



SIMULATION OF REACTIVE TRANSPORT PROCESSES: ACIDIZING TREATMENTS IN CARBONATE RESERVOIRS

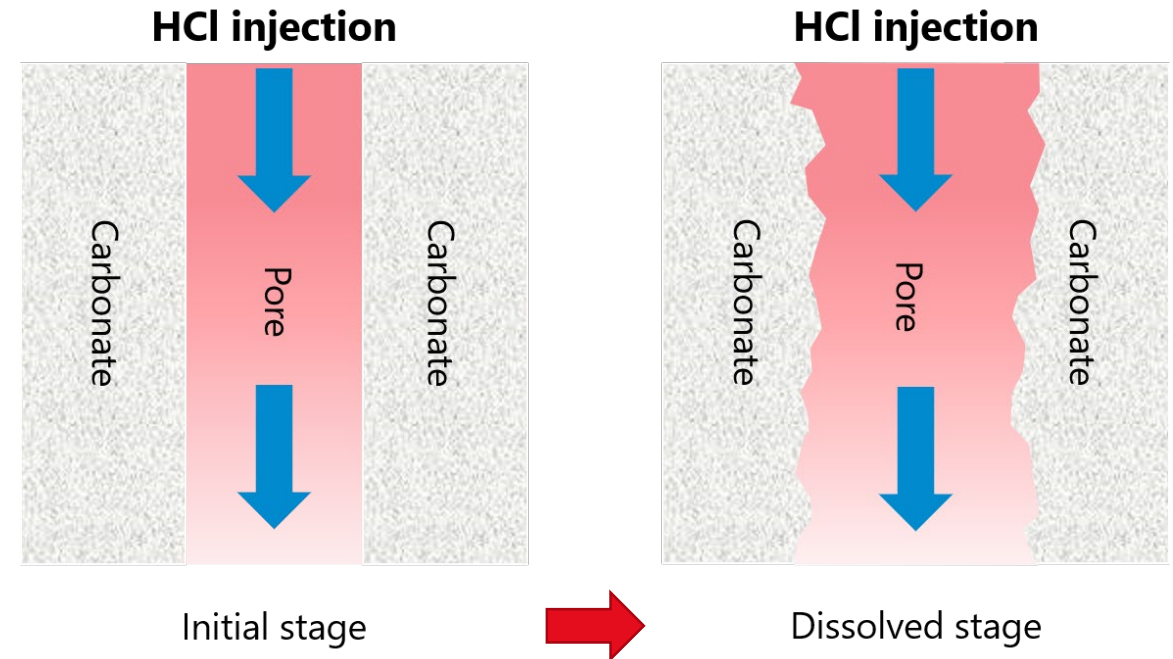
MATH
2 MARKET

Interpore Valencia 2019

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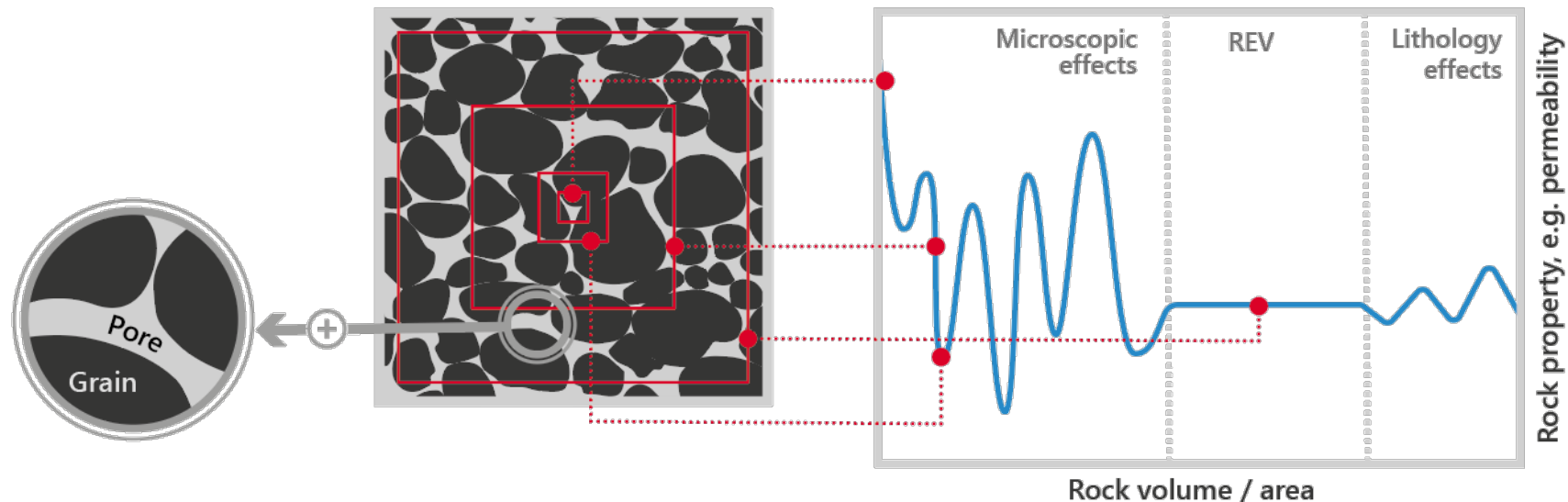
MOTIVATION – REACTIVE FLOW

- Reactive Flow: HCl injection into carbonate
- Effect: Dissolution, enlargement of the pore space (permeability enhancement)
- Establish a higher permeability
- Keep mechanical stability
- Use numerical simulation to optimize the process parameters, e.g. acid concentration, injection velocity, ...



WHY DO WE NEED A NEW NUMERICAL MODEL?

- Lesson learned from digital rock physics: structure at the pore scale influences rock properties at the core scale
- Simulations at the pore scale require REV and so **large** computational domains
- Need for **efficient** solvers and **simple** rules for structure manipulation
- We developed a simple numerical model which can be applied to large computational domains (REV)

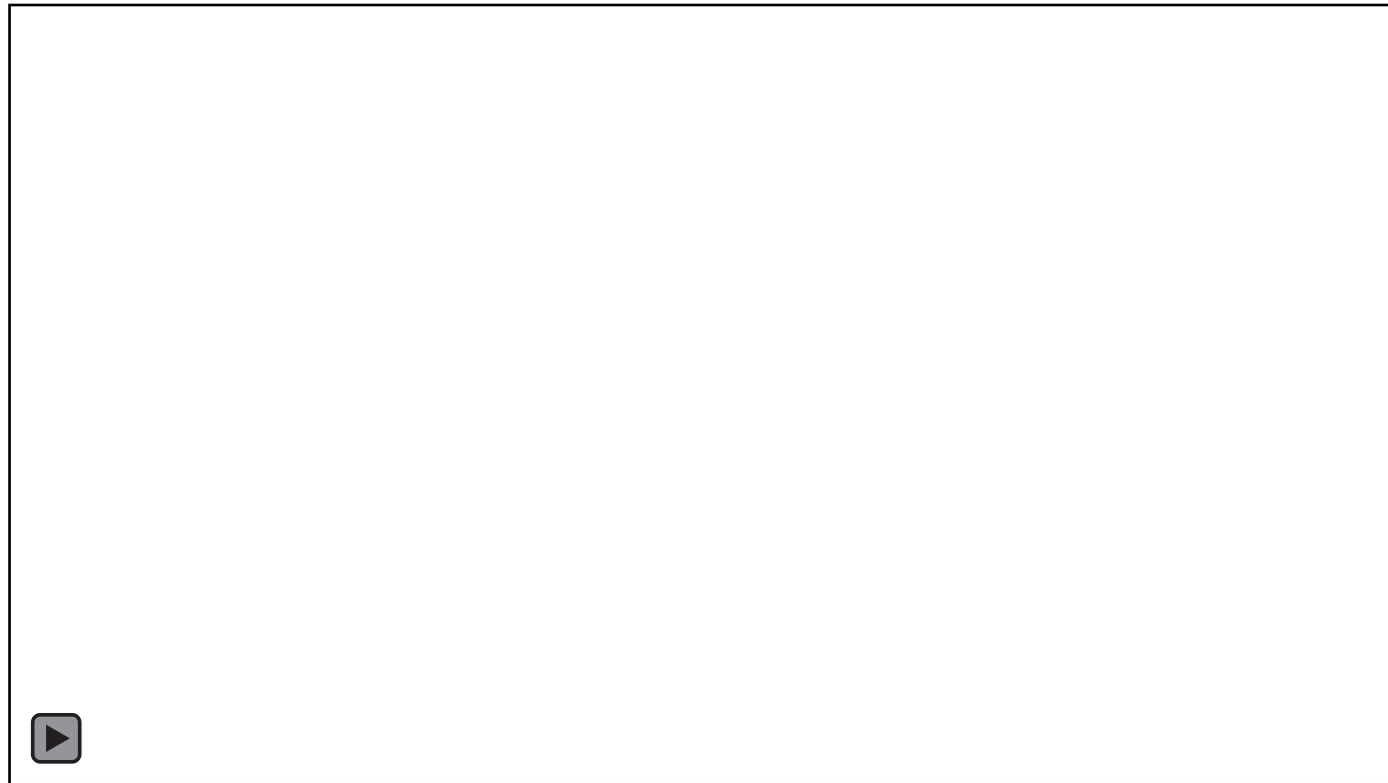


Model Description and Implementation

Simulate HCl injection into a carbonate sample

MODEL WORKFLOW – STEP 1

- Compute the flow field in the structure
- For a given fluid velocity or pressure drop
- Stokes or Navier-Stokes equations
- Export streamlines
- This step is implemented in GeoDict



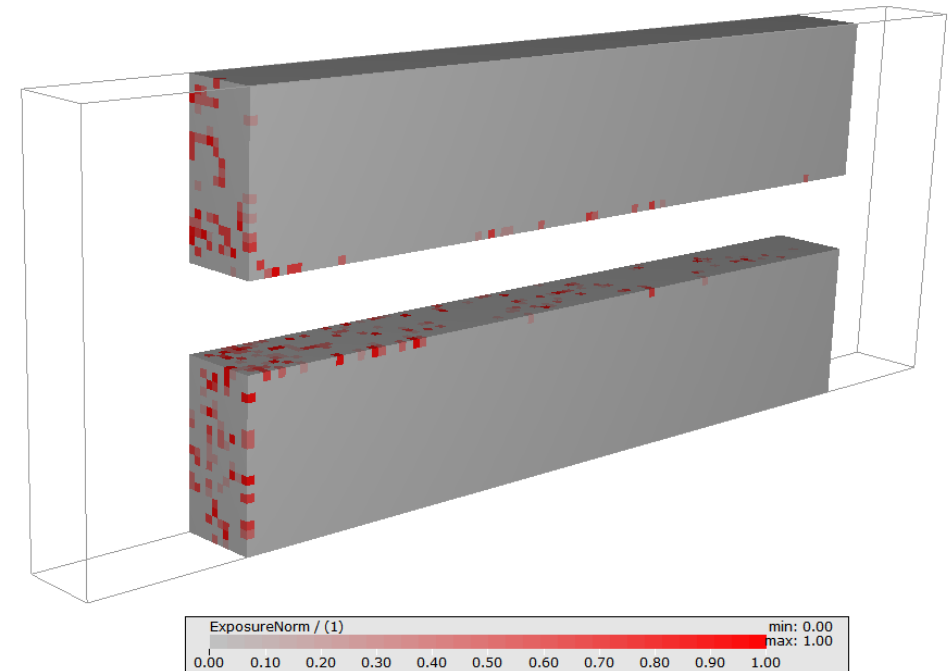
MODEL WORKFLOW – STEP 2

- Compute particle movement
- Particle transport is a combination of advective and diffusive motion (Streamlines + Brownian motion)
- A particle behaves like a single H^+ Ion, while it represents a larger number of ions (we call this concept *Multiplicity*).
- We keep track of the collision points with the rock interface
- This step is implemented in GeoDict



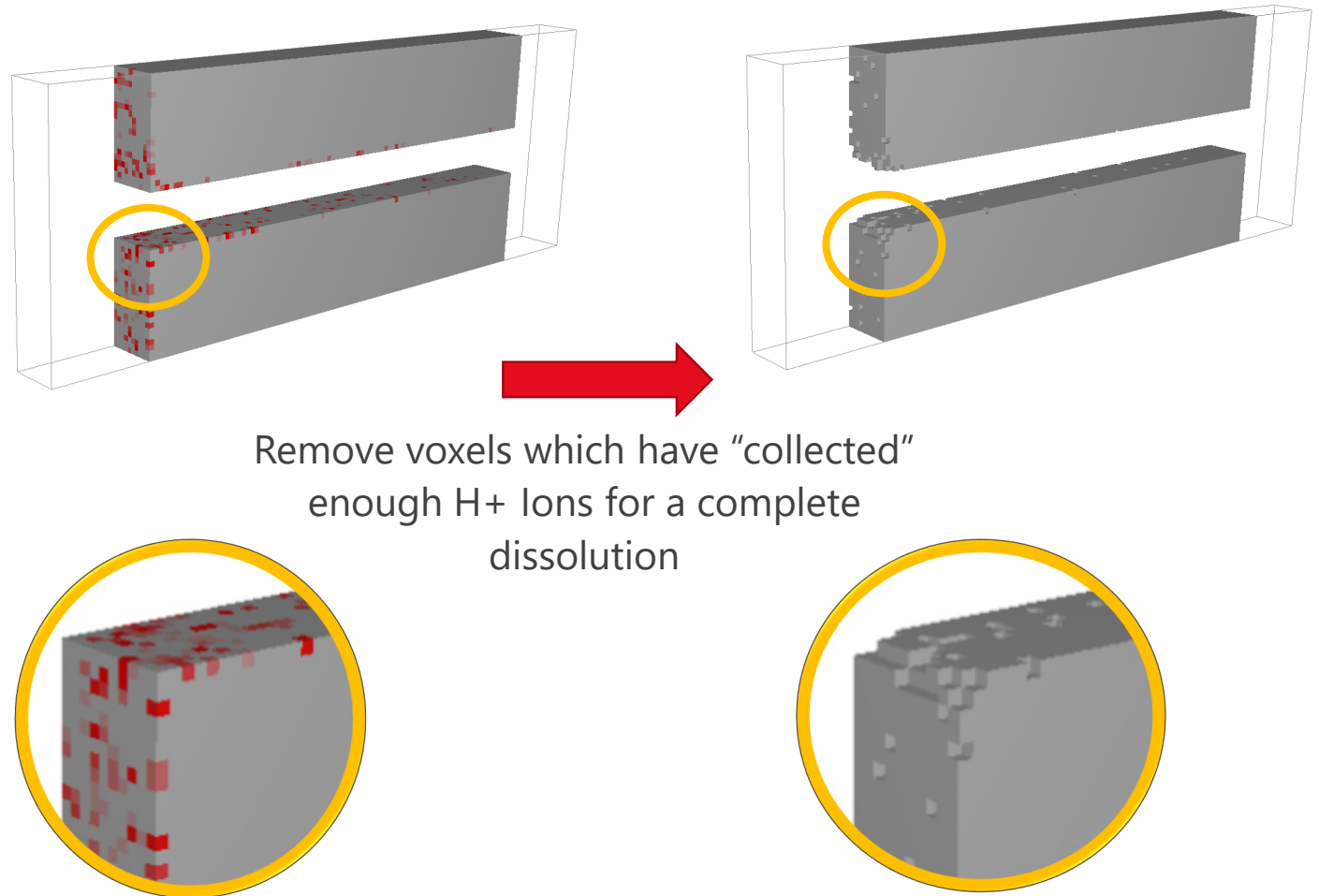
MODEL WORKFLOW – STEP 3

- Model the chemical reaction
- One particle represents a given number of H^+ ions
- At every collision point a given number of H^+ ions are transferred to the solid voxel
- We keep track of the consumed H^+ ions in the particles and solid voxels
- This step is implemented as a Matlab function



MODEL WORKFLOW – STEP 4

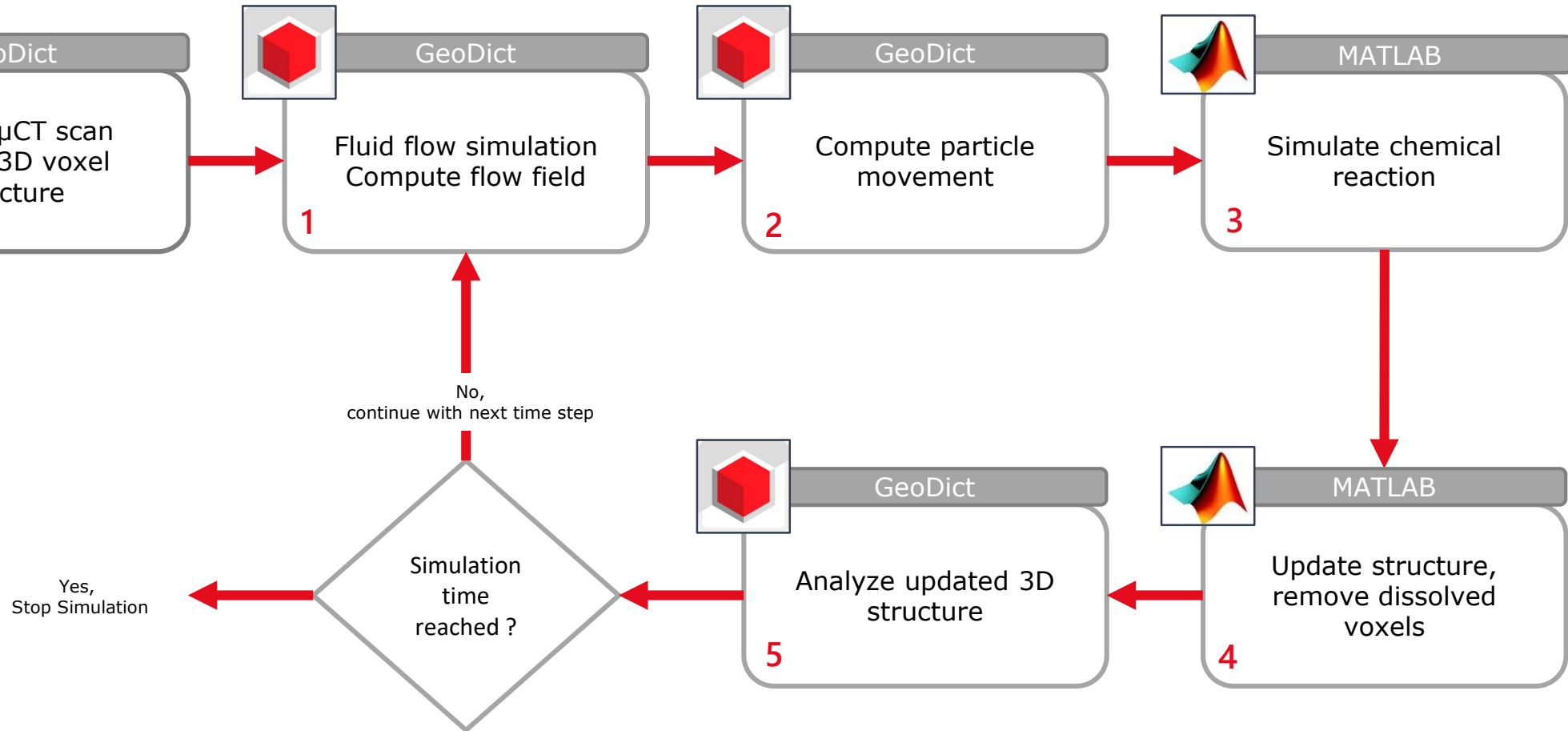
- Update rock structure
- Remove dissolved voxels
- The new structure is saved for the next iteration
- It can be used to analyze properties like: Mechanical stability (Bulk Modulus), Conductivity, Permeability
- This step is implemented as Matlab function



- Particle/Continuum approach
- Fluid flow as continuum (Stokes/ Navier-Stokes)
- Reactants (e.g. H⁺ ions) as particles
- One particle behaves like a single H⁺ ion, but represents a larger number
- Upon collision, H⁺ ions dissolve the rock (CaCO₃):
 $\text{CaCO}_3 + \text{H}^+ \rightarrow \text{Ca}^{2+} + \text{HCO}_3^-$
- Keep track of consumed H⁺ and dissolved volume



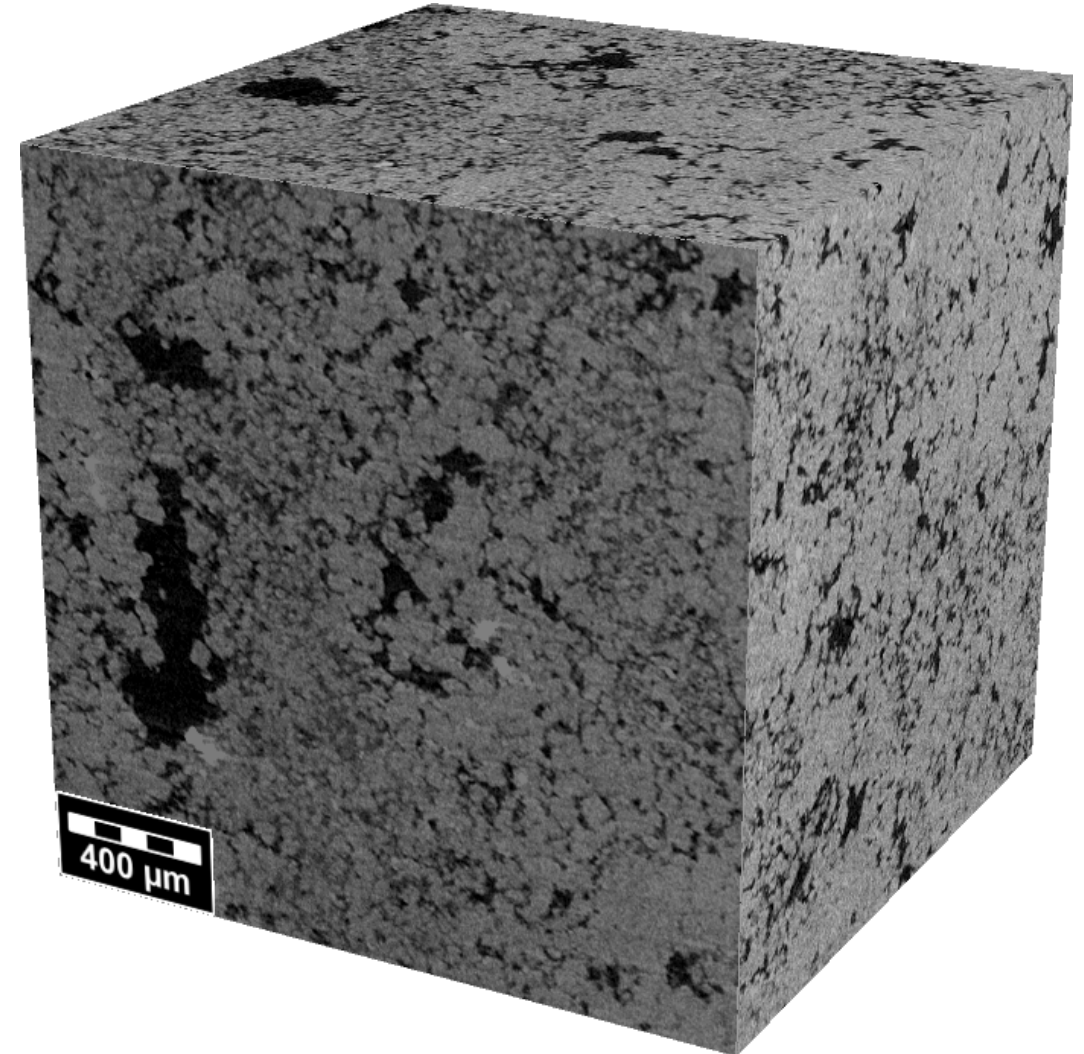
WORKFLOW - OVERVIEW



Simulation on a real rock structure

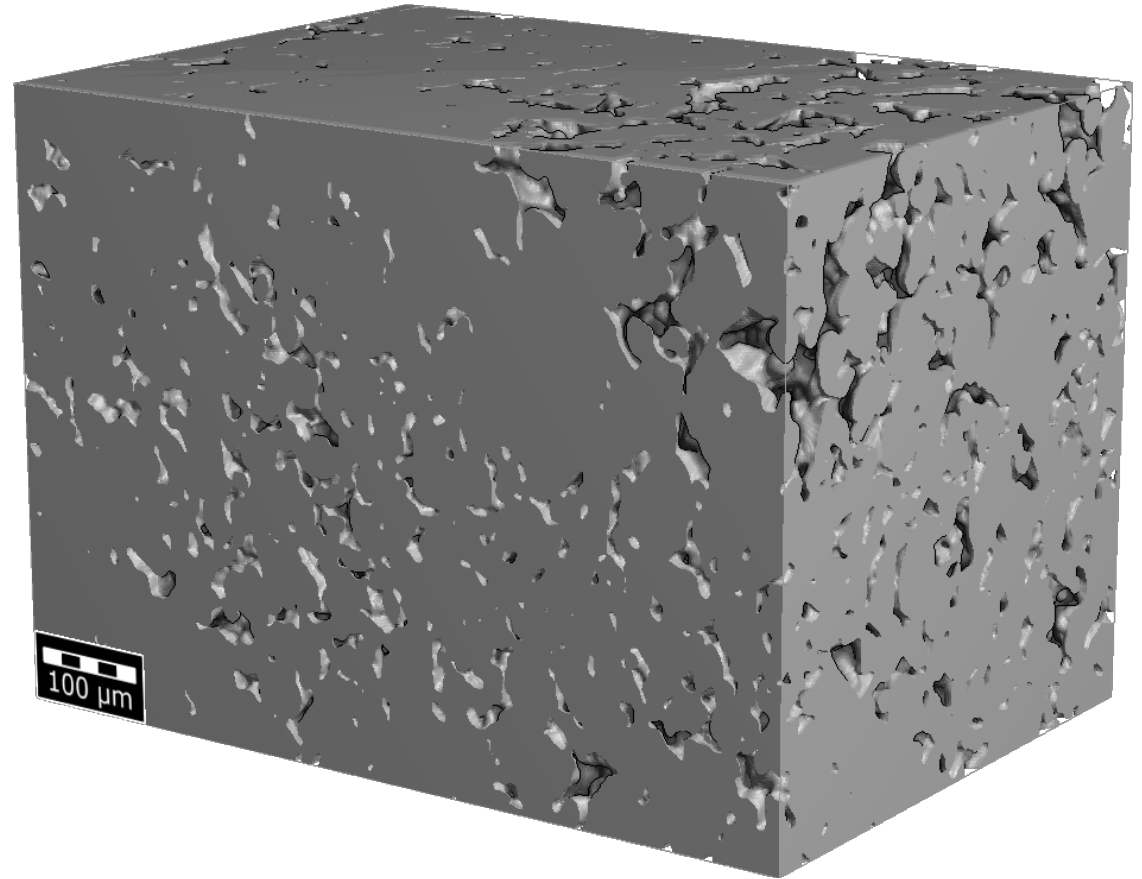
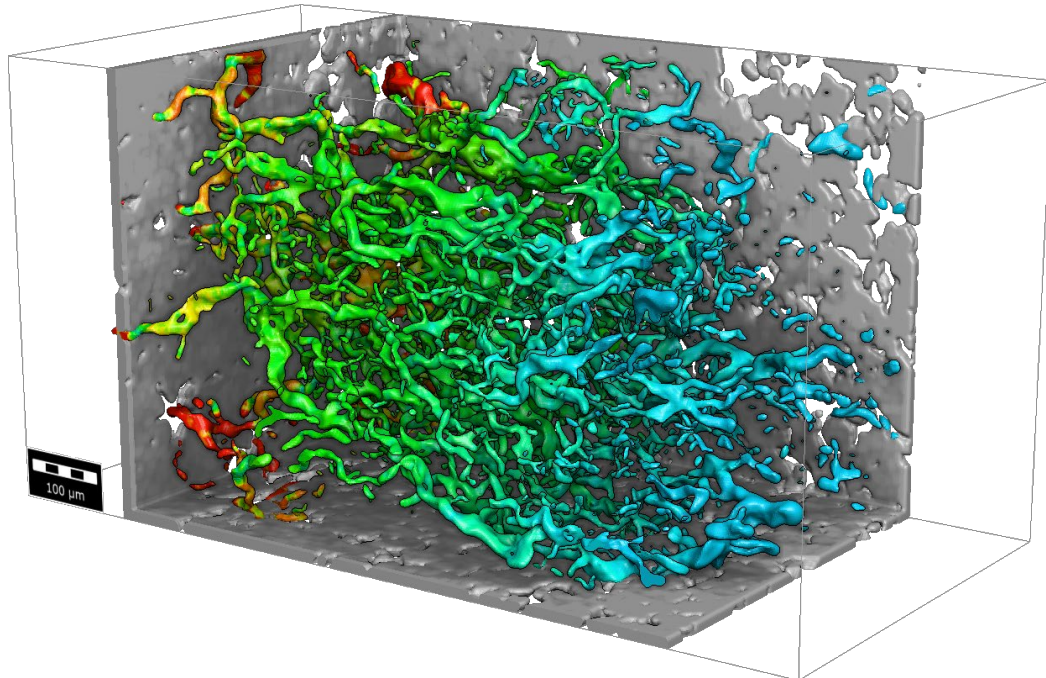
CARBONATE SAMPLE

- Grosmont formation, Alberta, Canada
- Dimensions: 1024x1024x1024 voxel
- Resolution: 2.02 μ m
- Porosity: 21%, permeability range: 150 mD – 470 mD -> heterogenous pore space
- Data set is published in DRP benchmark paper (Andrae et al. 2013)



CARBONATE SAMPLE - SUBVOLUME

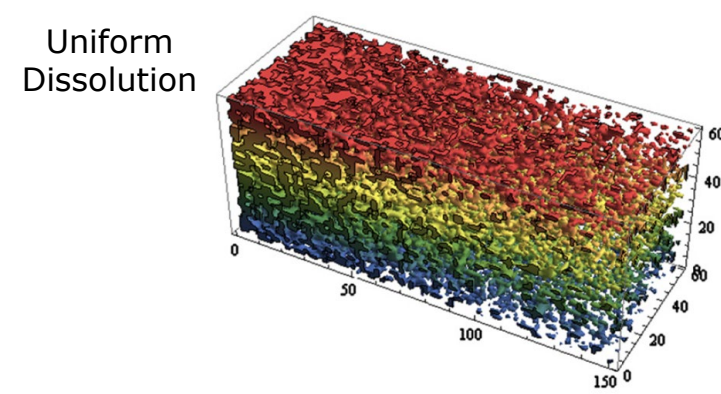
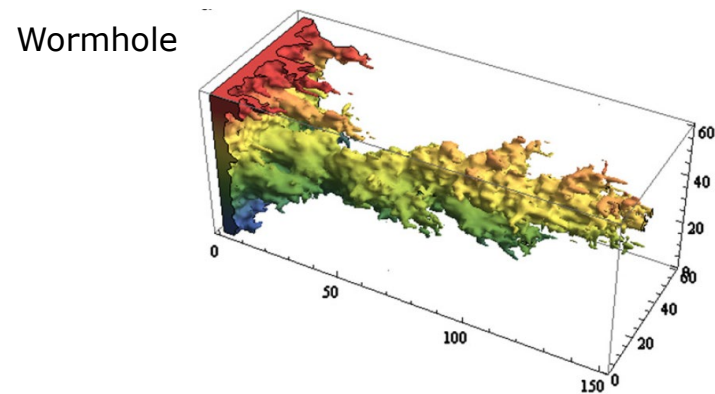
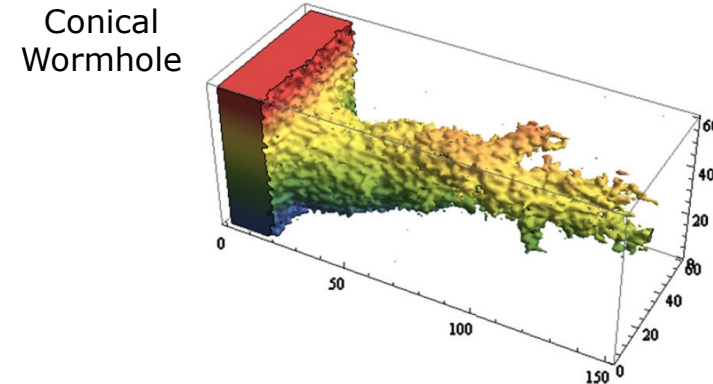
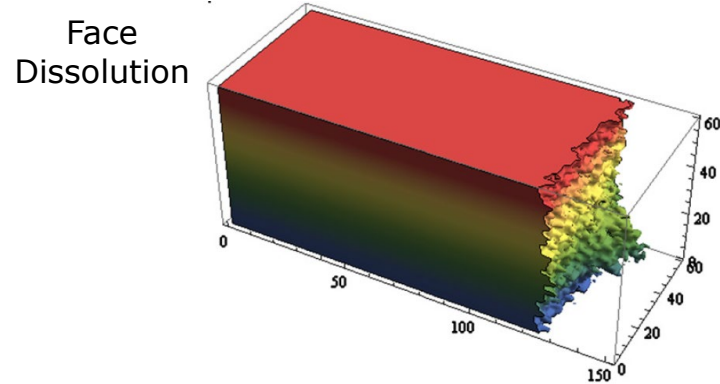
- Computational domain 256x256x362 voxel
- Porosity of subdomain: 21.9 %
- Homogeneous pore distribution



Flow simulation,
red: high pressure,
blue: low pressure

MODEL EVALUATION

- Goal: Replicate characteristic dissolution patterns



Images from
Maheshwari et al. 2013

DISSOLUTION PATTERN – FACE DISSOLUTION

Simulation settings:

Domain: 256x256x512 voxel

Runtime: 50 h

Average velocity: 0.001 m/s

pH value: 3.2

Simulation time: 700s

Number of particles: ~2000

Material Information:

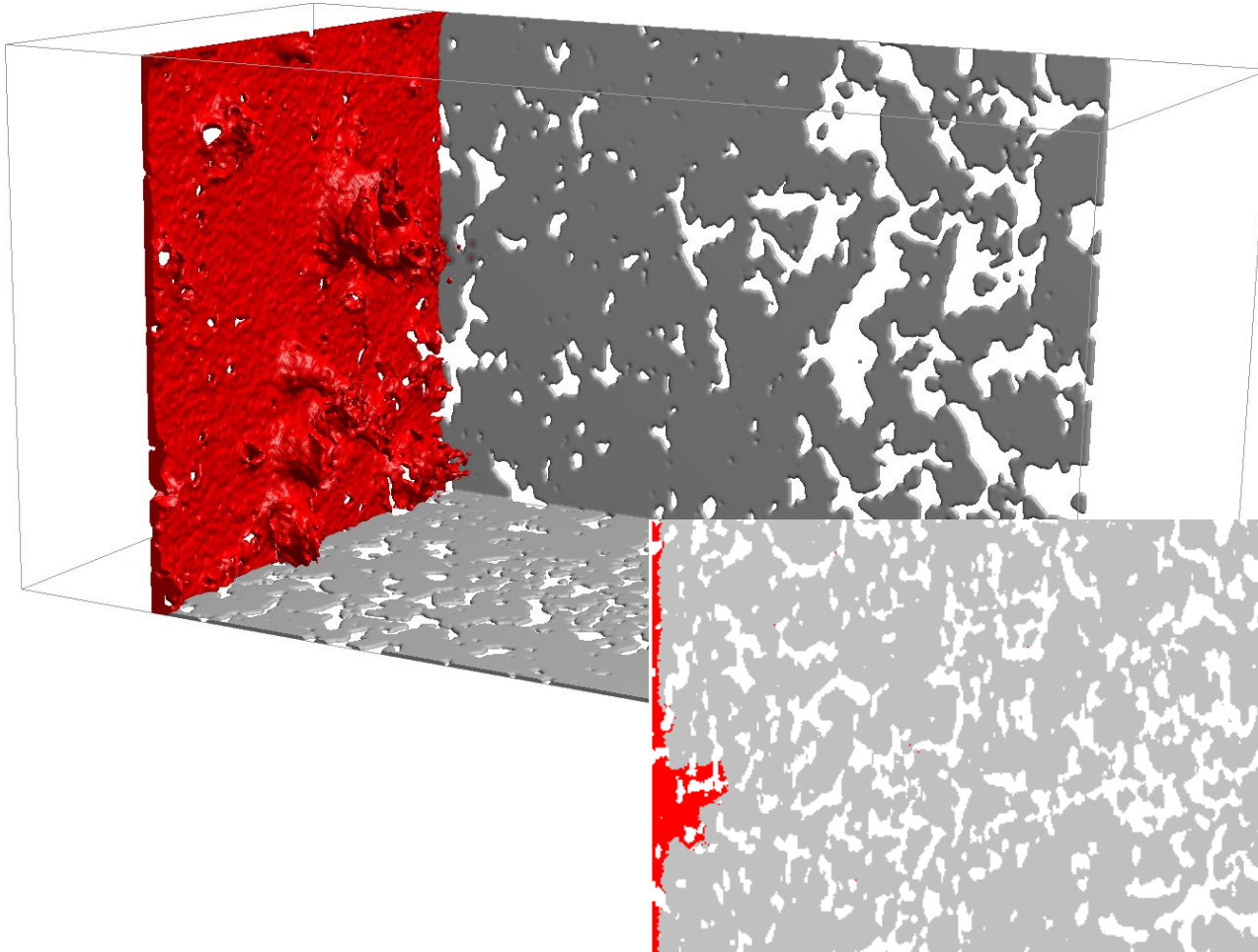
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 ID 01: Dissolved Structure

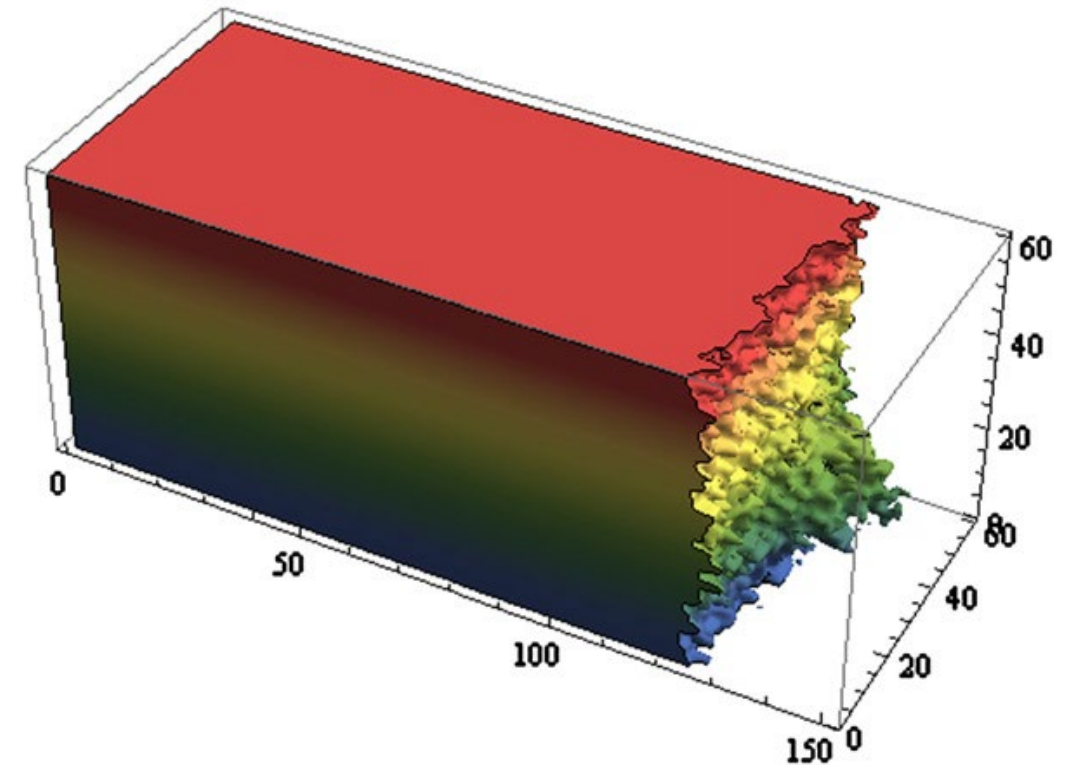
 ID 02: Original Structure



COMPARISON FACE DISSOLUTION PATTERN



GeoDict simulation



Maheshwari et al. 2013

DISSOLUTION PATTERN – CONICAL WORMHOLE

Simulation settings:

Domain: 256x256x362 voxel

Runtime: 36 h

Average velocity: 0.01 m/s

pH value: 3.2

Simulation time: 100s

Number of particles: ~2000

Material Information:

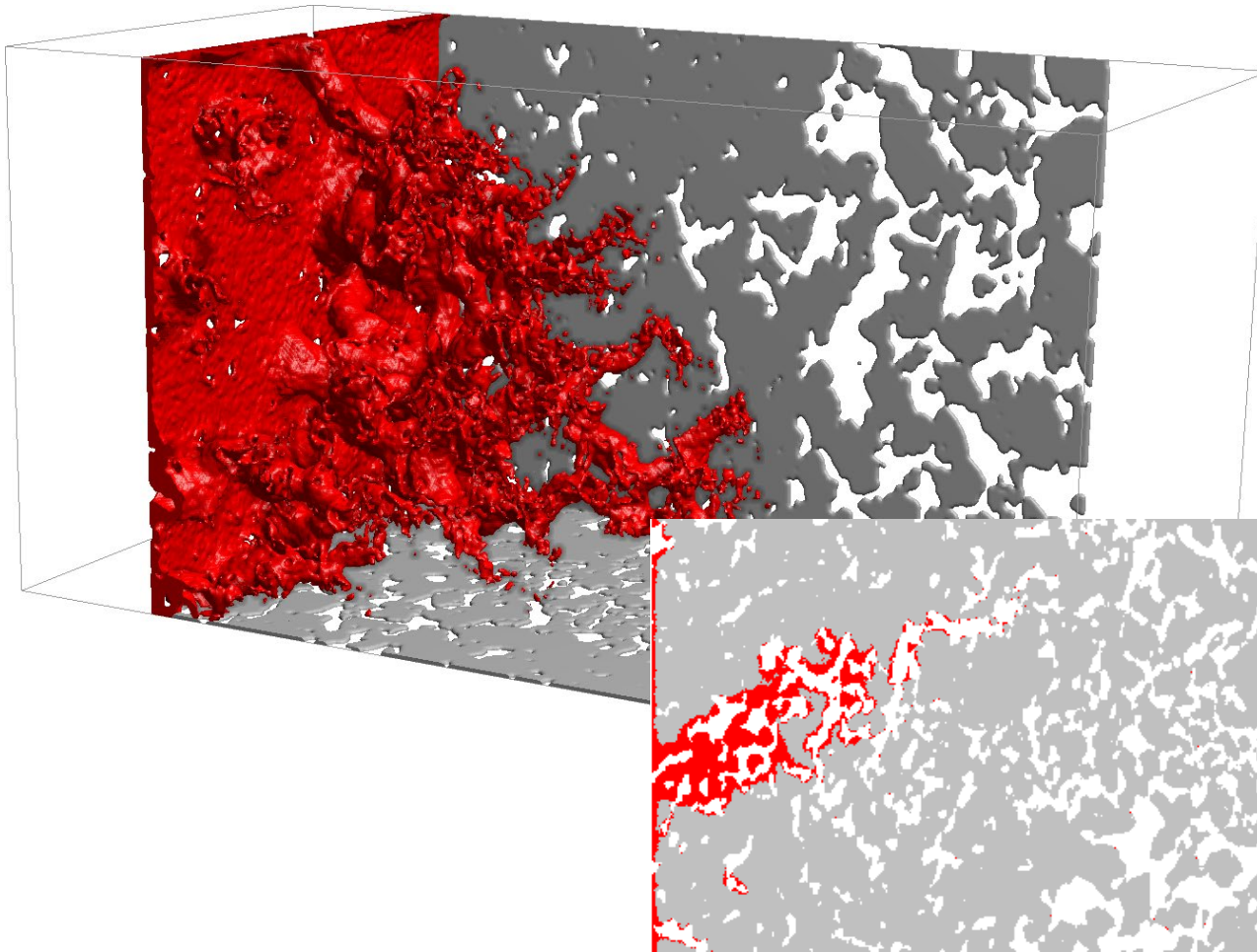
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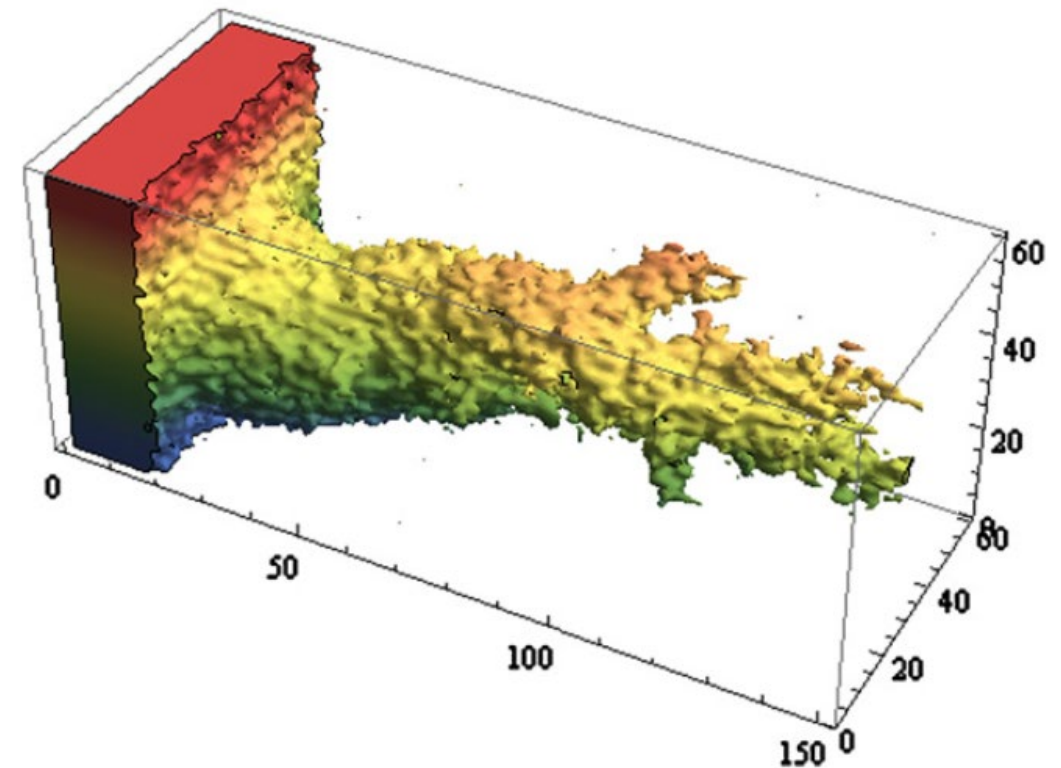
 ID 02: Original Structure



COMPARISON CONICAL WORMHOLE PATTERN



GeoDict simulation



Maheshwari et al. 2013

DISSOLUTION PATTERN – WORMHOLE

Simulation settings:

Domain: 256x256x362 voxel

Runtime: 28 h

Average velocity: 0.1 m/s

pH value: 3.2

Simulation time: 20s

Number of particles: ~2000

Material Information:

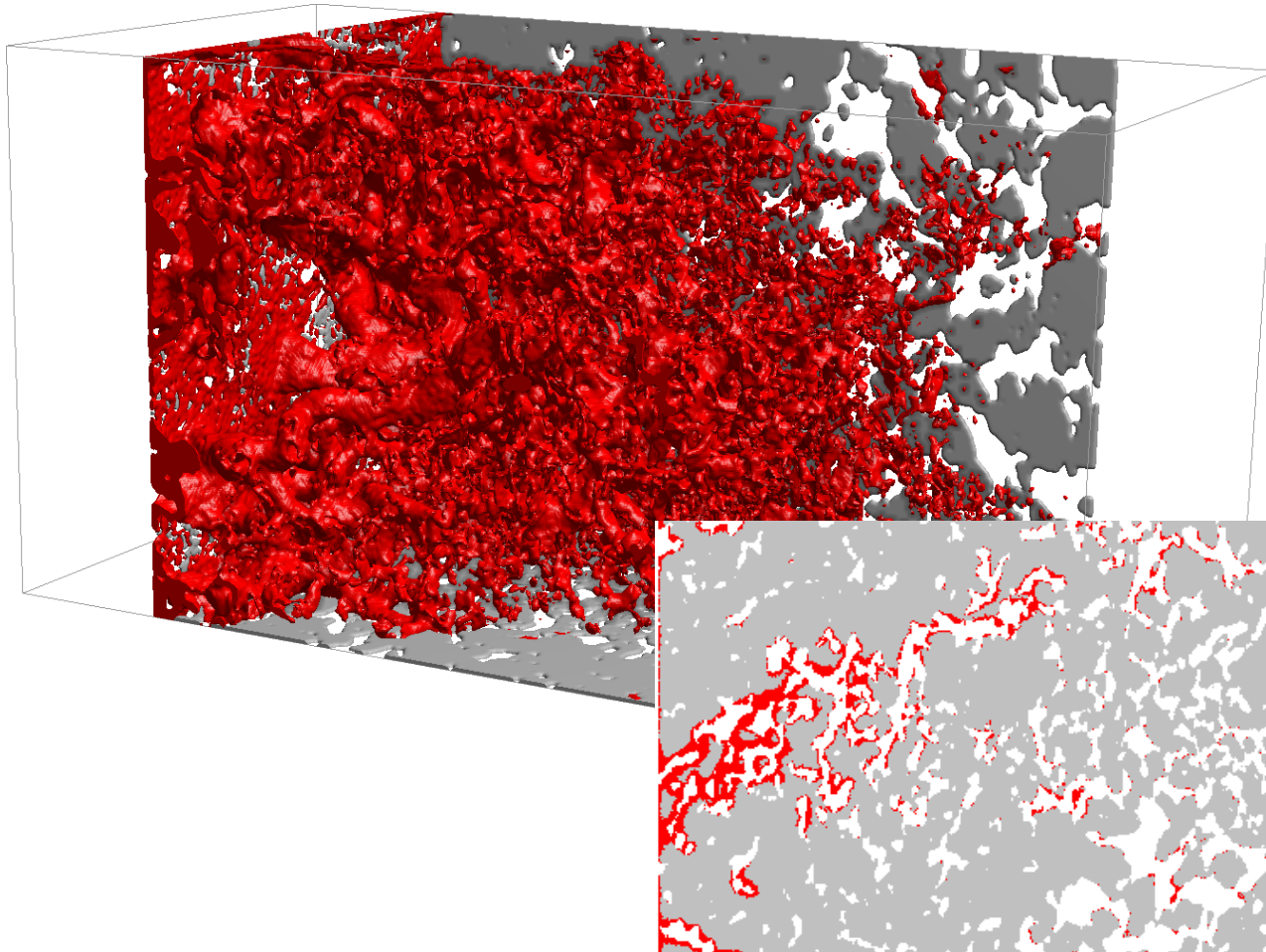
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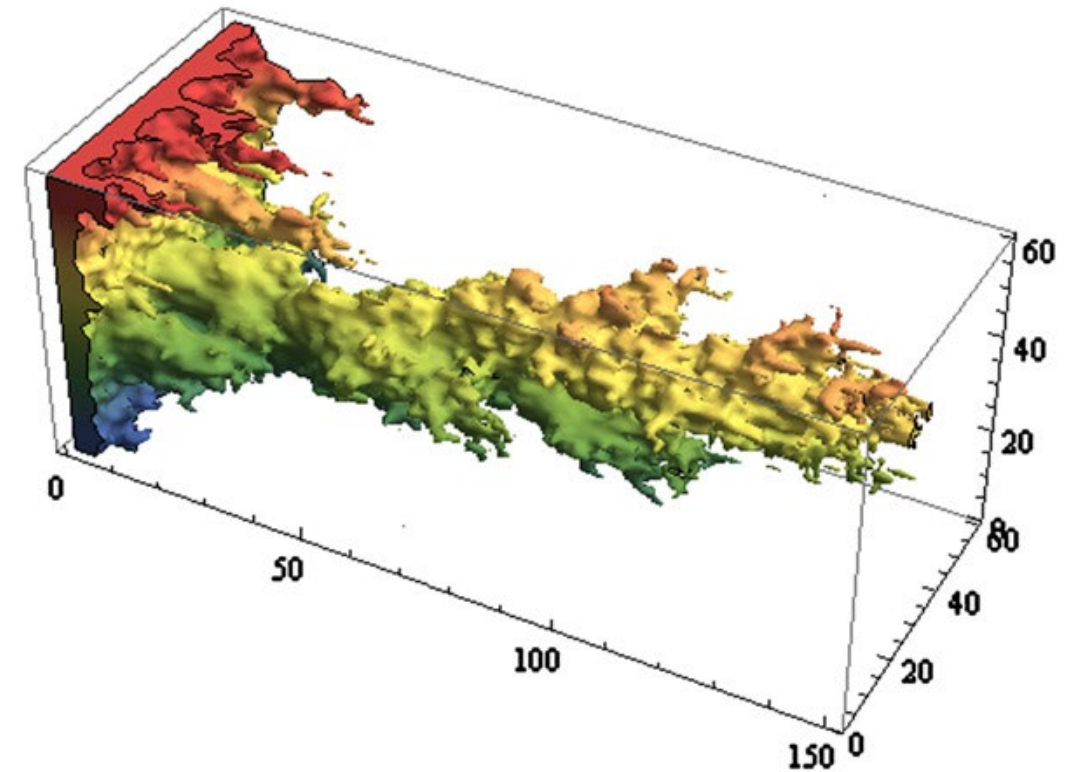
 ID 02: Original Structure



COMPARISON WORMHOLE PATTERN



GeoDict simulation



Maheshwari et al. 2013

DISSOLUTION PATTERN – UNIFORM DISSOLUTION

Simulation settings:

Domain: 256x256x362 voxel

Runtime: 29 h

Average velocity: 0.1 m/s

pH value: 2.8

Simulation time: 20 s

Number of particles: ~2000

Material Information:

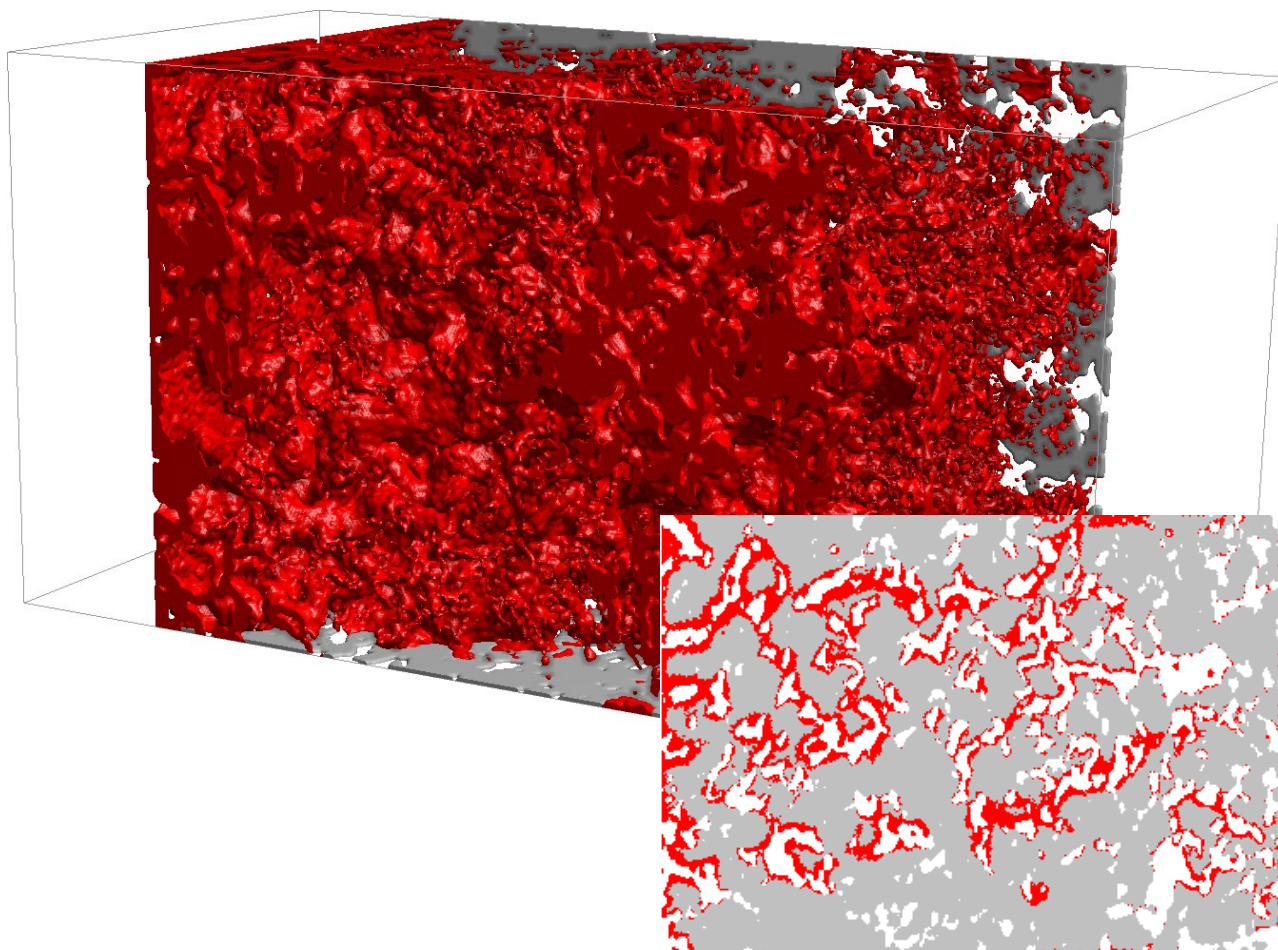
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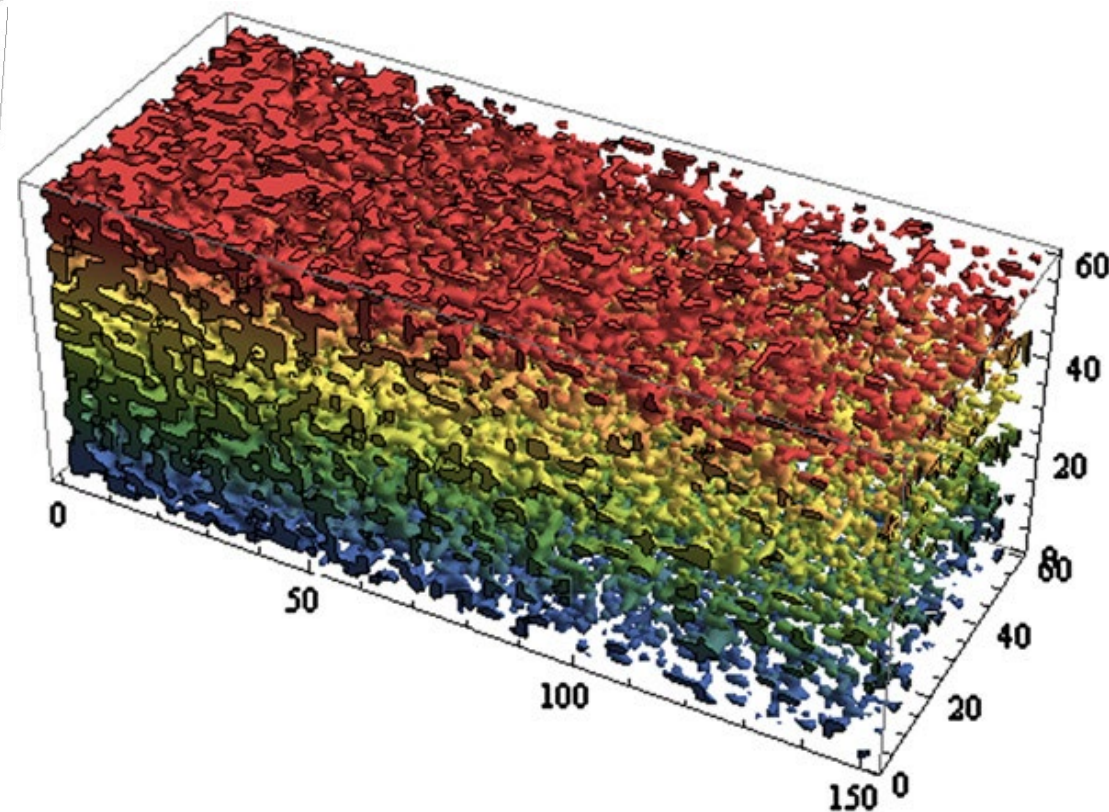
 ID 02: Original Structure



COMPARISON UNIFORM DISSOLUTION PATTERN

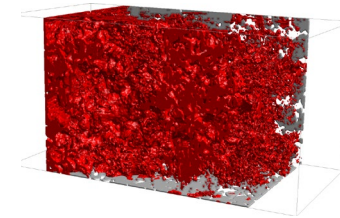
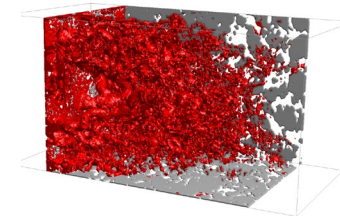
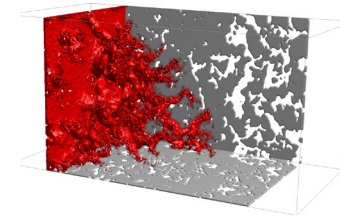
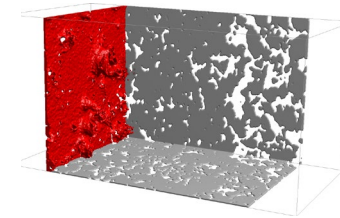
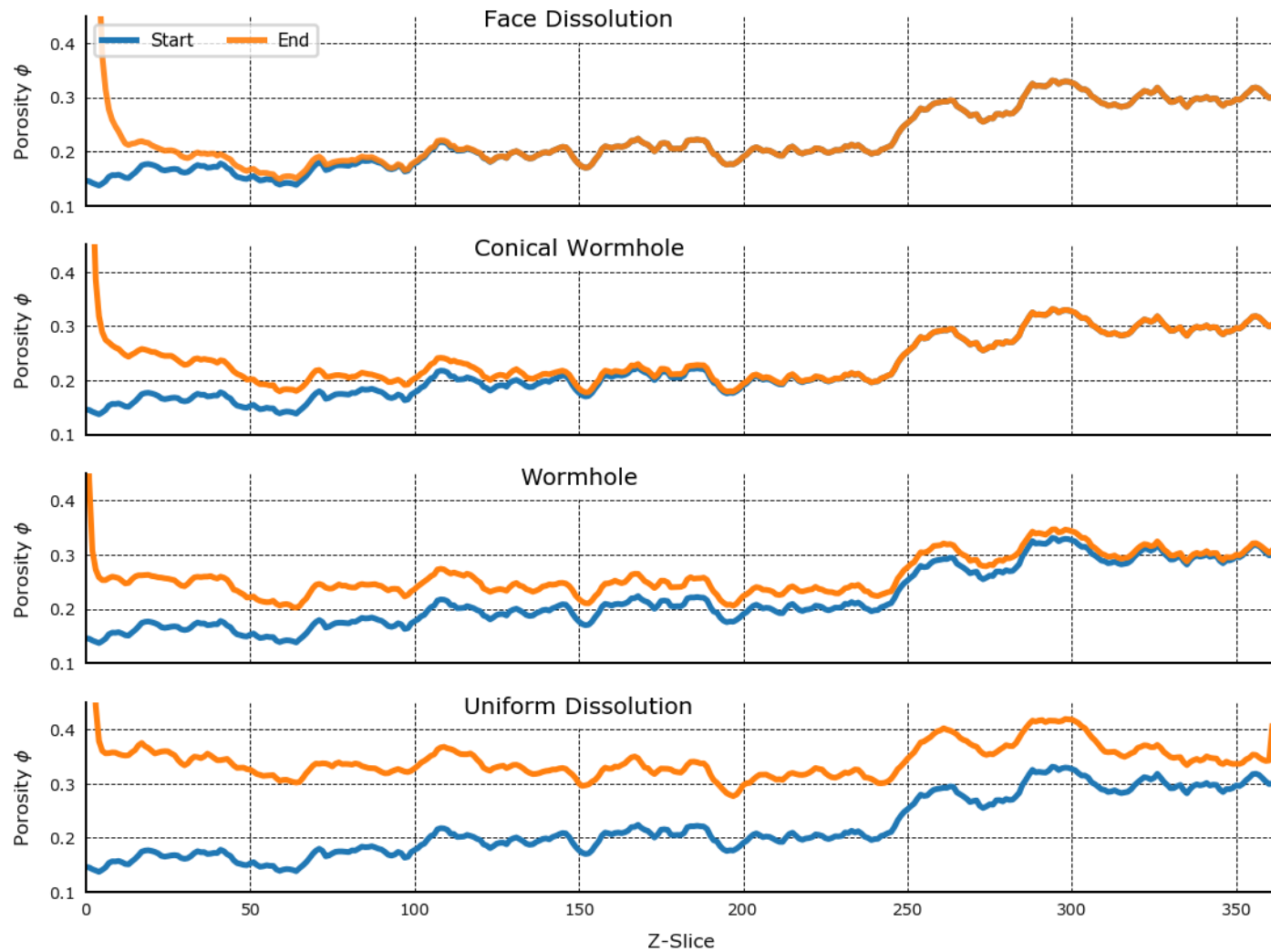


GeoDict simulation



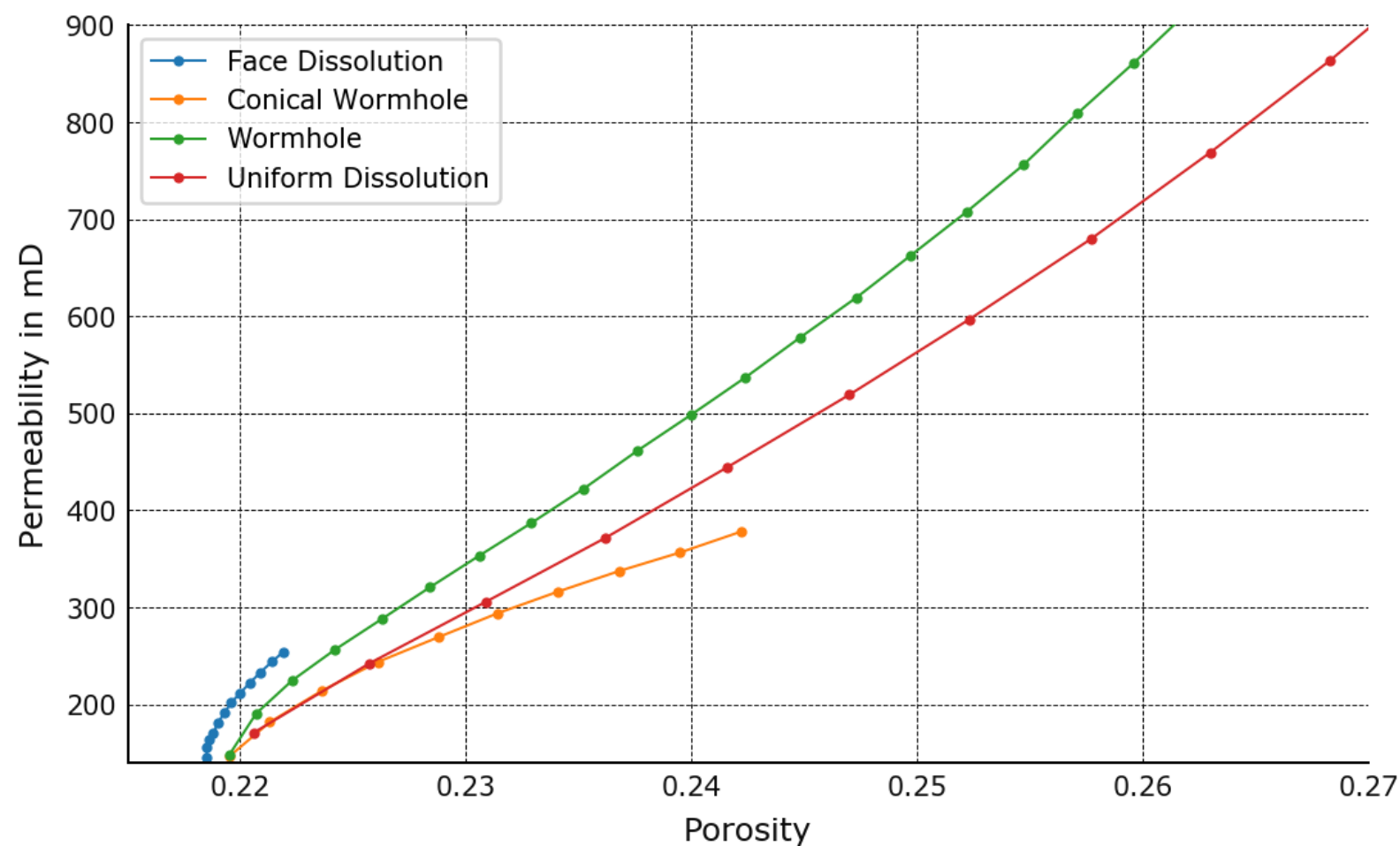
Maheshwari et al. 2013

POROSITY ANALYSIS



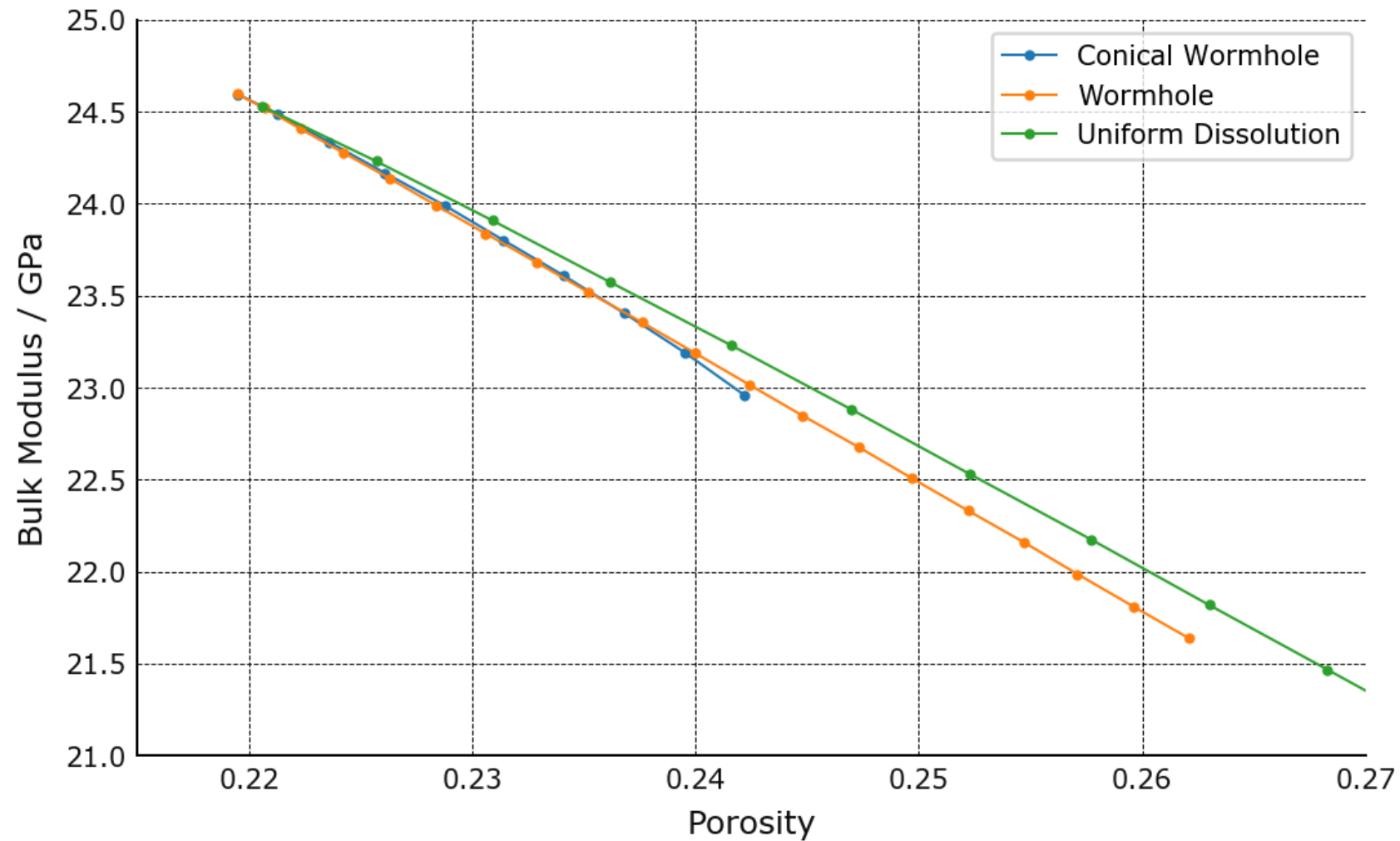
PERMEABILITY ANALYSIS

PERMEABILITY OVER POROSITY



MECHANICAL ANALYSIS

BULK MODULUS OVER POROSITY



„LARGE“ SIMULATION

Simulation settings

Domain: 512x512x76

Average velocity: 0.1

pH value: 3.2

Simulation time: 20 s

Number of particles:

Runtime: 120 h (16 cor

Material Information:

ID 00: Porespace [invis

ID 01: Dissolved Struct

ID 02: Original Structu



CONCLUSION & OUTLOOK

- We presented a numerical model to simulate reactive flow
- We evaluated the model by reproducing characteristic dissolution patterns
- Based on the commercially available DRP software GeoDict
- Using very efficient reliable numerical solvers, the simulations can be run on a state of the art desktop workstation
- We are currently working on incorporating the Matlab functions into GeoDict to reach computational domains of $> 2000^3$ voxels

THANK YOU FOR YOUR ATTENTION

Please come to our booth for more information about GeoDict®

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 www.math2market.de

REFERENCES

Andrae, H., Combaret, N., Dvorkin, J., Glatt, E., Junehee, H., Kabel, M., Keehm, Y., Krzikalla, F., Lee, M., Madonna, C., Marsh, M., Mukerji, T., Saenger, E., Sain, R., Saxena, N., Ricker, S., Wiegmann, A., Zhan, A., "Digital rock physics benchmarks Part I: Imaging and segmentation", Computers & Geosciences, 43, 25-32, 2013.

Lie, K. A. and Mallison, B. T. , Mathematical models for oil reservoir simulation. In *Encyclopedia of Applied and Computational Mathematics*, Springer-Verlag Berlin Heidelberg, 2015.

Maheshwari, P., Ratnakar, R.R., Kalia, N. and Balakotaiah, V., 3-D simulation and analysis of reactive dissolution and wormhole formation in carbonate rocks. Chemical Engineering Science, 90, 258-274, 2013.