A Hierarchical Modeling Framework for Geological Storage of Carbon

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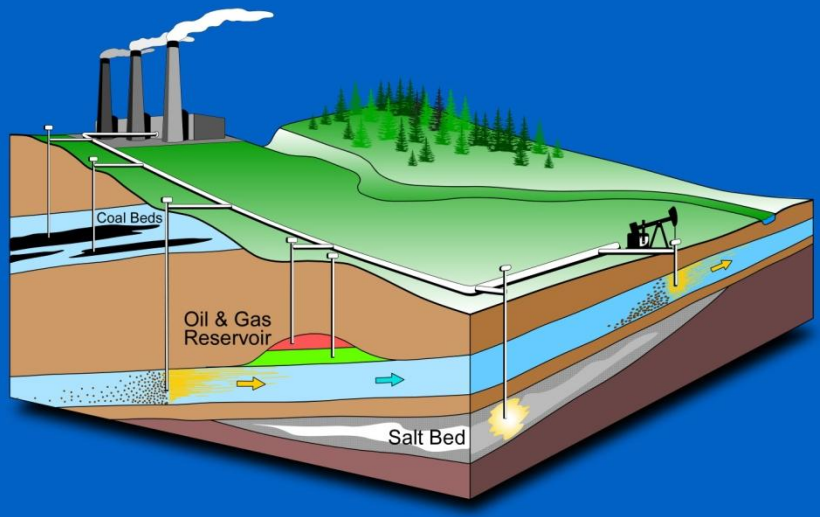
Outline

- Summary of Objectives
- Length and Time Scales
- Multi-scale Models
- Modeling Options: Analytical, Semi-analytical, Numerical, Hybrid
- Web Interface
- Conclusions



Summary of Objectives

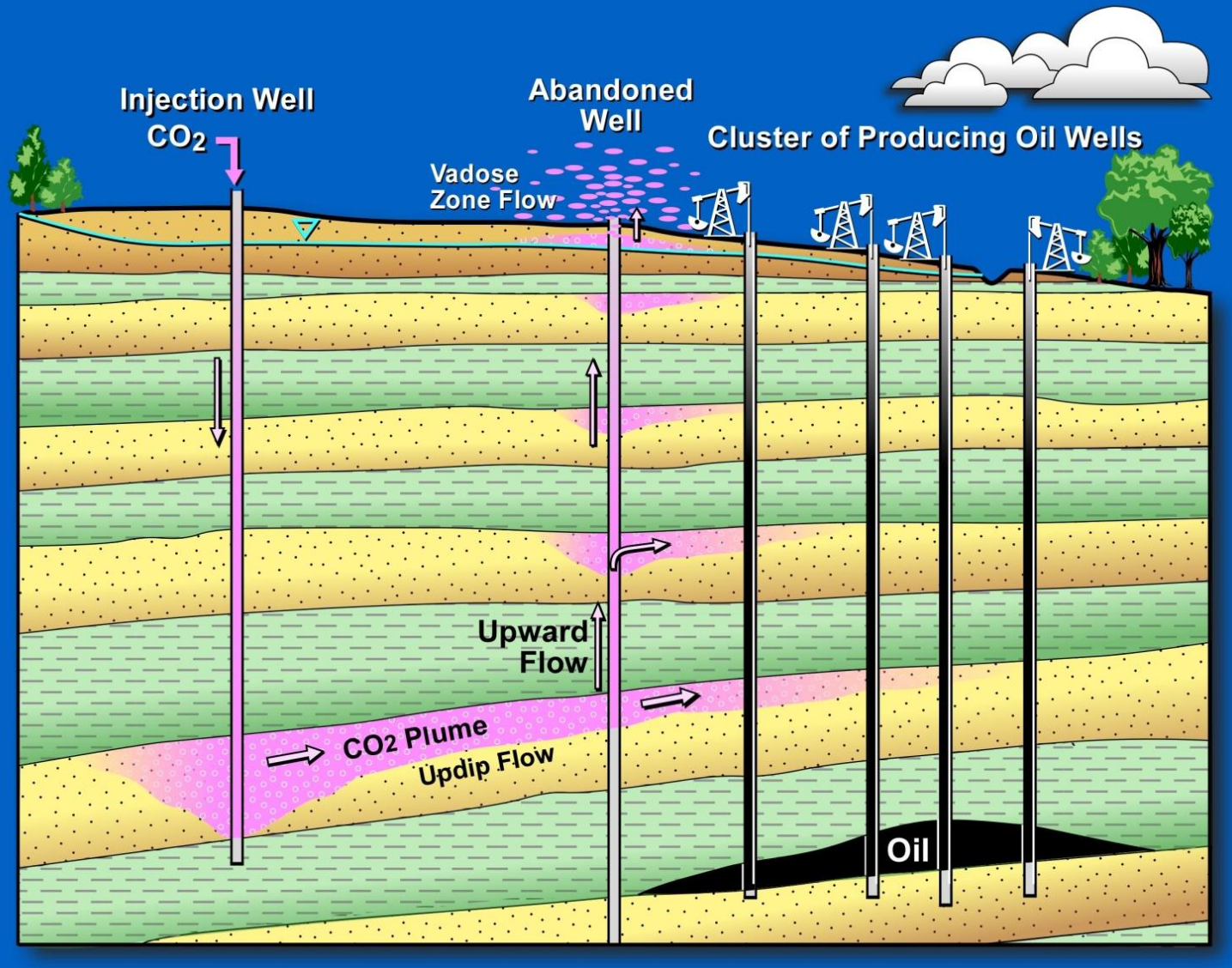
1. To develop and enhance a set of analytical and numerical computational tools to address a range of practical issues associated with geological storage of carbon dioxide, with a focus on CO_2 migration and leakage, brine migration and leakage, and the spatial extent of pressure increases in the subsurface.

2. To develop a 'hierarchical modeling framework' within which different kinds of models can be combined to produce effective hybrid models that can span a wide range of applications with a focus on risk assessment and leakage into shallow zones.

3. To provide guidance on the level of model complexity appropriate for different injection and leakage scenarios.

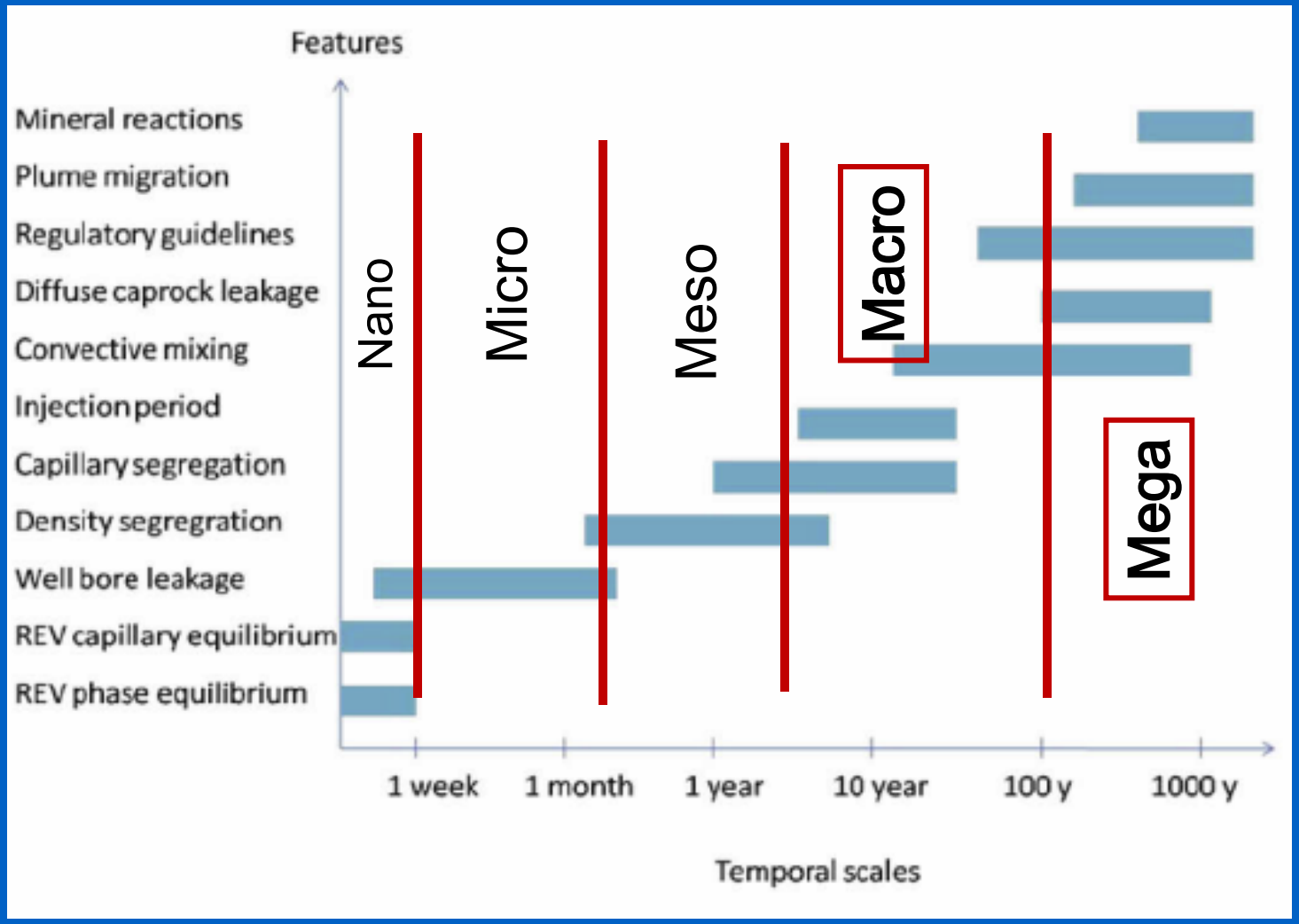
4. To provide simple web-based interfaces for different versions of our analytical models for CO_2 plume migration, brine movement, and pressure build-up.

Possible Leakage Scenario



Processes and Scales

(from Nordbotten and Celia, 2010)



"Multi-scale Modeling"

Our Modeling Approach

1. Write models at macro and mega scales ➔ Assume Buoyant Segregation of fluids and vertical equilibrium

2. Given #1, it is natural to vertically integrate the governing equations ➔ 2-D equations in each permeable formation.

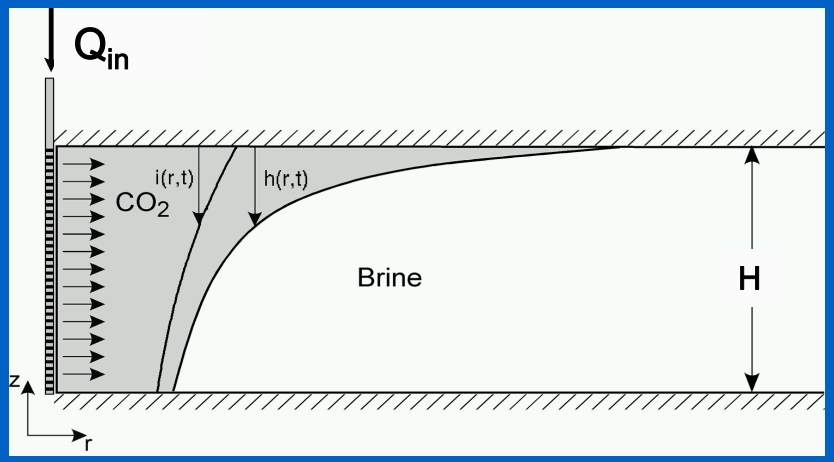
3. Write fairly general equations that can be solved numerically:

$$\phi(1 - s_b^{res})\frac{\partial(H - h_{T,I})}{\partial t} - \boldsymbol{\nabla} \cdot [\boldsymbol{K}\boldsymbol{\Lambda}_b(\boldsymbol{\nabla} p_B + \rho_b g \boldsymbol{\nabla} \zeta_B)] = \rho_b \Psi_b$$

$$\phi(1 - s_b^{res})\frac{\partial h_{T,I}}{\partial t} - \boldsymbol{\nabla} \cdot \left[\boldsymbol{K}\boldsymbol{\Lambda}_c\left(\boldsymbol{\nabla} p_B + \Delta_\alpha \rho g \boldsymbol{\nabla} h_{T,I} + \rho_c g \boldsymbol{\nabla} \zeta_T - \rho_b g \boldsymbol{\nabla} h_{T,B}\right)\right] = \rho_c \Psi_c$$

4. Additional assumptions can allow for analytical or semi-analytical solutions.

Analytical Solution



$$\Gamma \equiv \frac{2\pi\Delta\rho g k \lambda_w H^2}{Q_{in}}$$

$$\tau \equiv \frac{Q_{in} t}{2\pi H \varphi (1 - S_{res})}$$

$$\lambda_1 \equiv \frac{\lambda_c}{\lambda_w}, \quad \lambda_2 \equiv \frac{\lambda_{cw}}{\lambda w}, \quad \vartheta \equiv \frac{\rho_{cw} - \rho_c}{\rho_w - \rho_{cw}}$$

$$h' \equiv \frac{h}{H}, \quad i' \equiv \frac{i}{H}$$

$$\frac{dh'}{d\chi} = \frac{4\Gamma\gamma_1}{\chi}\frac{d}{d\chi}\left((1-h')\chi\frac{dp'}{d\chi}\right)$$

$$-\frac{di'}{d\chi} = \frac{4\gamma_2\Gamma\lambda_1}{\chi}\frac{d}{d\chi}\left(i'\chi\frac{d}{d\chi}(p'+h'+\vartheta i')\right)$$

$$\chi \equiv r^2/\tau$$

$$-\frac{d}{d\chi}(h'-i') = \frac{4\Gamma\lambda_2}{\chi}\frac{d}{d\chi}\left((h'-i')\chi\frac{d}{d\chi}(p'+h')\right) + \frac{4(1-\gamma_2)\Gamma\lambda_1}{\chi}\frac{d}{d\chi}\left(i'\chi\frac{d}{d\chi}(p'+h'+\vartheta i')\right) + \frac{4\Gamma(1-\gamma_1)}{\chi}\frac{d}{d\chi}\left((1-h')\chi\frac{dp'}{d\chi}\right)$$

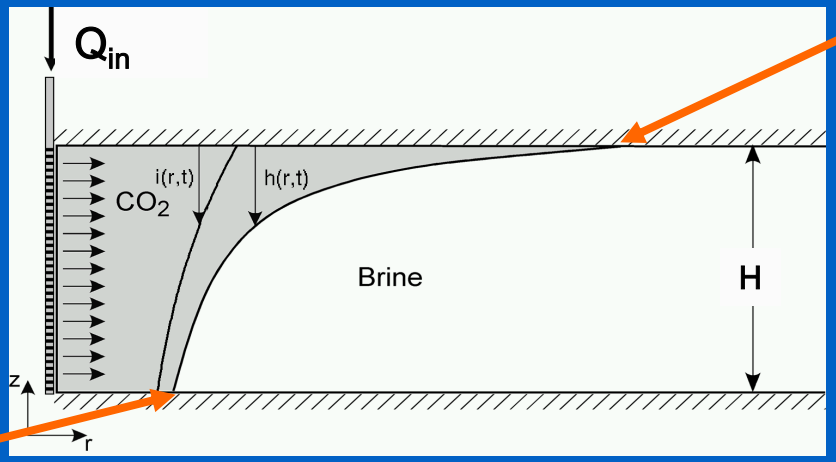
(From Nordbotten and Celia, *JFM*, 2006; See Celia and Nordbotten, 2009)

Similarity Solution: Simplified

When Γ<0.5:

$$h'(\chi) = \frac{h(\chi)}{H} = \frac{1}{\lambda - 1}\left(\sqrt{\frac{2\lambda}{\chi}} - 1\right)$$

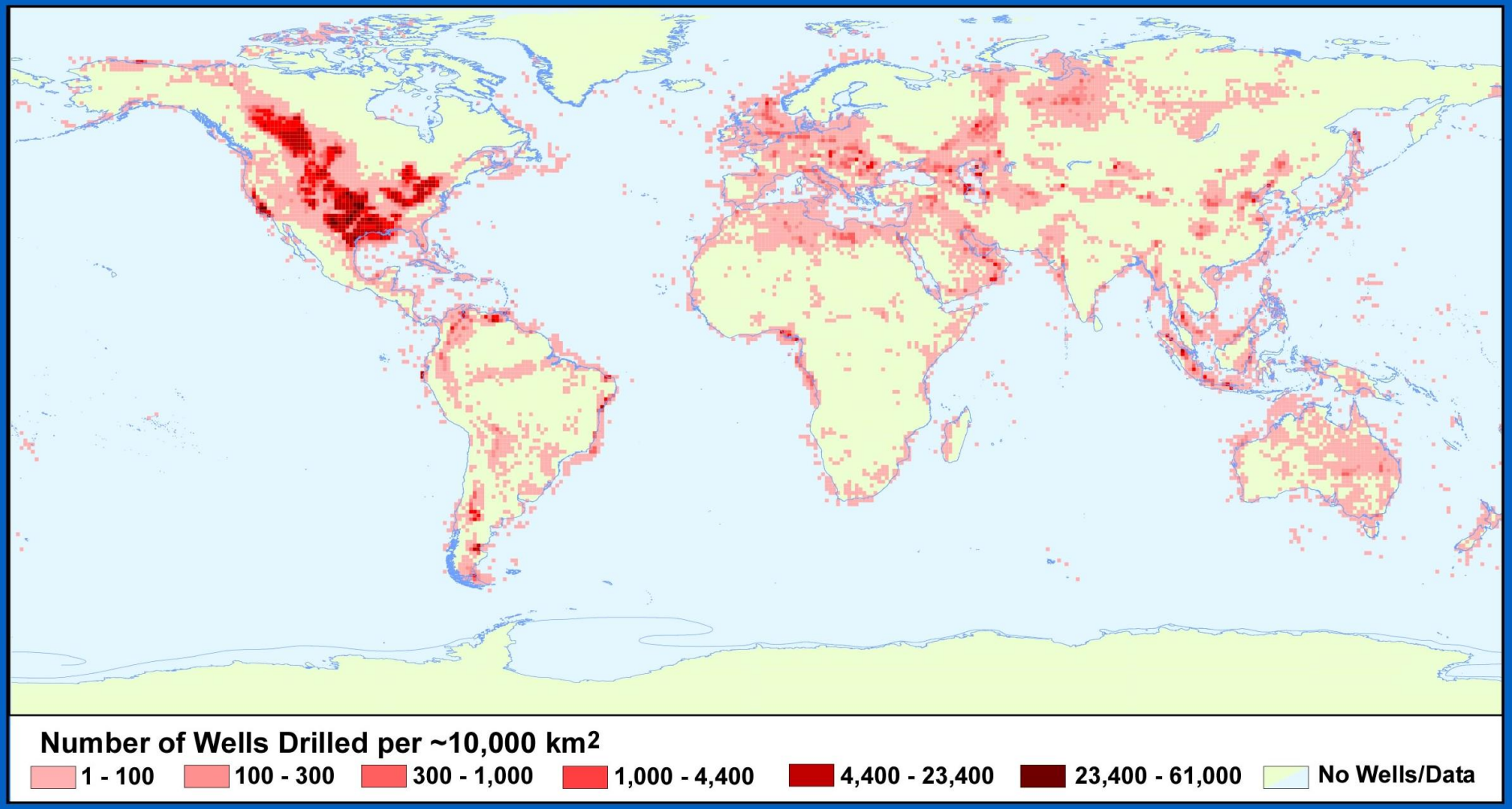
$$\chi_{\max} = 2\lambda$$



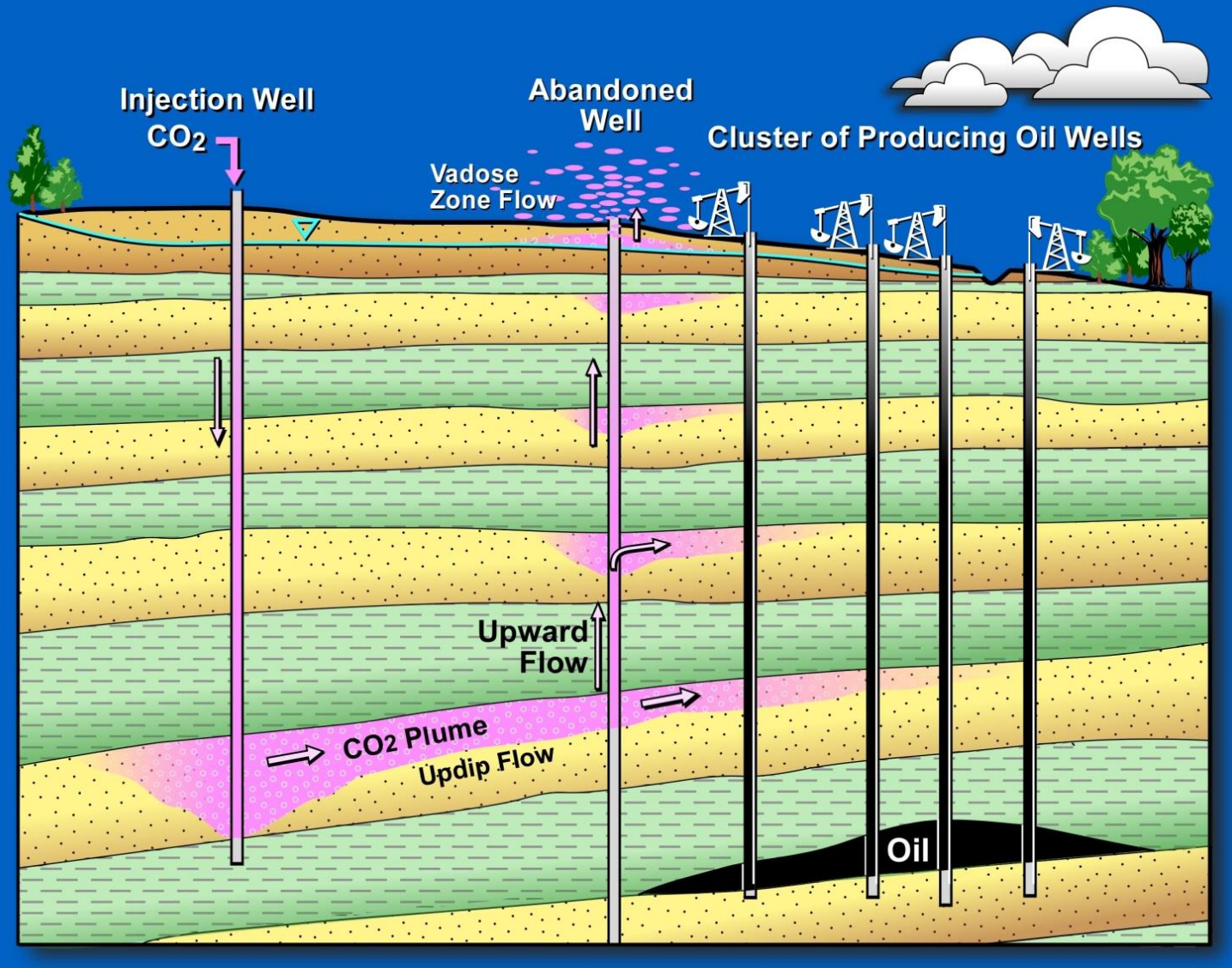
$$\chi_{\min} = \frac{2}{\lambda}$$

(From Nordbotten and Celia, *JFM*, 2006)

A Semi-analytical Model

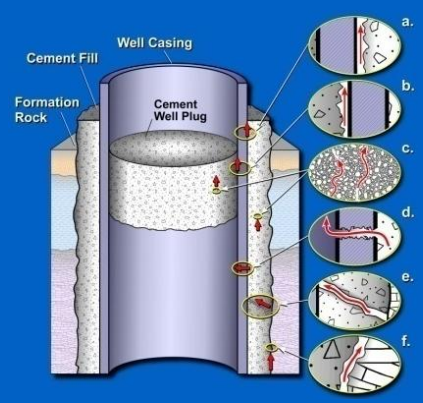


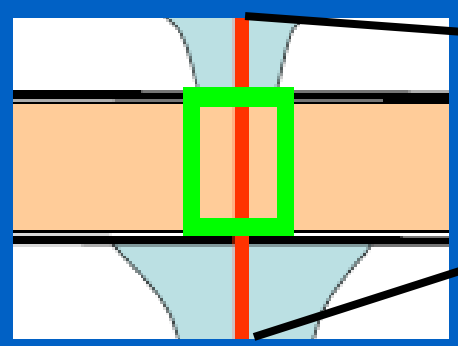
A Semi-analytical Model

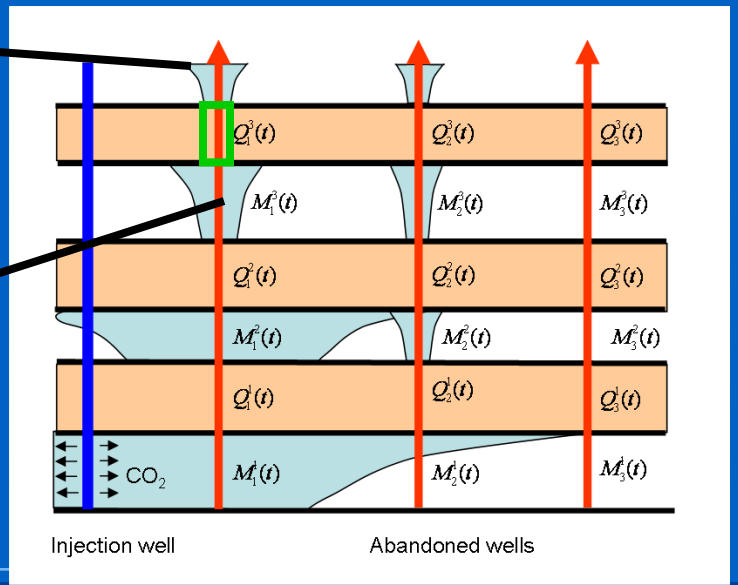


A Semi-analytical Model

1. Injection Plume, Secondary Plumes and Pressure Fields: Similarity Solution (*Nordbotten and Celia, JFM, 2006*)
2. Leakage Dynamics: Multi-phase Darcy Flow along Leaky Well Segments (*Nordbotten et al., ES&T, 2005, 2008*)
3. Upconing around Leaky Wells (*Nordbotten and Celia, WRR, 2006*)
4. Grid-free solutions: We can now solve 50 years of injection over 2,500 km^2, 12 layers, and 1,200 wells in about 15 minutes.

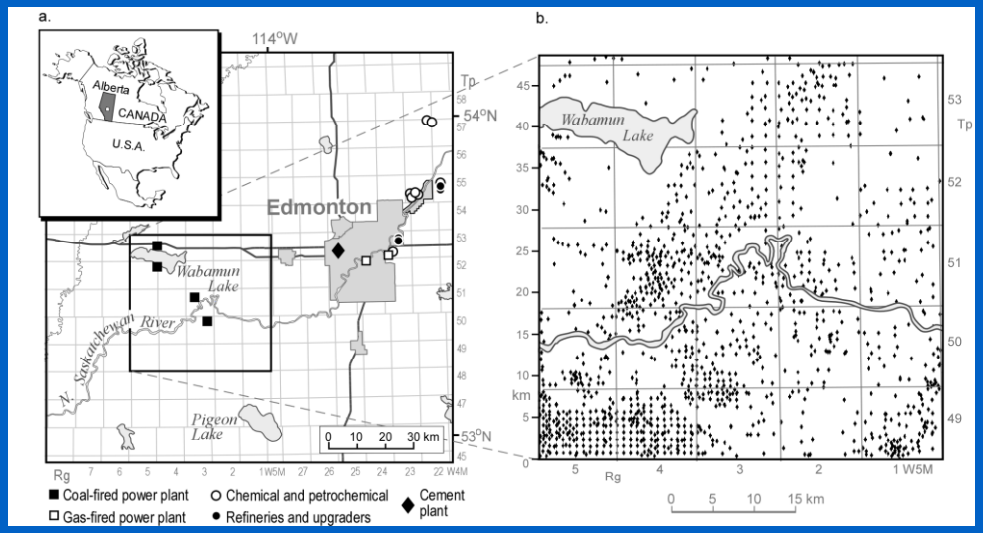


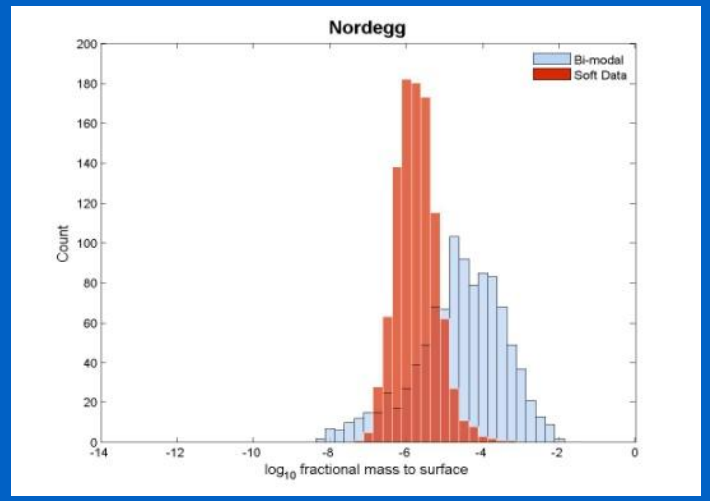


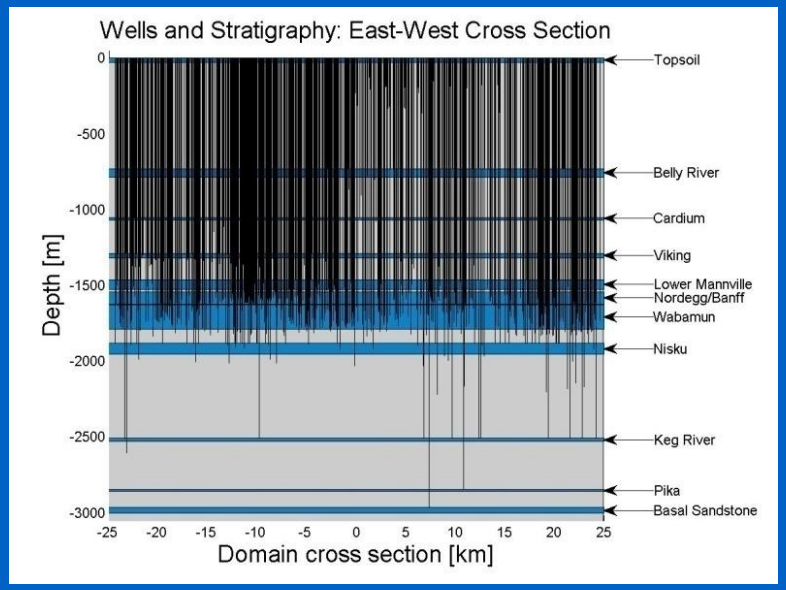


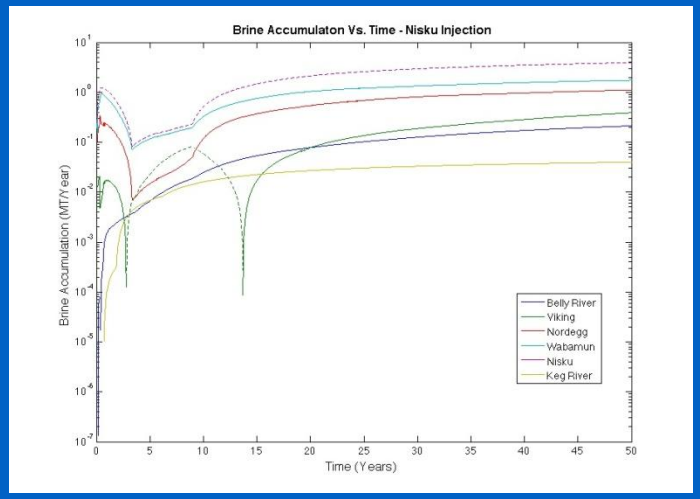
$$Q_{well} \propto K_{well} k(S_\alpha)\left(\frac{p_1 - p_2}{H} - \rho_\alpha g\right)$$

Wabamun Lake, Alberta

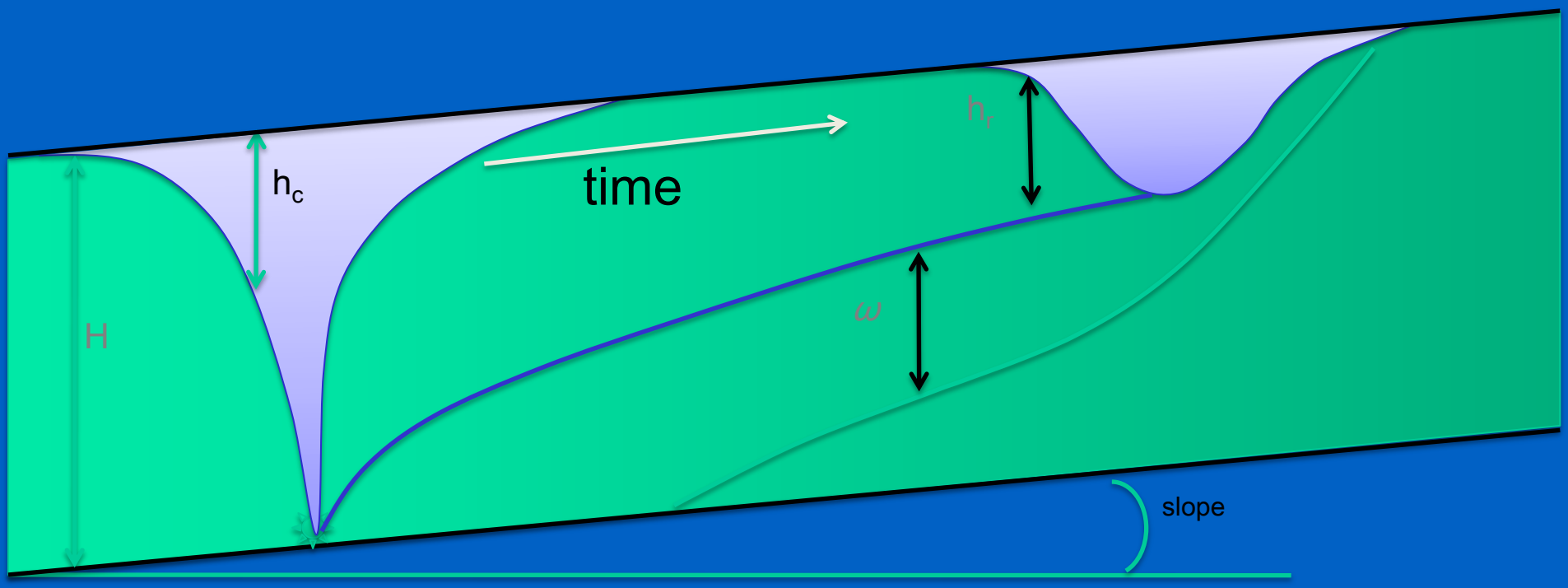






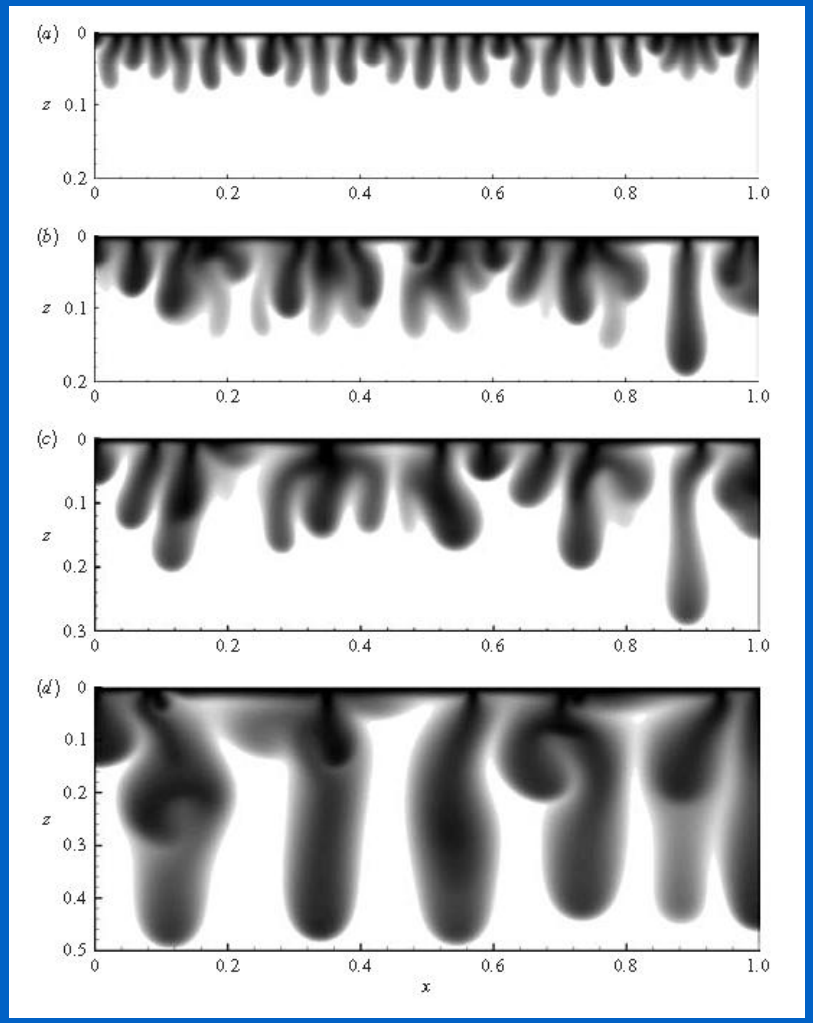


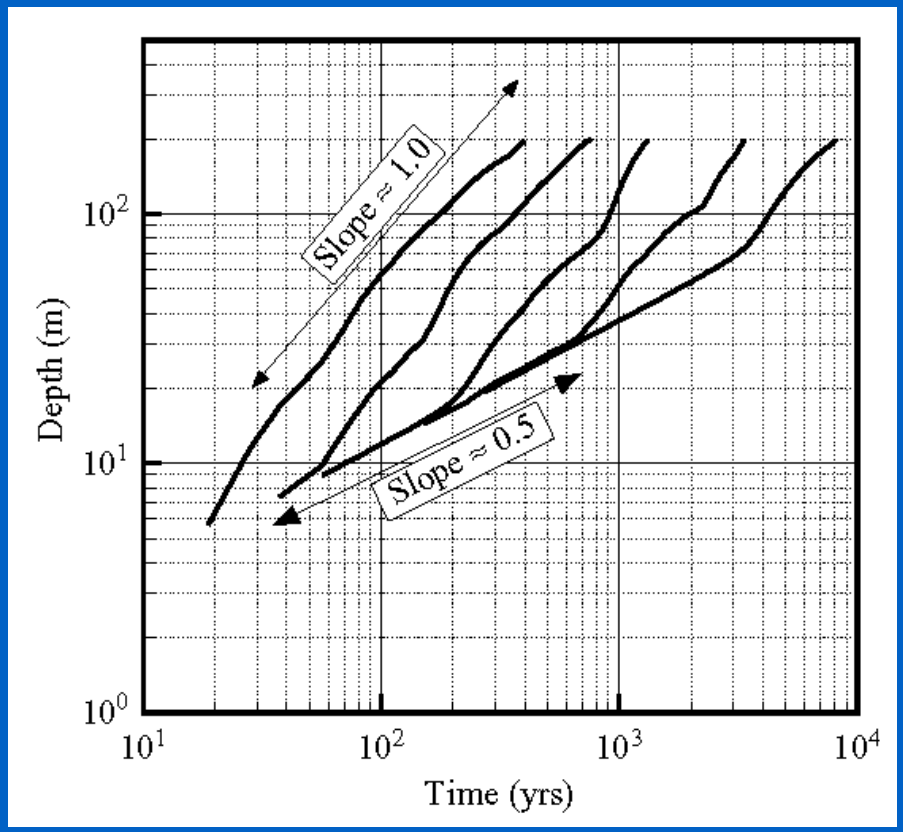
Long-term Predictions: Numerical Solutions



From: Gasda et al., 2010

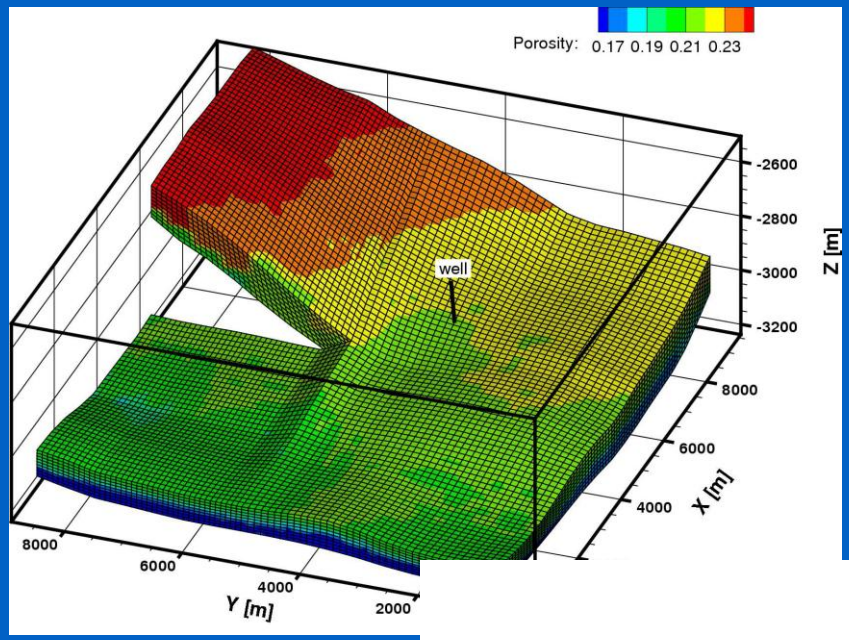
Long-term Predictions

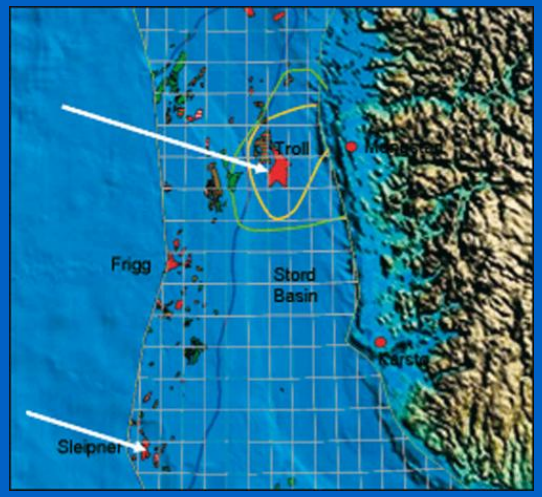


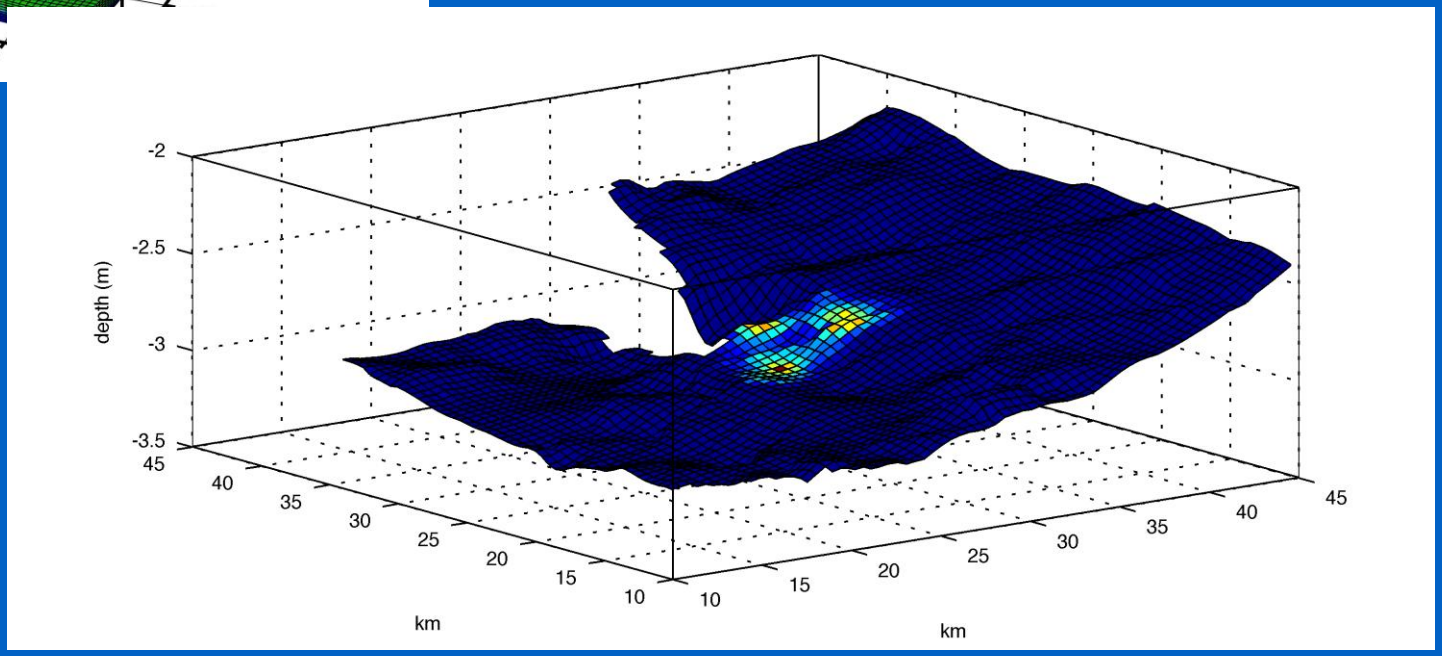


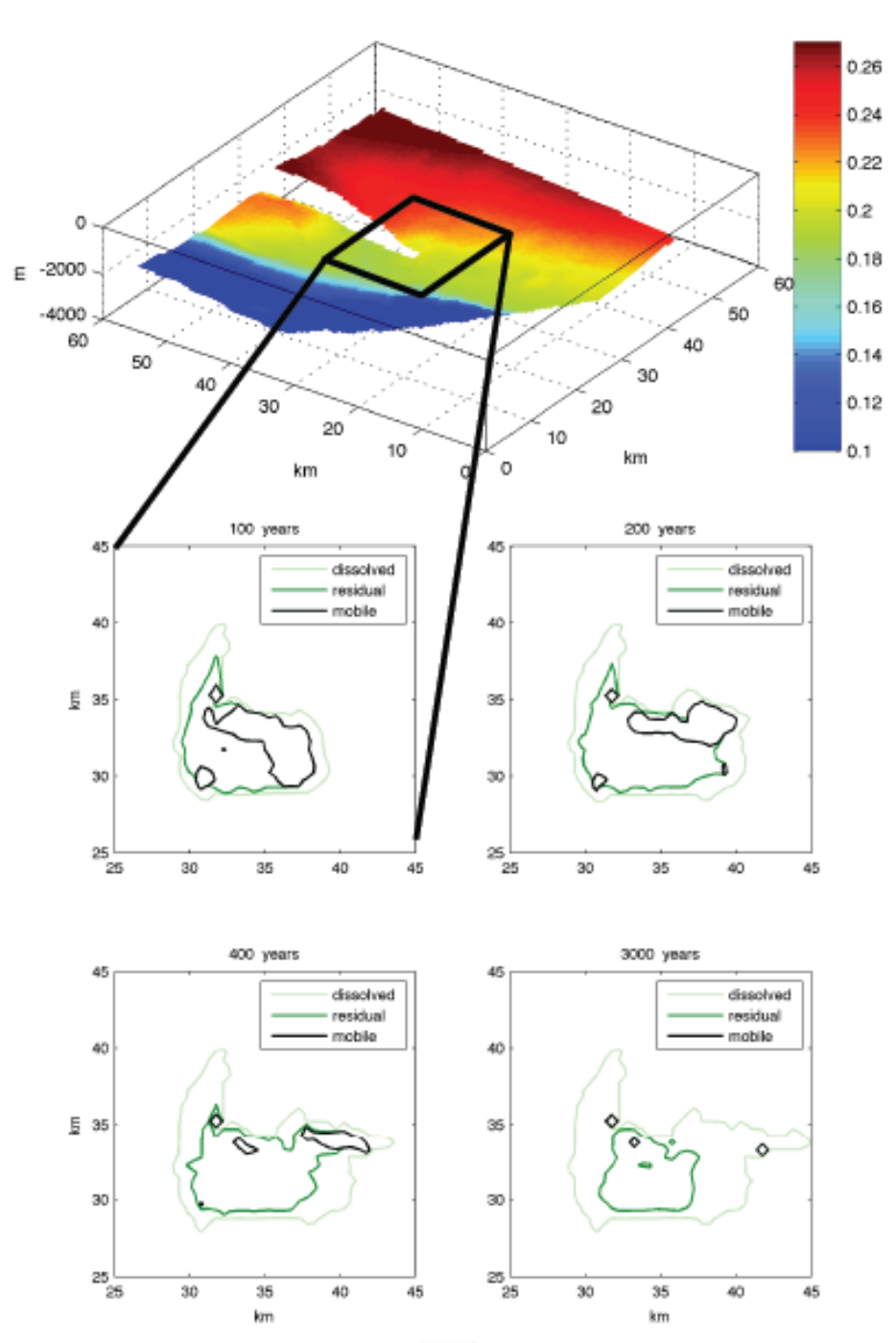
Advancement of dissolution fingers (Riaz et al. 05)

Long-term Predictions





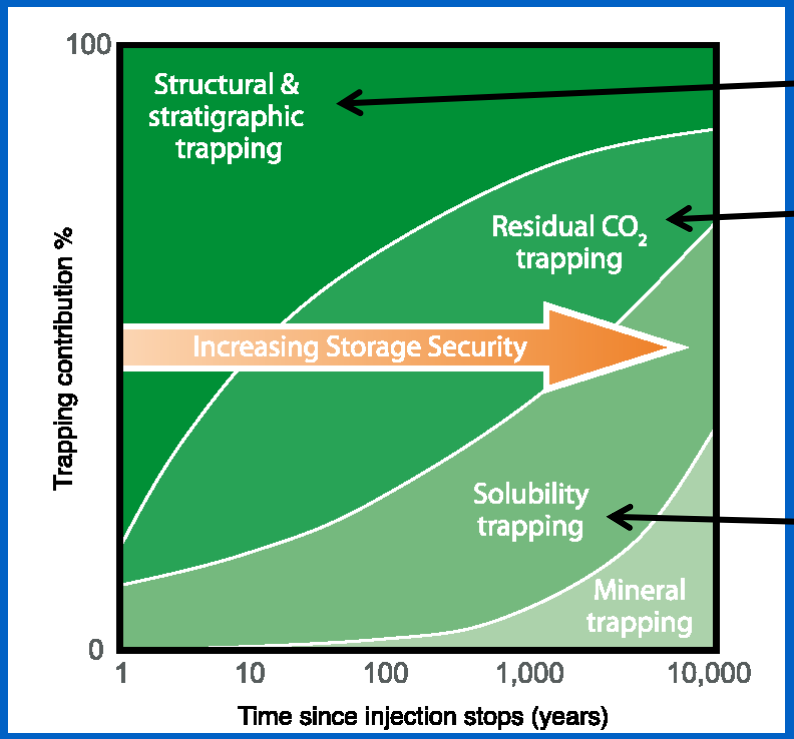


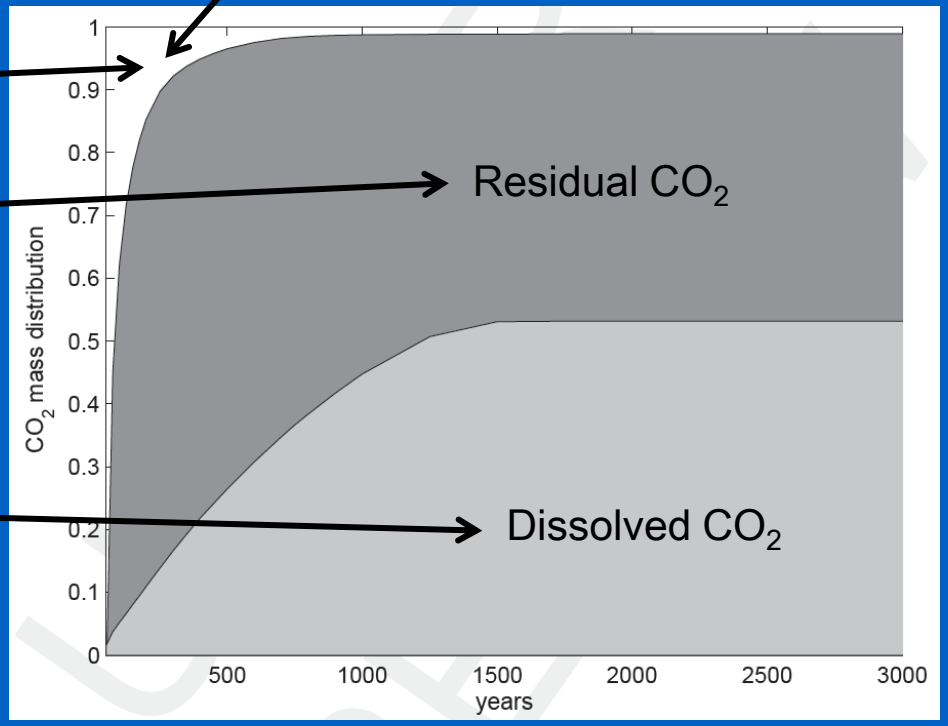


Numerical results of residual and solubility trapping in the Johansen formation during a 3,000-year post-injection period. The colored scale shows porosity. The contours indicate the outer edge of the different CO_2 regions (mobile, residual, dissolved) within the subregion indicated in the figure.

Results from Gasda et al., 2010.

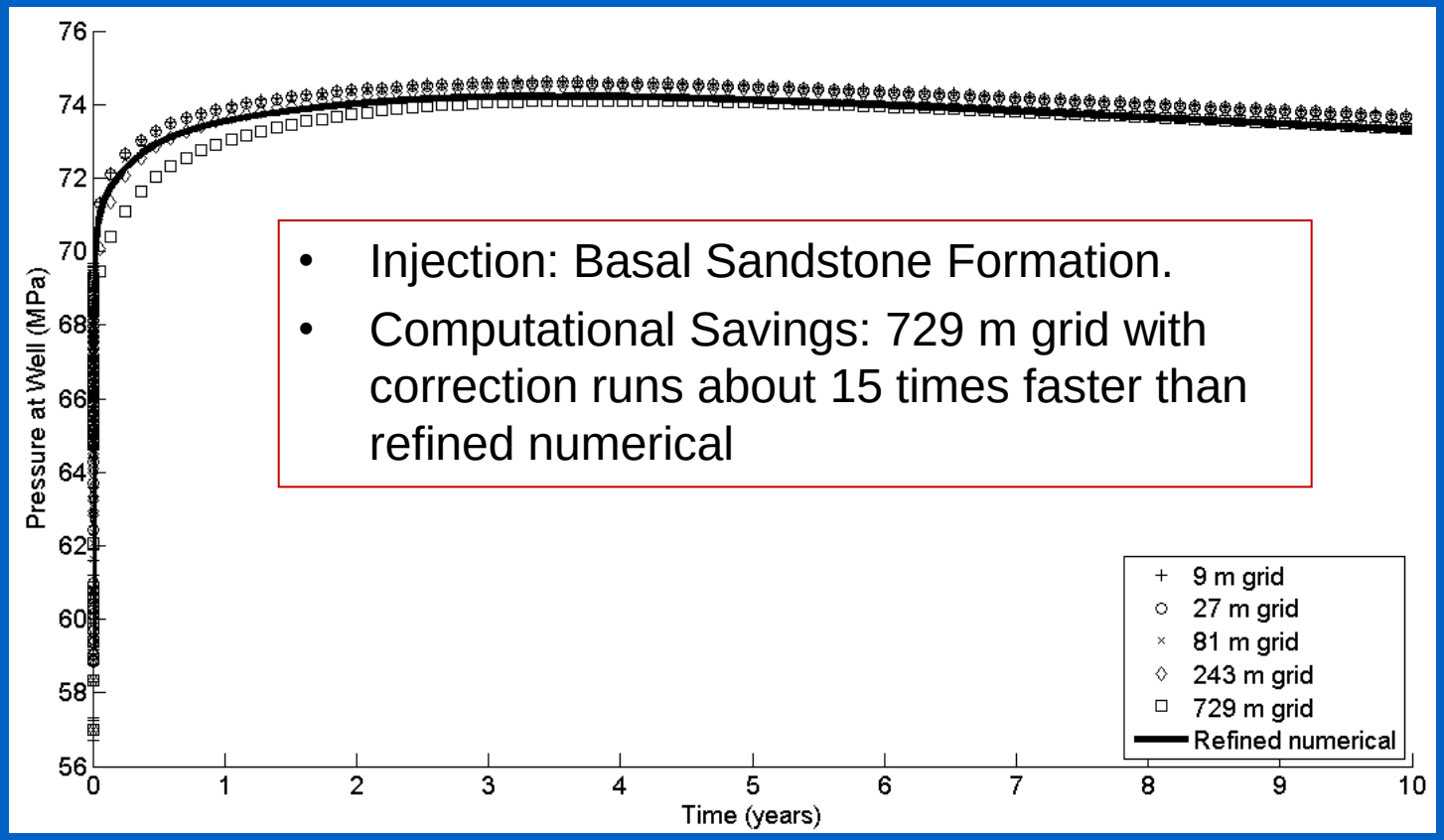
Long-term Predictions





Hybrid Multi-scale Models:

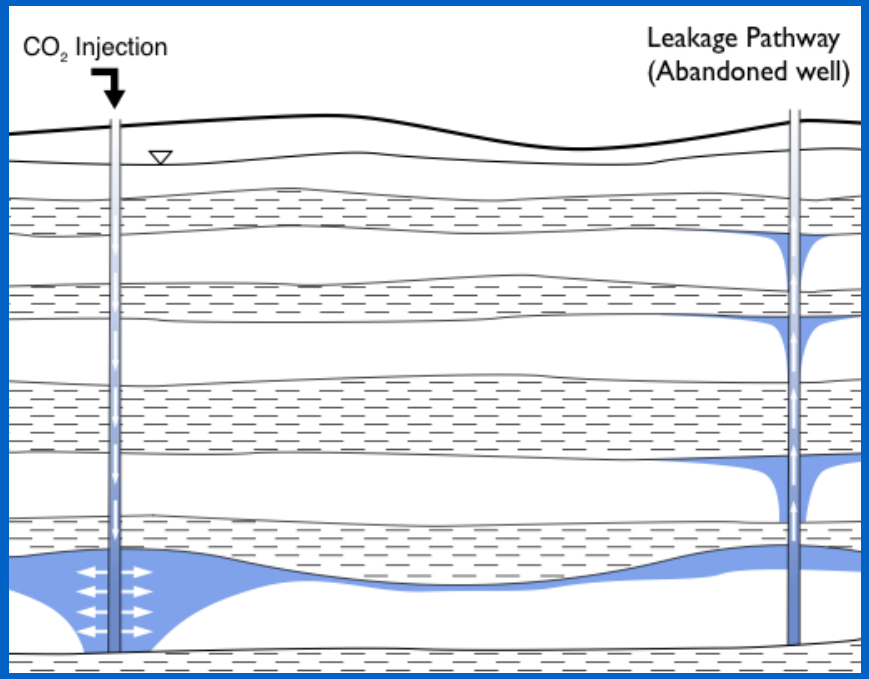
Local Analytical Corrections within Numerical Grid Block

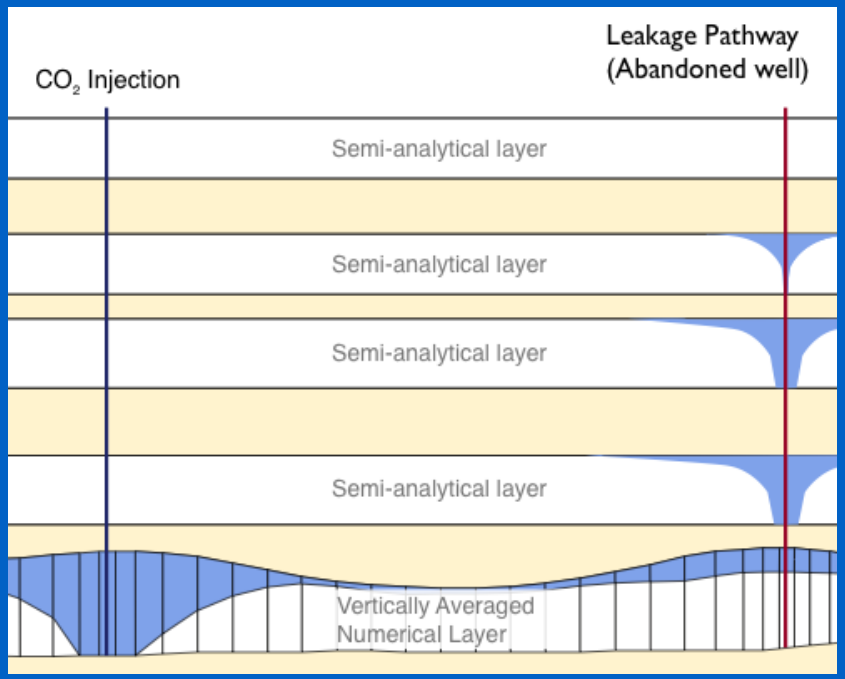


- Injection: Basal Sandstone Formation.
- Computational Savings: 729 m grid with correction runs about 15 times faster than refined numerical

Hybrid Multi-scale Models:

General Combination of Analytical and Numerical Solutions





Web-based User Interface V1

ELSAWeb | Simple Model | Complex Model

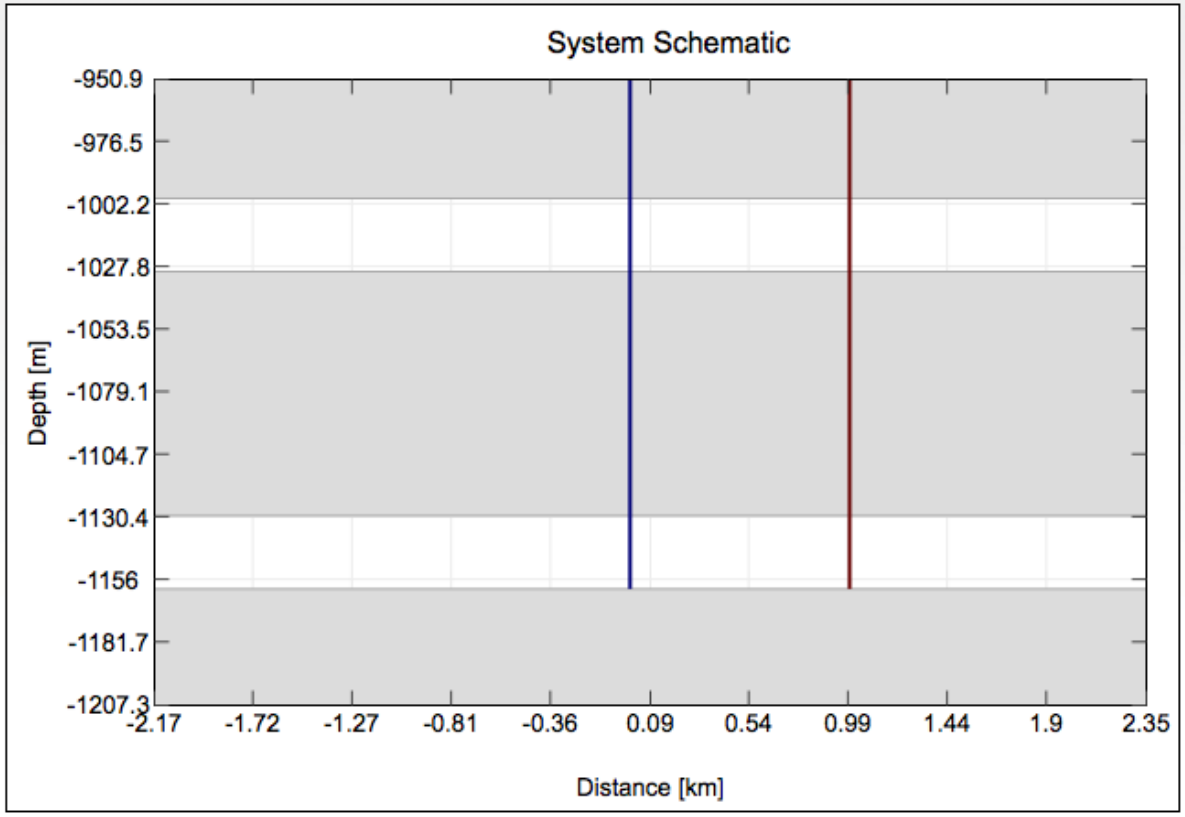
Display: System Schematic | Plume Evolution | Pressure

Simulation Parameters

Domain	
Outer Radius:	12000 m
Injection Aquifer	
Top Depth:	1130 m
Thickness:	30 m
Permeability:	2e-14 m^2
Porosity:	0.15
Compressibility:	4.2e-10 Pa^-1
Overlying Aquifer	
Top Depth:	1000 m
Thickness:	30 m
Permeability:	2e-14 m^2
Porosity:	0.15
Compressibility:	4.2e-10 Pa^-1
Injection Well	
Injection Rate:	0.4 mt/yr
Leaky Well	
Distance:	1000 m
Permeability:	1e-11 m^2
Porosity:	0.15 Pa^-1
Analysis	
Simulation Time:	50 years

Run Simulation | Reset Parameters

Visualization



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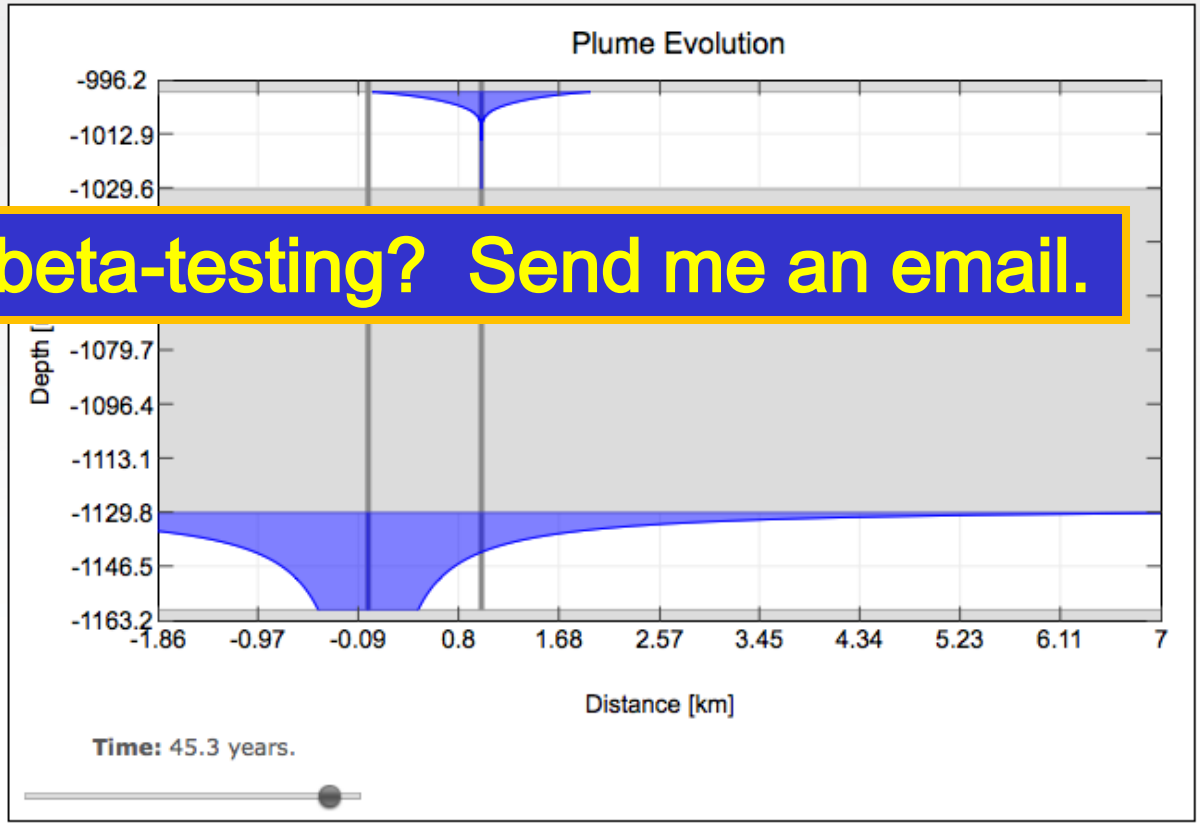
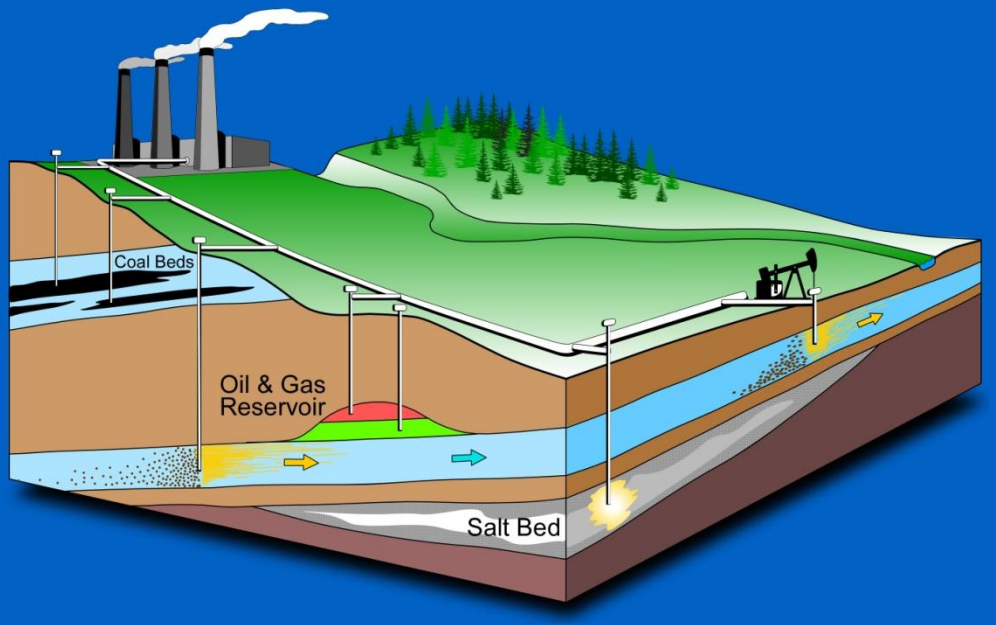


Volunteers for beta-testing? Send me an email.

Concluding Remarks

- Simplified models can be reasonable because:
  - Buoyancy provides strong vertical segregation
  - Space- and time-scale separation for critical processes
  - Large uncertainties in critical leakage parameters make detailed fine-scale simulation of marginal value.
- Fully coupled detailed models are appropriate for:
  - Fine resolution along critical leakage pathways
  - Computational upscaling for bulk parameters
  - Basic Science investigations
- We hope to provide models that use appropriate simplifications and modeling choices to answer practical questions.

Thank You!



Publications

Nordbotten, J.M. and M.A .Celia, *Geological Carbon Storage: Practical Models for Large-scale Simulation*, in press, John Wiley and Sons, 2010.

Celia, M.A., J.M. Nordbotten, B. Court, M. Dobossy, and S. Bachu, “Field-scale Application of a Semi-analytical Model for Estimation of Leakage Potential along Old Wells”, under review, *Int. J. Greenhouse Gas Technologies*, *2010*.

Gasda, S.E., J.M. Nordbotten, and M.A. Celia, “Vertically-averaged Approaches for CO_2 Injection with Solubility Trapping”, under review, *Water Resources Research, 2010*.

Celia, M.A. and J.M. Nordbotten, "Practical Modeling Approaches for Geological Storage of Carbon Dioxide", *Ground Water*, 47(5), 627-638, 2009.

Gasda, S.E., J.M. Nordbotten, and M.A. Celia, "Vertical Equilibrium with Sub-scale Analytical Methods for Geological CO_2 Sequestration", *Computational Geosciences*, published online 23 April 2009.

Nordbotten, J.M., D. Kavetski, M.A. Celia, S. Bachu, “Model for CO2 Leakage including Multiple Geological Layers and Multiple Leaky Wells”, *Environmental Science and Technology*, *43*(3), 743-749, 2009.

Gasda, S., J.M. Nordbotten, and M.A. Celia, "Upslope Plume Migration and Implications for Geological CO_2 Storage in Deep Saline Aquifers", *IES Journal of Civil Engineering, Vol. 1, No. 1*, page 1, 2008.

Gasda, S., J.M. Nordbotten, and M.A. Celia, "Determining Effective Wellbore Permeability from a Field Pressure Test: A numerical Analysis of Detection Limits", *Environmental Geology*, 54(6), 1207-1215, 2008.

Nordbotten, J.M. and M.A. Celia, "Similarity Solutions for Fluid Injection into Confined Aquifers", *Journal of Fluid Mechanics*, *561*, 307-327, 2006.