Modeling wormhole formation in digital rock samples: the role of segmentation and permeability-porosity relationships

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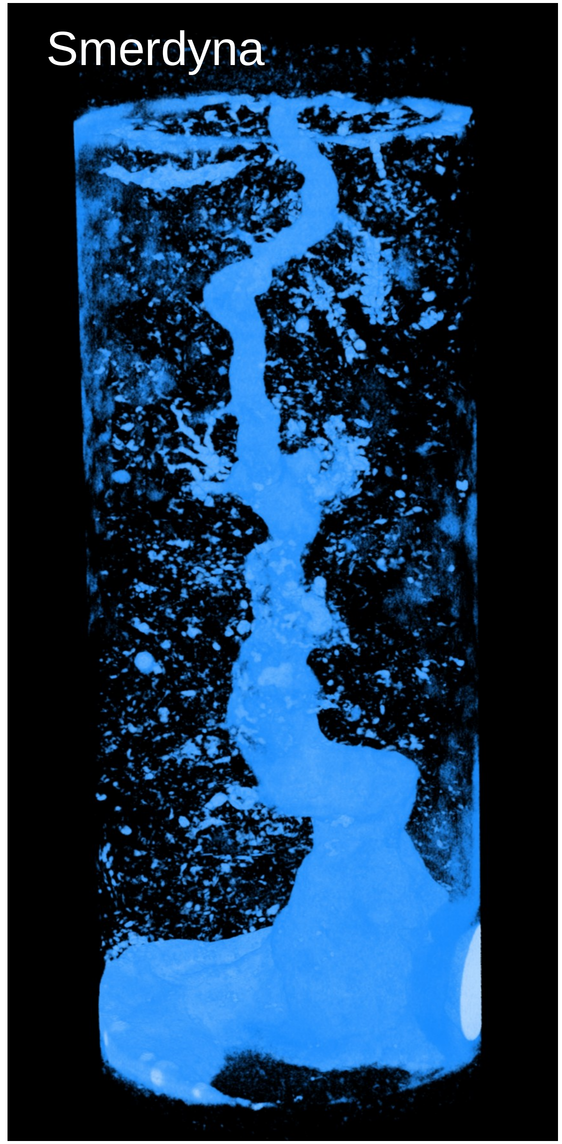
Introduction



- Dissolution of pore matrix by reactive fluids creates these beautiful patterns aka wormholes.
- The dissolution process is complex because of interaction of reactive fluid and medium.
- These dissolution channels can be numerically studied either with Darcy-models or with pore-scale models.

Sample used in Numerical simulation

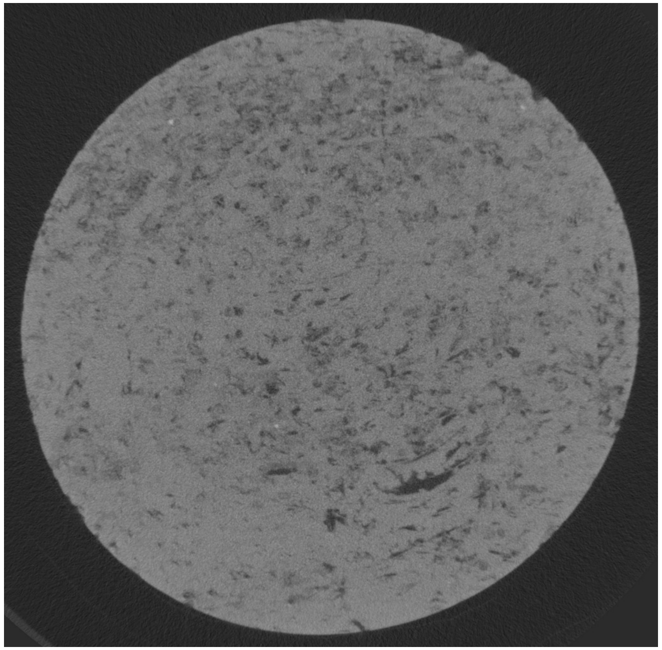


Fig-1: Slice of Wierzbica limestone sample

- Wierzbica limestone sample with porosity in range 15-20% and permeability around 2mD is used in numerical simulation.
- XCMT images of 60micron resolution are obtained.
- These images are further processed to remove noise.

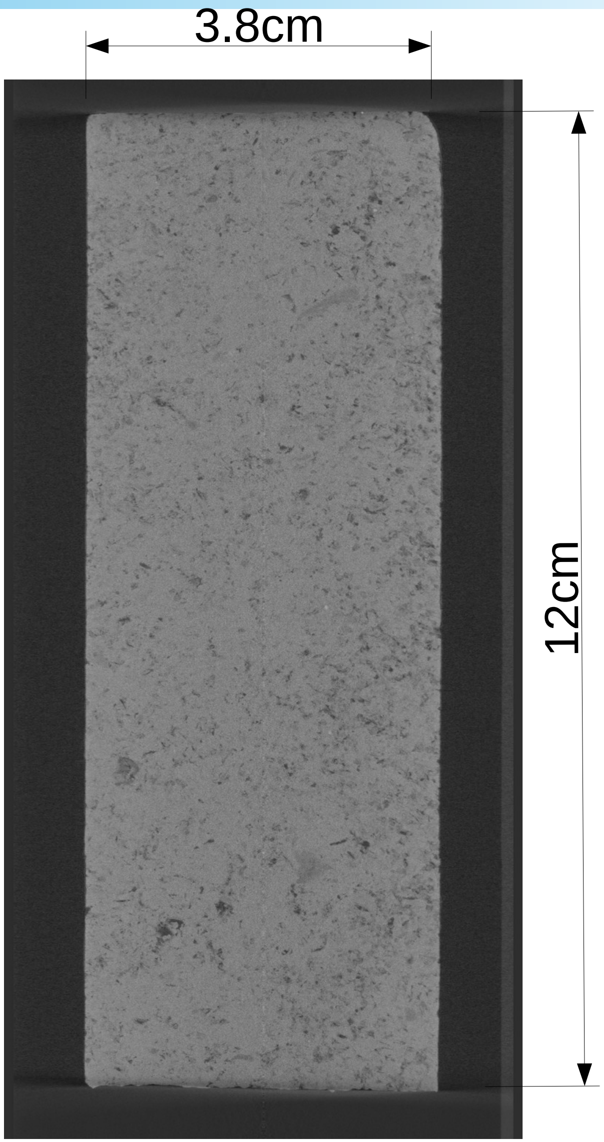
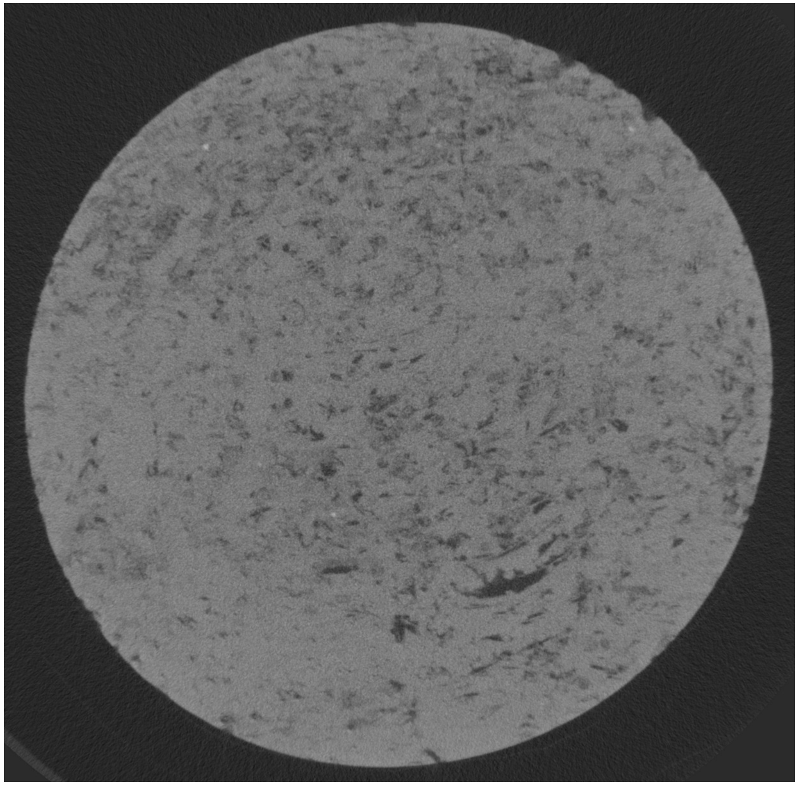
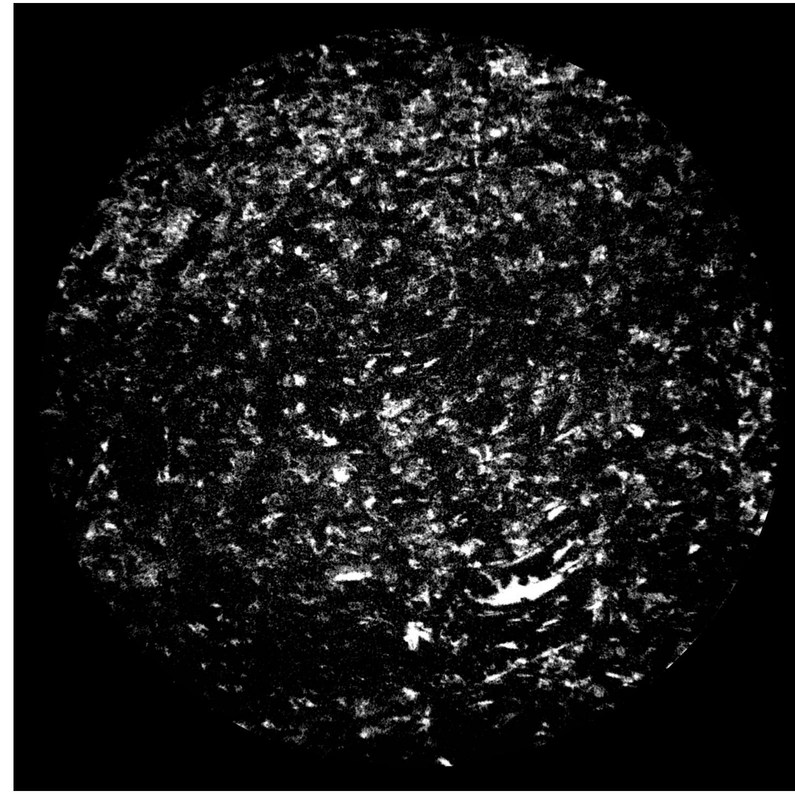


Fig-2: Wierzbica limestone sample with dimensions

Segmentation



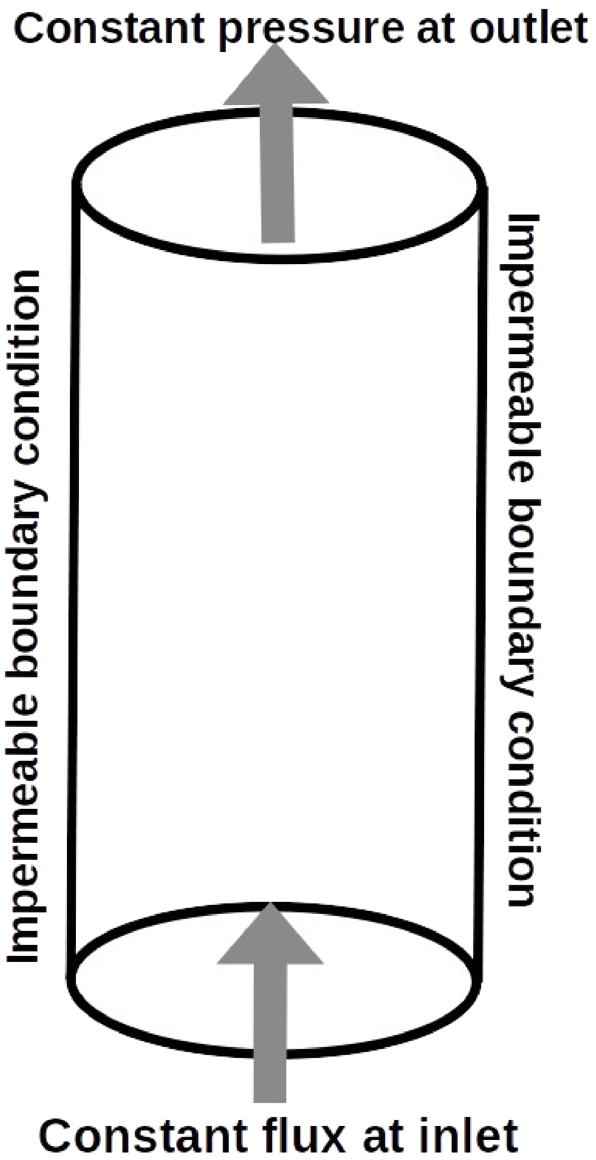
3-phase segmentation



- Segmentation is done by distinguishing the pores and solid matrix phase.
- Using the threshold value of pores and grains, porosity of sub-resolved phase is calculated [1]

[1] Luquot, L., Rodriguez, O., and Gouze, P.: Experimental characterization of porosity structure and transport property changes in limestone undergoing different dissolution regimes, Transport Porous Med., 101, 507–532, 2014.

Modeling



- Darcy-Brinkman Equation

$$\frac{-\mu}{\phi}\nabla^2 V + \frac{\mu}{K(\phi)} V = -\nabla p$$

- Convection-Diffusion-Reaction

$$-V\nabla c + \nabla\cdot(D\phi\nabla c) - R(c) = 0$$

- Kinetic rate law

$$R(c) = k\, s(\phi)\, c$$

- Porosity evolution

$$\frac{d\phi}{dt} = R(c)\, v$$

We are using an OpenFOAM based solver, PorousFOAM developed by Tony Ladd (https://github.com/tonyladd/porousFoam)

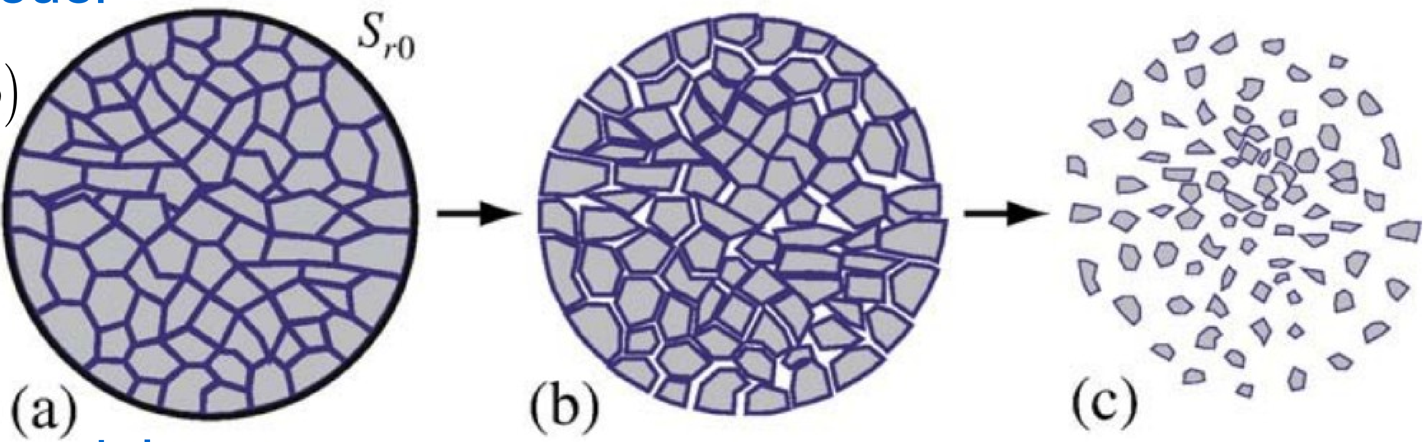
Modeling

- Porosity(ϕ)-Permeability (K) relation:

$$K = K_0 \frac{\phi^n}{(1-\phi)^2}$$

- Model of reactive surface area:
  - Sugar-Lump model

$$s(\phi) = a\,\phi(1-\phi)$$



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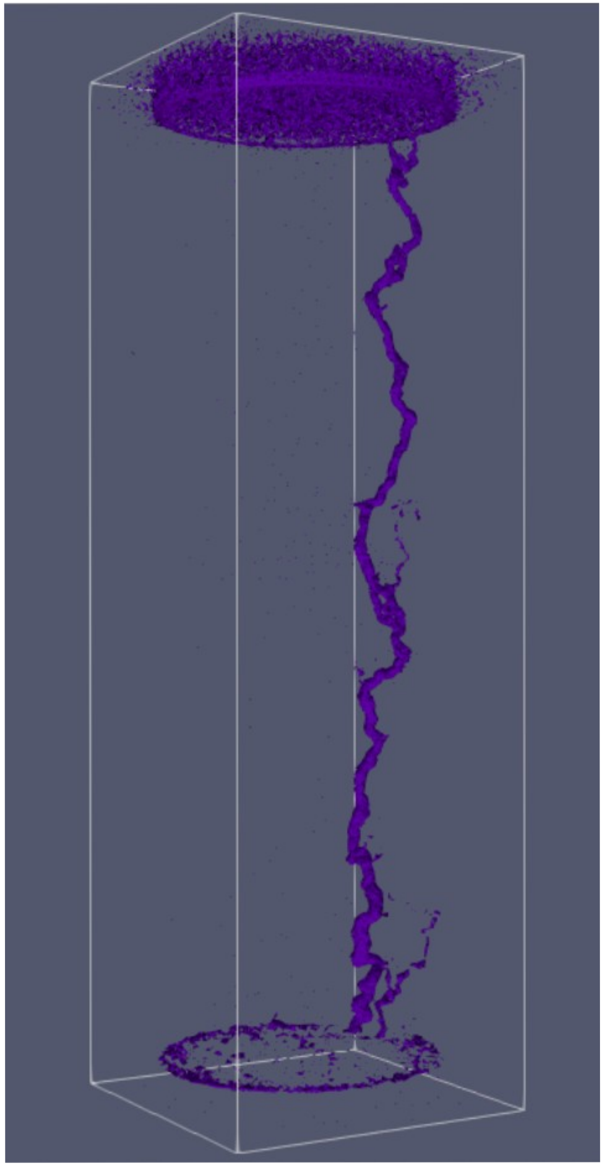
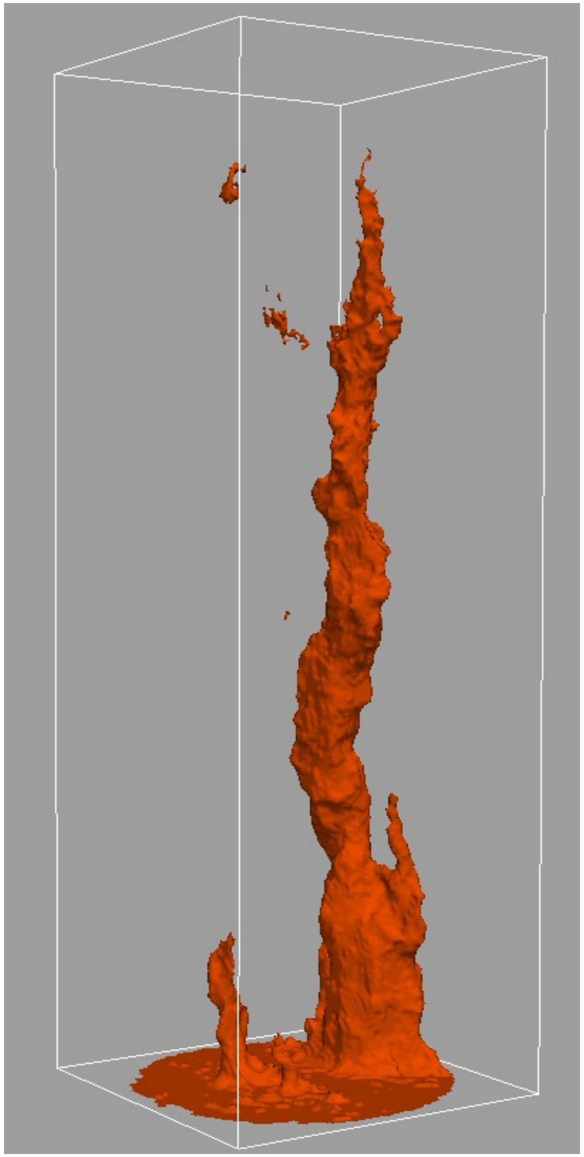
  - Constant area model

$$s(\phi) = const$$

Now by following the Darcy-scale models, can we correctly predict the wormhole formation?

Wormholes as porosity contours





- Darcy-Brinkman solver with Carman-Kozeny porosity-permeability relation and sugar-lump reactive surface area model has been used.
- The simulated wormhole grows at the same place but is quite thicker.
- The thickness of dominant wormhole at the inlet, where the competition between wormholes occur, is more which shows the limitation of model.

(a) (b)

Fig-3: Comparison of porosity contours of (a) lab-dissolved core with (b) simulated wormhole using Carman-Kozeny (n=3) porosity-permeability relation and sugar lump model

Other numerical experiments

Wormholes as porosity contours

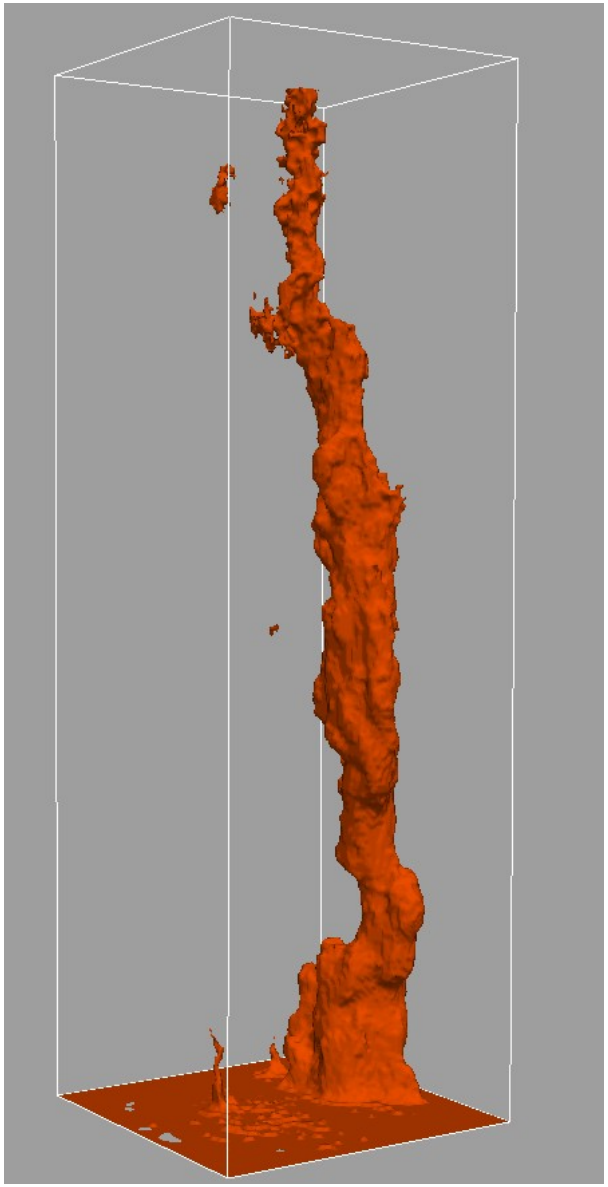


Fig-4: Wormhole with n = 6 using sugar lump model

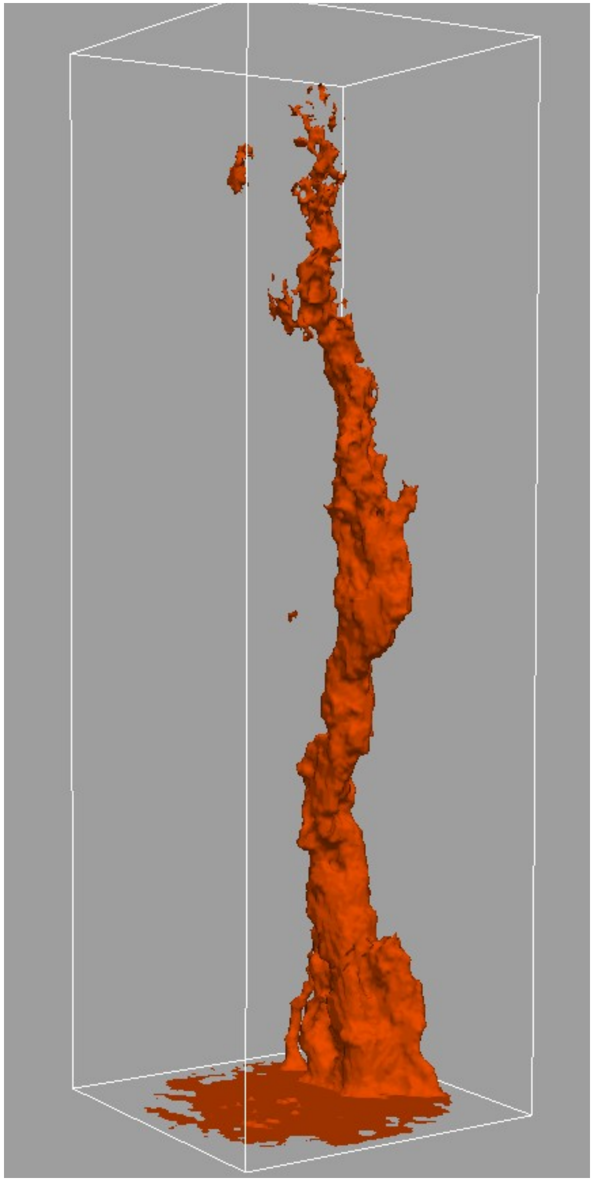
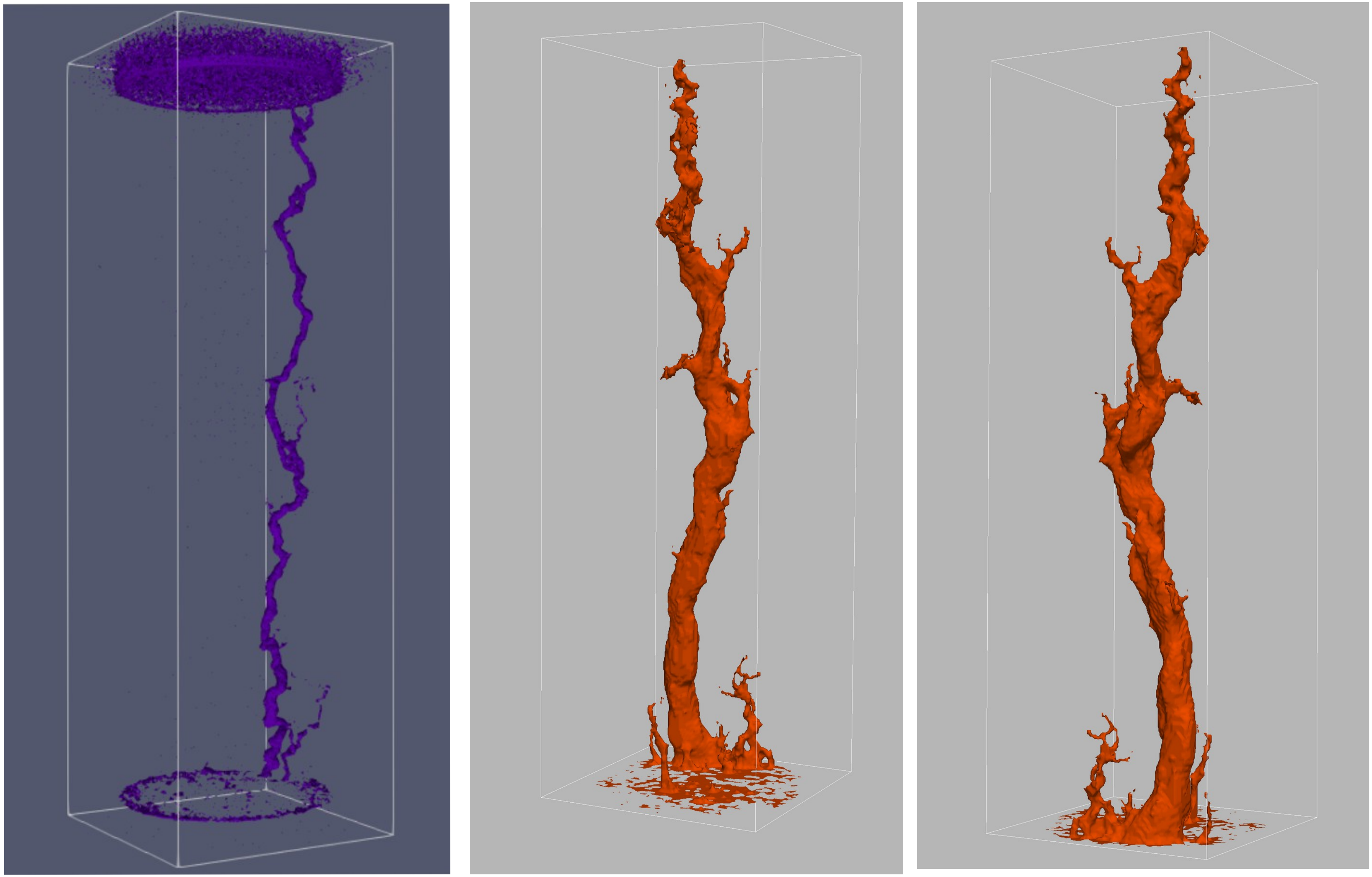


Fig-5: Wormhole with n = 10 using sugar lump model

Wormholes as porosity contours



(a) (b) (c)

Fig-6: Comparison of porosity contours lab-dissolved core (a) with simulated wormhole (b, c) for n = 6 using constant reactive surface area model

Conclusion

- The simulated wormholes are thicker than experimental wormholes.
- Higher thickness of simulated wormhole shows limitation of Darcy scale models.
- Numerical study of dissolution of pore matrix is very sensitive to reactive surface area models and porosity-permeability exponent.

Questions and Suggestions are welcomed