

## Supplementary Information

### Geometric design of microfluidic chip

Using the rock CT database provided by the Digital Porous Media Portal, filtered CT scan data for Bentheimer sandstone was downloaded. An image exhibiting both large and small pores was selected, as shown in Fig. S1a. After denoising and binarization, the rock matrix was segmented using a watershed algorithm to create connected throats (Fig. S1b). The throat size was adjusted to approximately 45  $\mu\text{m}$ . The boundary between black and white regions was then extracted, yielding the basic microfluidic chip pattern (Fig. S1c). To expand the chip area, Fig. S1c was arranged in a 4 $\times$ 5 matrix, resulting in a flow region measuring 22.5 mm  $\times$  18 mm. Finally, a two-dimensional microfluidic model with complex pore structures was fabricated using glass wet-etching

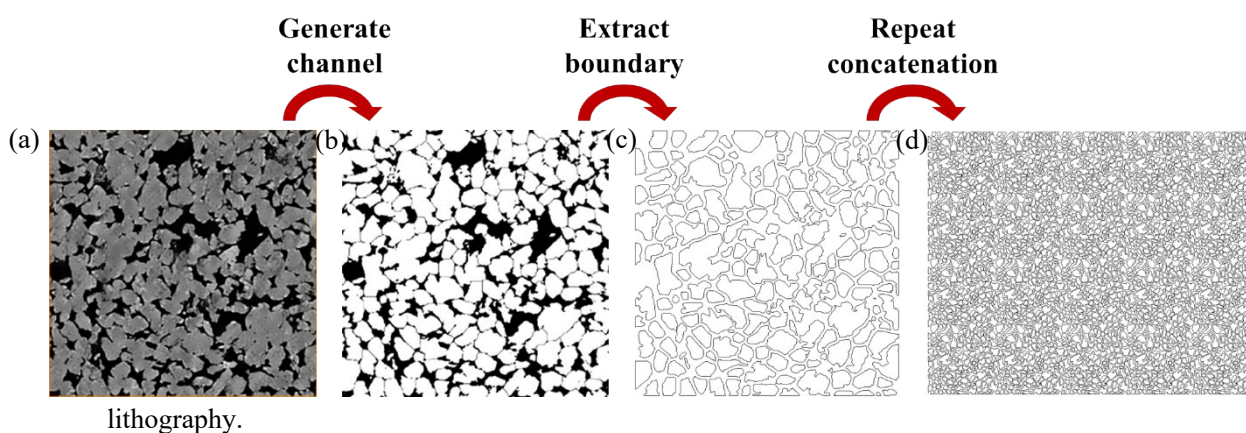


Fig. S1. The geometric pattern design flow of microfluidic chip.

### Uncertainty analysis for the image segmentation workflow

Manual image segmentation involves inherent subjectivity; consequently, we performed an uncertainty analysis to quantify and address these potential variations.

The same person performed image segmentation on the same image five times (hydrogen displacement under fully water-saturated conditions after reaction at 125mbar). The saturation values obtained from the five segmentations were 34.5%, 35.0%, 35.3%, 34.4%, and 35.6%, with a mean of 34.96% and a standard deviation (SD) of 0.51%. With a sample size of  $n=5$ , the standard error (SE) was calculated to be 0.23% (Eq. S1). When  $n=5$ , the t-distribution value ( $\alpha = 0.05$ ) is approximately 2.776, and the calculated error margin (EM) is 0.64% (Eq. S2).

$$SE = \frac{SD}{\sqrt{n}} = \frac{0.51}{\sqrt{5}} \approx 0.23\% \quad (\text{S1})$$

$$EM = t \cdot SE = 2.776 \times 0.23 \approx 0.64\% \quad (\text{S2})$$

Therefore, at a 95% confidence level, our measurement error is  $\pm 0.64\%$ . This small margin of error indicates that our operator has good reproducibility. All images in this study were processed by this operator. However, it should be noted that subjective bias may still be present.

## Reference

- [1] Digital Porous Media Portal. 11 Sandstones: Raw, Filtered and Segmented Data, <https://pprd.digitalrocks.tacc.utexas.edu/datasets/317>; 2026 [accessed 20 January 2026].