Too Much Choice: Benchmarking of Segmentation Algorithms for SEM Images of Calcite Microcrystals Using Distortion Simulation

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Abstract

Microporosity in mud-rich carbonate reservoirs is predominantly governed by interparticle microporosity, which is directly controlled by calcite microcrystalline morphology. Accurate quantification of microcrystalline morphology is paramount for subsurface characterization in such lithologies, being pertinent numerous applications (e.g., reservoir studies, carbon capture, and storage projects, aquifer management etc.). Currently, morphological characterization relies upon visual analysis of Scanning Electron Microscopy (SEM) images and manual measurements: practices fraught with subjectivity, inefficiency, and data loss, with the qualitative output challenging to fit into increasingly quantitative workflows. Digital image segmentation offers a more objective approach. However, selecting an optimal segmentation approach remains challenging due to the lack of robust benchmarks and accessible implementations. In this study, we benchmarked six segmentation approaches, representative of the major families adopted within the literature: namely, global thresholding, edge detection, k-means, watershed, supervised machine learning (Trainable Weka Segmentation), and deep learning (SAM: Segment-Anything-Model). To test for generalizability, we utilized 30 SEM images of diverse carbonate microtextures from studies performed worldwide. In addition, we mirrored current acquisition standards by simulating distortions across five parameters (each with 15 levels): Gaussian noise, diffraction-limited resolution, contrast, spatial resolution, and brightness. Furthermore, the distorted images underwent re-processing to ascertain performance enhancement. Segmentation quality was measured against two manual ground truths.

SAM significantly outperformed all approaches across all distortion profiles, with average object-level accuracies exceeding 80%, even approximating human visual perception in most cases. Watershed was the only other approach with average object-level accuracies exceeding 50-60%, with all others exhibiting <25% accuracy (including supervised machine learning). This study underscores the superiority of SAM as a segmentation tool for complex SEM images and we expect these accuracies to extend towards SEM images of other lithologies. The segmented images present unprecedented industrial and geological opportunities in quantifying interparticle microporosity within reservoirs and outcrops, as well as classification into shape classes to derive genetic insights. Besides practical recommendations, this study introduces a comprehensive framework for benchmarking segmentation approaches, complete with an interactive automated pipeline to comprehensively benchmark the aforementioned segmentation approaches across any image type. All software tools employed and the dataset are open-sourced for this study, ensuring broad accessibility and reproducibility within the community.