Submarine Gas Hydrate Reservoir Simulations – A Gas/Liquid Fluid Flow Model for Gas Hydrate Containing Sediments

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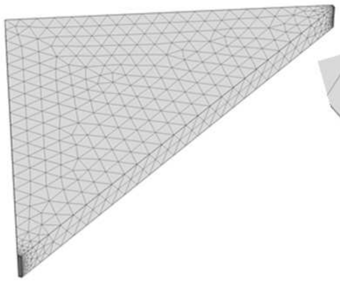

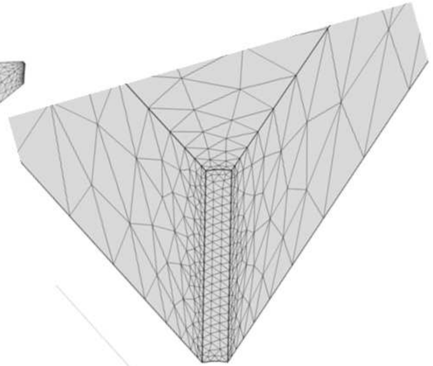

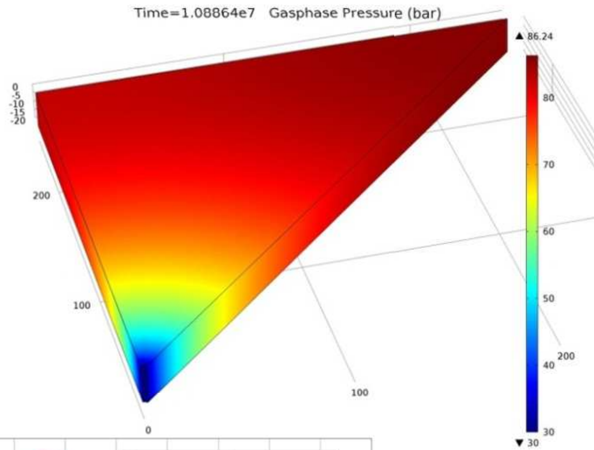

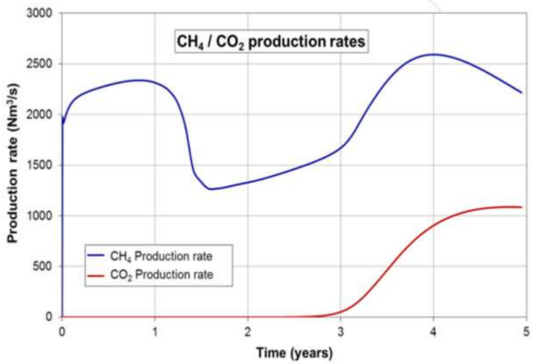

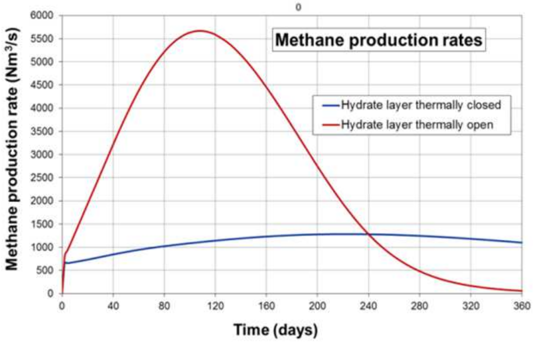

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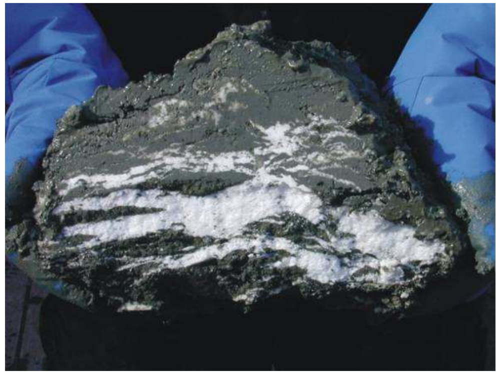
What are gas hydrates?

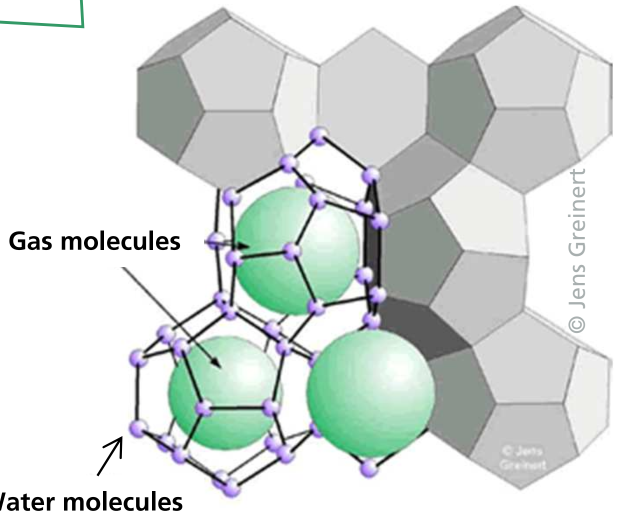


Temperature

Pressure

Additives

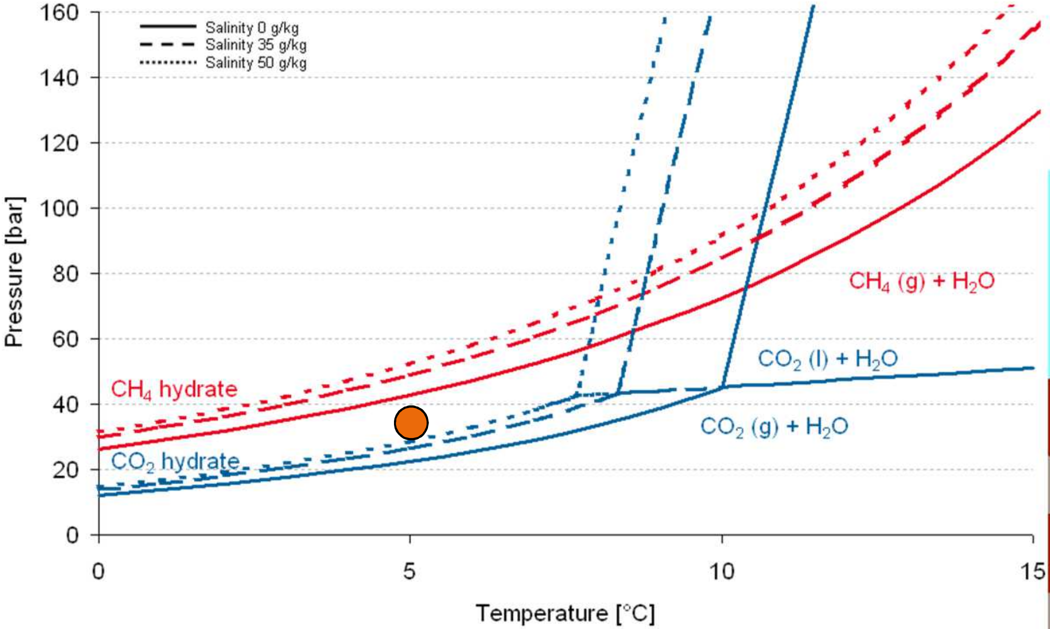
Gas



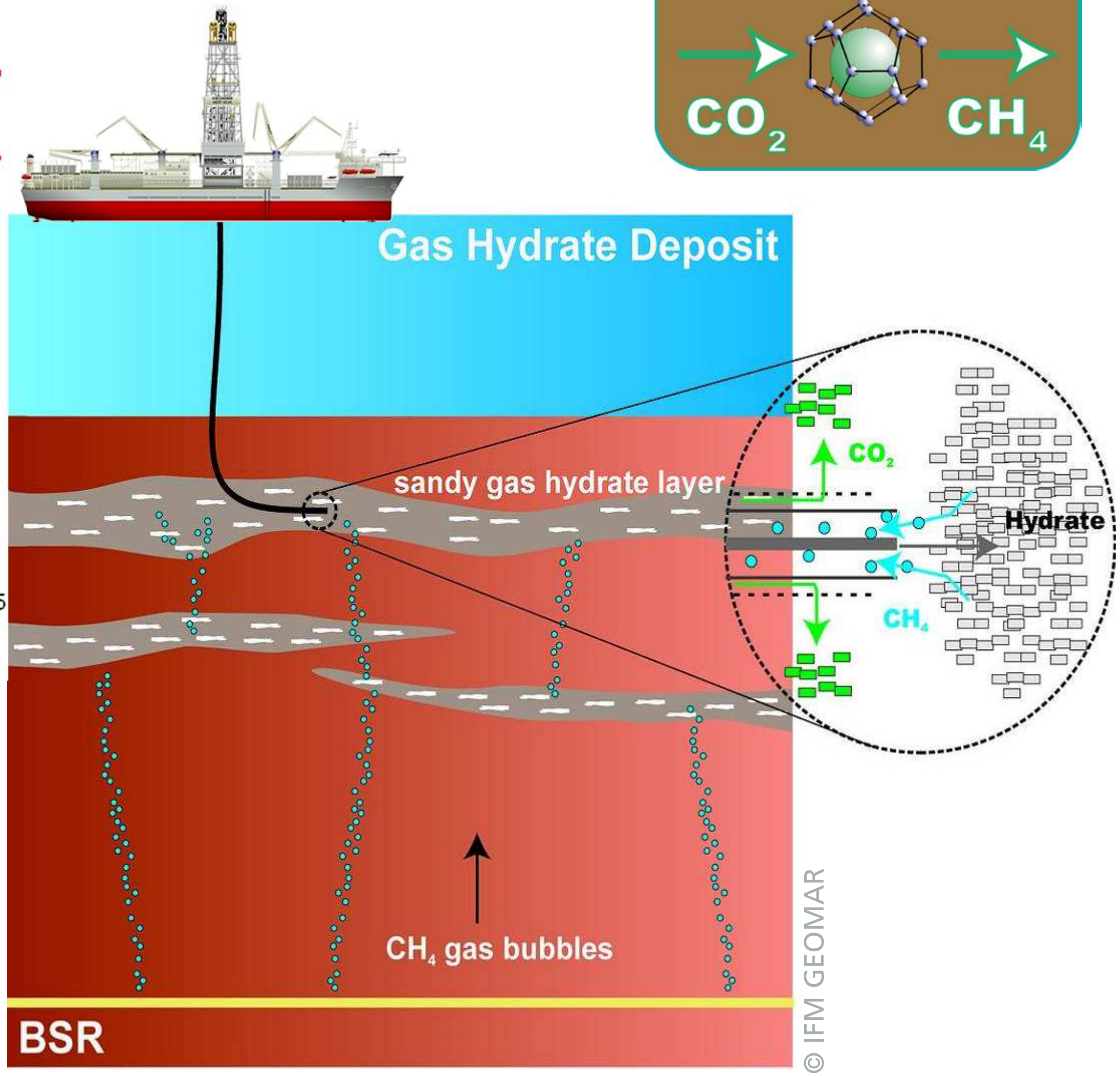
Water

Petrobras

Idea of the SUGAR project



- CO_2 hydrate stable at lower pressure / higher temperature
- replacing CH_4 by CO_2
- simultaneous production of CH_4 and storage of CO_2
- sustainable energy supply system



Reservoir model principles

Phases

- 3 solid phases: sediment, methane hydrate, CO_2 hydrate
- 2 fluid phases: gas phase, water (liquid) phase
- (1 supercritical phase: supercritical CO_2 – not implemented yet)

Components

- 2 gas phase components: methane, carbon dioxide
- 3 components solved in water: sea salt, methane, carbon dioxide

Pressure equation: advanced 2-phase Darcy model

Energy equation: flow through porous solid, hydrate extensions, latent heats, pressure work

Reservoir Model – Pressure/Saturation Equation

Continuity equations:

$$\left.\begin{aligned}\frac{\partial}{\partial t}\left(\phi S_G \rho_G\right) + \nabla\cdot\left(\rho_G \mathbf{u}_G\right) &= s_G \\ \frac{\partial}{\partial t}\left(\phi S_L \rho_L\right) + \nabla\cdot\left(\rho_L \mathbf{u}_L\right) &= s_L\end{aligned}\right\} \text{Euler/Euler}$$

$$\frac{\partial}{\partial t}\left(\phi S_{MH} \rho_{MH}\right) = s_{MH}$$

$$\frac{\partial}{\partial t}\left(\phi S_{CH} \rho_{CH}\right) = s_{CH}$$

Saturation:

$$S_j = \frac{\varepsilon_j}{1-\varepsilon_S} = \frac{\varepsilon_j}{\phi} = \frac{\text{volume fraction of phase } j}{\text{sediment free volume fraction}}$$

Convection splitted form:

$$\phi\frac{\partial S}{\partial t} + \phi S \frac{1}{\rho}\frac{\partial \rho}{\partial t} + \nabla\cdot\mathbf{u} + \mathbf{u}\cdot\frac{\nabla\rho}{\rho} = \frac{s}{\rho}$$

Reservoir Model – Pressure/Saturation Equation

Density derivatives: $\chi = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial P}\right)_{T,y_k}$, $\beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_{P,y_k}$, $\varphi_k = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial y_k}\right)_{P,T}$

$$\frac{1}{\rho}\frac{\partial \rho}{\partial t} = \chi\frac{\partial P}{\partial t} - \beta\frac{\partial T}{\partial t} + \sum_k \varphi_k \frac{\partial y_k}{\partial t}, \quad \frac{\nabla \rho}{\rho} = \chi \nabla P - \beta \nabla T + \sum_k \varphi_k \nabla y_k$$

General form:

$$\phi\frac{\partial S}{\partial t} + \phi S\left(\chi\frac{\partial P}{\partial t} - \beta\frac{\partial T}{\partial t} + \sum_k \varphi_k \frac{\partial y_k}{\partial t}\right) + \nabla \cdot \mathbf{u} + \mathbf{u} \cdot \left(\chi \nabla P - \beta \nabla T + \sum_k \varphi_k \nabla y_k\right) = \frac{s}{\rho}$$

Darcy equation: $\mathbf{u} = -\mathbf{K}_f \Lambda \left(\nabla P + \mathbf{g}\rho\right)$ with $\Lambda = \frac{k_{rel}}{\eta}$, $k_{rel} = f\left(S_H, S_L\right)$

Phase summation: $\sum_j S_j = 1$, $\sum_j \phi \frac{\partial S_j}{\partial t} = 0$

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Reservoir Model – Pressure/Saturation Equation

Insertion in general form and summation over phases leads to general pressure equation:

$$\phi \sum_j S_j \chi_j \frac{\partial P_j}{\partial t} + \nabla \cdot \left(-\mathbf{K}_f \sum_j \Lambda_j \left(\nabla P_j + \mathbf{g}\rho_j \right) \right)$$

$$- \mathbf{K}_f \sum_j \Lambda_j \left(\chi_j \left(\nabla P_j + \mathbf{g}\rho_j \right) - \beta_j \nabla T + \sum_k \varphi_{k,j} \nabla y_{k,j} \right) \nabla P_j =$$

$$\sum_j \frac{q_j}{\rho_j} + \phi \sum_j S_j \left(\beta_j \frac{\partial T}{\partial t} - \varphi_{k,j} \frac{\partial y_{k,j}}{\partial t} \right) - \mathbf{K}_f \mathbf{g} \sum_j \Lambda_j \rho_j \left(\beta_j \nabla T - \sum_k \varphi_{k,j} \nabla y_{k,j} \right)$$

Capillary pressure: $P_C = P_G - P_L$ with $P_C = f(S_H, S_L)$

Calculation pressure: $P = \frac{1}{2}\left(P_L + P_G \right) \rightarrow P_L = P - \frac{1}{2} P_C \,, \quad P_G = P + \frac{1}{2} P_C$

Reservoir Model – Pressure/Saturation Equation

COMSOL coefficient form PDE: $e\frac{\partial^2 u}{\partial t^2} + d\frac{\partial u}{\partial t} + \nabla\cdot\left(-c\nabla u - \alpha u + \gamma\right) + \beta\nabla u + au = f$

$$u = \begin{pmatrix} P \\ S_L \end{pmatrix}, \quad d = \begin{pmatrix} \phi\left(S_L\chi_L + S_G\chi_G + \left(S_{MH} + S_{CH}\right)\chi_H\right) & 0 \\ \phi S_L\chi_L & \phi \end{pmatrix}$$

artificial diffusion for S_L

$$c = \begin{pmatrix} \mathbf{K}_f\left(\Lambda_L + \Lambda_G\right) & 0 \\ \mathbf{K}_f\Lambda_L & \varepsilon \end{pmatrix}, \quad \gamma = \begin{pmatrix} -\mathbf{K}_f\left(\left(\Lambda_G - \Lambda_L\right)\frac{\nabla P_C}{2} + \mathbf{g}\left(\rho_L\Lambda_L + \rho_G\Lambda_G\right)\right) \\ -\mathbf{K}_f\Lambda_L\left(-\frac{\nabla P_C}{2} + \mathbf{g}\rho_L\right) \end{pmatrix}$$

$$\beta = \begin{pmatrix} -\mathbf{K}_f\begin{pmatrix} +\Lambda_L\left(\chi_L\left(\nabla P - \nabla P_C + \mathbf{g}\rho_L\right) - \beta_L\nabla T + \varphi_{S,L}\nabla c_S\right)\ldots \\ +\Lambda_G\left(\chi_G\left(\nabla P + \nabla P_C + \mathbf{g}\rho_G\right) - \beta_G\nabla T + \varphi_{C,G}\nabla y_C\right) \end{pmatrix} & 0 \\ -\mathbf{K}_f\Lambda_L\left(\chi_L\left(\nabla P - \nabla P_C + \mathbf{g}\rho_L\right) - \beta_L\nabla T\right) & 0 \end{pmatrix}, \quad f = \ldots$$

Reservoir Model – Energy Equations

Summation over single phase energy equations with $T_G = T_L = T_H = T_S$

$$\phi S_G \rho_G c_{P,G} \frac{\partial T_G}{\partial t} + \nabla \cdot \left(-\phi S_G \boldsymbol{\lambda}_G \nabla T_G \right) - \mathbf{K}_f \Lambda_G \left(\nabla P_G + \mathbf{g} \rho_G \right) \rho_G c_{P,G} \nabla T_G = \dot{q}_P$$

$$\phi S_L \rho_L c_{P,L} \frac{\partial T_L}{\partial t} + \nabla \cdot \left(-\phi S_L \boldsymbol{\lambda}_L \nabla T_L \right) - \left(\mathbf{K}_f \Lambda_L \left(\nabla P_L + \mathbf{g} \rho_L \right) + \varepsilon \nabla S_L \right) \rho_L c_{P,L} \nabla T_L = \dot{q}_L$$

$$\phi \left(S_{MH} \rho_{MH} c_{P,MH} + S_{CH} \rho_{CH} c_{P,CH} \right) \frac{\partial T_H}{\partial t} - \nabla \cdot \left(\phi \left(S_{MH} \boldsymbol{\lambda}_{MH} + S_{CH} \boldsymbol{\lambda}_{CH} \right) \nabla T_H \right) = \dot{q}_H$$

$$\left(1 - \phi \right) \rho_S c_{P,S} \frac{\partial T_S}{\partial t} + \nabla \cdot \left(-\left(1 - \phi \right) \boldsymbol{\lambda}_S \nabla T_S \right) = 0$$

Pressure work: $$\dot{q}_P = \phi S_G \beta_G T_G \frac{\partial P_G}{\partial t} + \mathbf{K}_f \Lambda_G \left(\nabla P_G + \mathbf{g} \rho_G \right) \left(1 - \beta_G T_G \right) \nabla P_G$$

real gas behaviour

Latent heats: $$\dot{q}_H = -\left(R_{MH} \Delta \tilde{h}_{MH} + R_{CH} \Delta \tilde{h}_{CH} \right)$$ (heats of formation)

Reservoir Model – Single Component Equations

Gas phase component, molar fraction conservative form

$$\phi S_G \tilde{\rho}_G \frac{\partial y_i}{\partial t} + y_i \frac{\partial}{\partial t}(\phi S_G \tilde{\rho}_G) + \nabla \cdot \left(-\phi S_G \boldsymbol{\delta}_{i,G}^{eff} \tilde{\rho}_G \nabla y_i + \mathbf{u}_G y_i \tilde{\rho}_G \right) = \tilde{q}_{i,G}$$

$$\frac{\partial}{\partial t}(\phi S_G \tilde{\rho}_G) = \phi S_G \tilde{\rho}_G \left(\frac{1}{S_G} \frac{\partial S_G}{\partial t} + \chi \frac{\partial P_G}{\partial t} - \beta \frac{\partial T}{\partial t} + \sum_{k=1}^{n-1} \left(\varphi_k - \frac{\tilde{M}_k - \tilde{M}_n}{\tilde{M}_G} \right) \frac{\partial y_k}{\partial t} \right)$$

Liquid phase component, molar concentration conservative form

$$\phi S_L \frac{\partial c_{i,L}}{\partial t} + c_{i,L} \phi \frac{\partial S_L}{\partial t} + \nabla \cdot \left(-\phi S_L \boldsymbol{\delta}_{i,L}^{eff} \nabla c_{i,L} - \left(\mathbf{K}_f \Lambda_L \left(\nabla P_L + \mathbf{g} \rho_L \right) + \varepsilon \nabla S_L \right) c_{i,L} \right) = \tilde{q}_{i,L}$$

Reservoir Model – Gas Hydrate Equations

Methane and Carbon Dioxide hydrate saturation

$$\phi \frac{\partial S_{MH}}{\partial t} + \phi S_{MH} \left(\chi_{MH} \left(\frac{\partial P_G}{\partial t} - \frac{\partial P_C}{\partial t} \right) - \beta_{MH} \frac{\partial T}{\partial t} \right) = \frac{s_{MH}}{\rho_{MH}}$$

$$\phi \frac{\partial S_{CH}}{\partial t} + \phi S_{CH} \left(\chi_{CH} \left(\frac{\partial P_G}{\partial t} - \frac{\partial P_C}{\partial t} \right) - \beta_{CH} \frac{\partial T}{\partial t} \right) = \frac{q_{CH}}{\rho_{CH}}$$

Hydrate kinetics (linearized partial pressure kinetic)

$$R_{MH} = \frac{1}{V} \frac{\partial N_{MH}}{\partial t} = k_{MH} a_{MH} \left(y_M P_G - P_{MH}^{*} \right)$$

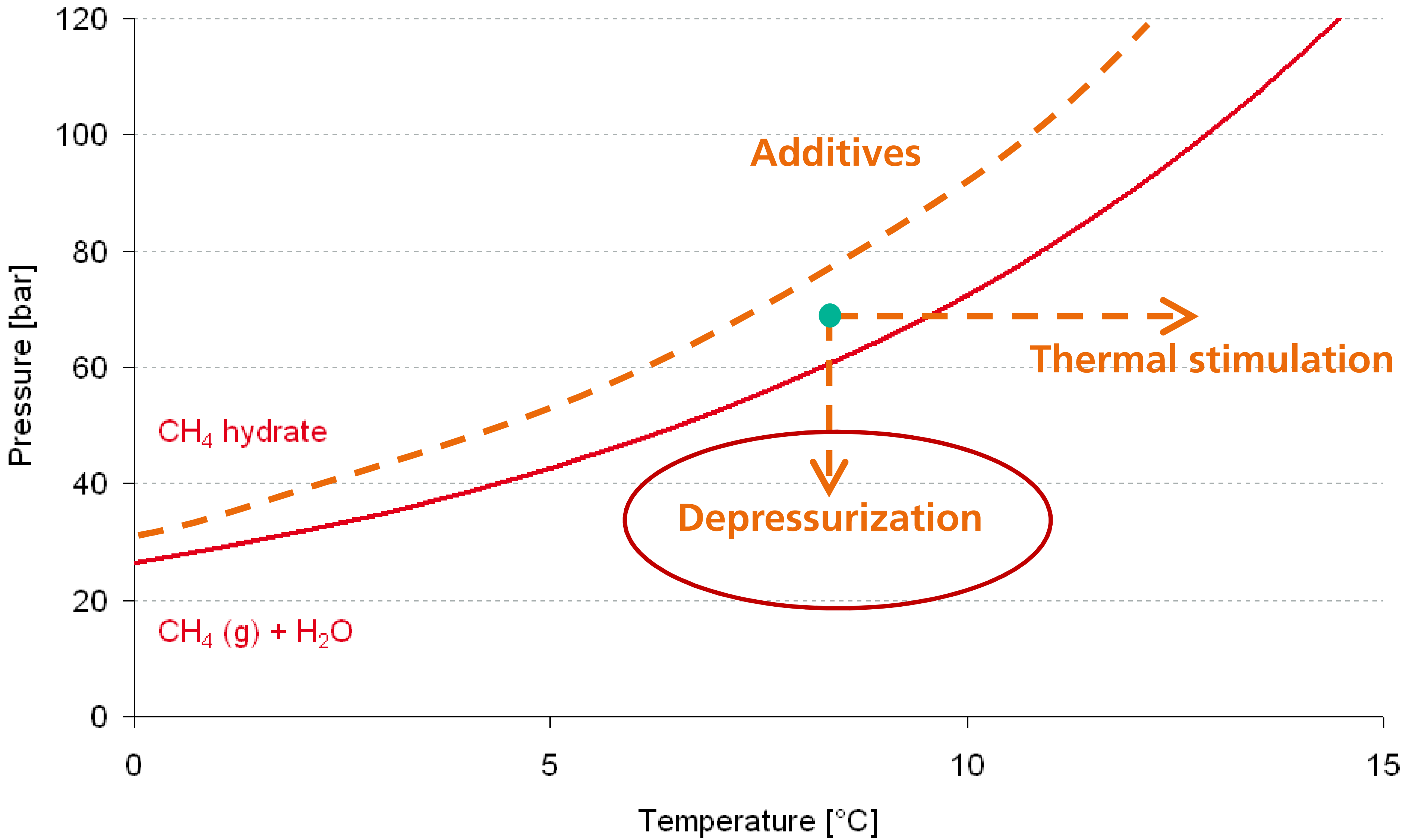
$$R_{CH} = \frac{1}{V} \frac{\partial N_{CH}}{\partial t} = k_{CH} a_{CH} \left(y_C P_G - P_{CH}^{*} \right)$$

COMSOL Implementation

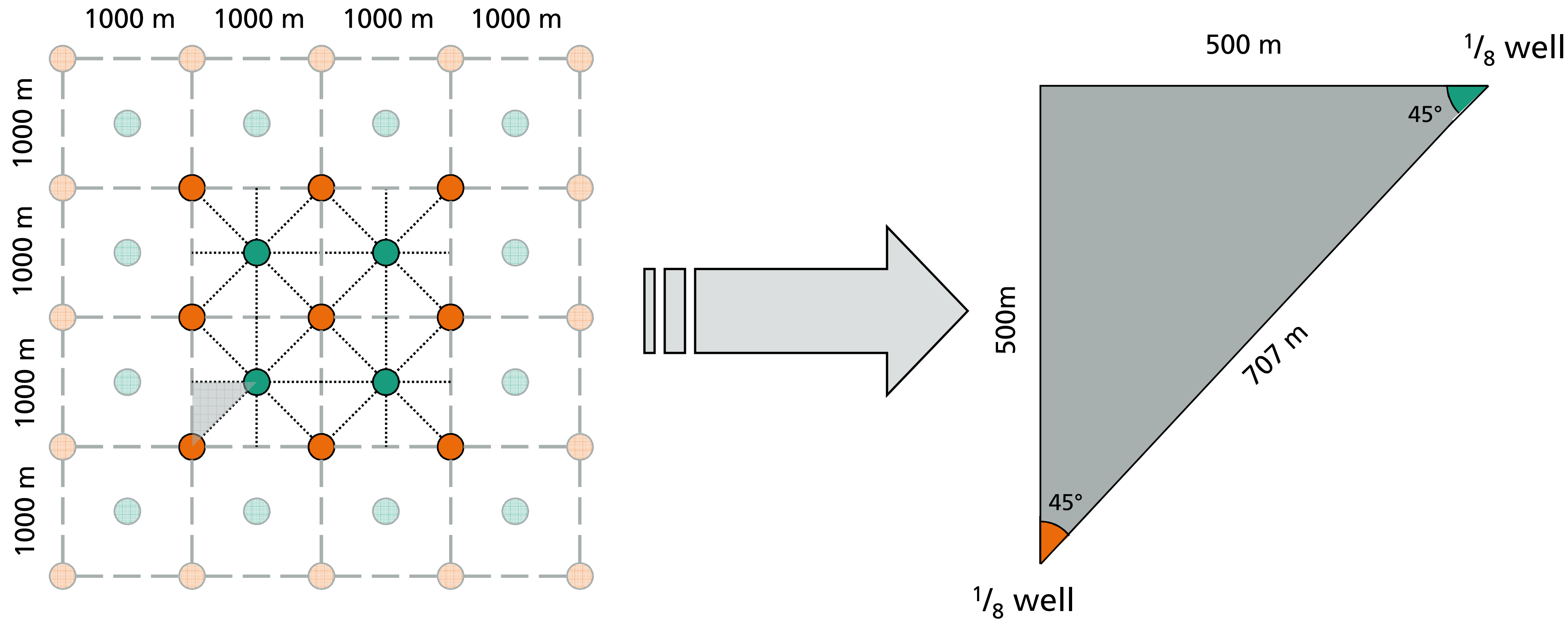
COMSOL Multiphysics implementation essentials

- 3D and 2D axisymmetric models
- Coefficient Form PDE + Heat Transfer in Porous Media
- Discretization/Stabilization as default
- Fully Coupled solution, Direct linear solver (PARDISO)
- Pressure Dirichlet boundary condition given as Weak Constraint
- Initial time step 10 s, maximum time step $5 \cdot 10^6$ s
- maximum mesh size = 15 m, fine meshing at the well

Methods for gas hydrate decomposition



Field production plan

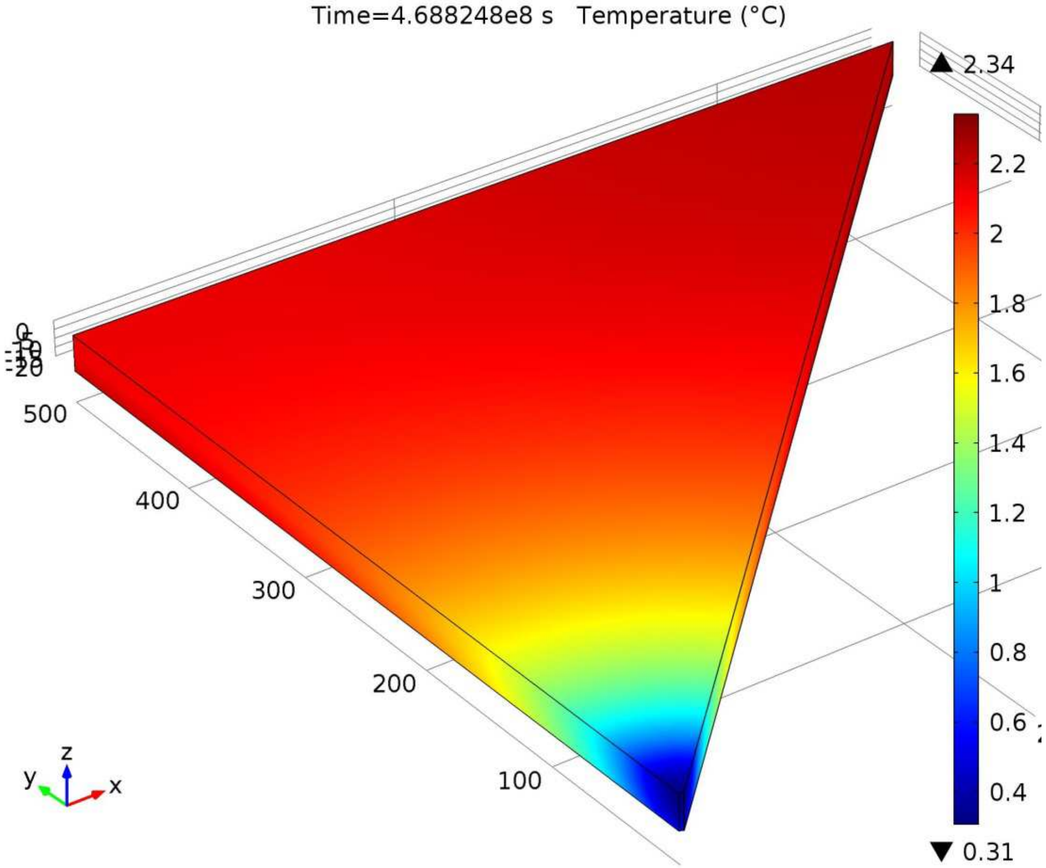


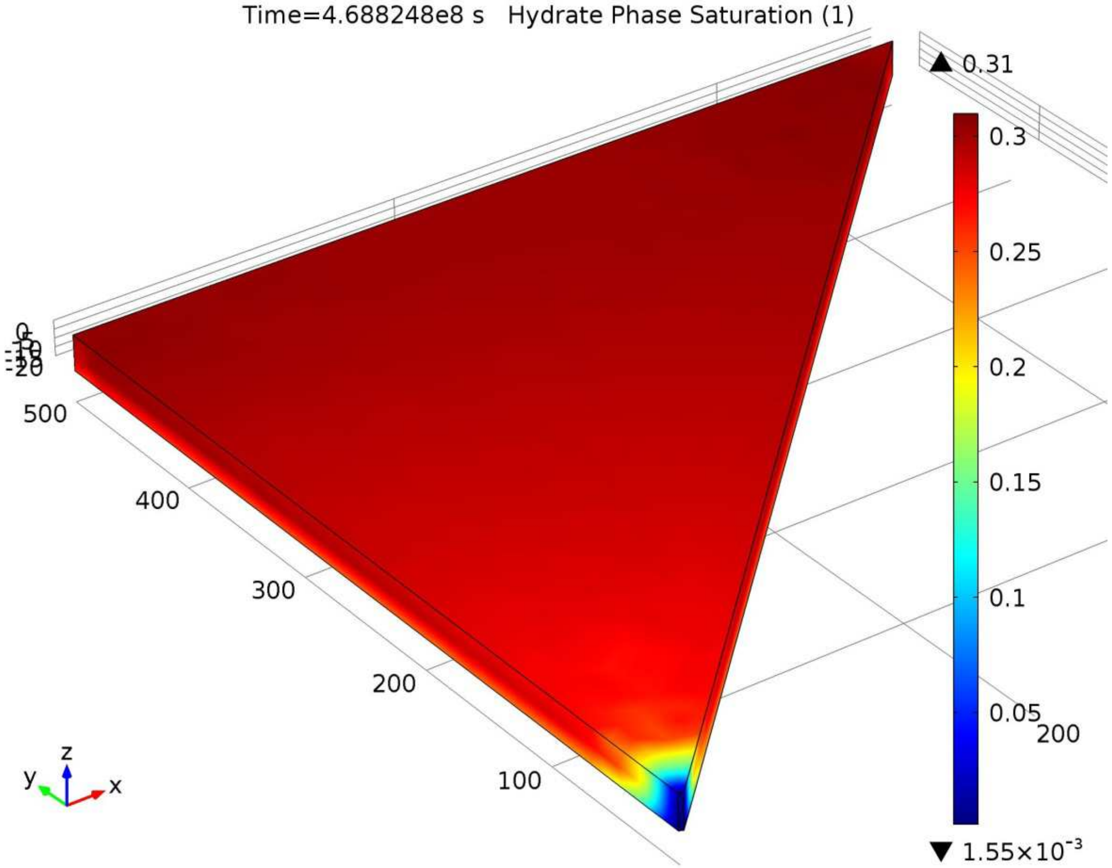
Injection well

Production well

Case Study I – Methane production by Depressurization

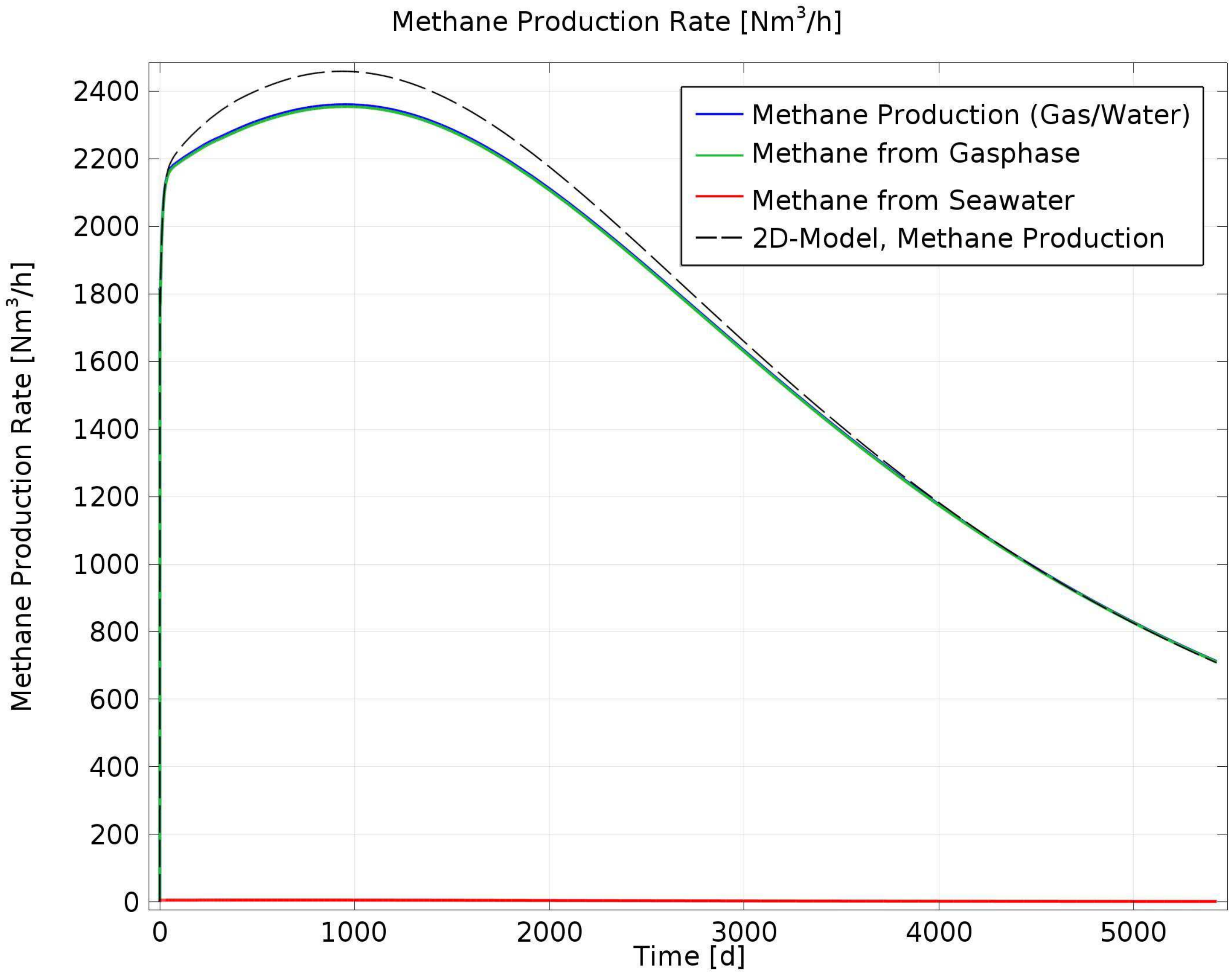
$P_0 = 92$ bar $T_0 = 10{,}0°C$ $S_{h0} = 0{,}40$ $H_{res} = 20$ m





t = 15 years

Case Study I – Methane production by Depressurization



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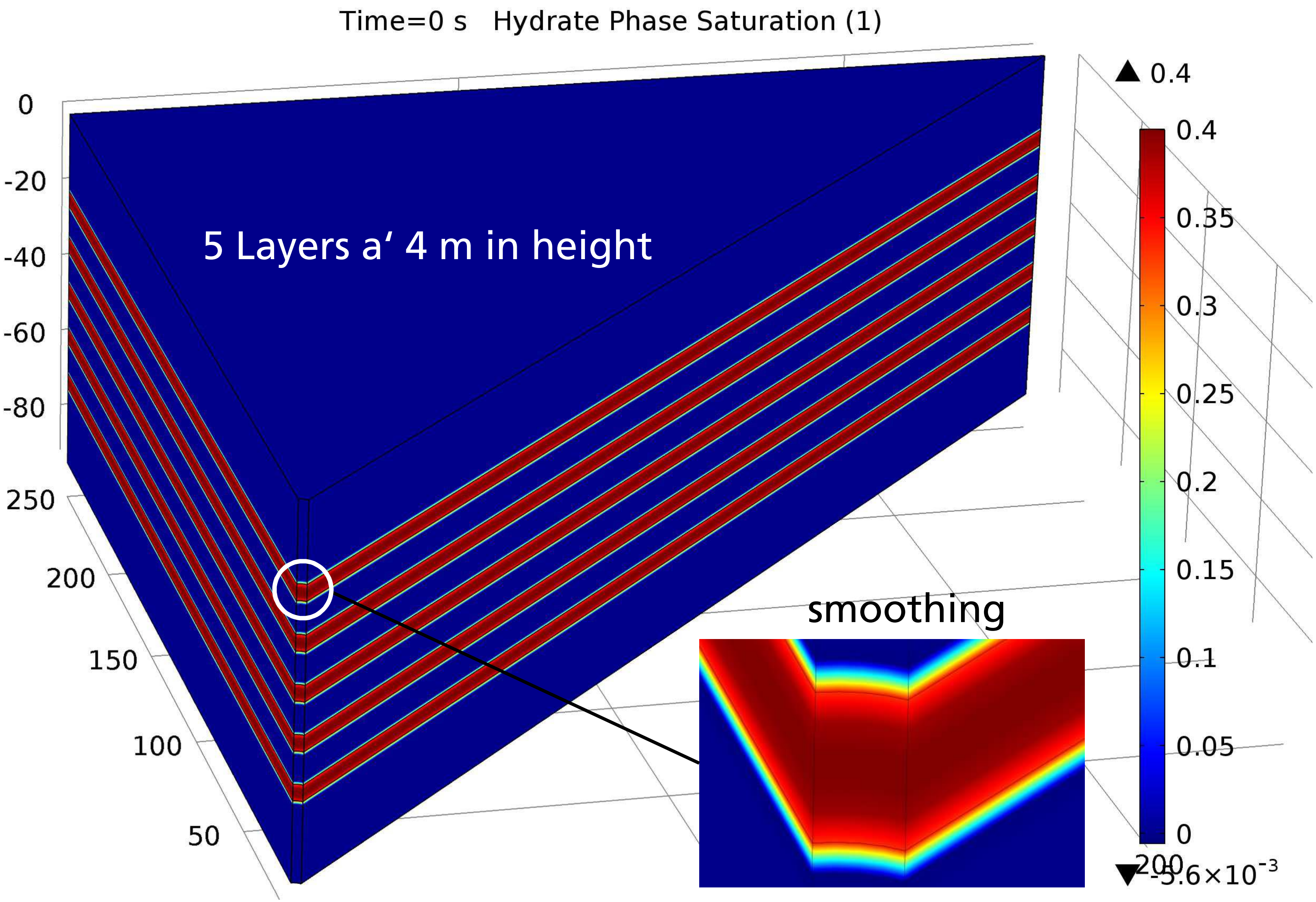
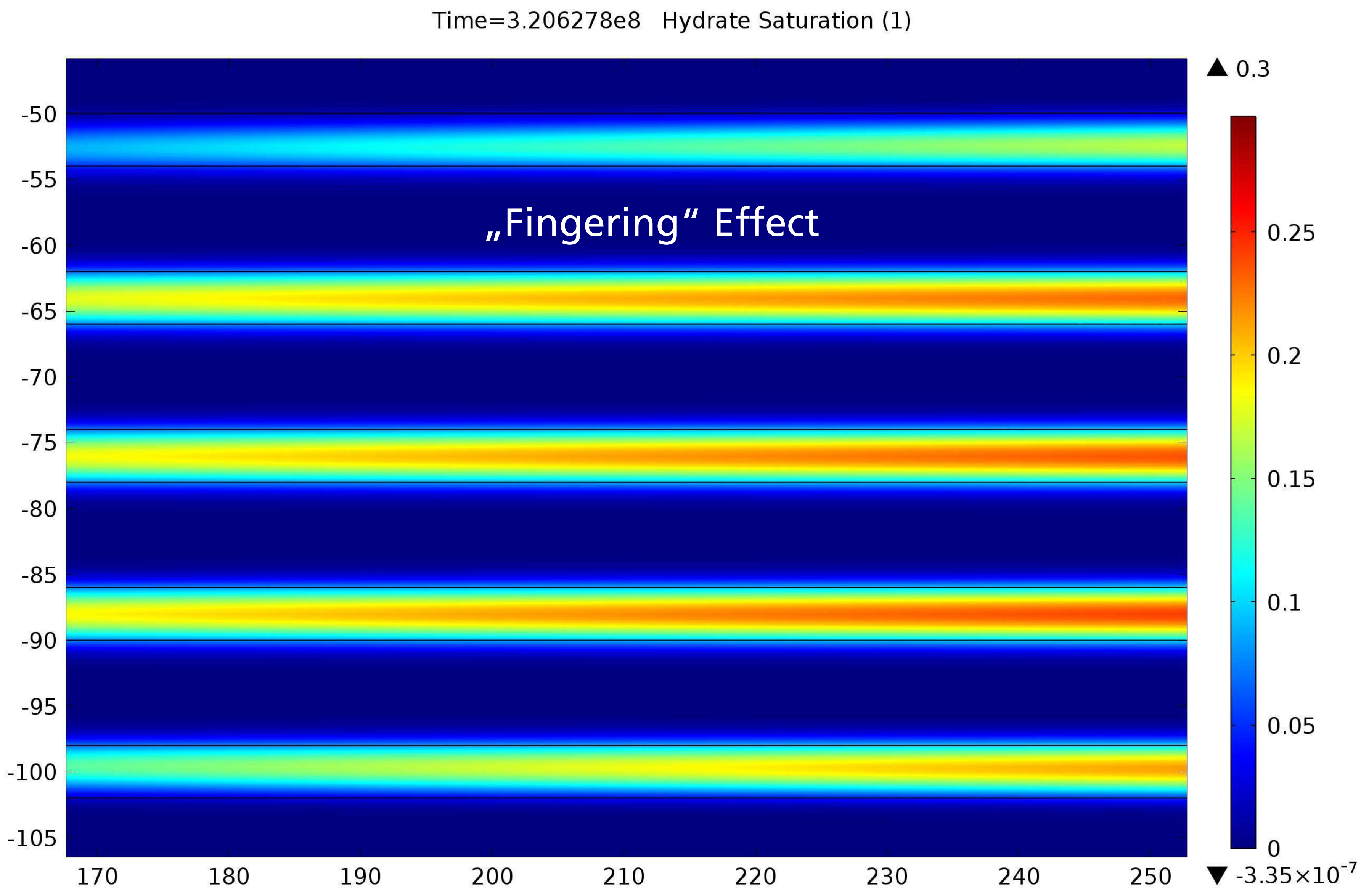
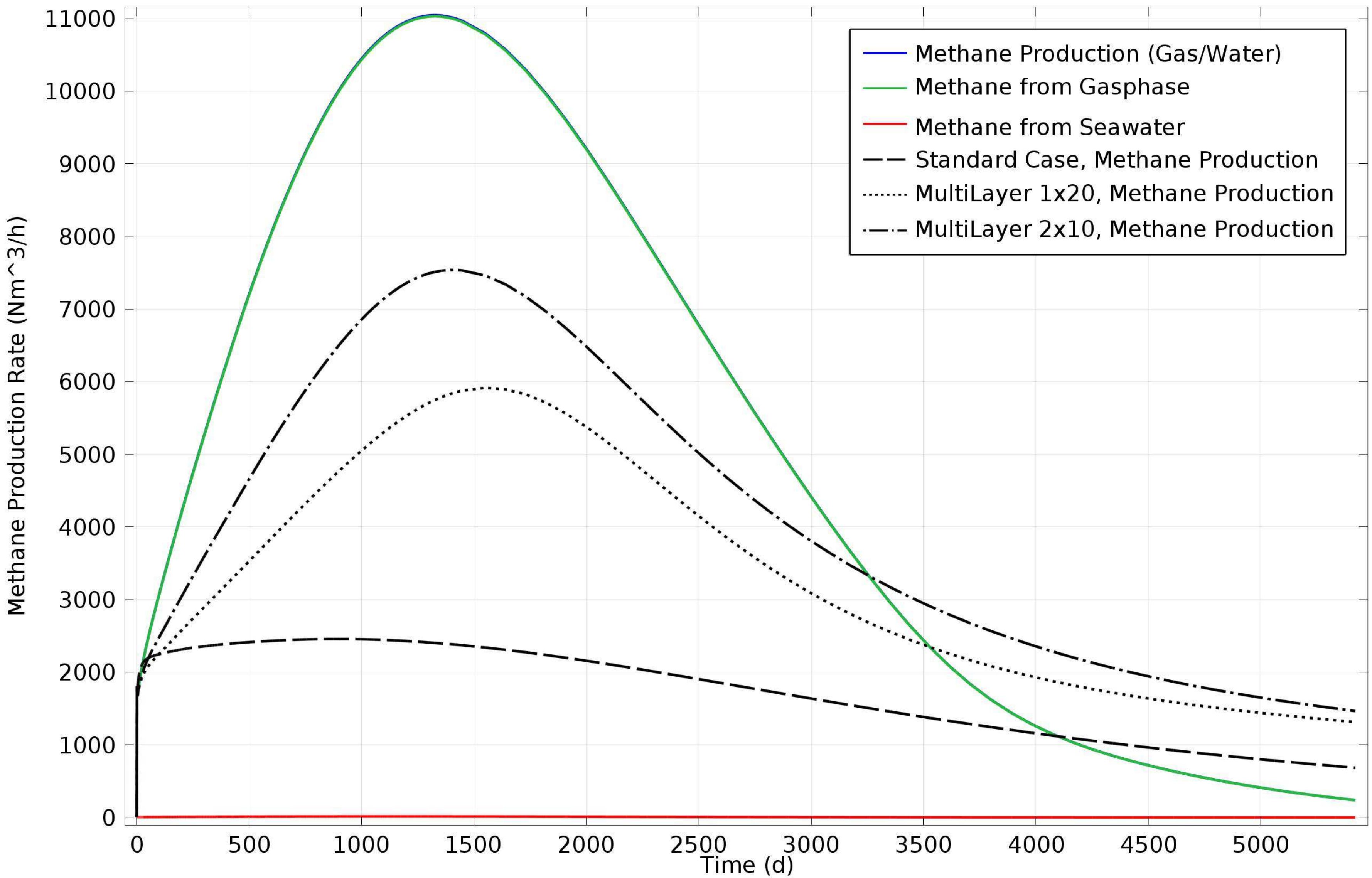
Case Study II – Depressurization of Multi-Layer Reservoir



Case Study II – Depressurization of Multi-Layer Reservoir



Case Study II – Depressurization of Multi-Layer Reservoir



SUGAR project – case studies

More case studies developed with COMSOL:

- Injection of Carbon Dioxide with parallel Methane production (2 wells)
- Reservoir simulations for the Ulleung Basin, South Korea (UGBH 2.6)
- Simulation cases for process safety and reservoir integrity issures
- Production upriser pipe simulations (1D / 2Ph Euler Equations)

Summary

State

- Development of a gas hydrate reservoir model in COMSOL Multiphysics
- Usage of the Coefficient Form PDE tool of the Mathematics branch
- Highly nonlinear model, needs the fully coupled approach with direct solution
- Simulation of important reservoir production cases were successful

Outlook

- New 3. project phase starts in October 2014
- Field development simulations in preparation of a real field test
- Production safety simulations

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Thank you for your attention!

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