construction of geologically robust models from sparse reservoir data. The authors also present an experimental tool to predict porosity and permeability from objective visual descriptors of carbonate rock samples, via extrapolation from a proprietary catalogue of core plug measurements.

Natural fractures are an obvious further source of heterogeneity in carbonate reservoirs. While discrete fracture models (Bear *et al.* 1993) and discrete fracture–matrix models (Matthai *et al.* 2007) are now proven approaches, to some extent, there remains a large space in which to explore flow behaviours as influenced by different fracture–matrix interaction scenarios, and the sensitivities of permeability and recovery predictions to modelling methods and assumptions. Furthermore, current modelling methods can be extremely burdensome in terms of fracture-data gathering and analysis, geometrical construction and meshing, efficient upsampling, and computation times. Streamlining these processes could offer significant uplift over the current situation. Two papers tackle these issues. The first paper by *Boro et al.* examines the variations in fracture populations associated with distinct depositional–diagenetic domains in a carbonate platform (Latemar Platform, Dolomites). Their approach integrates outcrop studies of fractures with first-order investigations of partitioning of flow behaviours across the platform, outlining a novel workflow to explore sensitivities to permeability predictions. Based on the outcomes of their experiments, they were able to determine those factors that have the most impact on permeability prediction for a given scenario of burial history and associated stress-field evolution. This example also reinforces the need to develop suitable proxies to represent the combined impacts of structural and sedimentological-diagenetic features on flow (Agar *et al.* 2010). In some situations, a quick approximation of fracture permeability may offer a reasonable alternative to flow-based calculations of permeability via a discrete fracture network model. With this in mind, the second paper by *Malinoukskaya et al.* illustrates a method to rapidly estimate the permeability of a fracture network, using fracture data from outcrops of a Jurassic carbonate ramp in Morocco (Amellago, High Atlas). While a geological approach would typically develop a fracture model based on the distributions of distinct fracture sets, Malinoukskaya *et al.* show that simplification is possible by using a single distribution to describe the characteristics of the overall fracture population at this location. Furthermore, by comparing applications of the Snow equation (Snow 1969) with numerical simulations of flow for the fracture networks, they find little difference between the permeability estimates. Malinoukskaya *et al.*’s method not only offers insights that can accelerate estimates of permeability for fracture systems in outcrops, but is well suited for applications in the subsurface, using inputs such as borehole image logs and core data.

The various stratigraphic, sedimentological, diagenetic and structural heterogeneities investigated in the papers described above are challenging to combine, both in a conceptual sense (can some features be used to condition others?) and a practical sense (what is spatially and geometrically reasonable?) (e.g. Pöppelreiter *et al.* 2008). Consequently, it is common practice to preselect a subset of these heterogeneities as the focus of reservoir modelling studies based on interpretation of sparse subsurface data, an approach that is susceptible to *a priori* assumptions and personal bias. Several of the papers in this issue address the need to identify which heterogeneities control flow for particular fluid types and production schemes. Two papers use data from an outcrop analogue for Middle Eastern carbonate ramp reservoirs (Jurassic Assoul Formation, High Atlas, Morocco: Amour *et al.* 2011, 2013; Christ *et al.* 2012) to benchmark the impact of all types of heterogeneity on flow at interwell scale. The first paper by *Shekhar et al.* documents a systematic and streamlined investigation of the impact of the different geological heterogeneities on flow behaviour and recovery. These authors conclude that the continuity of any geological feature with extreme high or low permeability has the most significant impact on flow under the simulated freshwater conditions, and they establish a preliminary hierarchy of such features, ranging from continuous baffles (e.g. stylolite zones) to zones of elevated permeabilities (e.g. mollusc banks) and discontinuous baffles (e.g. hardgrounds). The second paper by *Agada et al.* extends this work further to explore the various heterogeneities using numerical well tests. The well tests enable the generation of synthetic but systematic pressure responses for different combinations of geological heterogeneities. Their results show that the sedimentological, diagenetic and structural heterogeneities included in the model cannot be linked to a unique pressure-transient signature, and that the simulated well-test responses of most heterogeneities appear to be inconsequential compared to those of subseismic faults and high-permeability ‘sweet spots’ (e.g. mollusc banks). Associated flow simulations indicate that high-permeability layers act to channel fluid flow, as the primary control on oil recovery. This effect becomes more pronounced with increasing viscosity contrast between the injected fluid and the crude oil in the modelled reservoir, but can be mitigated by selecting the appropriate injection fluid and well configuration.
The final paper in the thematic set deals with measurement of relative permeability, one of the key rock and fluid properties that govern flow in carbonate rocks. Li et al. present verification of a semi-analytical model developed to infer relative permeability from resistivity measurements, using a combination of laboratory experiments and specifically acquired data from a Middle Eastern carbonate reservoir. Their results demonstrate that relative permeability calculated from resistivity logs is close to that measured from corresponding core plugs, for carbonate rocks with a low clay content and a simple, unimodal pore system. This study supports the value of field experiments in transferring technology from the laboratory to the reservoir, despite the attendant high costs and risk.

RECURRING THEMES AND FUTURE DIRECTIONS

Together, the papers in this thematic set introduce several potential avenues for future research directions, reinforcing the six themes identified below.

1. Novel modelling approaches that attempt to short circuit some of the conventional barriers between geoscience and engineering practice, such as upscaling from static to dynamic models or time-consuming analysis of flow-based fracture permeabilities.

2. The co-ordinated acquisition of outcrop data with a view to the design of geological models that capture the full range of geological heterogeneity.

3. The use of reservoir models as experimental tools to evaluate the impact of reservoir heterogeneity on different scales of flow behaviour. Approaches discussed provide a way to identify and retain geological information that is important to the flow simulation while removing superfluous detail that slows model construction and computations.

4. The use of “what if?” scenarios to capture the wide range of uncertainty within geologically plausible boundaries. This approach recognizes the value of outcrops to guide model content as a reasonable representation of the subsurface, but avoids the trap of trying to replicate every detail.

5. The need to validate laboratory and computer modelling experiments with targeted acquisition of subsurface or outcrop data.

6. The benefit of broad, cross-disciplinary and industry–academic collaboration in bringing new eyes and different perspectives to old problems, which fosters understanding in such a way that the overall results are more than the sum of their parts.

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REFERENCES


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