The Role of Existing Wells as Pathways for CO_2 Leakage*

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Abstract

Injection of CO_2 into deep formations leads to a multi-phase flow problem that may involve important mass exchange between phases, non-isothermal effects, and complex geochemical reactions. In addition, because enormous quantities of CO_2 must be injected to have any significant impact on the atmospheric carbon problem, the spatial scale of the subsurface problem becomes very large. Broad questions involving the fate of the injected CO_2, including possible leakage of CO_2 out of the formation, as well as the fate of displaced fluids like resident brines, lead to very challenging modeling and analysis problems.

Because important leakage pathways such as existing wells can be highly localized, and their properties can be highly uncertain, an overall analysis of the system requires resolution of multiple length scales in the context of a probabilistic approach. These requirements render standard numerical simulators ineffective due to excessive computational demands. A series of simplifying assumptions may be proposed, in the context of multi-scale modeling, to provide more efficient numerical calculations, even to the point of allowing for analytical or semi-analytical solutions. Such simplifications, while somewhat restrictive in their assumptions, allow for large-scale analysis of leakage in a probabilistic framework while capturing much of the essential physics of the problem. Example calculations illustrate the utility of these methods, and show the current state of leakage estimation. Specific applications to the Wabamun Lake area of Alberta, Canada show how large numbers of existing oil and gas wells can lead to complex leakage patterns across multiple formations. Simulations involving multiple realizations allow various well parameters to be correlated to estimated leakage levels. Numerical results also provide guidance on options for monitoring by providing estimates of sizes of leakage plumes and pressure perturbations across multiple layers in the sedimentary sequence.

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The Role of Existing Wells as Pathways for CO_2 Leakage

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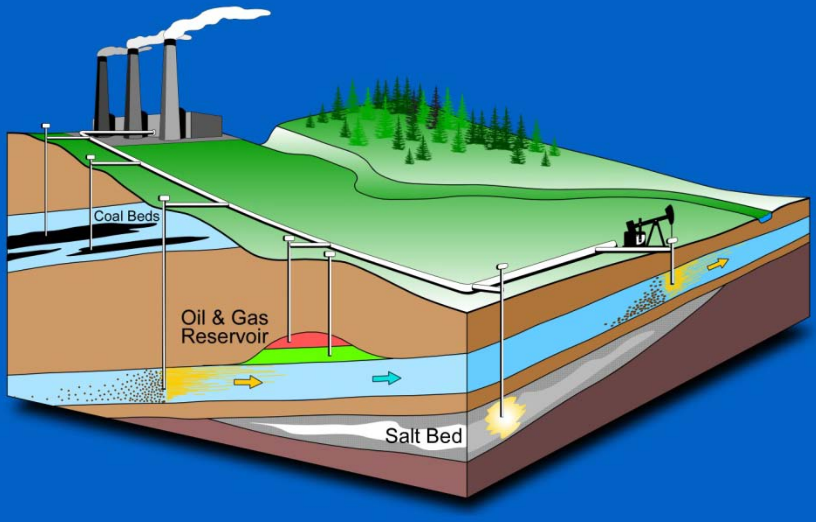
CMI Carbon Mitigation Initiative Princeton University

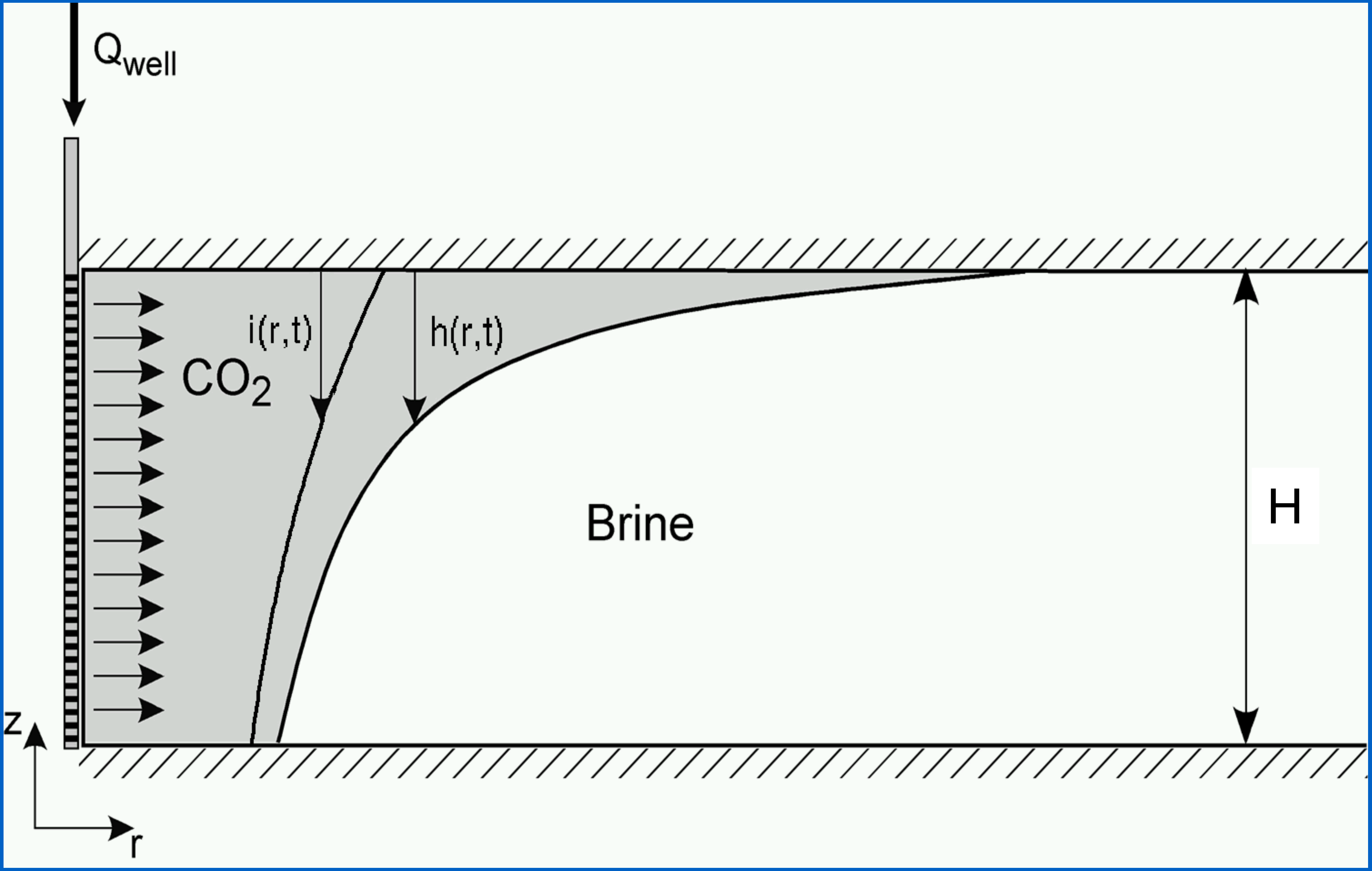
PEI Princeton Environmental Institute

Outline

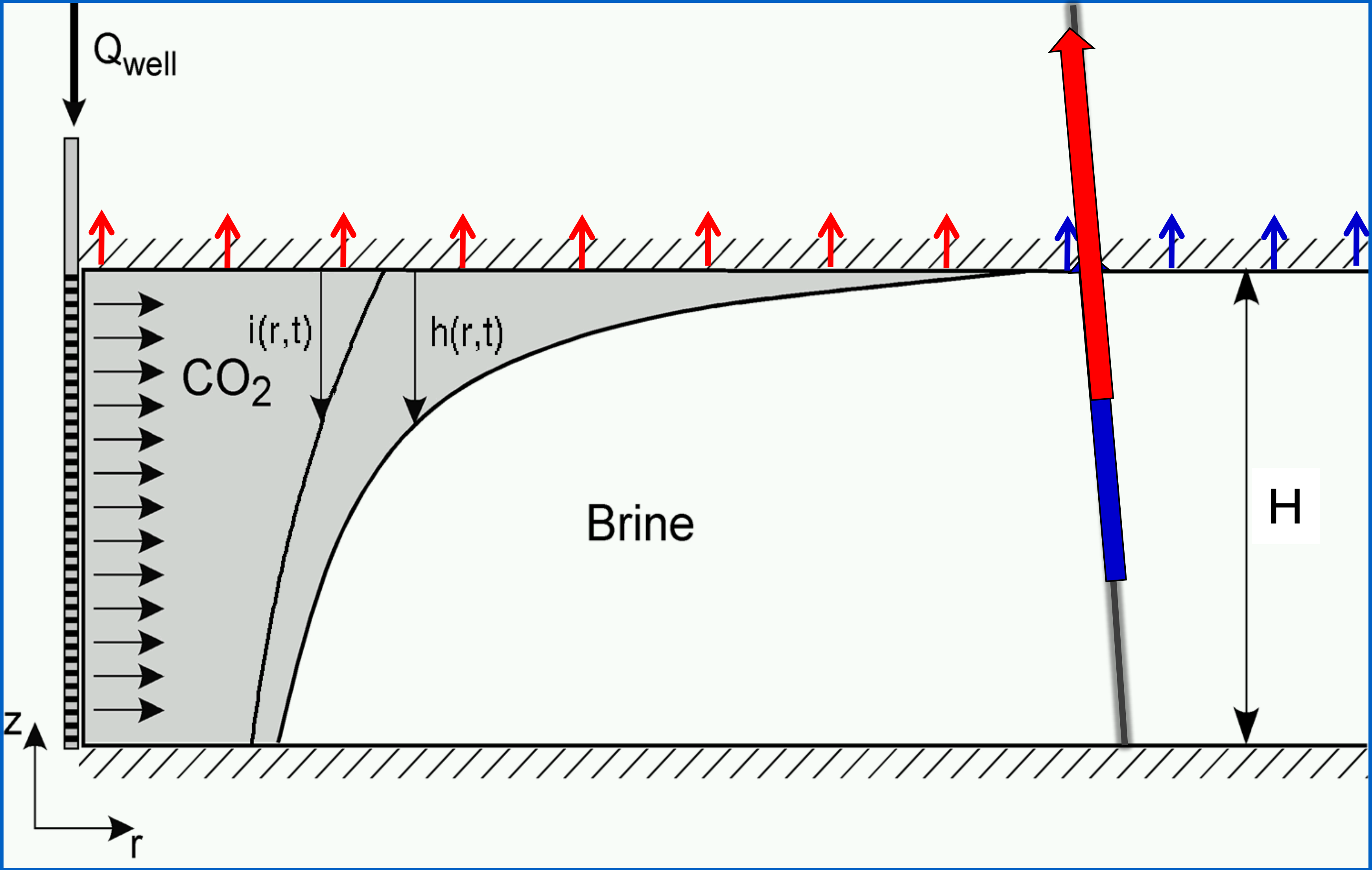
- Carbon Storage and Leakage
- Wells as Leakage Conduits
- Modeling Strategies for Storage and Leakage
- Example Application
- Conclusions



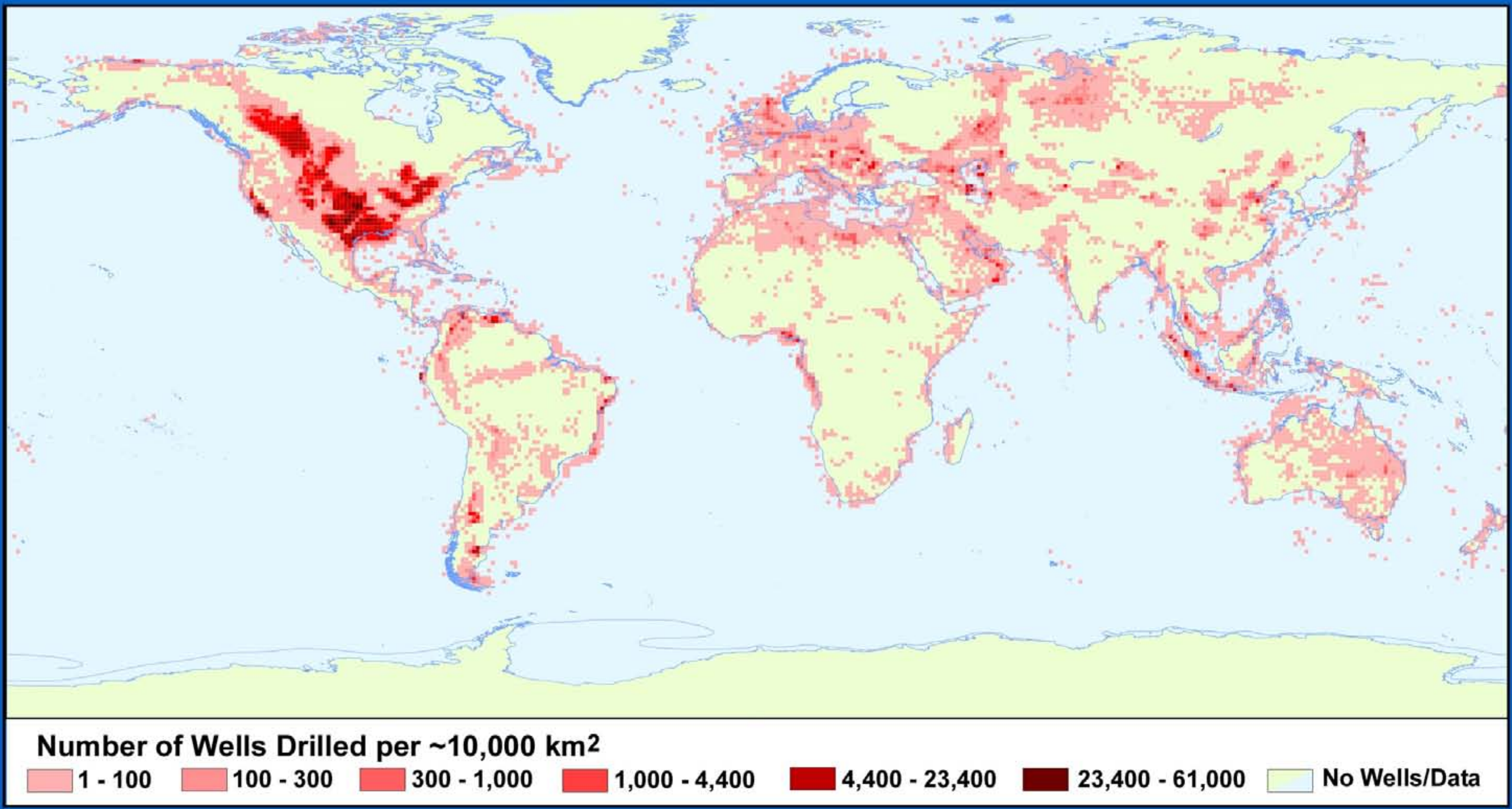
Plume of Injected CO_2



Plume of Injected CO_2



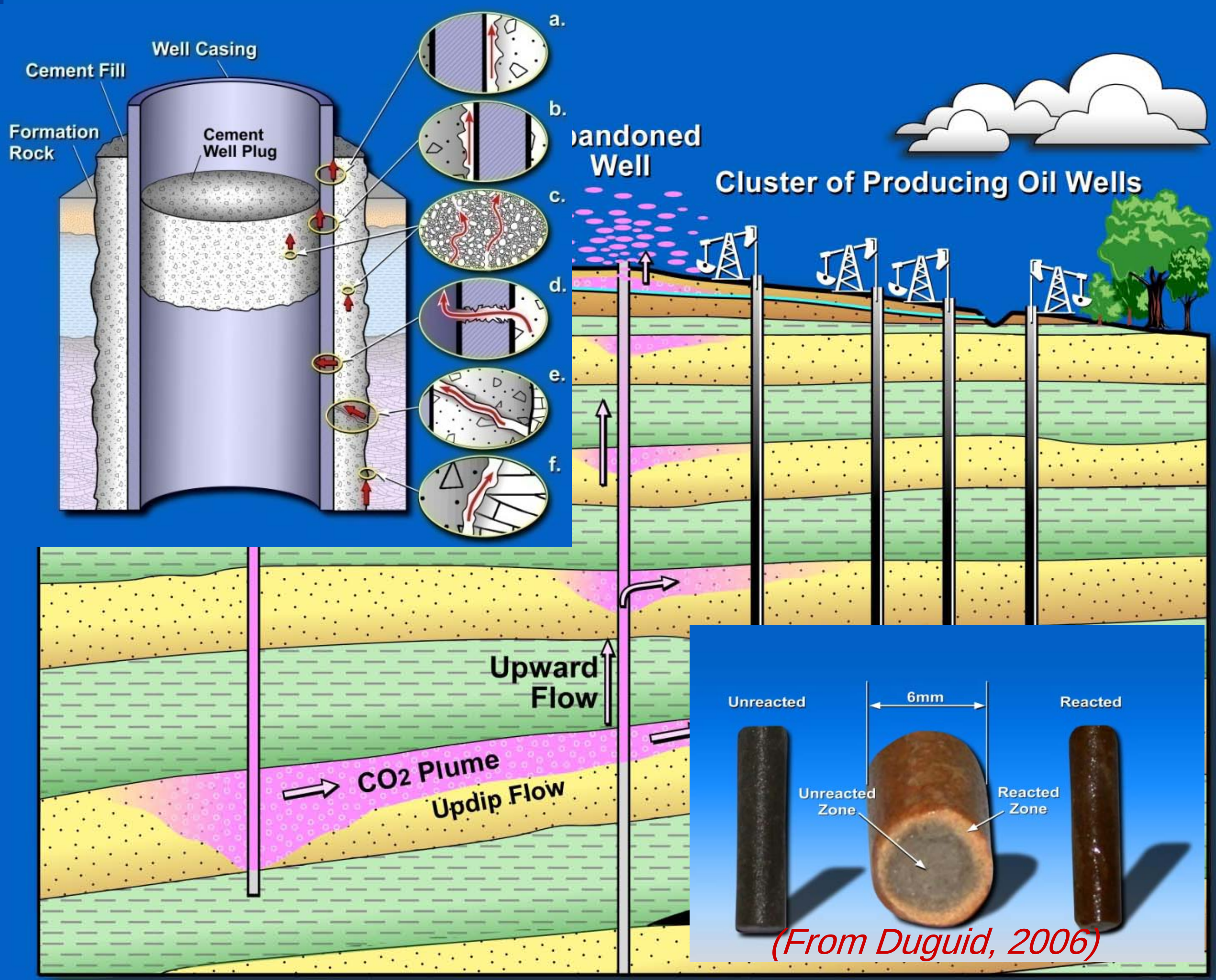
Worldwide Density of Oil and Gas Wells



End of 2004

From IPCC SRCCS, 2005

Injection and Leakage



(From Duguid, 2006)

- How to model this system?
- Domain Size: 1,000 km^2
- Leakage Pathways: 0.001 m^2.
- Flow Properties along well highly uncertain.
- Possible Material Degradation.

Three Important Quantities

- Amount of CO_2 leaked
  - Where does it go?
  - What is the consequence?
- Amount of brine leaked
  - Where does it go?
  - What is the consequence?
- Spatial extent of “significant” pressure increase
  - What is the “radius of influence”?
  - How do we define “significant”?

Issues for Well Leakage

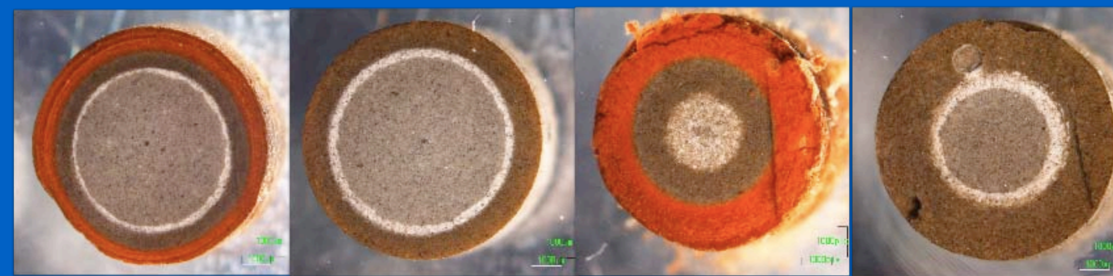
- Properties of Well Materials (Quantitative)
- Material Degradation (Properties = Function of time)

- Simulations across scales
- Simulation under Large Uncertainty
- Practical Risk Analysis

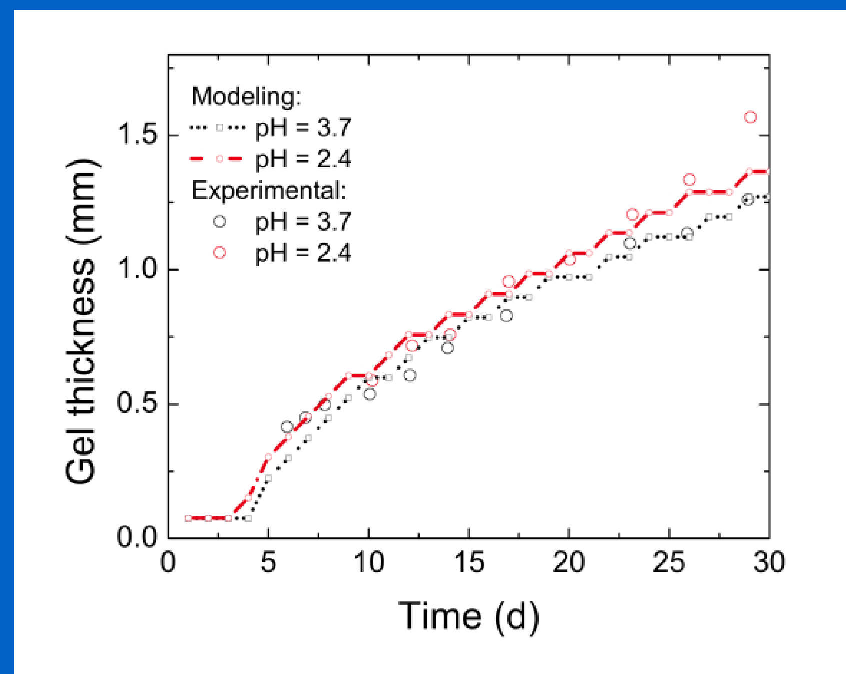
Kinetics of Corrosion

Experimental rates of attack (A. Duguid)

23°C pH 2.4	23°C pH 3.7	50°C pH 2.4	50°C pH 3.7



correctly predicted by model (B. Huet)



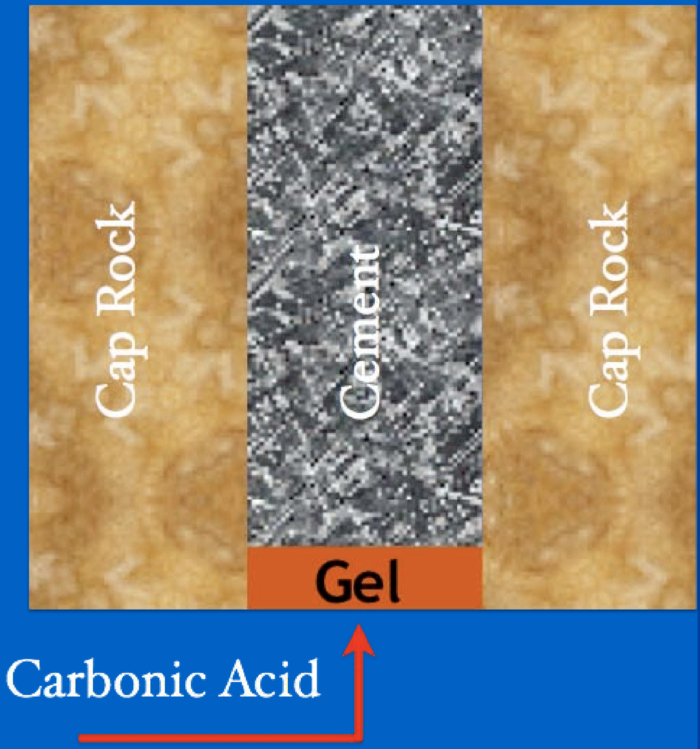
Kinetics of Corrosion

- Without leak, time to dissolve:

  2 m of cement ~100 yrs

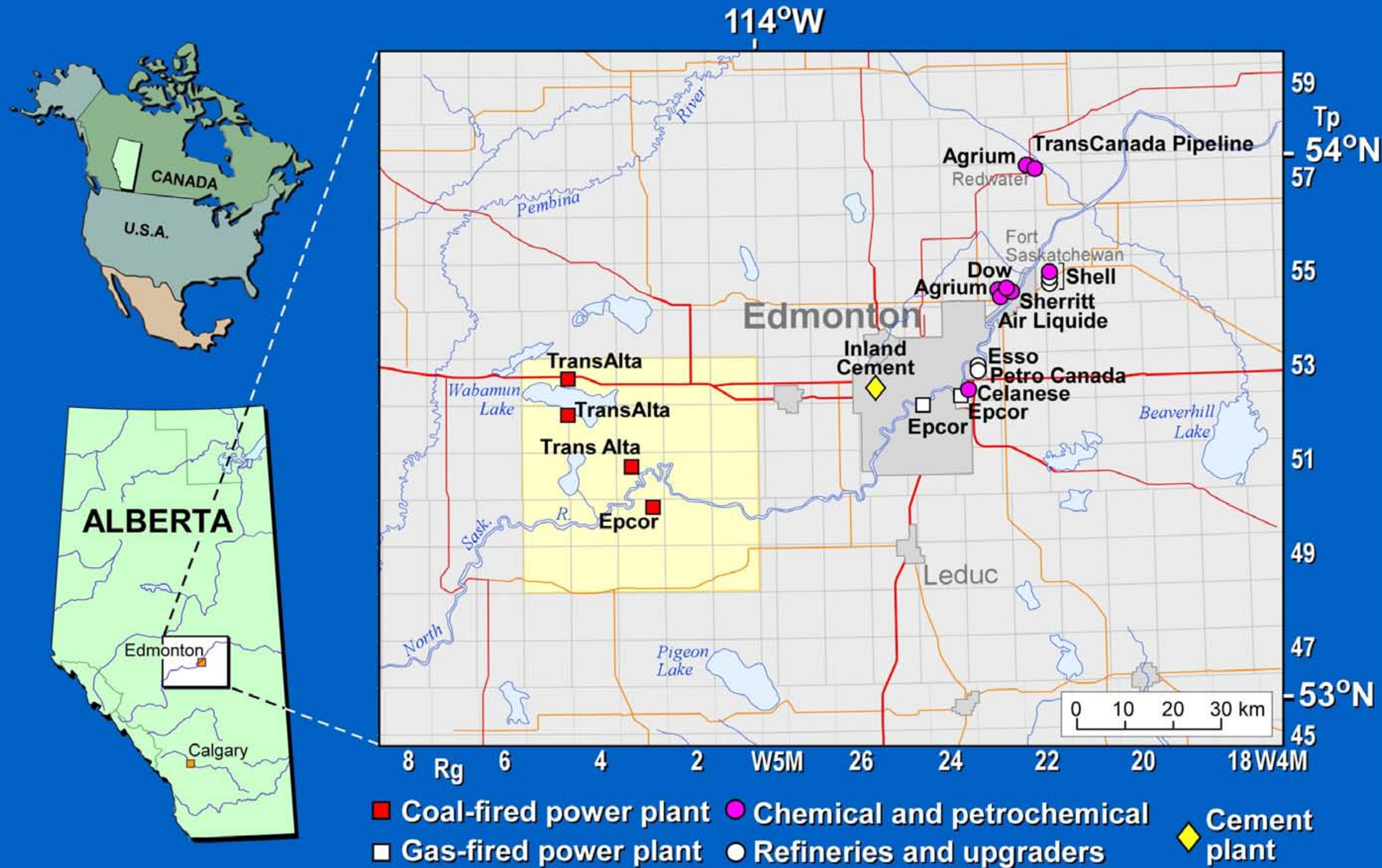
  6 m of cement ~1000 yrs

- Therefore, leakage is unlikely without some pre-existing annulus or crack

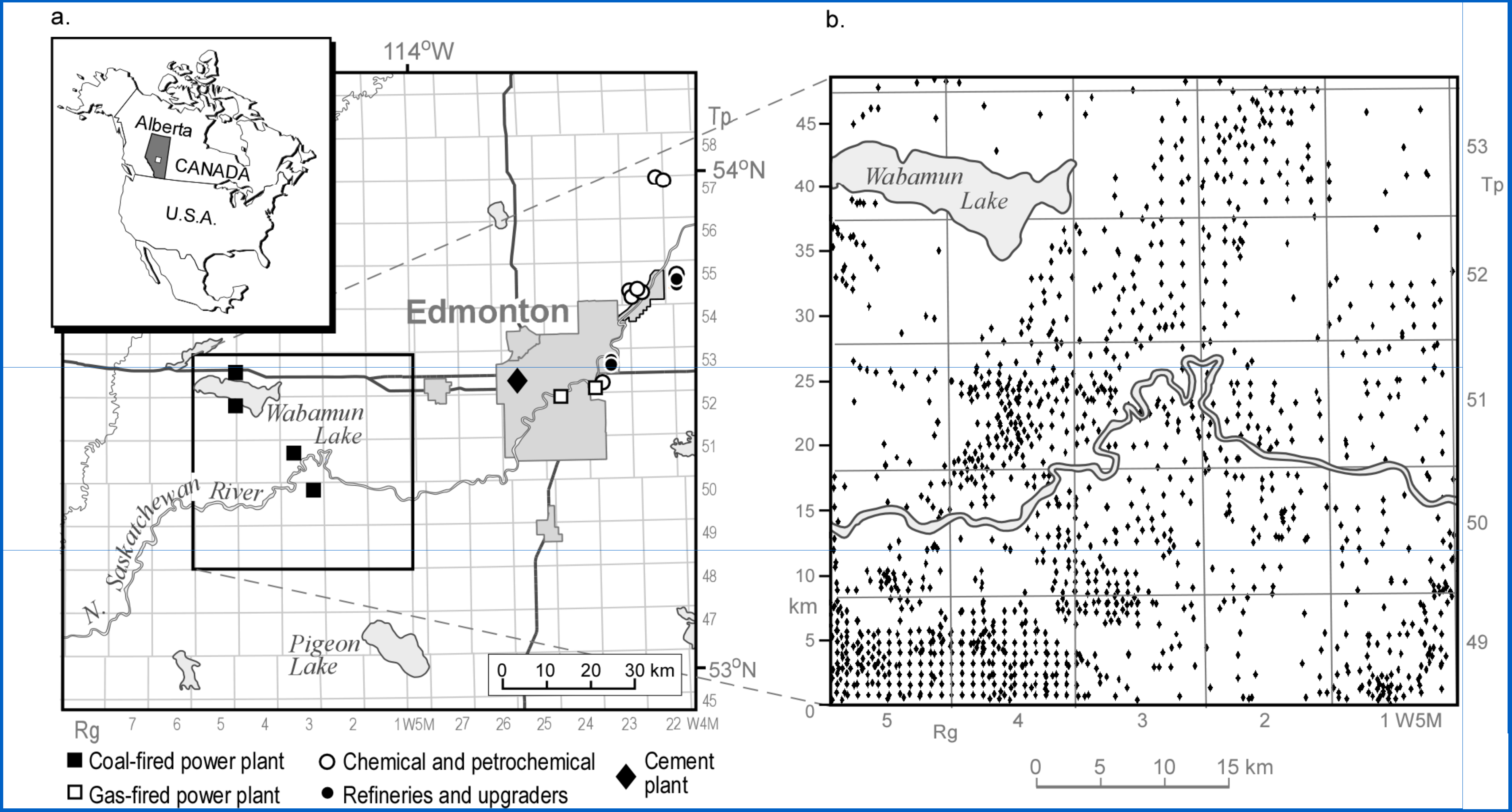


(From G. Scherer, Princeton University)

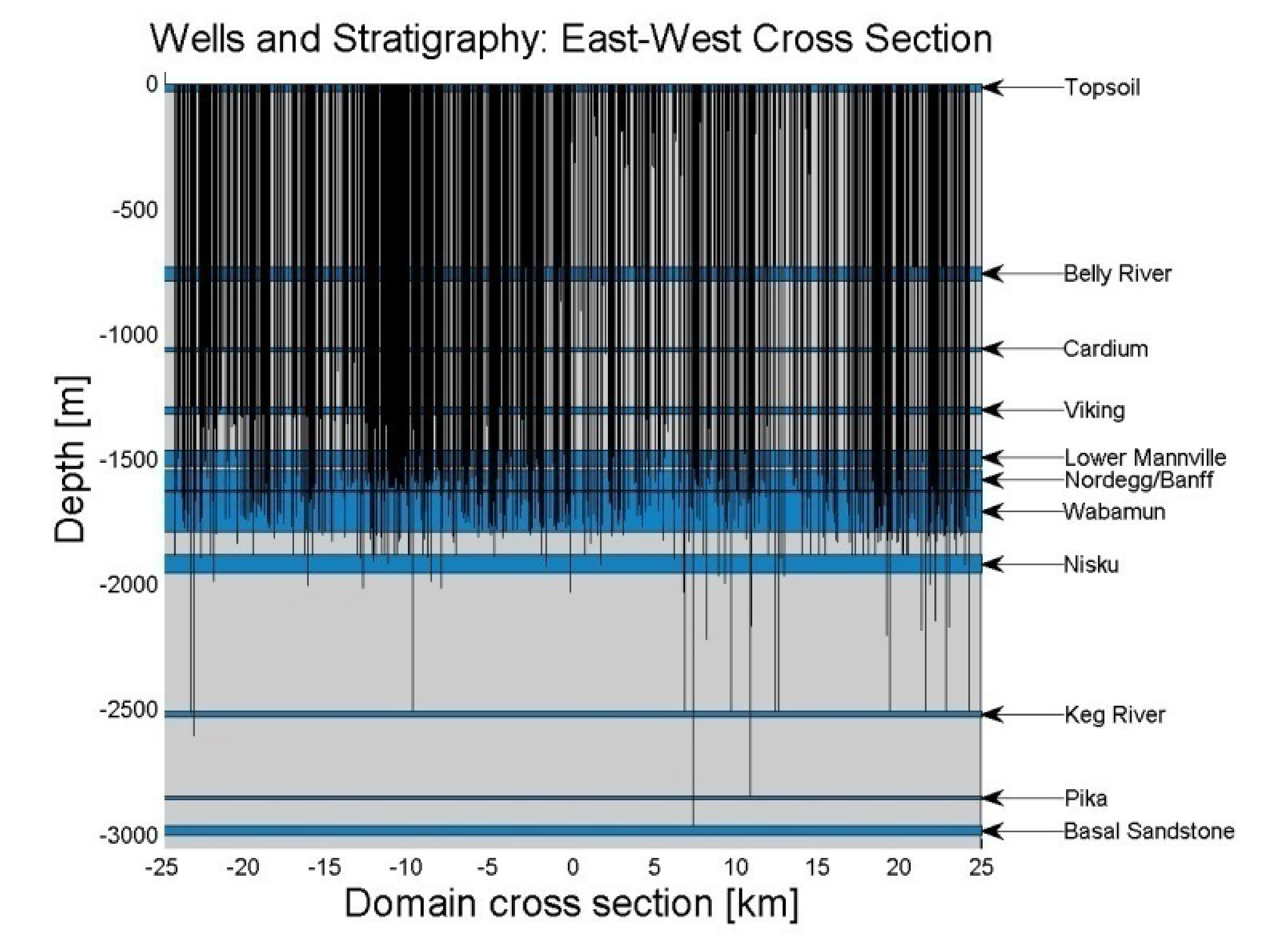
Location of Major CO_2 Sources in the Edmonton – Wabamun Lake Area



Wabamun Lake, Alberta

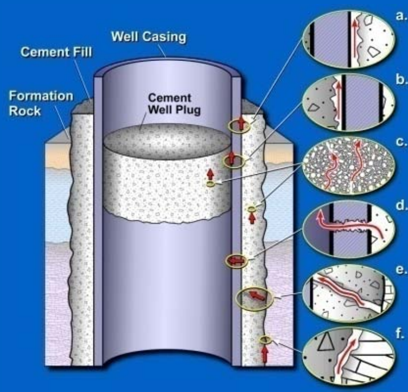


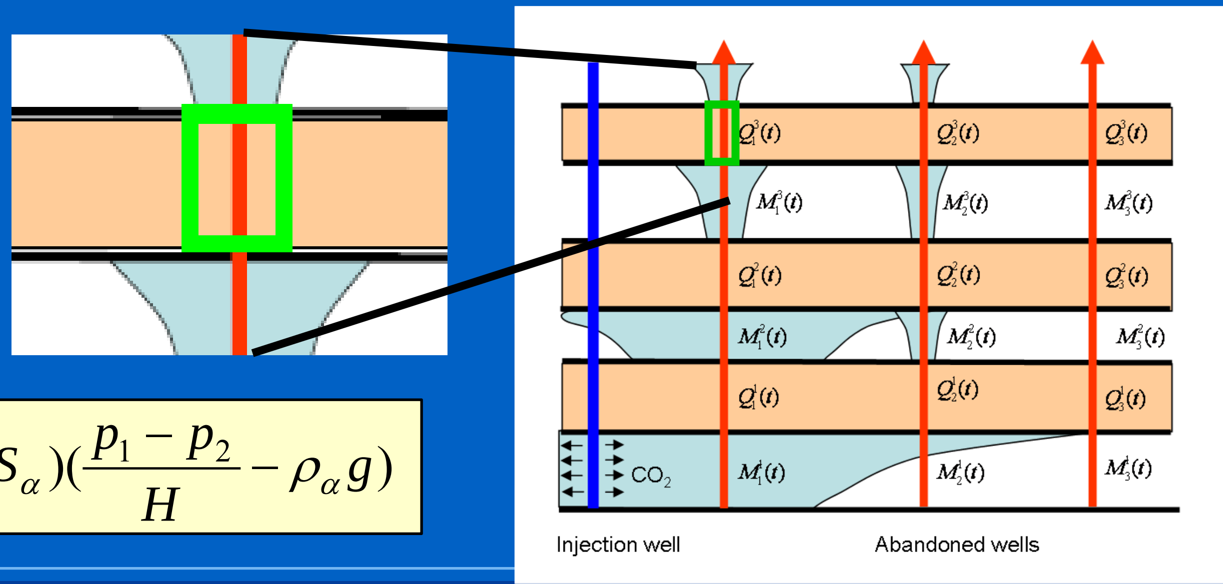
Wabamun Lake, Alberta



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 5 minutes.





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

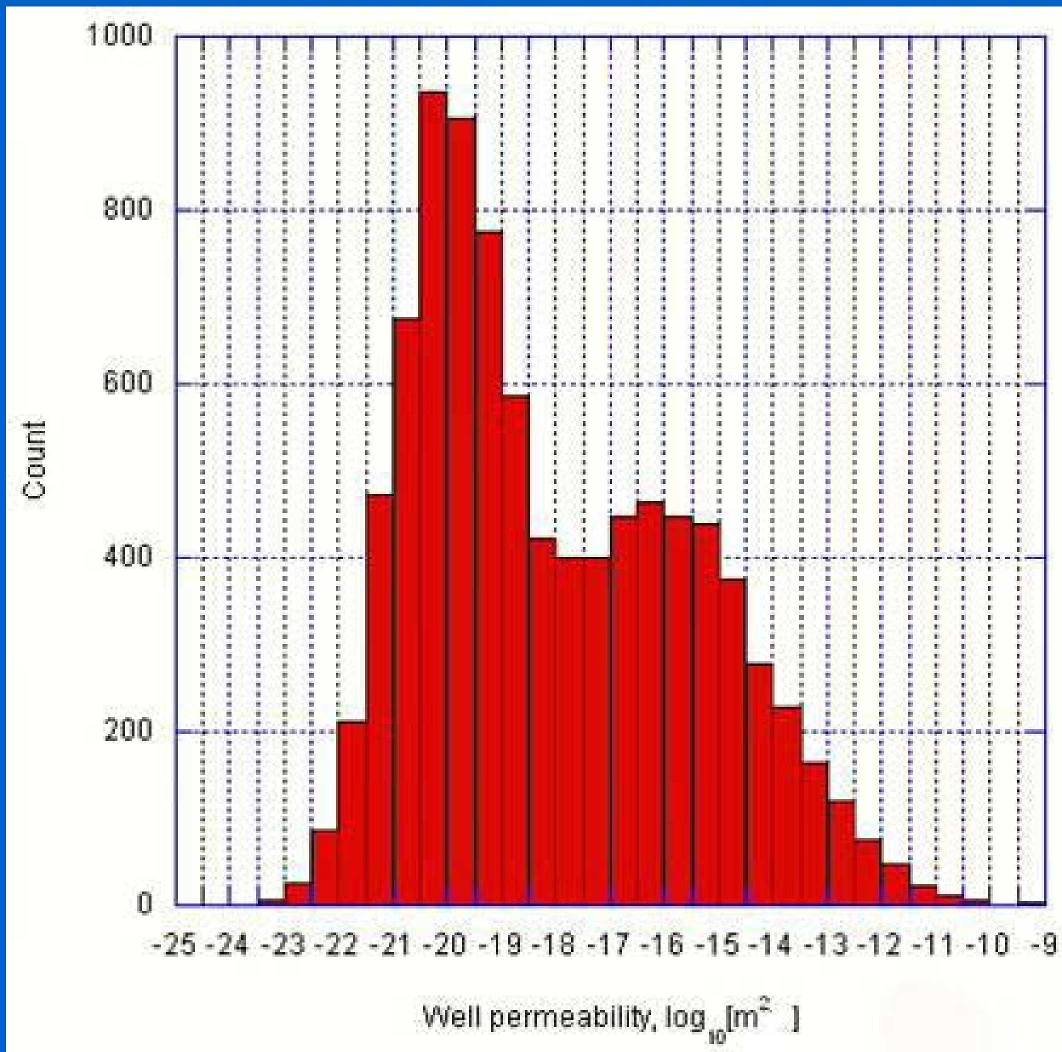
Injection Scenarios

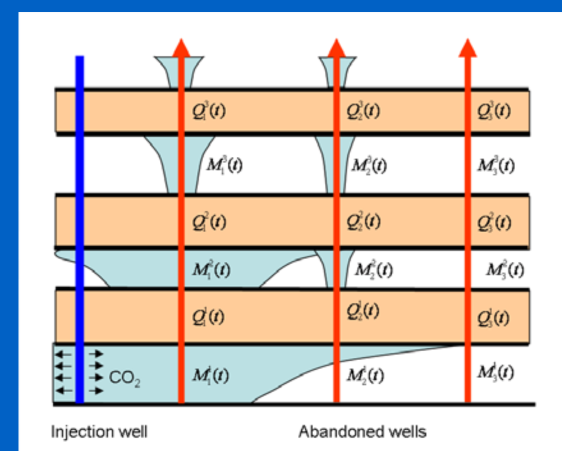
- One vertical injection well
  - Injects into only one formation
  - Injection at center of domain
  - Injection rate constant and constrained by fracture pressure
- All formation properties assigned deterministically
- Well properties are assigned stochastically
- Calculate leakage of CO_2 and Brine, and pressure evolution.

Effective Well Permeability

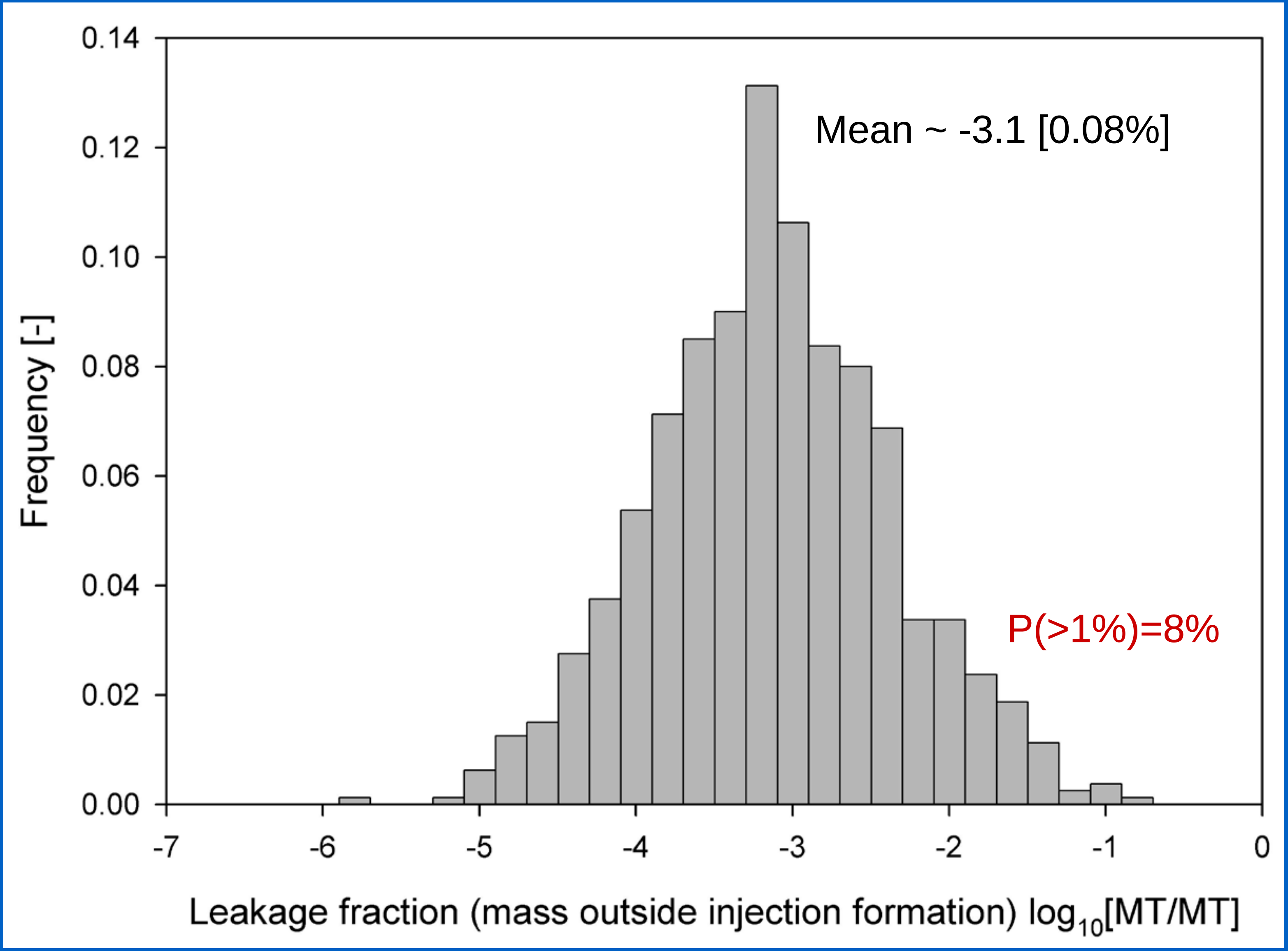
- Fully Random:
  - Bi-modal lognormal distribution
  - Vertical correlation structure
- Soft Data and Well Scoring System:
  - Watson and Bachu (2008) well scores
  - Conditional probability distribution
- Direct Measurements:
  - Approach of Gasda et al. (2008) and Crow et al. (2009, 2010)
  - Needs to be integrated into modeling framework

Probability Distribution for Well Permeabilities

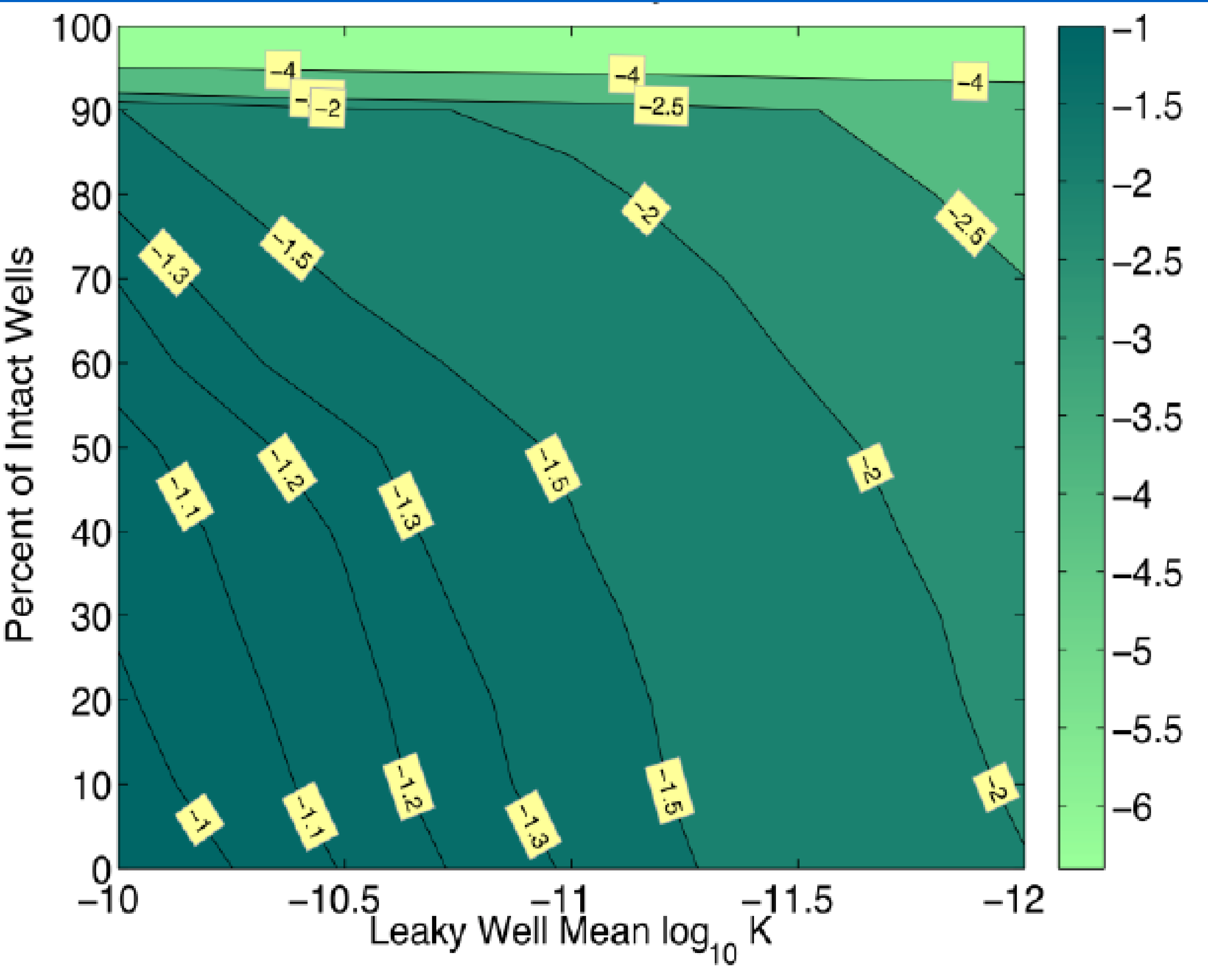




Leakage statistics after 50 years



Maximum Leakage at 95% Confidence

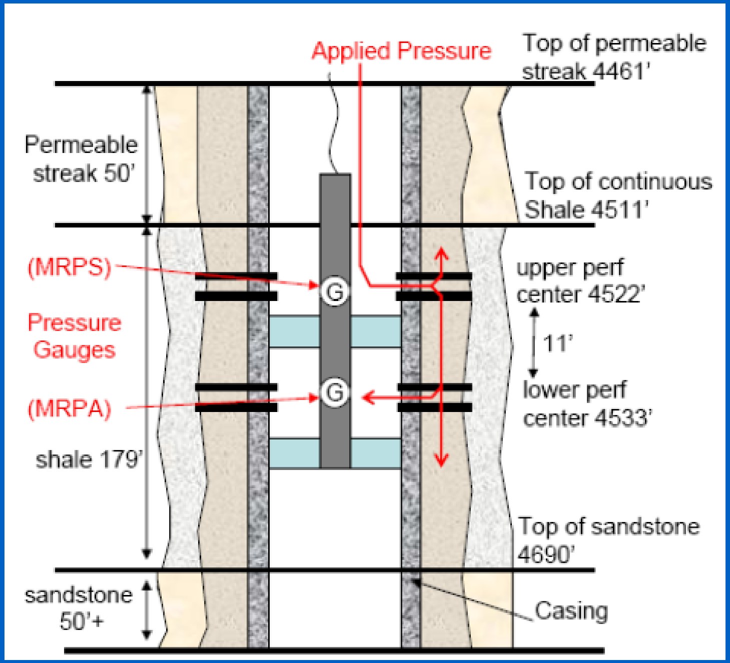


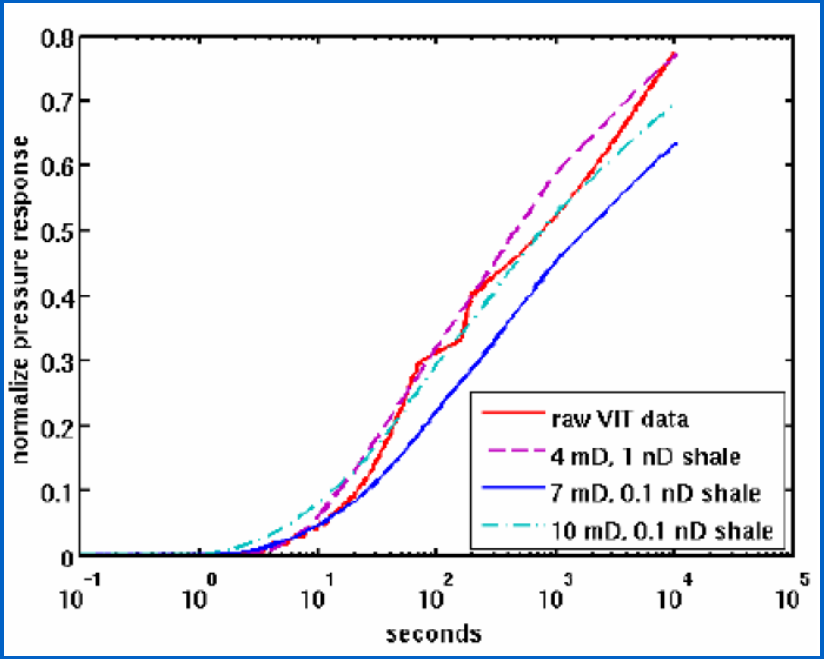
Borehole-scale Measurements

GHGT-9

Wellbore integrity analysis of a natural CO_2 producer

Walter Crow[a], D. Brian Williams[a], J. William Carey[b], Michael Celia[c], Sarah Gasda[d] *

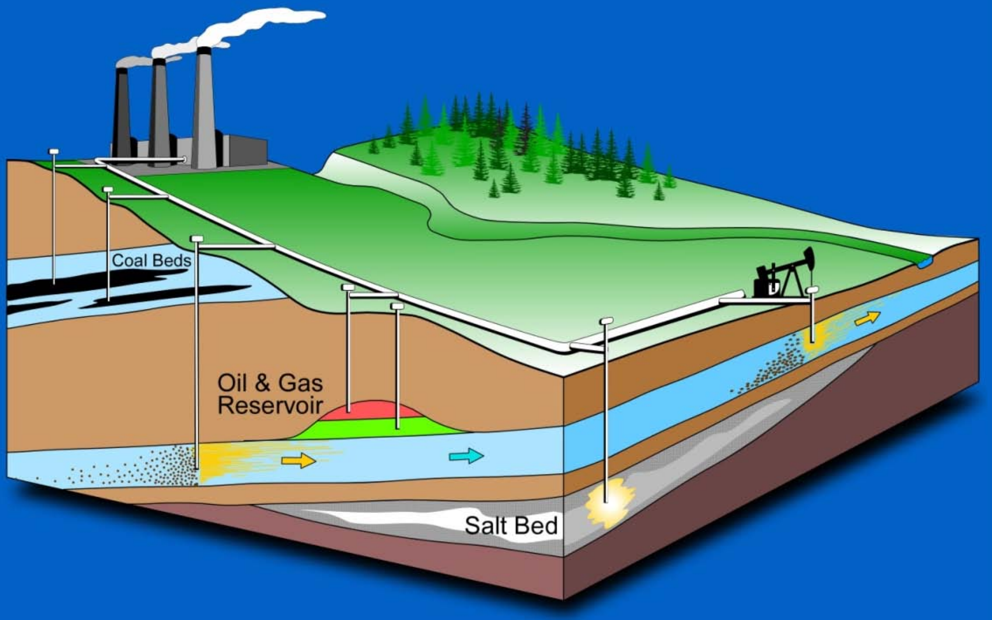




Concluding Remarks

- Risk of leakage along old wells must be quantified.
- Nontraditional models are needed to quantify leakage and risk.
- Practical issues include the fraction of otherwise good pore space that will not be used due to excessive risk.
- Systematic measurement program could greatly reduce uncertainties.

Thank You!



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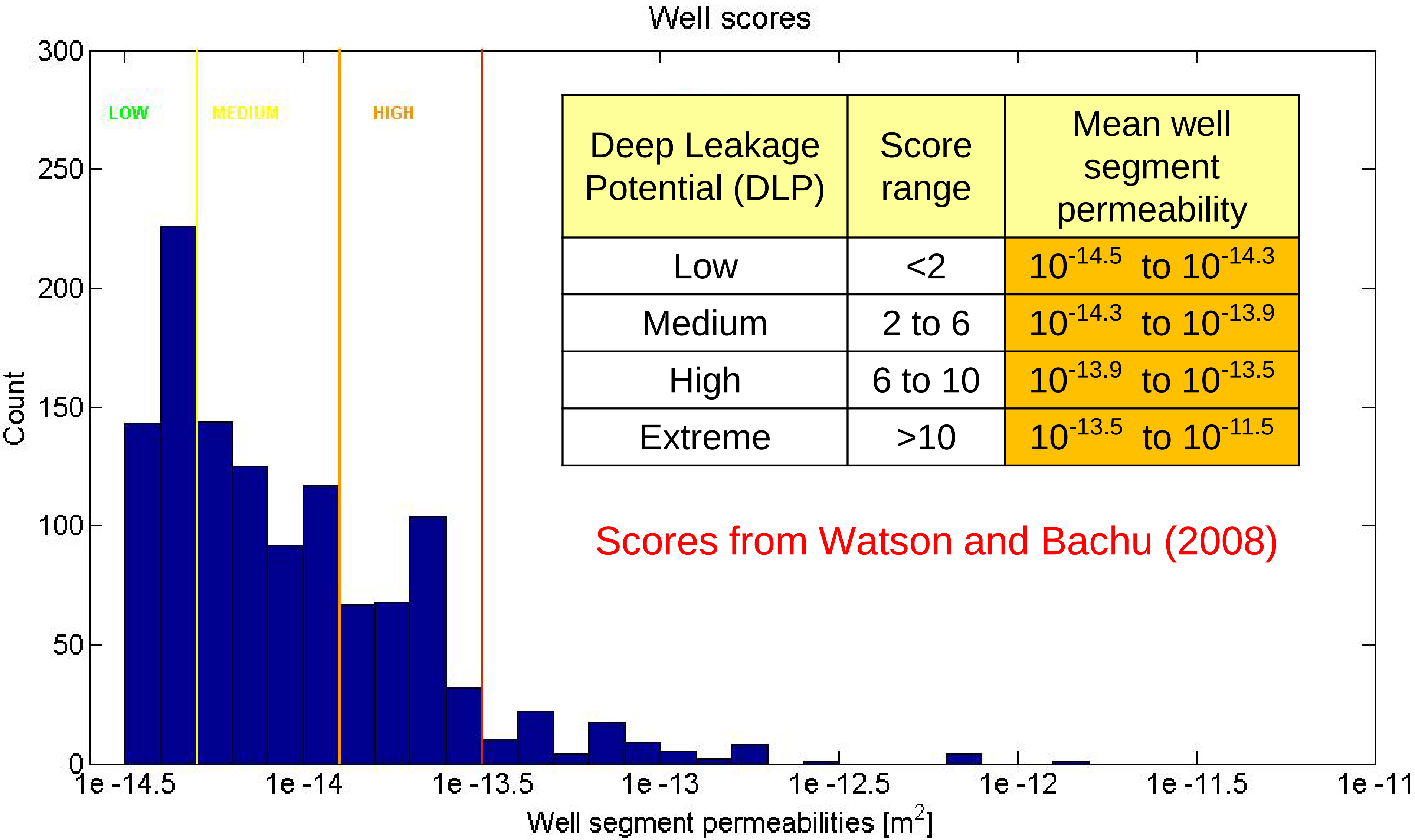
Soft Data and Well Scores



Deep Leakage Potential (DLP)	Score range	Mean well segment permeability
Low	<2	$10^{-14.5}$ to $10^{-14.3}$
Medium	2 to 6	$10^{-14.3}$ to $10^{-13.9}$
High	6 to 10	$10^{-13.9}$ to $10^{-13.5}$
Extreme	>10	$10^{-13.5}$ to $10^{-11.5}$

Scores from Watson and Bachu (2008)