Changes in Porous Media Properties by Modeling Dissolution and Morphological Transformations in Micro-CT images

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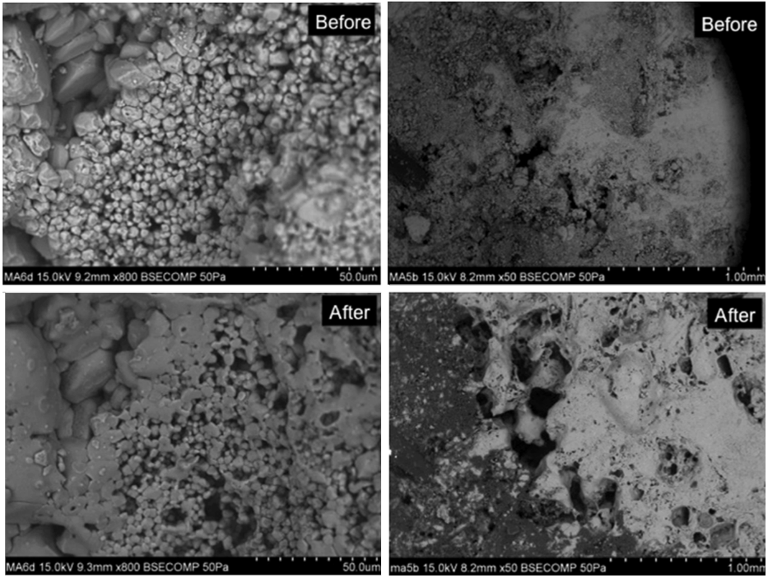
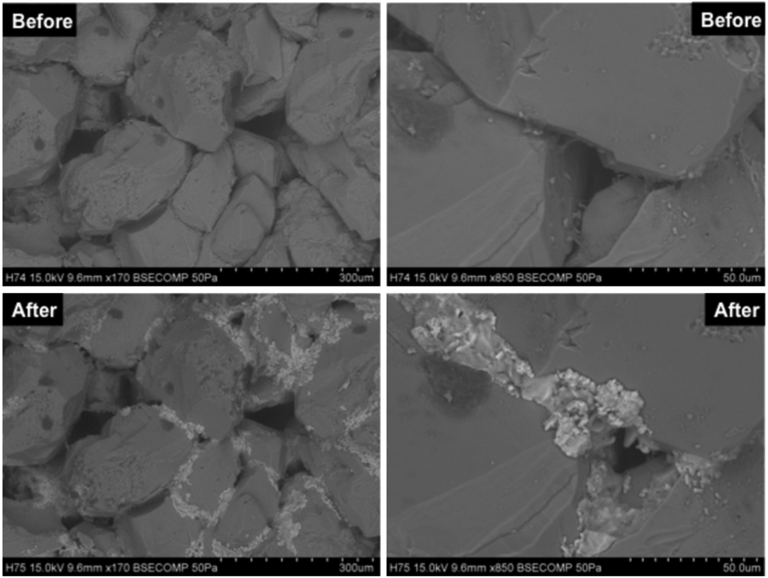
Dissolution by CO_2 Rich Water

(Vanorio, Nur & Ebert, 2011)



Salt Precipitation

(Vanorio, Nur & Ebert, 2011)



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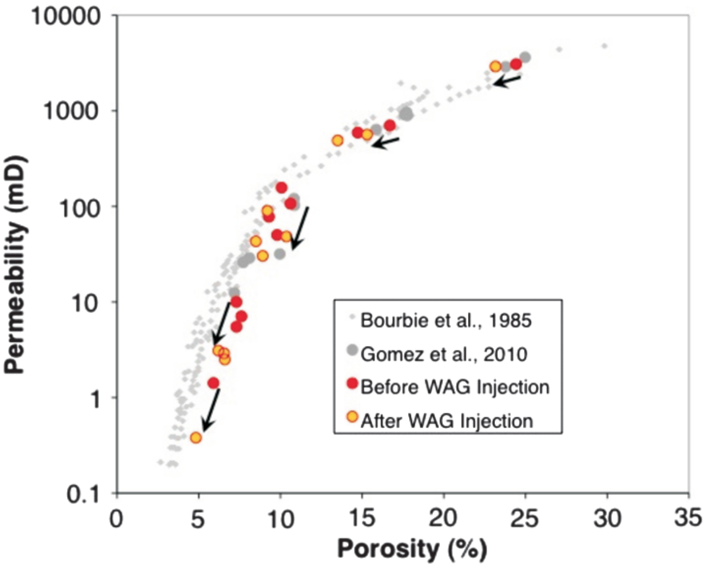
Permeability – Porosity Evolution

(Vanorio, Nur & Ebert, 2011)



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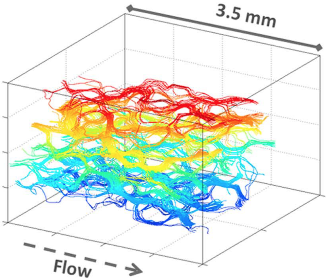
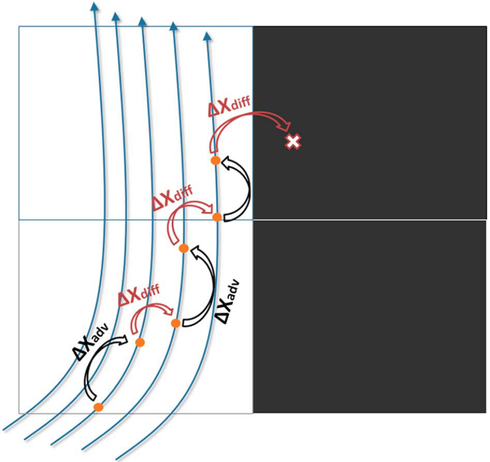
Previous Work

Pore-scale simulation of carbonate dissolution in micro-CT images. Nunes, Blunt 2016.

- κ: Navier-Stokes flow model.
- C: Advection-diffusion equation.
- Diffusive term with a random walk.
- Dissolution as particle tracking.
- Dissolution rate, number of particles that hit a voxel, with a threshold ϕ.





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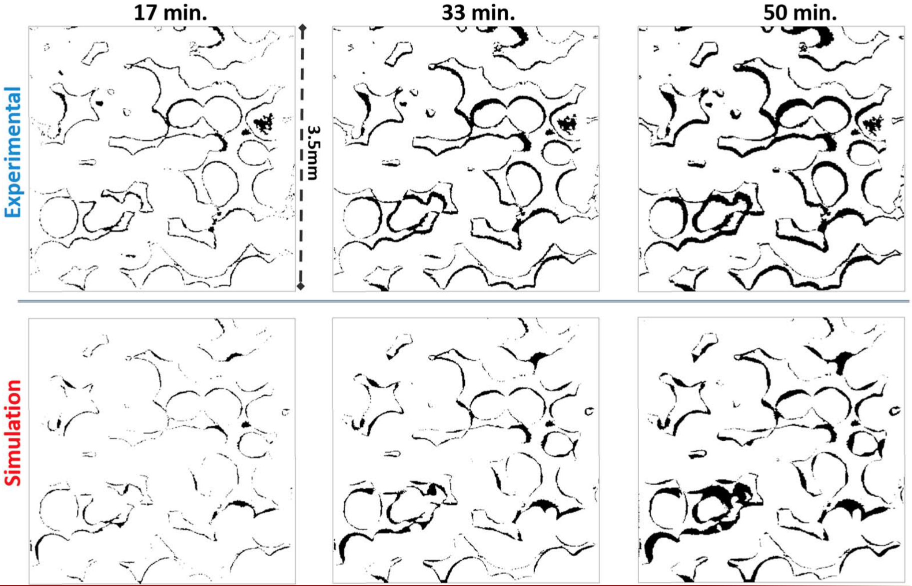

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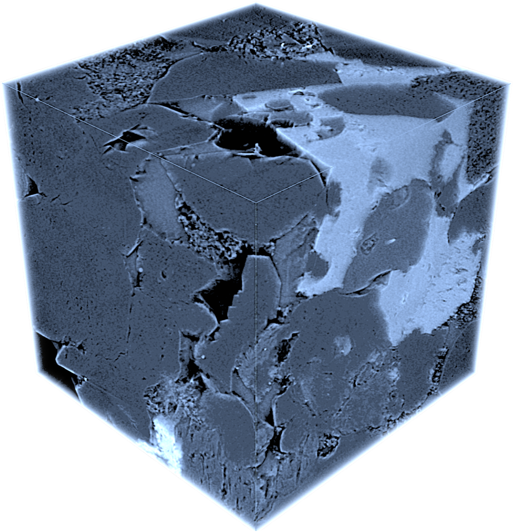
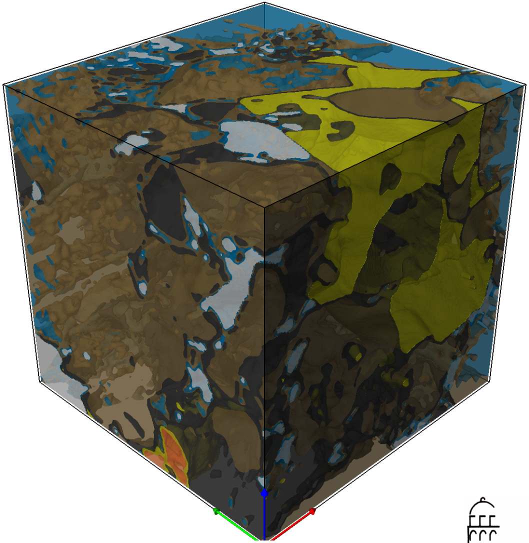
Micro-CT scan scale

Berea Sandstone $\approx 500\mu m$





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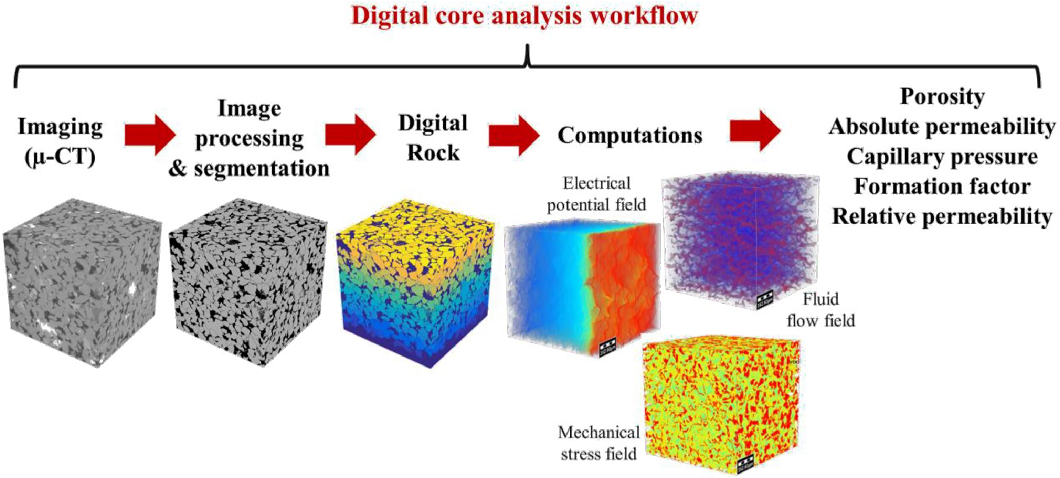
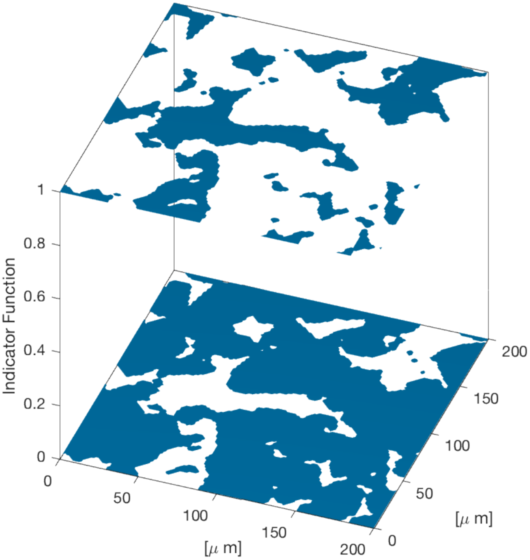
Present processing of CT-scan Data

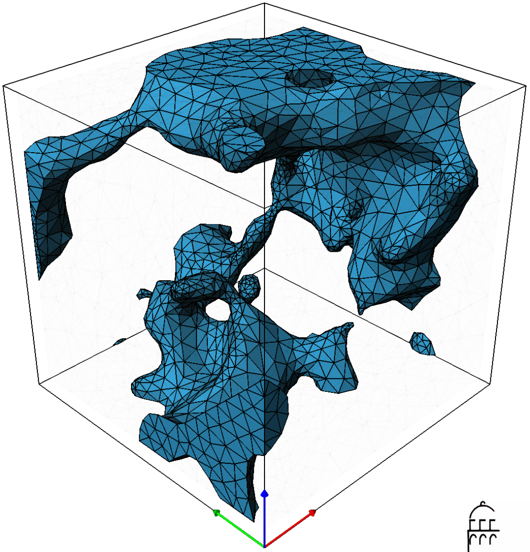
N. Saxena(2017)



Present Rock Geometry Representations

Indicator Function and Tetrahedral Meshes





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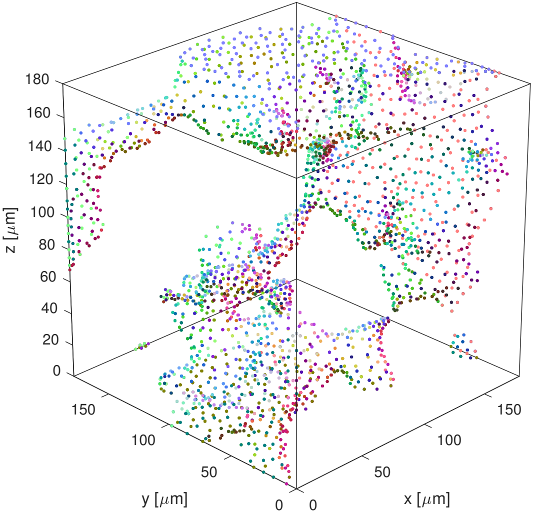
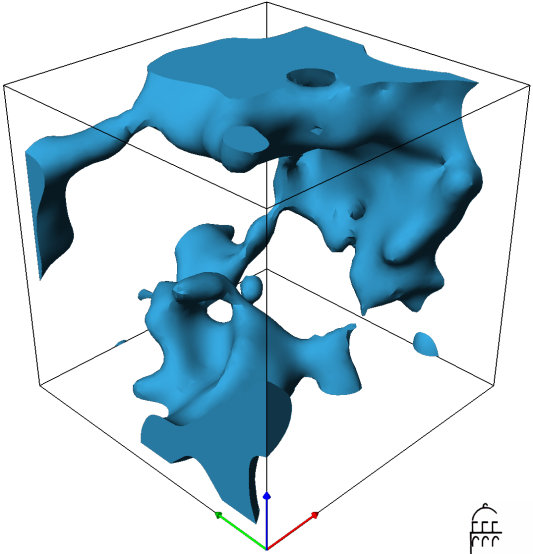
Other Ways to Express Rock Geometry

Implicit Functions and Point Clouds





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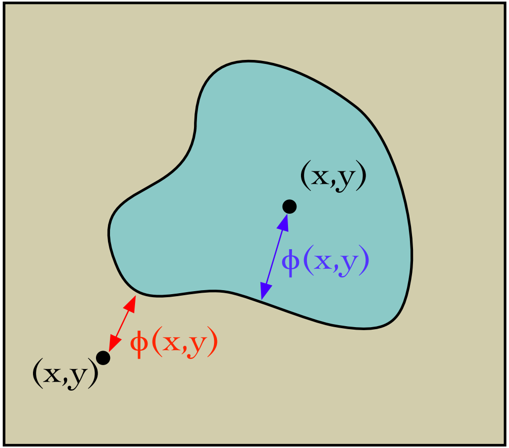
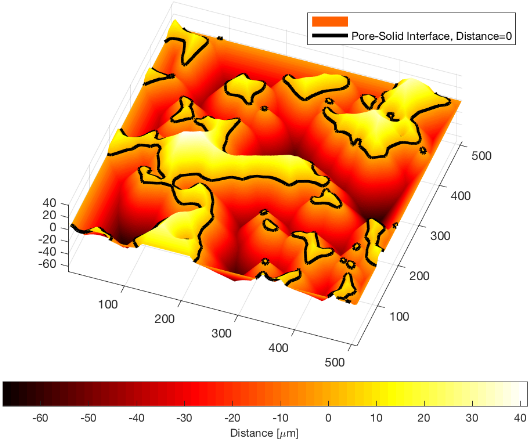
Distance Function

Osher, S., & Sethian, J. A. (1988). Journal of Computational Physics, 79(1)





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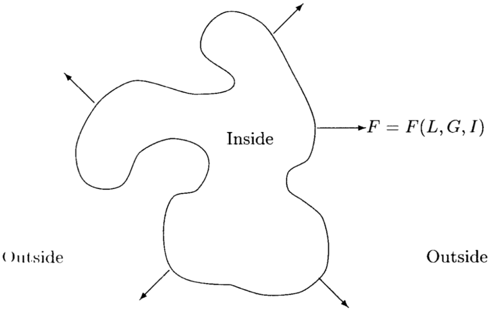
Propagating boundaries

The time view



The boundary value.

- F is the normal velocity field.
- $T(\vec{x})$ arrival time.
- $|\nabla T| F = 1$ with $T = 0$ on Γ

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Propagating Boundaries

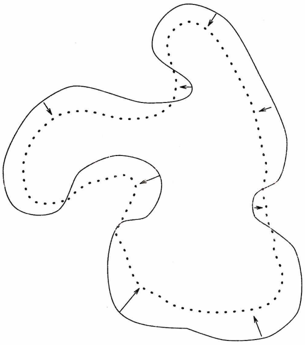
Implicit Function view

Move the boundary with a velocity field $\vec{\boldsymbol{v}}(t)$

$$\frac{\partial \phi}{\partial t} + \vec{\boldsymbol{v}}(\vec{x}, t) \cdot \nabla \phi = 0$$

$$\phi(\vec{x}, 0) = 0$$

- The solution is not a distance function.
- The starting function does not need to be a distance function.(Barles, 1993).



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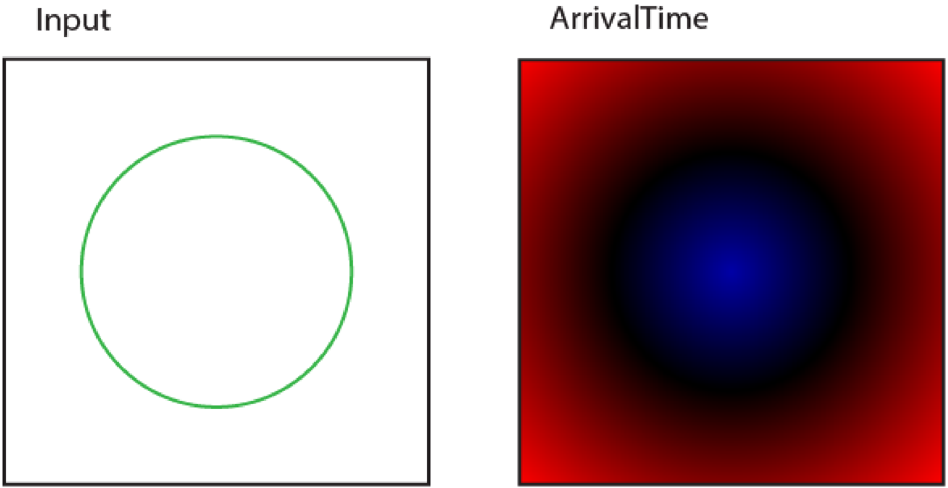
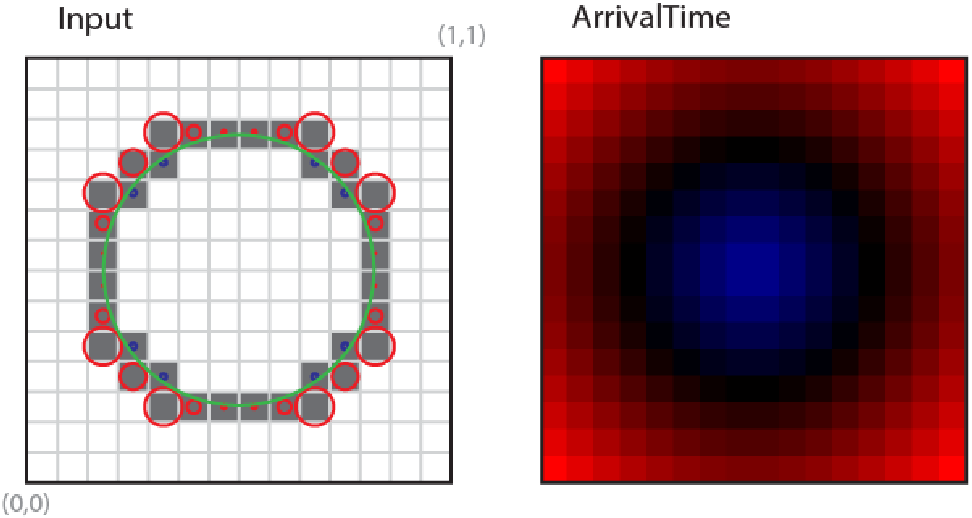
Fast Marching Methods

Using the time view



Fast Marching Methods

Using the time view



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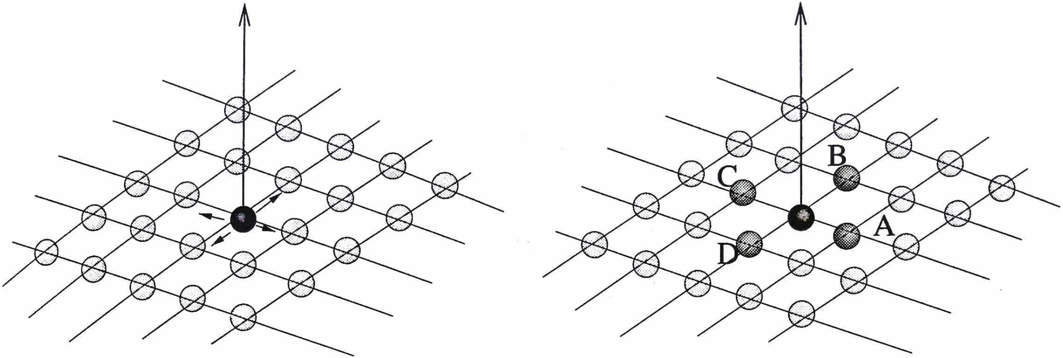
Fast Marching Methods

Using the time view



Update "downwind"   Compute new possible values

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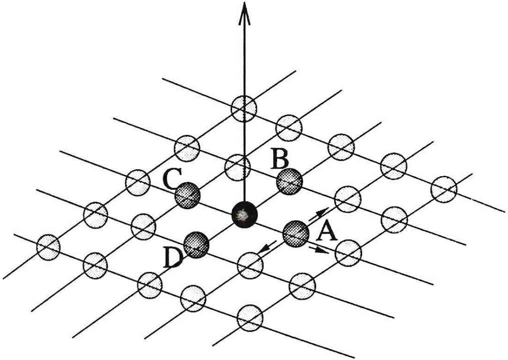
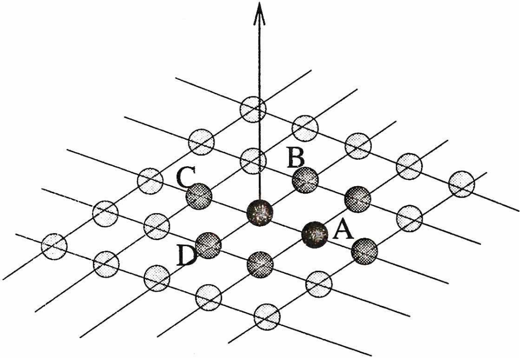
Fast Marching Methods

Using the time view



Choose smallest dark gray sphere (for example, "A")



Freeze value at A, update neighboring downwind points

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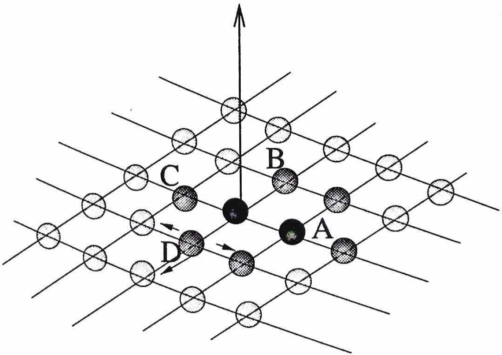
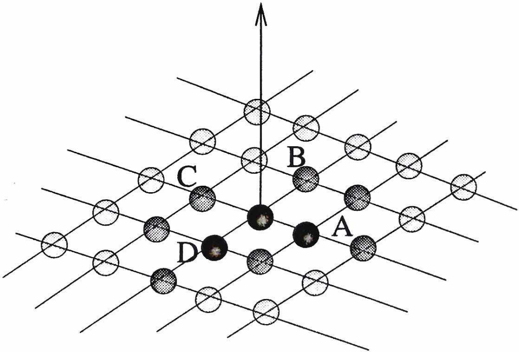
Fast Marching Methods

Using the time view



Choose smallest dark gray sphere (for example, "D")



Freeze value at D, update neighboring downwind points

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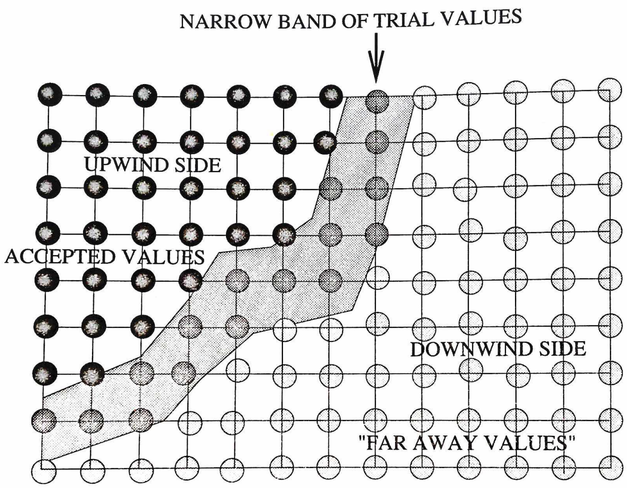
Fast Marching Methods

Using the time view



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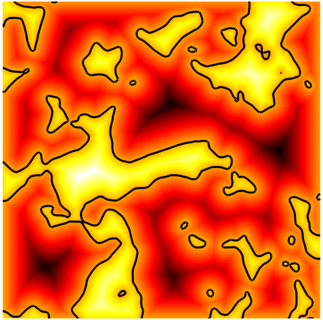
Properties of the Distance Function



- The boundary is clearly defined at the zero distance.
- Unit normal is give by:

$$\vec{N} = \frac{\nabla \phi}{|\nabla \phi|}$$

- The mean curvature is given by:

$$\kappa = -\nabla \cdot \left[\frac{\nabla \phi}{|\nabla \phi|} \right]$$

- The indicator function is readily available.
- The norm of the gradient is one:

$$|\nabla \phi| = 1$$

Moving the boundary

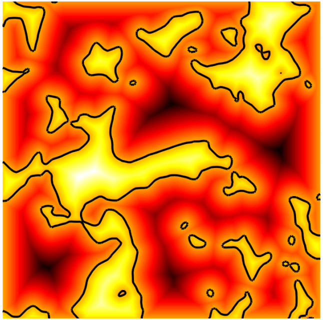
Osher, S., & Sethian, J. A. (1988). Journal of Computational Physics, 79(1)

Move the boundary with a velocity field $\vec{\boldsymbol{v}}(t)$

$$\frac{\partial \phi}{\partial t} + \vec{\boldsymbol{v}}(\vec{x}, t) \cdot \nabla \phi = 0$$

$\vec{\boldsymbol{v}}(\vec{x}, t)$ Can be defined as a function of the processes present.

- The solution is not a distance function.
- The starting function does not need to be a distance function.(Barles, 1993).



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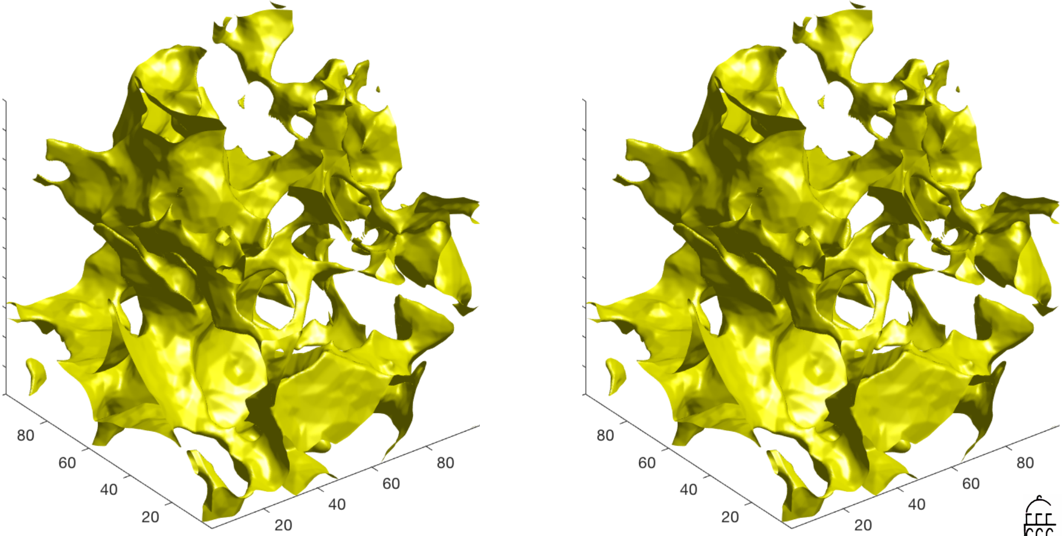
$$\vec{v} = \pm c\,\hat{n}$$

Dissolution and Deposition, Berea Sandstone $200\mu m$



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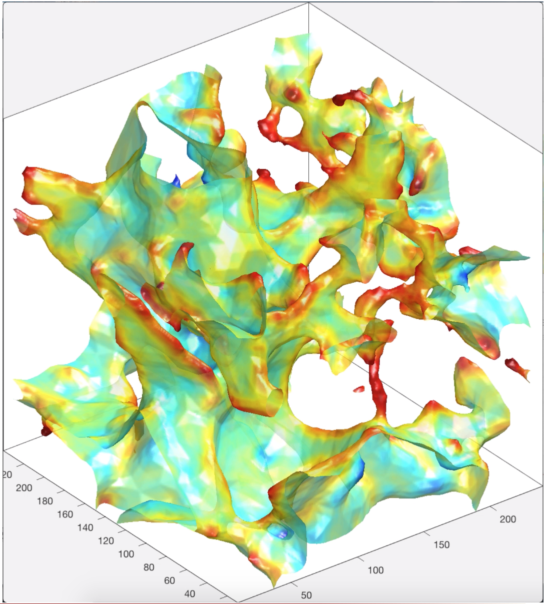
Advection by Surface Curvature

$$\frac{\partial \phi}{\partial t} + \vec{\boldsymbol{v}}(\vec{x}, t) \cdot \nabla \phi = 0$$

$$\vec{\boldsymbol{v}} = -\left(\nabla \cdot \left[\frac{\nabla \phi}{|\nabla \phi|}\right]\right) \hat{\boldsymbol{n}}$$

- Surface curvature is implicit in the chemical potential *(Miller 2016, Personal Communication)*
- Berea Sandstone $200\mu m$

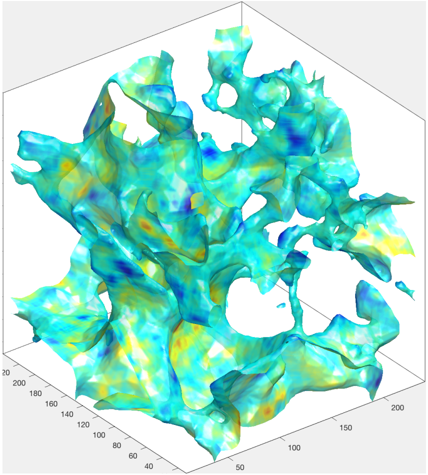


Surface Diffusion

- Preserves volume.
- Destroys the distance function.
- Fourth order derivative, unstable.
- Implicit in space, explicit in time.
- Destroys the distance function.

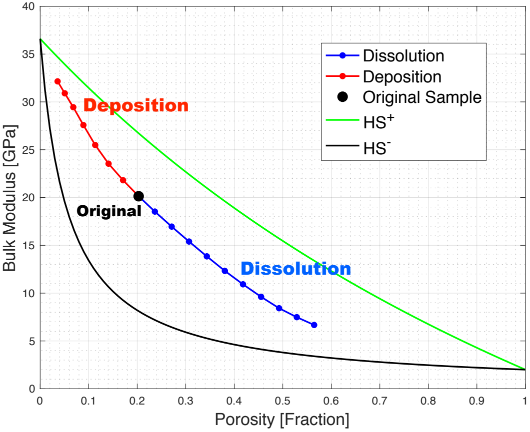
$$\vec{v} = \nabla_s \kappa \hat{n}$$

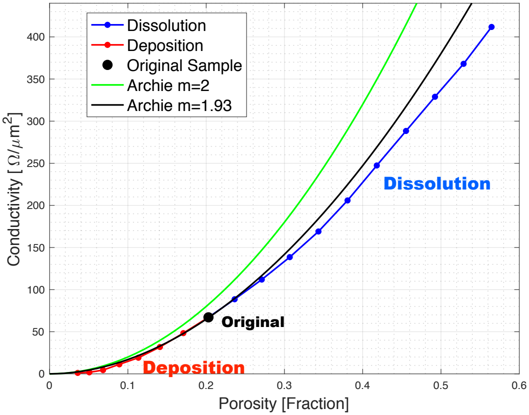
$$\vec{v} = (\nabla - \partial_n)\cdot(\nabla - \partial_n)\left(\nabla \cdot \left[\frac{\nabla \psi}{|\nabla \psi|}\right]\right)\hat{n}$$



Elastic and Electrical Properties

Motion at Constant Velocity





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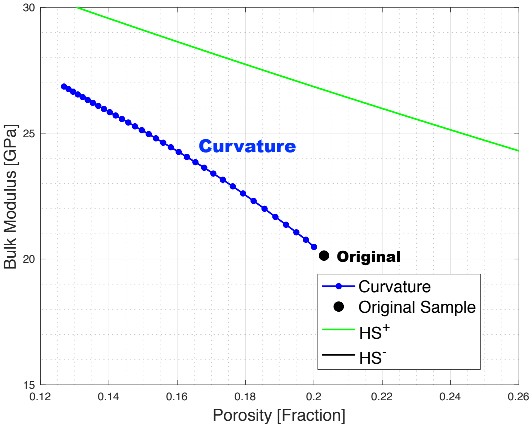
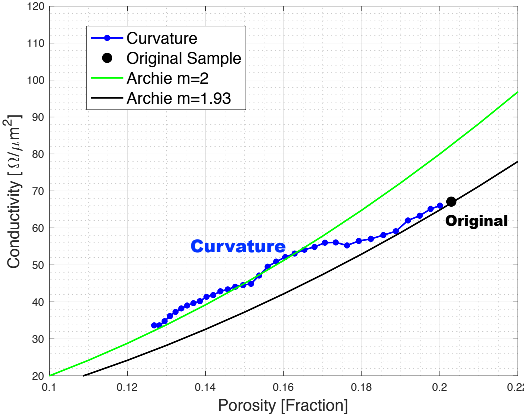
Elastic and Electrical Properties

Motion proportional to Curvature





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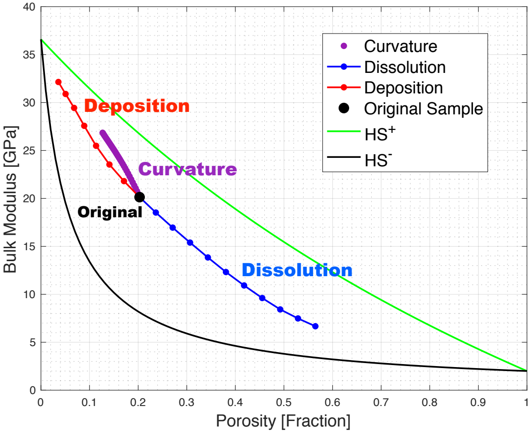
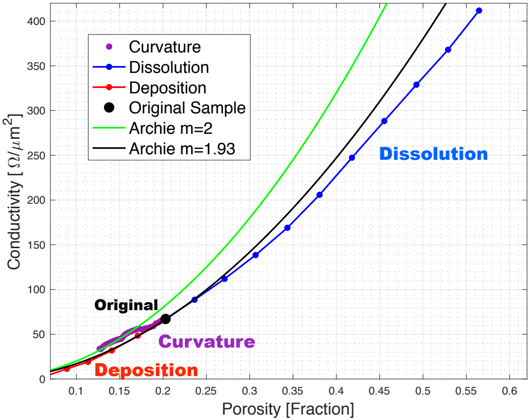
Elastic and Electrical Properties

Comparison





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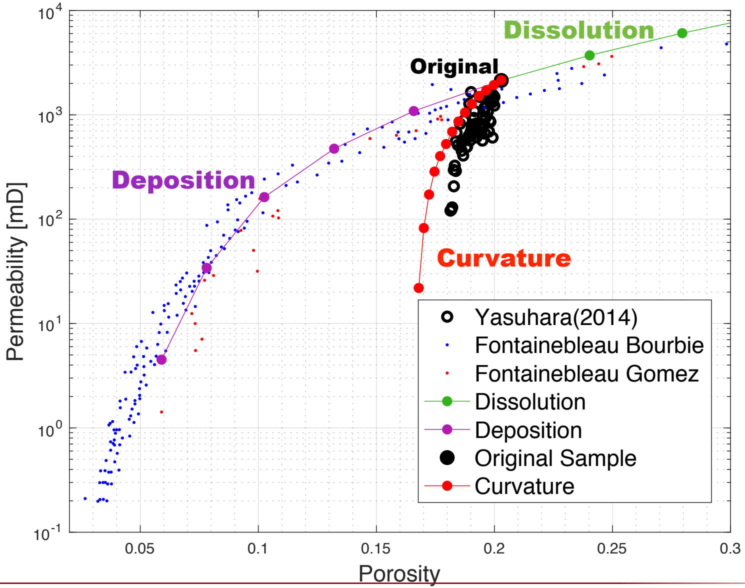
Transport Properties

Motion proportional to Curvature



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Future Work: Processes Present

Fluid Flow, Dissolution, Stress

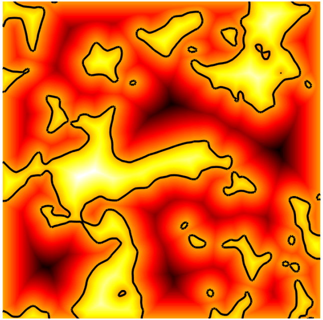
$$\vec{\mathbf{v}}(t) = \vec{\mathbf{v}}(\vec{\nu}(\vec{x}, t),\ C(\vec{x}, t),\ \boldsymbol{\sigma}(\vec{x}, t))$$

Where:

- $\vec{\nu}(\vec{x}, t)$ is the fluid flow field.
- $C(\vec{x}, t)$ is the chemical process that dissolves the rock.
- $\boldsymbol{\sigma}(\vec{x}, t)$ is stress.

In more detail:

- $C(\vec{\nu}(\vec{x}, t), t)$
- $C(\vec{\nu}(\vec{x}, t),\ \boldsymbol{\sigma}(\vec{x}, t), t)$



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Future Work: Dissolution $C(\vec{\nu}(\vec{x}, t), t)$

$$CaCO_3 + CO + H_2O \longleftrightarrow Ca^{2+} + 2HCO_3^-$$

Diffusion, Advection

$$P_e = \frac{d\, v_{df}}{D}$$

Advection, Dispersion

$$P_{e,D} = \frac{L_c v_{df}}{f(D)}$$

Advection, Reaction

$$D_a = \frac{\alpha S_r k(T) L}{C_{eq} v_{df}}$$

$$\frac{\partial C}{\partial t} + \boldsymbol{\nu} \cdot \nabla C = D \nabla^2 C + K_{\text{eff}}(C_{\text{eq}} - C)$$

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Conclusions

- With this computational approach it is becoming possible to rigorously simulate pore space diagenesis in rocks.
- Predict the associated changes of rock's physical properties.

Acknowledgments

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- Gary Mavko
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