Simulation of Brine Reflux and Geothermal Circulation in Large Carbonate Platforms: An Attempt to Predict Dolomite Geo-bodies

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Shell Intl. E&P, The Netherlands

COMSOL Conference, Stuttgart 2011

Outline

- Dolomitization in large Carbonate platforms
- Dolomitization and density driven flows
- Modeling density driven flows
- Results
- Conclusions

Dolomitization in large Carbonate platforms

- Dolomitization
  - is a diagenetic process
  - Replacement of Calcite ($CaCO_3$) by Dolomite ($CaMg(CO_3)_2$)

$$\underset{\text{(Calcite)}}{2CaCO_3} + Mg^{2+} \leftrightarrow \underset{\text{(Dolomite)}}{CaMg(CO_3)_2} + 2Ca^{2+}$$

- Why is dolomitization important ?
  - Dolomitization creates porosity
  - Dolostones makes excellent reservoirs for oil/gas

Dolomitization & density driven flows

- Dolomitization demand large scale supply of Mg^{2+}

$$\underset{\text{(Calcite)}}{2CaCO_3} + Mg^{2+} \leftrightarrow \underset{\text{(Dolomite)}}{CaMg(CO_3)_2} + 2Ca^{2+}$$

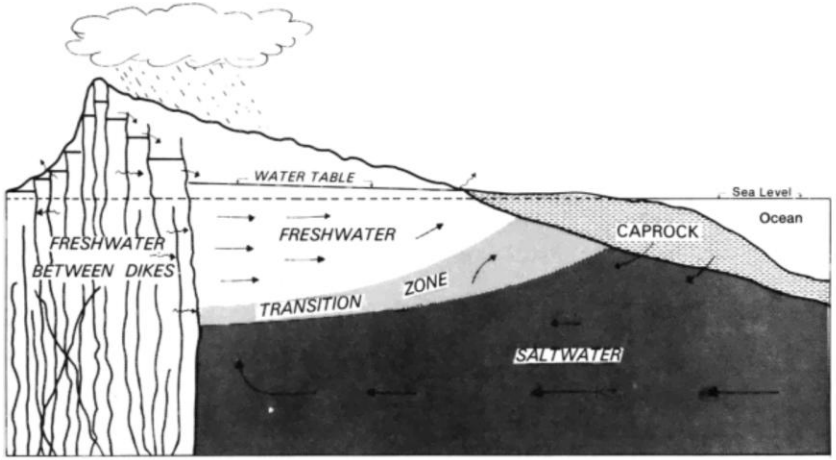
- Sea water is rich source of magnesium
- Processes supplying magnesium rich fluid
  - Density driven flows, e.g.,
    - Brine reflux
    - Geothermal circulation

What causes density driven flows ?

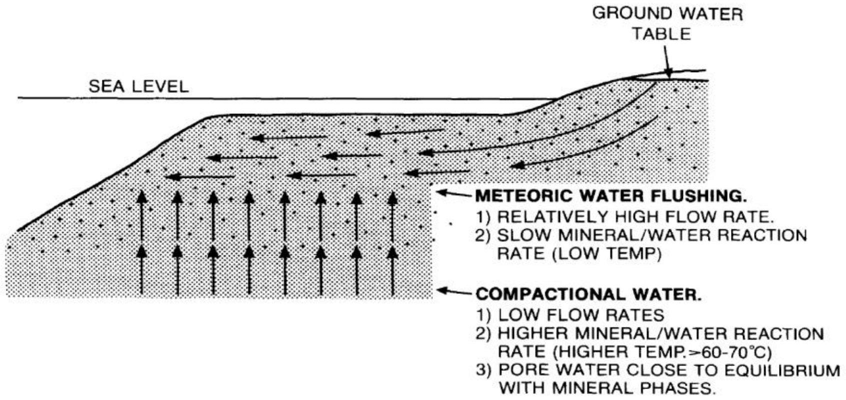
- Density variation in natural fluid systems
- Density variation due to naturally occurring salts
- Subsurface temperature changes
- Migrating pollutants
- Migration of fluids due to compaction

Some density driven flow systems

- Salt-Lakes
- Saline-disposal basins
- Dense contaminant and leachate plumes
- Geothermal reservoirs
- Shallow marine basins
- Saline brines in deep basins



Voss & Souza, Water Resource Research, Vol. 23, No. 10, 1987



Bjorlykke et.al., Marine and Petroleum Geology, Vol. 5, 1998

Conceptual model & dolomite patterns

E. N. Wilson, L. A. Hardie, & O. M. Phillips—Dolomitization

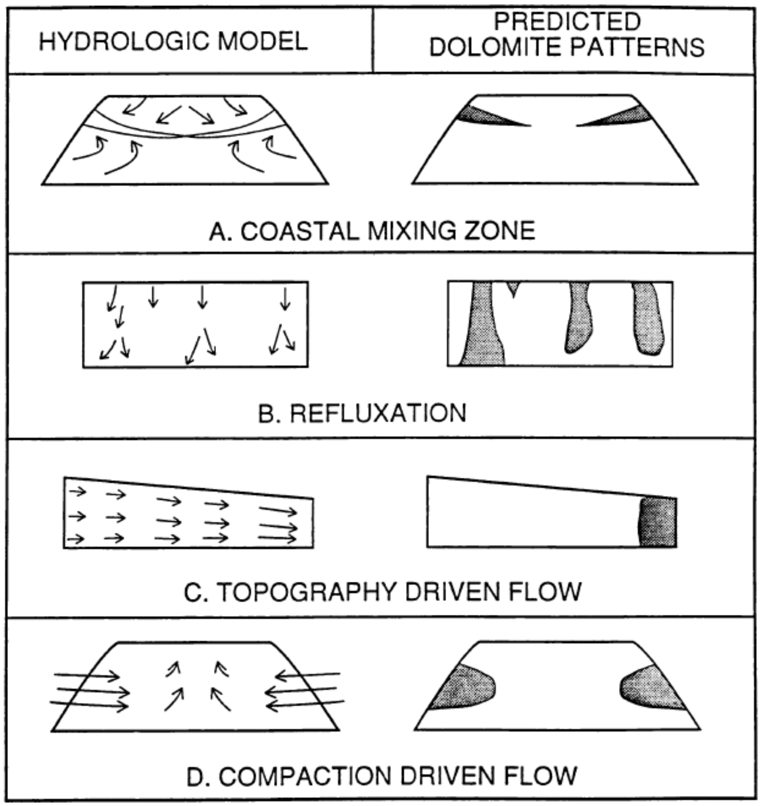
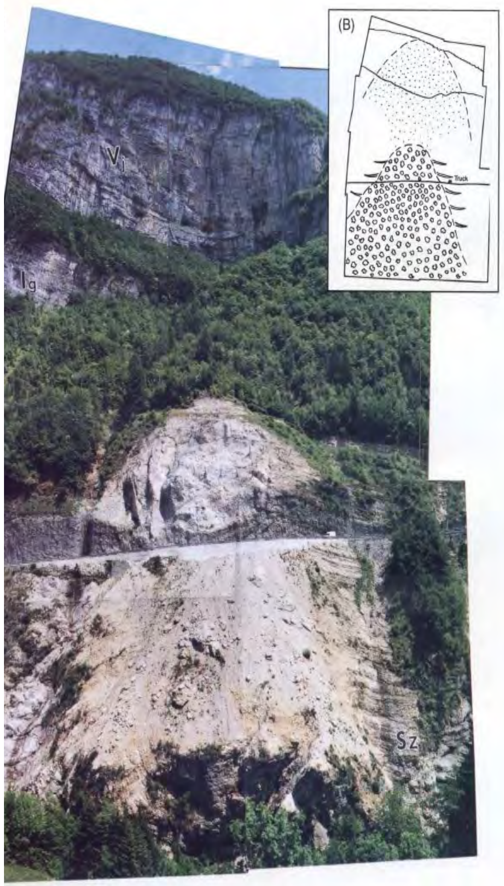


Fig. 13. Hydrologic systems associated with possible dolomitizing environments are shown on the left (arrows indicate flow direction), and the dolomite pattern predicted to result from each is shown on the right (dolomite is stippled). See text for further details.

Zempolich and Hardie



Ref - I. SHARP ET AL.

Modeling density driven flow

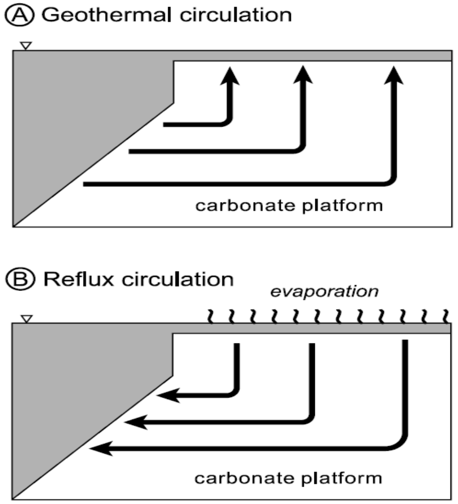
- Coupled flow and transport through:
  - Darcy's law for flow in porous media
  - Solute transport through advection and diffusion

$$\rho S \frac{\partial p}{\partial t} + \theta \frac{\partial \rho}{\partial c} \frac{\partial c}{\partial t} + \nabla \cdot \left[-\rho \frac{\kappa}{\eta} (\nabla p + \rho g \nabla D) \right] = 0$$

$$\rho = \rho_0 + \gamma (c - c_0) = \rho_0 + \frac{\rho_s - \rho_0}{c_s - c_0} (c - c_0)$$

$$\theta_s \frac{\partial c}{\partial t} + \nabla \cdot [-\theta_s D_L \nabla c + \mathbf{u} c] = 0$$

$$\mathbf{u} = -\frac{\kappa}{\eta} (\nabla p + \rho g \nabla D)$$



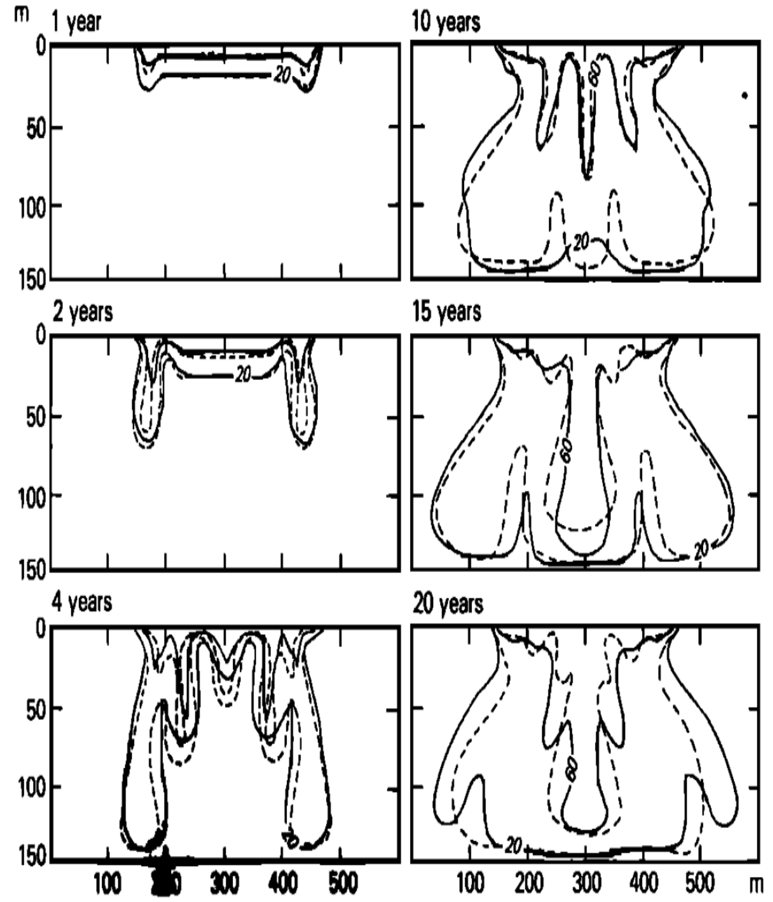
Gareth Jones et.al., American Journal of Science, Vol.304, 2004.

Physical parameters governing density driven flow

- Salinity differences in circulating fluids
- Density differences in circulating fluids
- Permeability/Hydraulic conductivity of the porous medium
- Presence or absence of local hydraulic gradient

Dimensionless parameters governing density driven flow

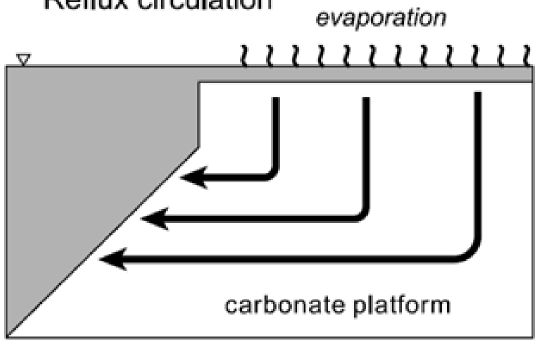
- Rayleigh number R_a - ratio between buoyancy forces tending to cause flow and other forces resisting flow
- Peclet number P_e - ratio between rate of advection of a physical quantity to rate of diffusion of the same quantity
- Damkohler number D_a represents rate of reaction relative to advection rate
- R_a , P_e & D_a governs the flow and reaction in a porous medium



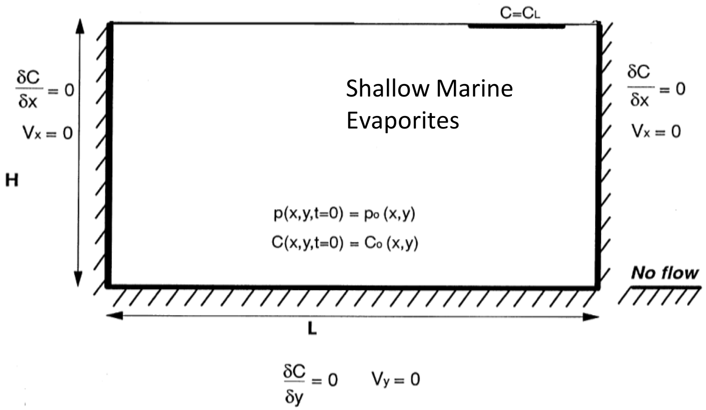
Elder, J. Fluid Mech. , Vol. 27, Part 3, 1967

Modeling density driven flow in Carbonates

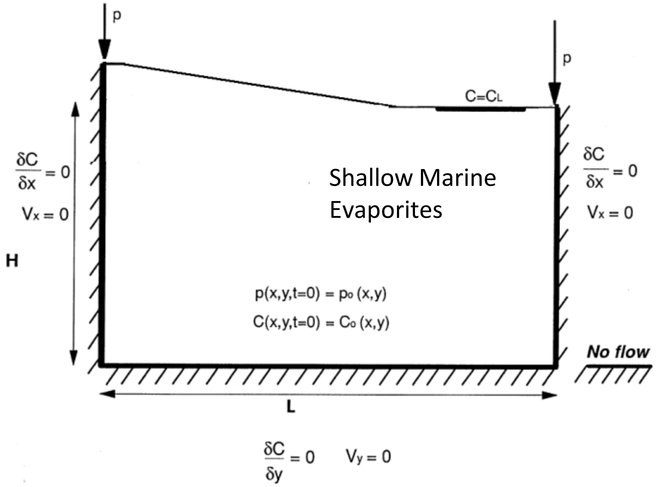
- Density driven flow due to reflux circulation
- In absence of hydraulic gradient
- In presence of hydraulic gradient



Model Setting in absence of hydraulic Gradient



Model Setting in presence of hydraulic Gradient



Modelling changes in porosity and permeability

Approach 1

Relation to porosity

If there is a net mass transfer either to or from the fluid phase, the porosity of the rock must change. The relations obtained above can be related to porosity by recalling that porosity, ϕ, is the fraction of total volume V occupied by void space, v_f,

$$\phi = v_f/V \qquad (12)$$

and then computing the volume occupied by solids as

$$1 - \phi = \Sigma\, m^i/\varrho_i \qquad (13)$$

where ϱ_i is the density of the ith solid phase.

The rate of change of porosity with time is then

$$\mathrm{d}\phi/\mathrm{d}t = \varrho_f\{\Sigma\, \alpha_{T(i)}/\varrho_i\}\mathbf{V} \cdot \mathrm{grad}\, T. \qquad (14)$$

For a system which consists of the two minerals calcite and dolomite plus an aqueous pore fluid, this expression can be expanded to

$$\mathrm{d}\phi/\mathrm{d}t = \varrho_f[\alpha_{T(c)}/\varrho_c + \alpha_{T(d)}/\varrho_d]\,\mathbf{V} \cdot \mathrm{grad}\, T \quad (15)$$

where the subscript c refers to calcite and the subscript d refers to dolomite. This equation gives the change in total porosity with time; the change in porosity due to calcite dissolution/precipitation is given by

$$\mathrm{d}\phi_{(c)}/\mathrm{d}t = \varrho_f[\alpha_{T(c)}/\varrho_c]\,\mathbf{V} \cdot \mathrm{grad}\, T \qquad (16)$$

while the porosity change due to dolomite dissolution/precipitation is

$$\mathrm{d}\phi_{(d)}/\mathrm{d}t = \varrho_f[\alpha_{T(d)}/\varrho_d]\,\mathbf{V} \cdot \mathrm{grad}\, T. \qquad (17)$$

J.R.Wood, Applied Geochemistry, Vol. 2, pp 629-638, 1987

Approach 2

We specified a kinetic rate law developed from the precipitation of dolomite at temperatures 116–192°C (55–58 mol% $CaCO_3$) by Arvidson and Mackenzie (1999) and identical to that used in reactive transport simulations of seawater dolomitization by Wilson et al. (2001)

$$r_{\mathrm{dol}} = S_A A e^{\frac{-E_a}{RT}}\left(1 - \frac{Q}{K_{\mathrm{eq}}}\right)^{2.26} \qquad (1)$$

where r_{dol} is the reaction rate of dolomite; S_A is the specific surface area of dolomite; Q is the activity quotient for ordered dolomite; K_{eq} is the equilibrium constant for dolomite; A, the preexponential factor, is 11.2 mol/cm^2/s; E_a, the activation energy, is 1.335×10^5 J/mol; 2.26 is the reaction order; R is the universal gas constant; and T is the temperature (in Kelvin).

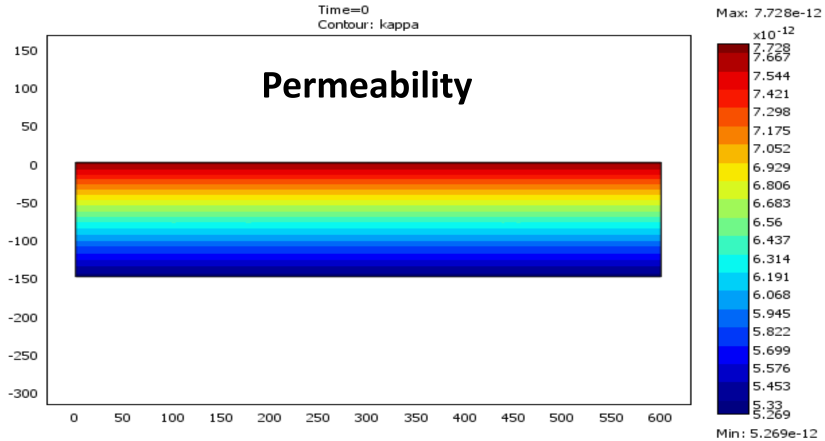
Changes in Permeability

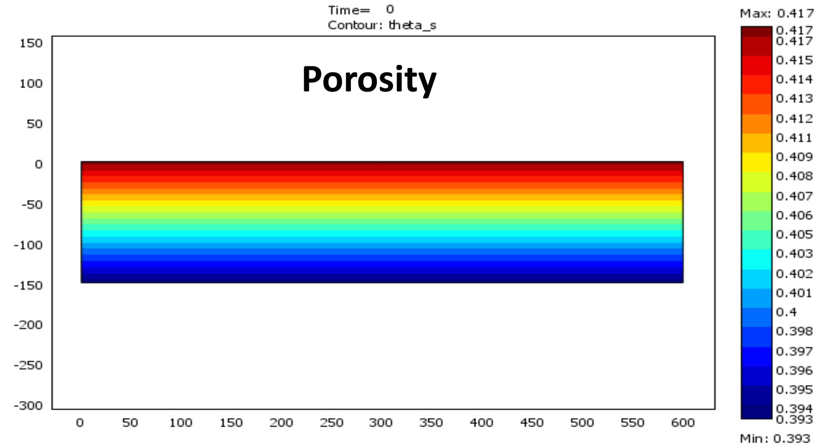
In this study, we used a simplified Carmen-Kozeny equation (equation 4) (Bear, 1972) to modify permeability.

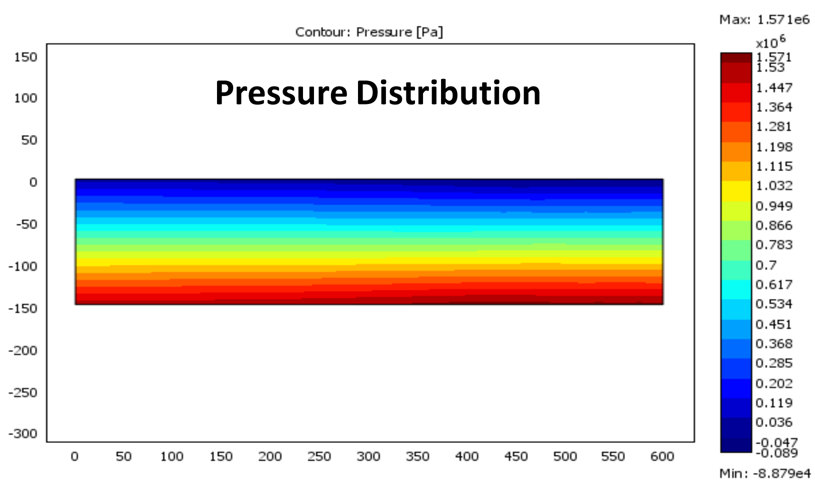
$$k_j = k_i \frac{(1-\phi_i)^2}{\left(1-\phi_j\right)^2}\left(\frac{\phi_j}{\phi_i}\right)^3 \qquad (4)$$

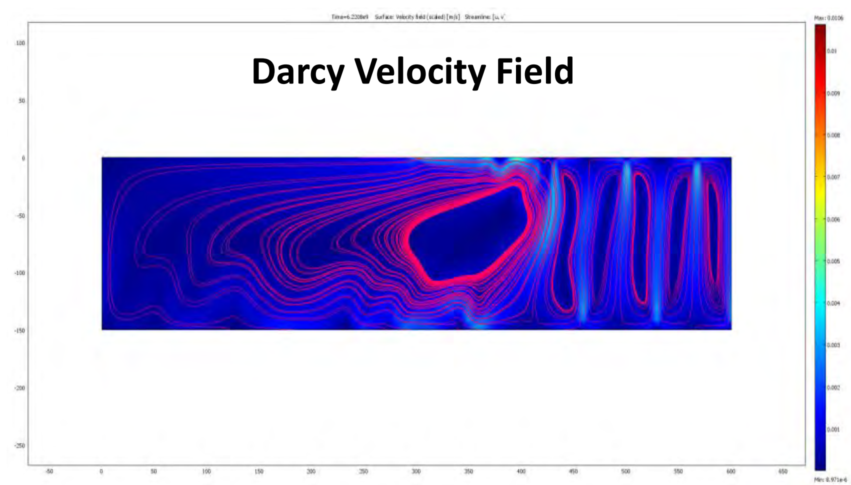
where k is permeability (in square meters), ϕ is porosity, and i and j are the previous and subsequent time steps. This equation ignores the effects of changes in grain size, tortuosity, and specific surface area.

Model without hydraulic gradient – static/dynamic properties

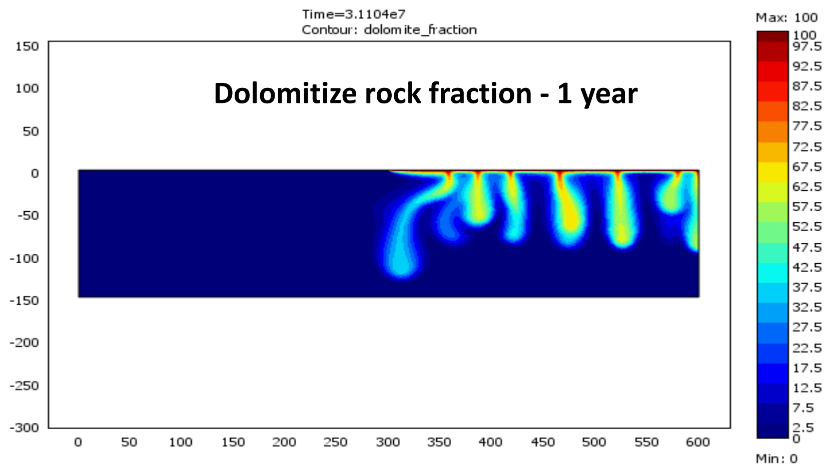


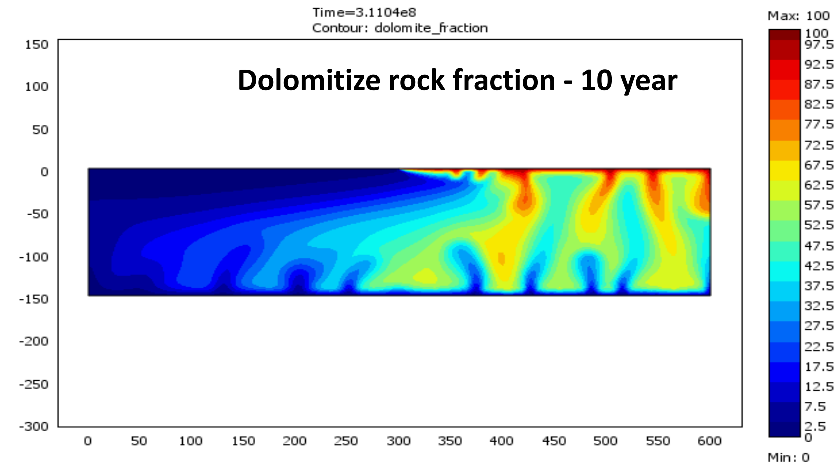


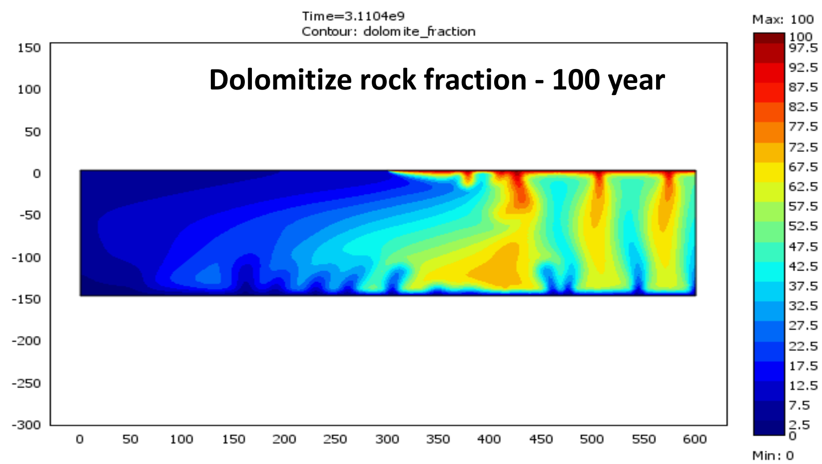


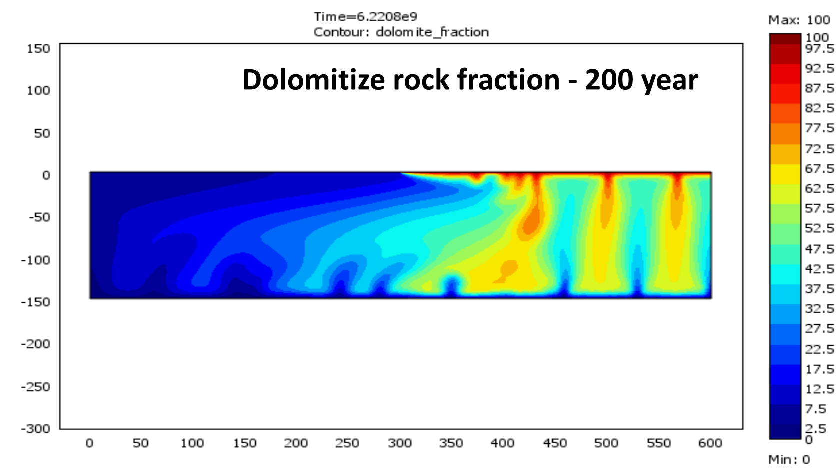


Model without hydraulic gradient – dolomitize rock fraction

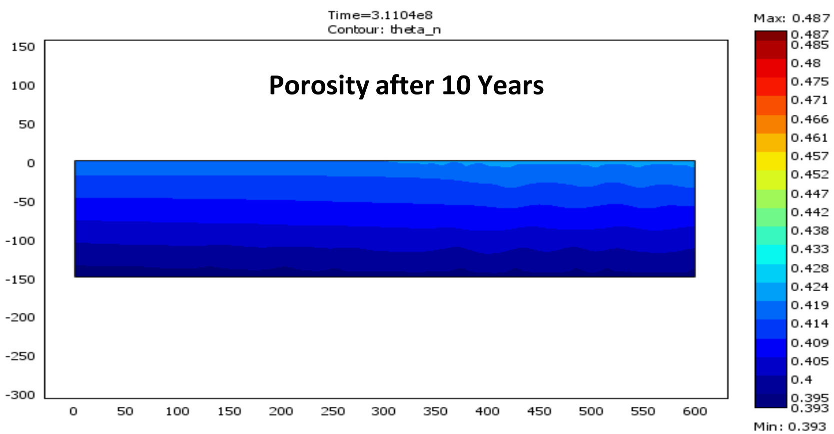


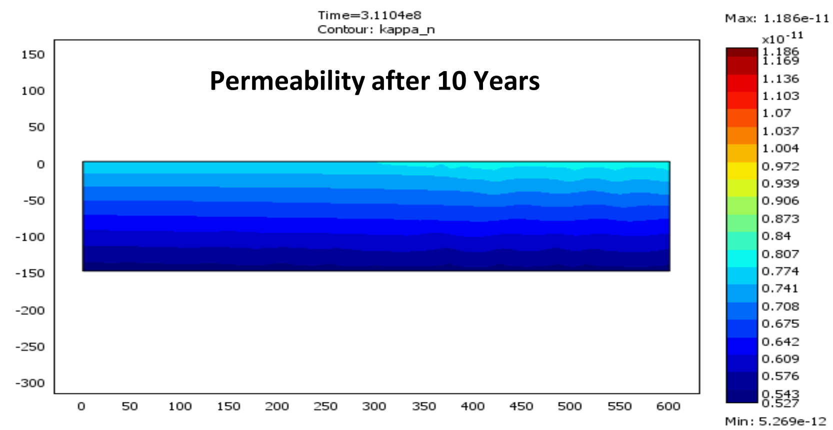


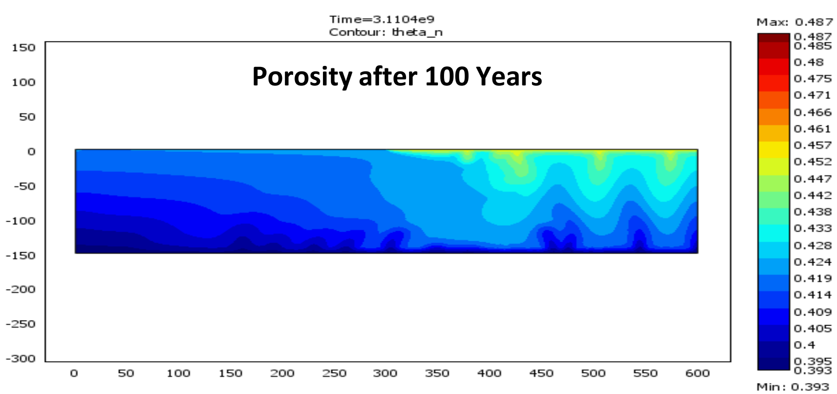


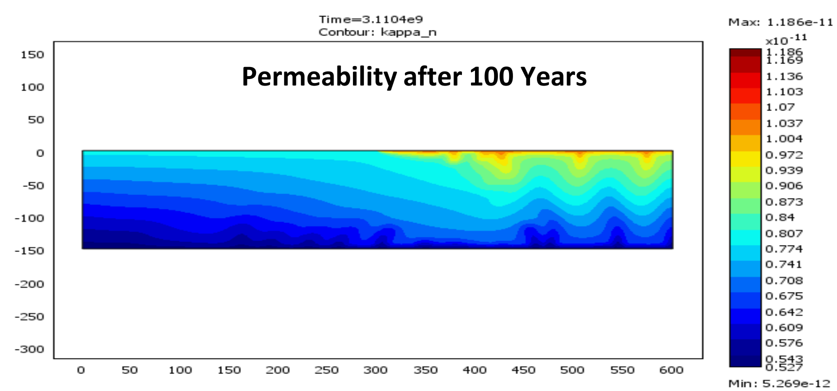


Estimate of poro/perm changes assuming 100% ion exchange & no dolomite cementation



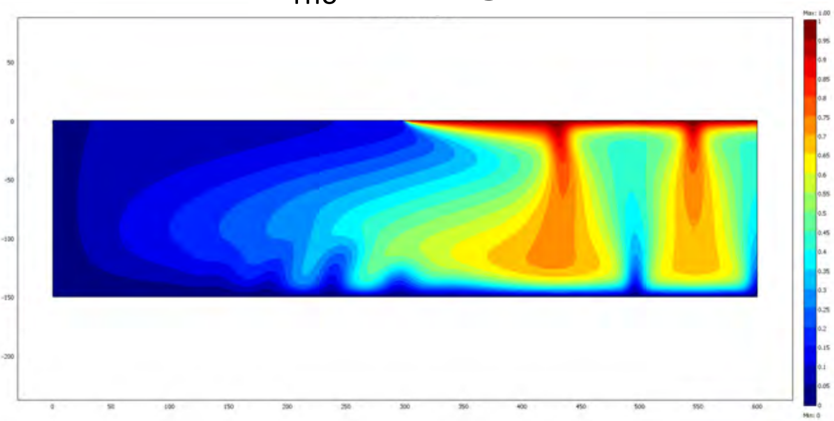




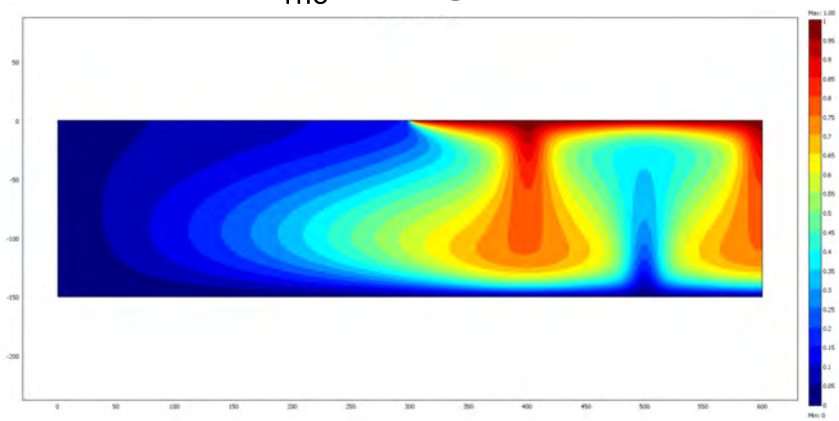


Impact of density difference on reflux dolomitization

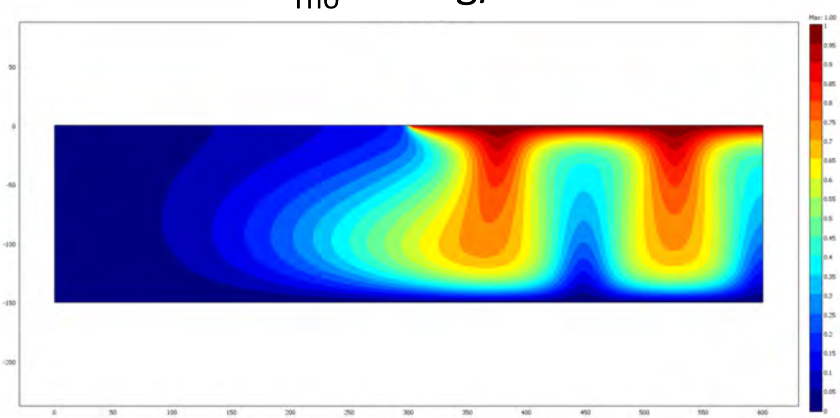
d_{rho} – 100kg/m^3



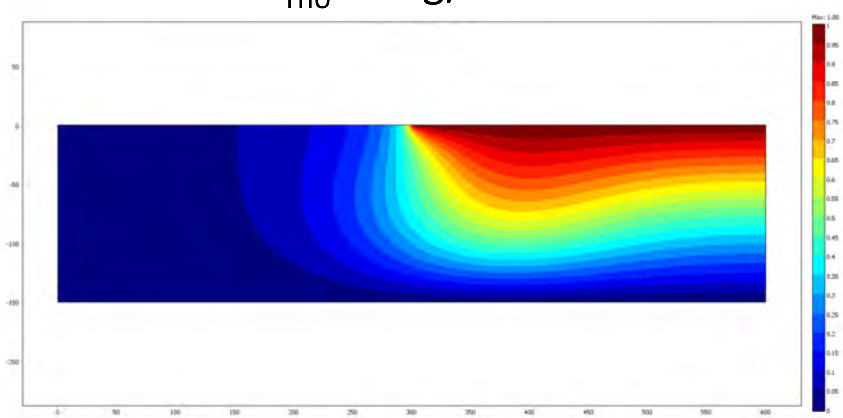
d_{rho} – 50kg/m^3



d_{rho} – 25kg/m^3

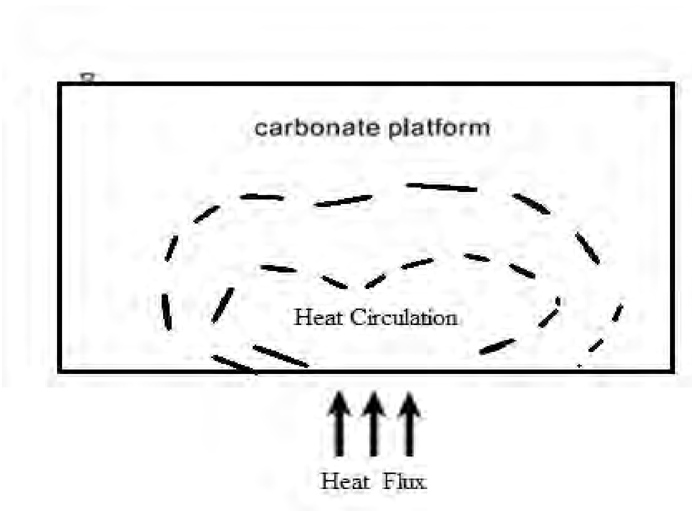


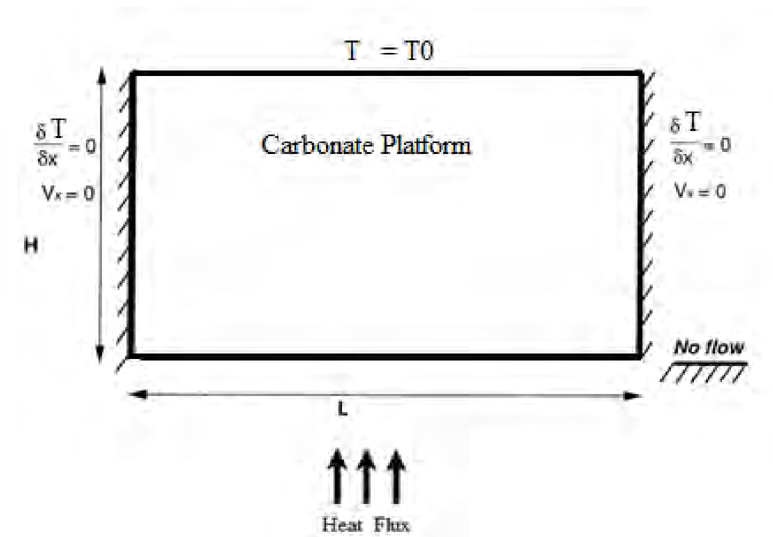
d_{rho} – 5kg/m^3



Modeling density driven flow due to Geo-thermal heating

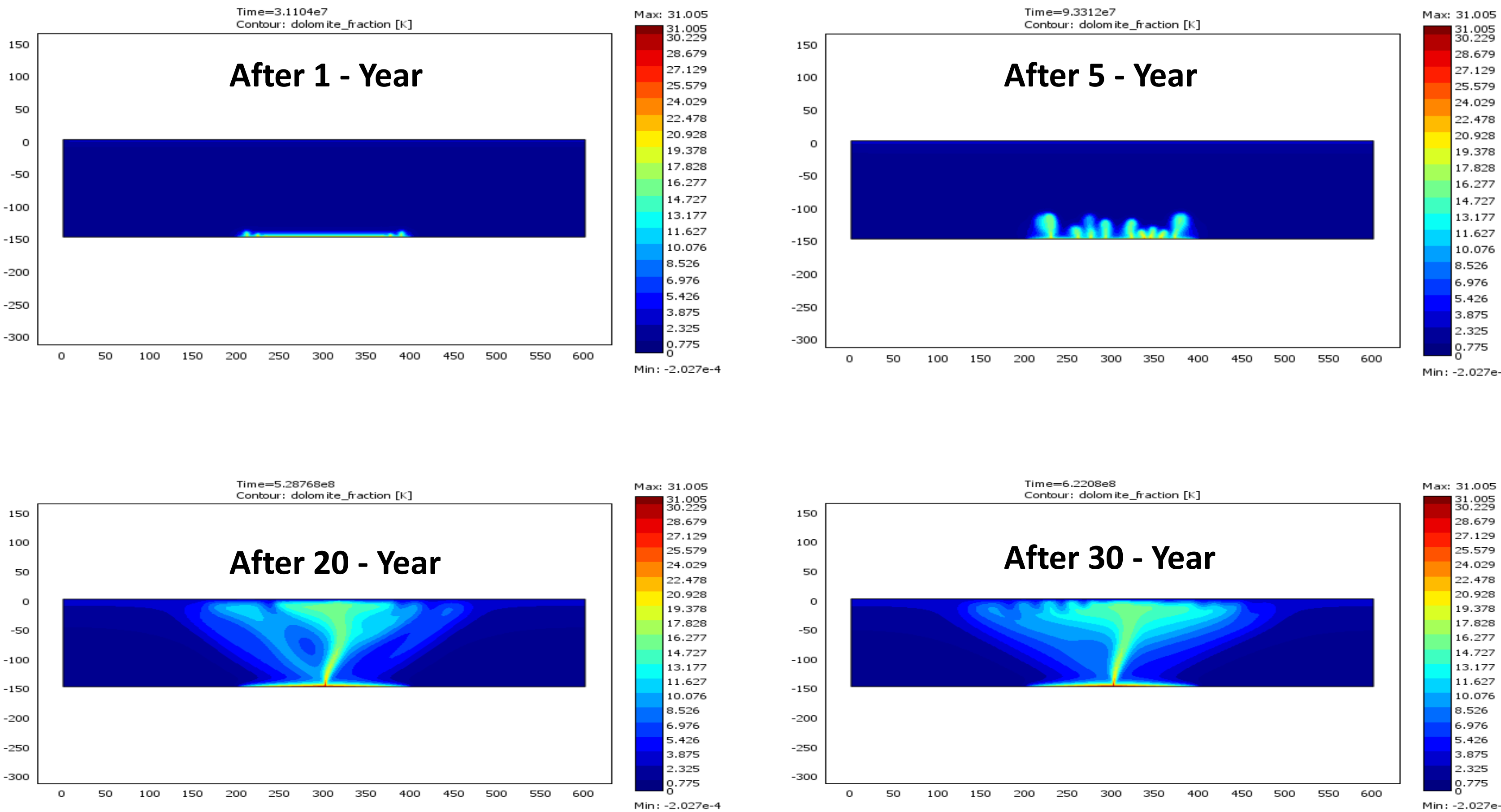
- Density driven flow due to geo-thermal gradient



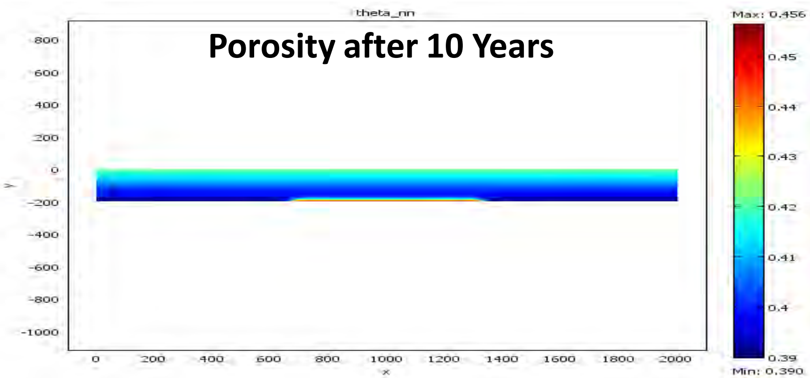


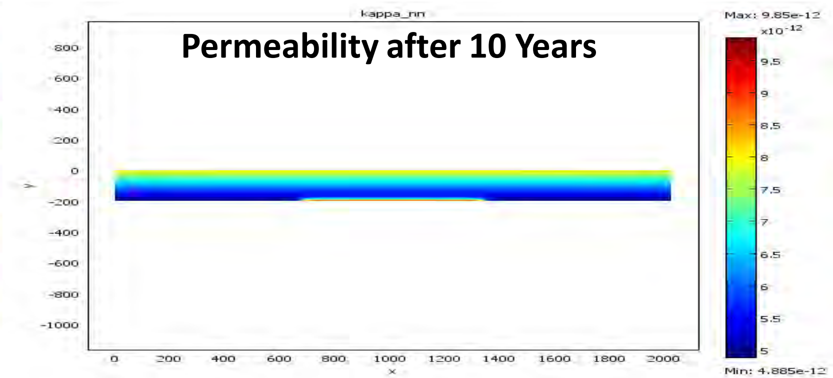
- In absence of hydraulic gradient

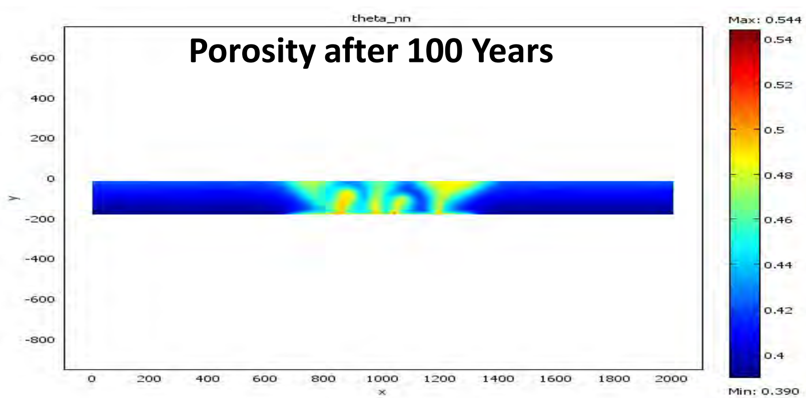
Simulation model geo-thermal circulation – dolomitize rock fraction

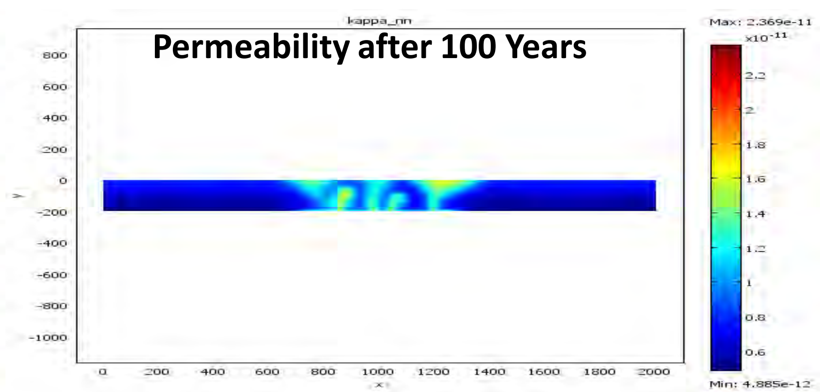


Estimate of poro/perm changes assuming 100% ion exchange & no dolomite cementation



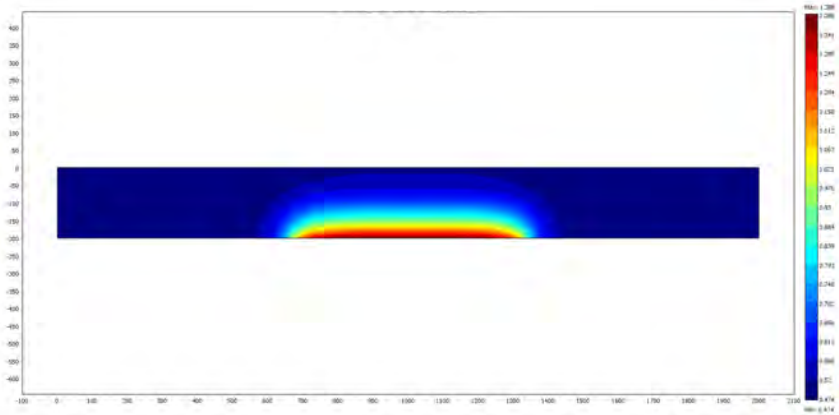




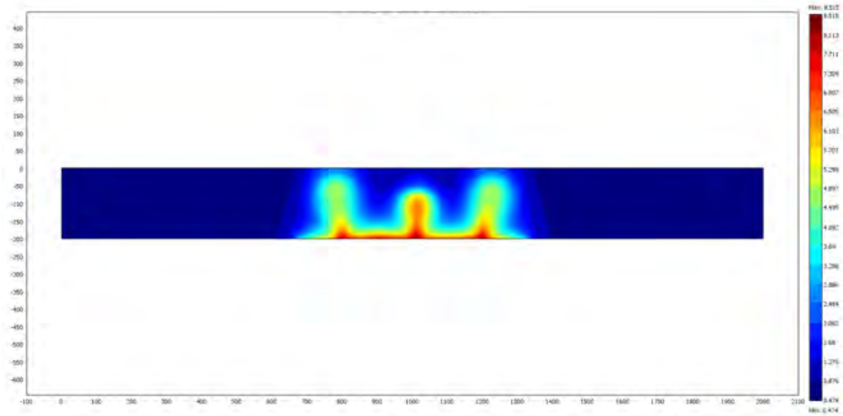


Impact of magnitude of geo-thermal heat flux

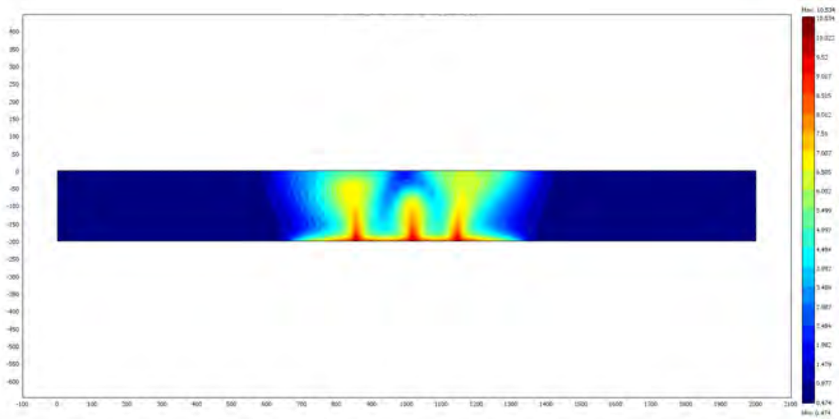
Q – 0.06 W/m^2



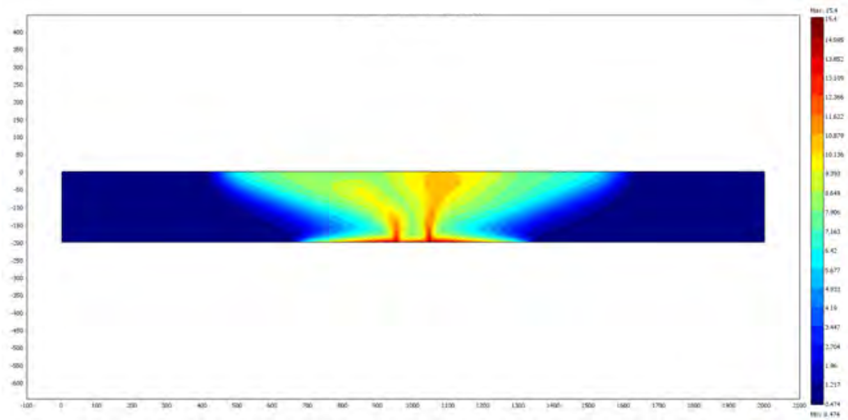
Q – 0.6 W/m^2



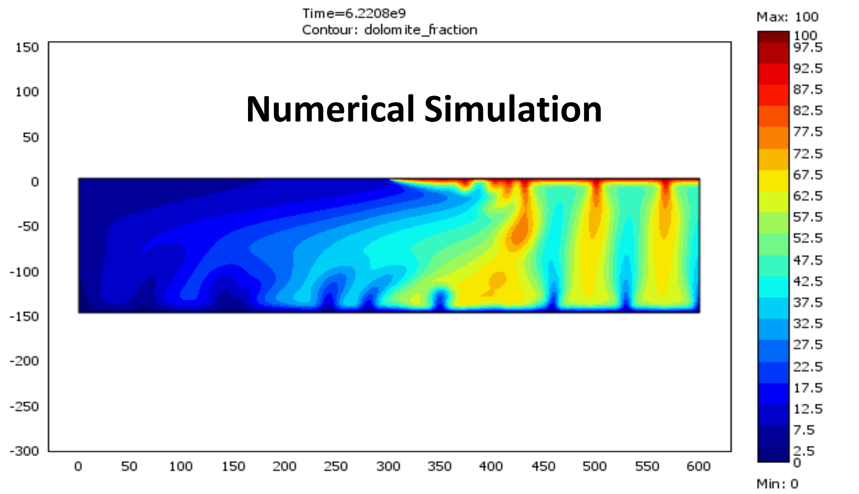
Q – 1.0 W/m^2

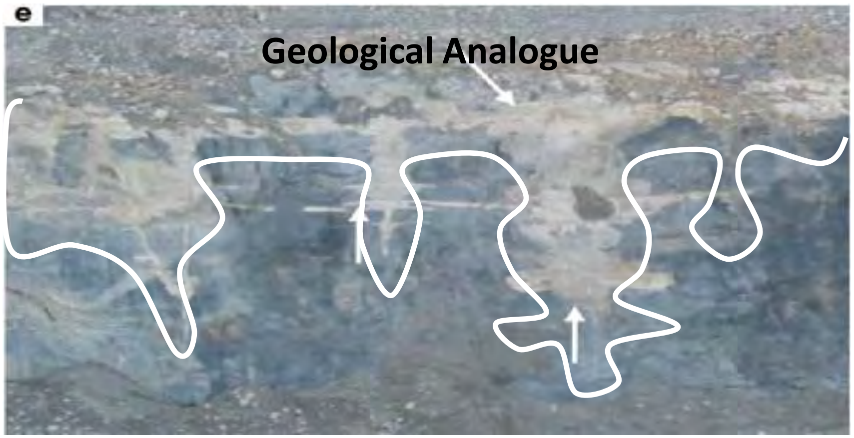


Q – 2.0 W/m^2

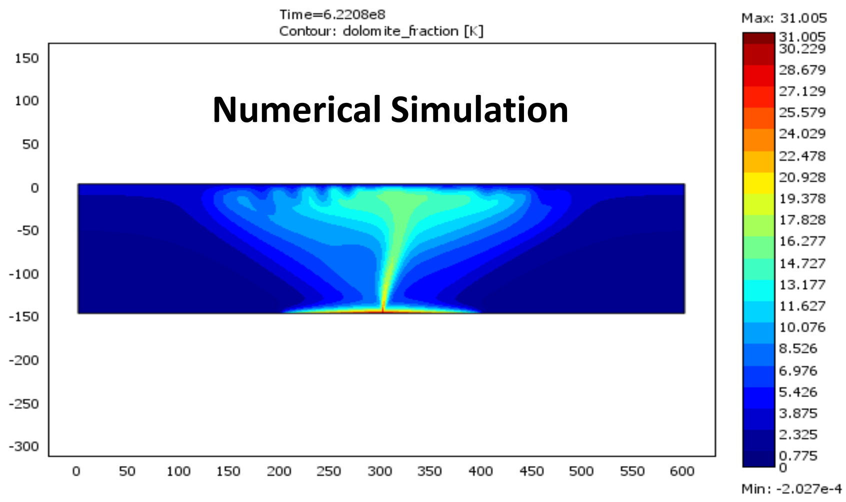


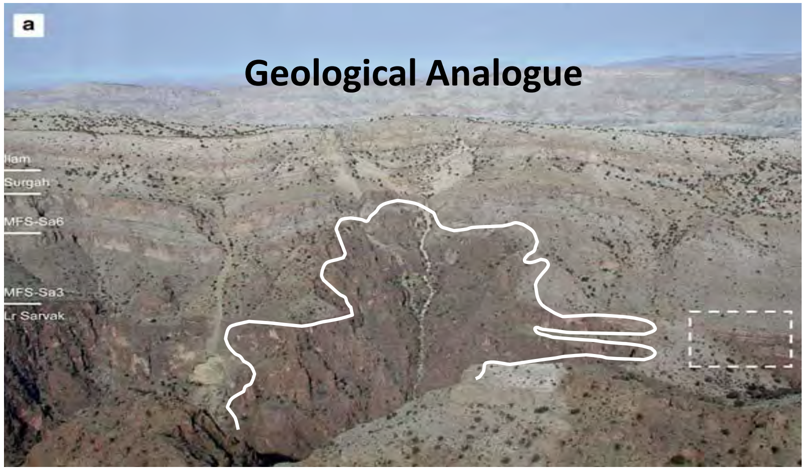
Field example - geological analogues





Ref - I. SHARP ET AL.





Ref - I. SHARP ET AL.

Conclusions

- Density driven flow modeling should be used prior to RTM:
  - To quantify extent of dolomitization
  - To predict shapes of dolomite bodies
  - To possibly predict the parameters controlling dolomitization process
  - Identify end-members to use in RTM approach
- Density driven flow modelling has less uncertainty compared to RTM due to less control parameter dependency

Question ?