Integrated core-scale volumetric analysis: a Precambrian carbonates case study

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Summary

Quantifying and classifying pore systems in carbonates is notoriously challenging, particularly in rocks associated with complex diagenetic histories. Here we report novel computed tomography (CT) core and thin section image analyses through key reservoir intervals in the Buah Formation and Khufai Formation, both part of the Precambrian (Ediacaran) Nafun Group, from two wells located onshore Oman. Our primary objective is to constrain the volume, shape, connectivity, and distribution of vugs down-core in two and three dimensions – this is a key control on reservoir quality. We combine classic sedimentological core descriptions with image analysis on a range of data types. In this paper we focus on the analysis of core CT scan data, but we also introduce a high-level analysis of thin section images from discrete samples from the same boreholes, where available (sidewall core plugs, ditch cuttings and conventional cores). Finally, we integrated the results to (1) provide a holistic understanding of pore systems in the Buah and Khufai Formations; (2) identify the key uncertainties and weaknesses in our approach, and (3) plan for further reservoir assessment.

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Introduction

Quantifying and classifying pore systems in carbonates is notoriously challenging, particularly in rocks associated with complex diagenetic histories. Here we report novel computed tomography (CT) core and thin section image analyses through sections of the Buah Formation (ca. 562-547 Ma) and Khufai Formation (ca. 578 Ma), both part of the Precambrian (Ediacaran) Nafun Group (e.g., Cozzi et al., 2012; Osburn et al., 2014), from two wells located onshore Oman. Here the Buah and Khufai Formations comprise calcareous to dolomitic stromatolitic, grainstone and mudstone lithofacies deposited primarily in middle- and inner-ramp settings, and are separated by mudstones and limestones of the Shuram Formation (e.g., Visser, 1991). The petroleum system is potentially self-sourcing; the Khufai and underlying Masirah Bay Formations are the candidate hydrocarbon sources. Stratigraphically confined, vuggy, stromatolitic lithofacies represent the key reservoirs in the Buah and Khufai Formations (Cozzi and Al-Siyabi, 2004). Fractures are also considered to play a significant role in production. In addition, the studied successions span a critically important period of Earth history associated with step-changes in the evolution of life and biogeochemical cycling (e.g., Rooney et al., 2020).

We report the results of high throughput CT scan analysis through key reservoir intervals within the Buah and Khufai Formations. Our primary objective is to constrain the volume, shape, connectivity, and distribution of vugs down-core in two and three dimensions – this is a key control on reservoir quality. We combine classic sedimentological core descriptions with image analysis on a range of data types. In this paper we focus on the analysis of core CT scan data, but we also introduce a high-level analysis of thin section images from discrete samples from the same boreholes, where available (sidewall core plugs, ditch cuttings and conventional cores). Finally, we integrated the results to (1) provide a holistic understanding of pore systems in the Buah and Khufai Formations; (2) identify the key uncertainties and weaknesses in our approach, and (3) plan for further reservoir assessment.

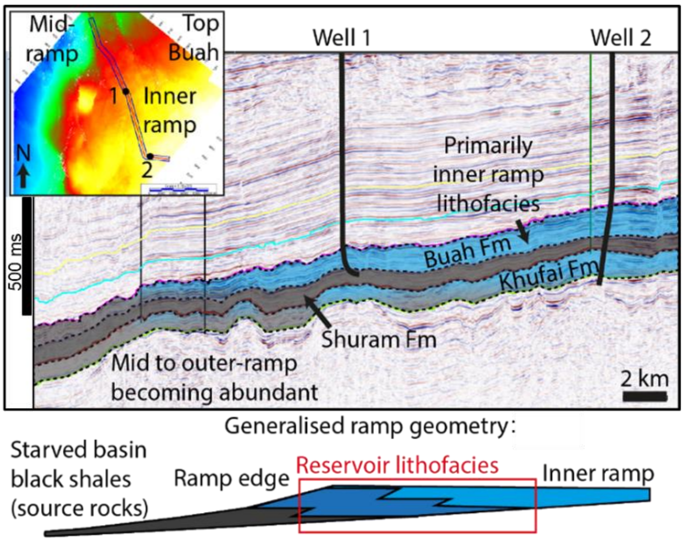

Figure 1. *Seismic line and top Buah surface, study well locations and high-level lithofacies interpretations. Generalized ramp geometry after Cozzi and Al-Siyabi (2004).*

Method

Single energy whole-core CT scans spanning ca. 36 m from two wells (Well 1, Well 2) were analysed in this study. CT scan processing and segmentation was implemented using ThermoFisher PerGeos software. Data analysis, integration with other datasets (such as optical photography, discrete sample data, lithological logs) and production of the composite logs was performed using CGG’s in-house technology. We initially applied standard pre-processing techniques to the CT volumes (e.g., cylindrical cropping, non-local means filtering to remove noise). Following pre-processing, we developed a bespoke 7-phase multiphase segmentation workflow, involving a series of threshold filters, gradient filters, gradient, and closing/opening operations (top hat transforms) and flood fill methods. The 7 phases (Figure 2) correspond broadly (but not absolutely) to the density of the materials; background (outside core, not included in further analysis), vugs (unambiguous void space), low density phases (a subjective phase potentially representing low density lithologies enriched in organic matter, clay minerals and/or tight porosity and tight fractures), solid rock, high density phases (e.g., pyrite-cemented zones) and fractures. Fractures were further subdivided according to shape into those with (1) an unambiguous artificial genesis and (2) a natural or ambiguous origin.

Following deployment of the 7-phase segmentation, the vugs were extracted and separated (partitioned) by deploying the algorithm of Youssef et al. (2007). This is a well-established method for the separation of void space. The partitioning algorithm was originally implemented in carbonates and is reasonably accurate, but linear or planar features (such as fractures, tubular features, etc.) tend to become over-segmented. This is a limitation of the partitioning technique. We calculated the down-core volume fractions of each segmented phase, together with the vug size, diameter, shape, and orientation. We also applied neighbourhood analyses to constrain connectivity. In our first approach, ‘connected vugs’ are vugs in contact with at least one other vug. Additionally, the low-density intervals may act as conduits for fluid flow in the subsurface. Thus, a vug-low density connectivity analysis represents the proportion of voids in contact with low density phase networks (laminae, fractures, tightly packed small voids).

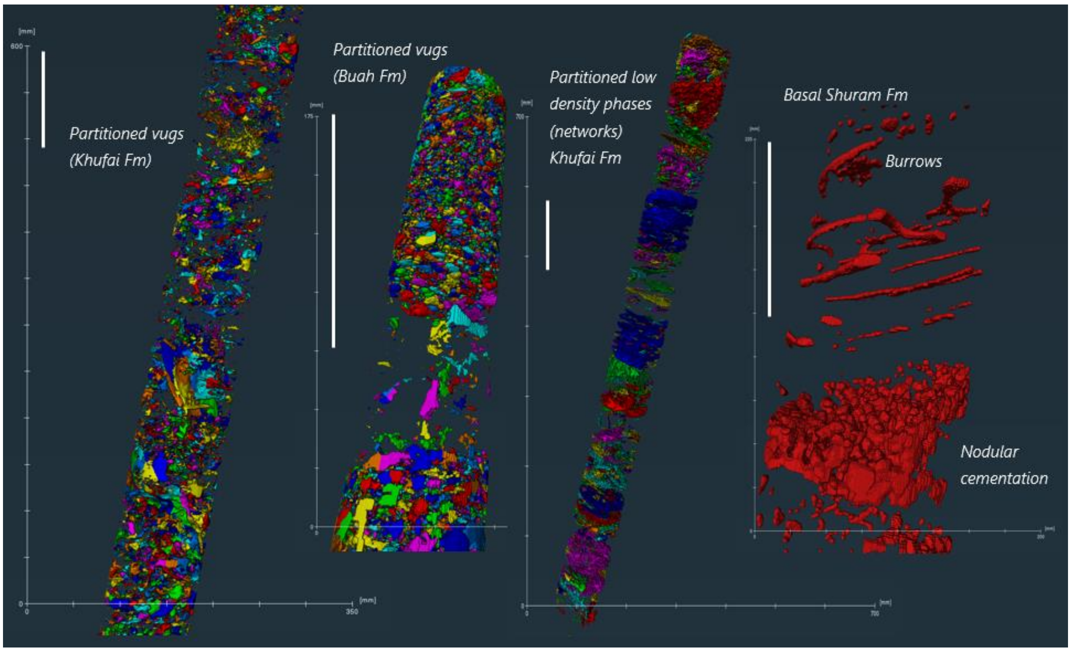

Figure 2. *Example 3D rendered CT volumes. Left, centre left: partitioned vugs in the Khufai Formation and Buah Formation, respectively. Centre right: partitioned low-density phases, filtered for large, interconnected features. Right: Nodules and cemented trace fossils at the base of the Shuram Formation, above the contact with the Khufai Formation. The segmented burrows (or grazing traces) are a high-density phase, plausibly pyrite. All scale bars = 100 mm.*

Results and Discussion

We analysed the size, shape, and connectivity of more than 1 million discrete vugs. We classified connectivity using a traffic-light system; >50% vug-vug and >50% vug-low density (green), >50% vug-vug and <50% vug-low (yellow), <50% vug-vug and >50% vug-low density (orange) and <50% vug-vug and <50% vug-low density (red). The whole core CT voxel resolution is 273x273x400 µm (x, y, z), meaning our analysis does not consider features below the voxel resolution, such as pores within the solid rock matrix. Thus, the vug neighbourhood analyses are a proxy for the macropore connectivity. The composite logs display the key results (Figure 3), which show higher and more consistent vug volume fractions but potentially increased compartmentalisation in Well 1 (Buah), whereas Well 2 (Khufai) is a bipartite stack of mid-ramp vuggy, stromatolitic, interconnected lithofacies in the basal section overlain by tight, low connectivity inner ramp tidal dolo-mudstone lithofacies.

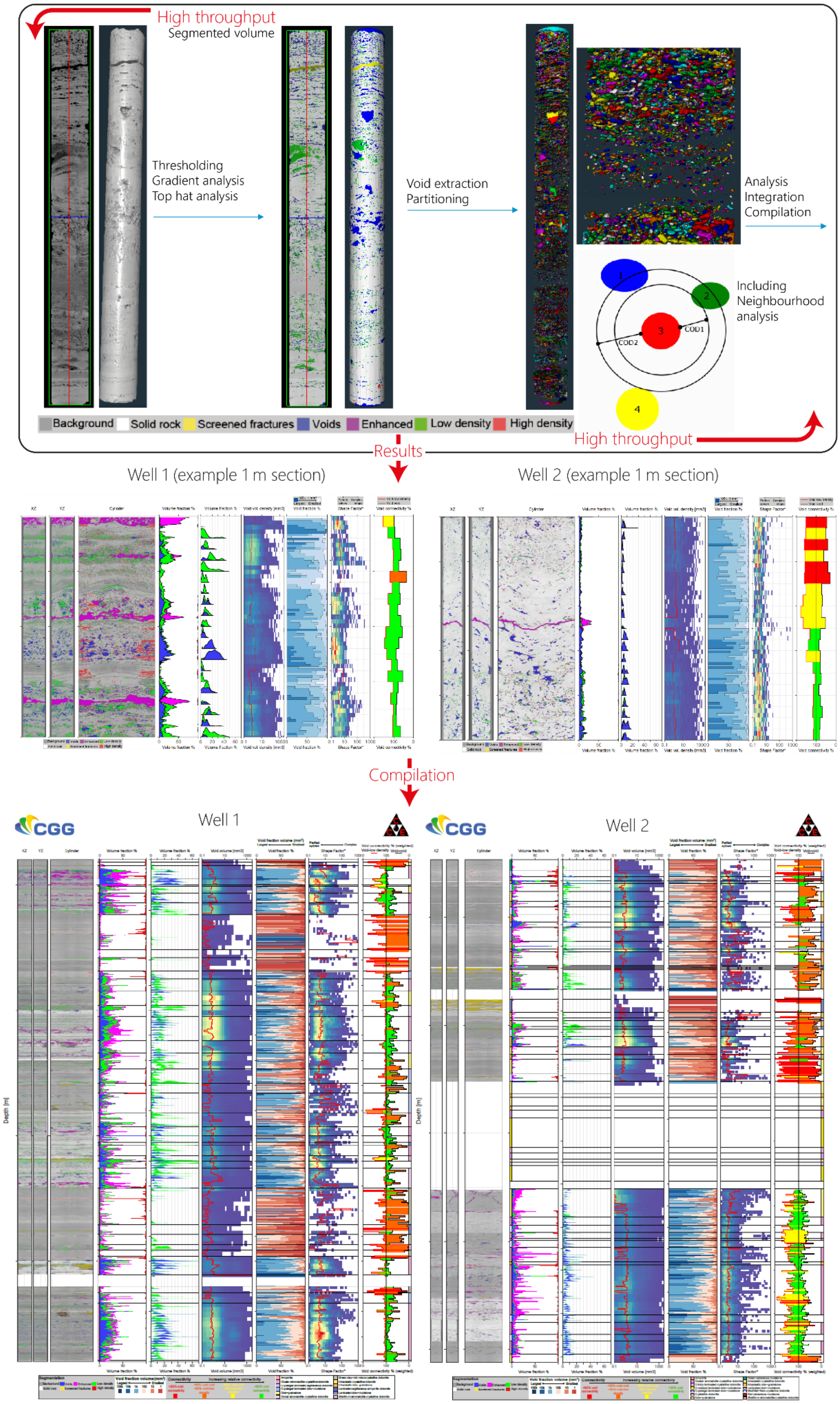

Figure 3. *CT scan workflow summary including composite logs displaying orthoslices through the CT volumes, the volume vug fractions, shape factor, and connectivity (traffic light system, far right column).*

Probabilistic analysis provides a robust and quantitative means to compare the wells. Well 1 exhibits a consistently higher vug volume fraction versus Well 2 (Figure 4a). Integration of the CT analysis results with the sedimentological core descriptions and the lithofacies scheme is consistent with the hydrocarbon play model of Cozzi and Al-Siyabi (2004); stromatolitic facies exhibit high void fractions (Figure 4b) and exhibit relatively high void connectivity compared to argillaceous dolomite and mudstone facies (Figure 3).

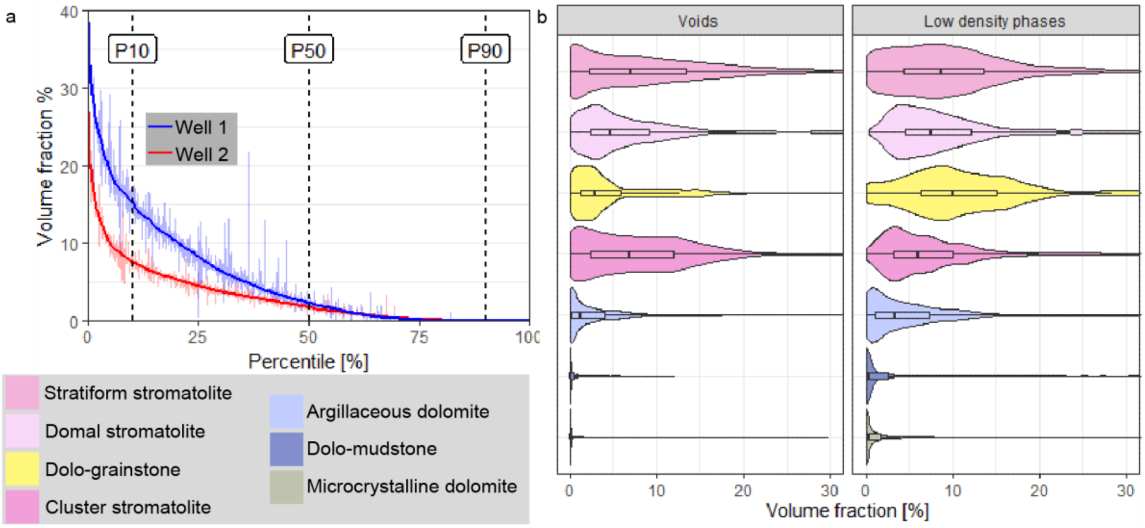

Figure 4. *a) CT vug volume probabilistic volumetrics. b) void connectivity by lithofacies (Buah).*

A high throughput CT scan segmentation and analytical workflow was successfully applied to two Precambrian carbonate reservoirs from two wells onshore Oman (Figures 1-3). Our approach provides a means to improve understanding of carbonate reservoirs by quantification of vug volume fractions, shapes, and connectivity down-core, and enables the objective comparison of key units of interest within and between wells (Figure 4). The Buah Formation (Well 1) exhibits generally higher vug fractions and potentially a greater degree of compartmentalisation compared to the Khufai Formation in Well 2. Finally, whilst not the primary study objective, the Nafun Group is not known to host any Ediacaran biota apart from stromatolites (Rooney et al., 2020). The candidate cemented trace fossils observed at the base of the Shuram Formation (Figure 2) resemble the traces of *Helminthopsis* seen in equivalent successions in North America (Rooney et al., 2020). To our knowledge, this is the first recognition of Ediacaran biota in the Shuram Formation in Oman and thus may warrant more detailed investigation.

Acknowledgements

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