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Predicting reservoir properties: why carbonate diagenesis is the key to understanding pore systems and fluid flow

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Summary

Carbonate diagenesis encapsulates the physical, chemical, and biological processes that modify sediment after deposition. It begins as sediment is deposited, continues during burial and uplift of carbonate strata, and can dramatically transform mineralogy and rock physical properties. Diagenesis has a fundamental control on the type, size, and connectivity of pores in carbonate reservoirs- parameters that are notoriously hard to predict. As a result, the prediction of fluid flow during injection into, and production from, carbonate reservoirs requires geoscientists to build conceptual models that consider all the facets of, and interactions between, deposition, deformation, and diagenesis.

Over the last decade there have been significant advances in our understanding of diagenetic processes in terrestrial and marine settings, driven in part by cutting-edge geochemical instruments and experimental methods that utilizes experimental methods. This has led to a substantial improvement in our ability to unravel the complexity of the geochemical and geomicrobial processes governing the precipitation and dissolution of carbonate minerals and our ability to interpret palaeoenvironmental conditions from diagenetic signatures. Furthermore, the integration of fundamental hydrological and geochemical concepts into advanced reactive transport models has allowed us to interpret the distribution of diagenetic products in the context of realistic geological processes. This talk focuses on the opportunities raised by these fundamental advances and how they challenge our understanding of the evolution of pore systems in carbonate strata. It concentrates on how we can use our knowledge of basin-scale fluid flow and geochemical reactions to predict the distribution of diagenetic products and quantify uncertainty in these predictions.

Method and Workflow

Central to predicting the distribution of diagenetic products is the concept of process-to-product, which integrates observed patterns and measured data with hydrogeological principles and geochemical reaction pathways. It is critical to start with an evaluation of the burial history, palaeogeography and palaeoclimate, the stratal architecture of the basin and it's burial and deformational history because these elements control the composition of reactive fluids and their flow paths and fluxes. By integrating these data with fundamental hydrological principles, we can better model how fluids flow within sedimentary basins and have higher confidence in our predictions than if we pattern-match our data to pre-defined conceptual models. Although basin-scale analysis and stratal architecture provides context for modelling reactive fluid flow, micron-scale heterogeneities in physical and chemical properties significantly influence reaction pathway of carbonate rocks and a multi-scale paragenetic framework is needed. Such multi-scale evaluations combine X-ray computed tomography (CT) and hyperspectral imaging with scanning electron, transmitted light, and cathodoluminescence microscopy to better understand diagenetic products and pore systems. Individual paragenetic stages and growth zones of a single crystal can then be isolated by electron probe micro-analysis and *in situ* laser ablation technologies for trace element, rare earth element, and stable isotopic analyses. However, it is still critical that care is taken to appropriately sample the reservoir, spatially and stratigraphically, and quantify the uncertainty that is imparted by missing information. Where complexity is introduced by the range of scales, multi-proxy datasets and potentially inadequate sampling interrogation of multiple hypotheses can be useful to constrain the likelihood of one or more processes that can then be tested by further targeted data collection (e.g. Gallois et al., 2022).

Results, Observations, Conclusions

In this presentation, we demonstrate how an iterative workflow can be used to improve diagenetic models and make a step-forward in our ability to predict porosity and permeability and quantify uncertainty in these predictions by coupling fundamental research with robust data analysis. Such an approach is particularly important to understanding the processes that govern dolomitization, where many studies still use pre-defined rules and conceptual models, for example, drawn from textural analysis and dolomite distribution, to interpret the dolomitization process. However, experimental data (e.g. Hashim and Kaczmarek, 2020) and reactive transport models have deepened our understanding of the conditions that favor dolomitization and provide more detailed and predictive models regarding how different fluids might flow and react to form stratabound and non-stratabound dolomite bodies (e.g., Al Helal et al. 2012; Gabellone and Whitaker, 2016; Benjakul et al. 2020). Relative to conceptual models, these reactive transport models facilitate a stronger predictive capacity by allowing us to implement fundamental principles of fluid-rock reaction; the model outputs can then be calibrated with empirical geological data, improving confidence in the modelling process.

In the Western Canada Sedimentary Basin (WCSB), the integration of multi-scale, process-driven models has led to a re-evaluation of the mechanisms by which fault-controlled dolomite bodies form. These dolomite bodies, situated in middle Cambrian strata, have been widely used as exemplars for hydrothermal dolomitization (e.g., Davies and Smith, 2006) because they formed from fluids that were significantly hotter than the host rock (Fig. 1). A series of detailed studies that integrate basin-scale sedimentology, petrography, and geochemistry (Koeshidayatullah et al. 2020a; Stacey et al. 2021; McCormick et al. *In Press*) have shown that dolomitization took place in a shallow burial setting from a mixture of seawater and hot crustal fluids. These crustal fluids circulated within the underlying Gog Group, mixed with seawater, and convected along faults (Koeshidayatullah et al. 2020a; Stacey et al. 2021). This interpretation was verified by U-Pb geochronology (McCormick et al. *In Press*), who demonstrated that dolomitization occurred during the middle Cambrian (Miaolingian) to Middle Ordovician. As the platform strata were sealed by mudrocks, the pore-fluid pressure increased, and gave rise to the formation of dolomite breccias, boxwork textures, and zebra textures; multi-hypothesis testing was used in this case to assess the relative importance of depositional texture, deformation and diagenesis in controlling the occurrence of these features (McCormick et al. 2023). High resolution sampling across dolomite – limestone contacts also provided new information on the evolution of dolomitization fronts, which back-step towards the faults as porosity is sequentially closed off during dolomitization (Koeshidayatullah et al. 2020b, 2021; McCormick et al. 2021).

Such detailed petrographical and geochemical analyses, and the delineation of the timing and processes driving dolomitization has clear applications in the subsurface. A meta-analysis of geochemical data from Devonian strata in the WCSB concluded that dolomitization occurred by the circulation of seawater in a shallow burial setting, followed by saddle dolomite precipitation from residual evapo-concentrated Devonian seawater (Stacey et al. 2020). These Devonian brines also interacted with basal clastic aquifers, which gave rise to lithium rich fluids in the West Shale Basin and Peace River Arch areas. Dolomitized reservoirs in the WCSB have historically been important hydrocarbon reservoirs, and are now potential reservoirs for CO_2 storage because of their well-connected intercrystalline, mouldic, and vuggy porosity (Stacey et al. *In Press*). The best reservoirs are those that are hosted in dolomitized reefal facies, because they have vertical and lateral transitions to low porosity, undolomitized facies. Assessing pre-existing datasets, collecting new data, and modelling diagenetic processes across the WCSB allows for the creation of new data-driven models that can optimize the injection and storage of CO_2 in these intervals.

Figure 1. Panorama of the fault-controlled, hydrothermal dolomite that is situated within the Cathedral Formation (middle Cambrian) at Whirlpool Point, ~60 km southeast of Nordegg, WCSB.

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