Fourth Annual Conference on Carbon Capture & Sequestration

Developing Potential Paths Forward Based on the Knowledge, Science and Experience to Date

Geologic Sequestration

Numerical Approaches to Wellbore leakage and Fluid/Stress Interaction

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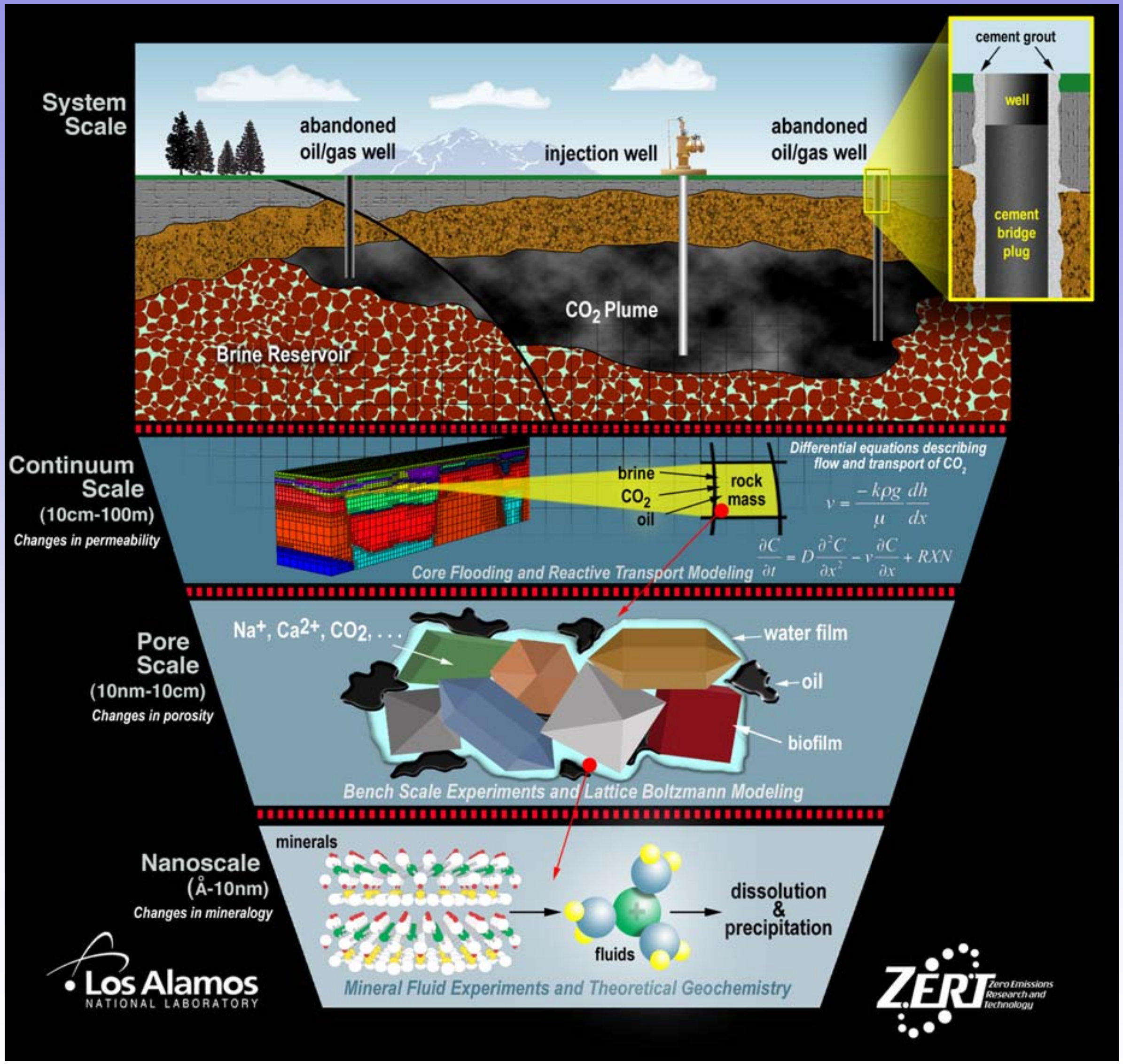
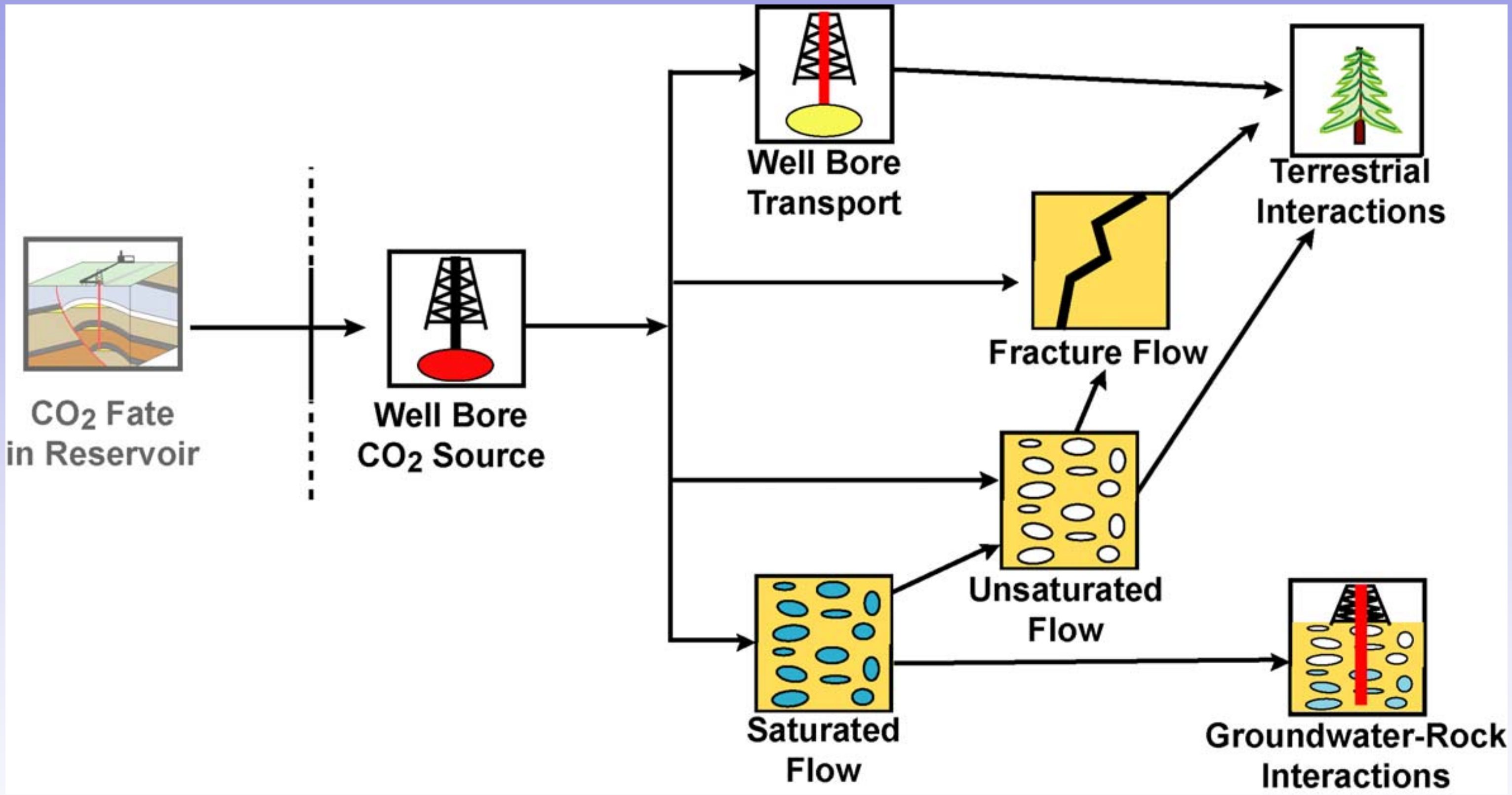
Overview of Contribution to ZERT

- Overall performance assessment framework for simulating geologic carbon dioxide sequestration
- Coupling systems models and process models
- Focus on possible release pathways of CO_2 from a borehole to the accessible environment

Systems and Process Level Models are being Integrated with Experimental and Field Observations



Framework: Borehole Critical Path



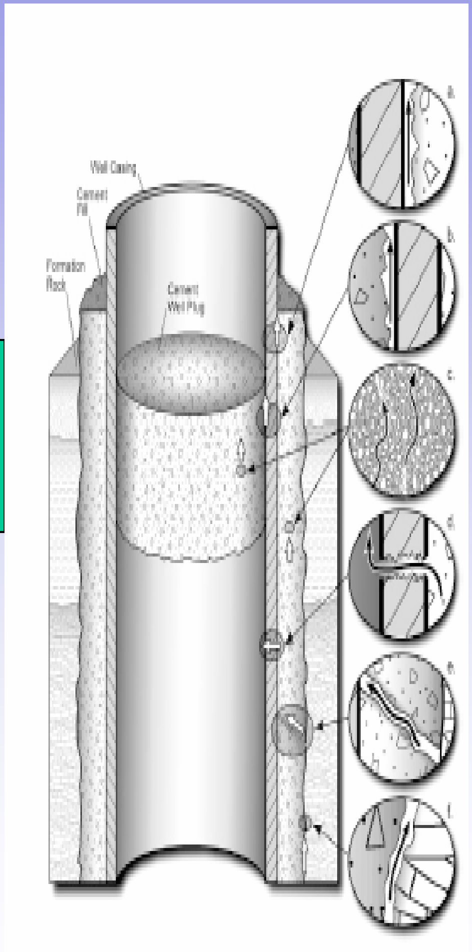
Along The Critical Path (outline of this talk)

- Wellbore Processes
  - Failure Mechanisms
  - Processes
  - Approach
- Coupled Fluid Stress
  - Stress Environment
  - Background, Computational Effort
  - LANL Simulation Model
- Validation is important (another talk)

Borehole Failure Scenarios

Wellbore Failure

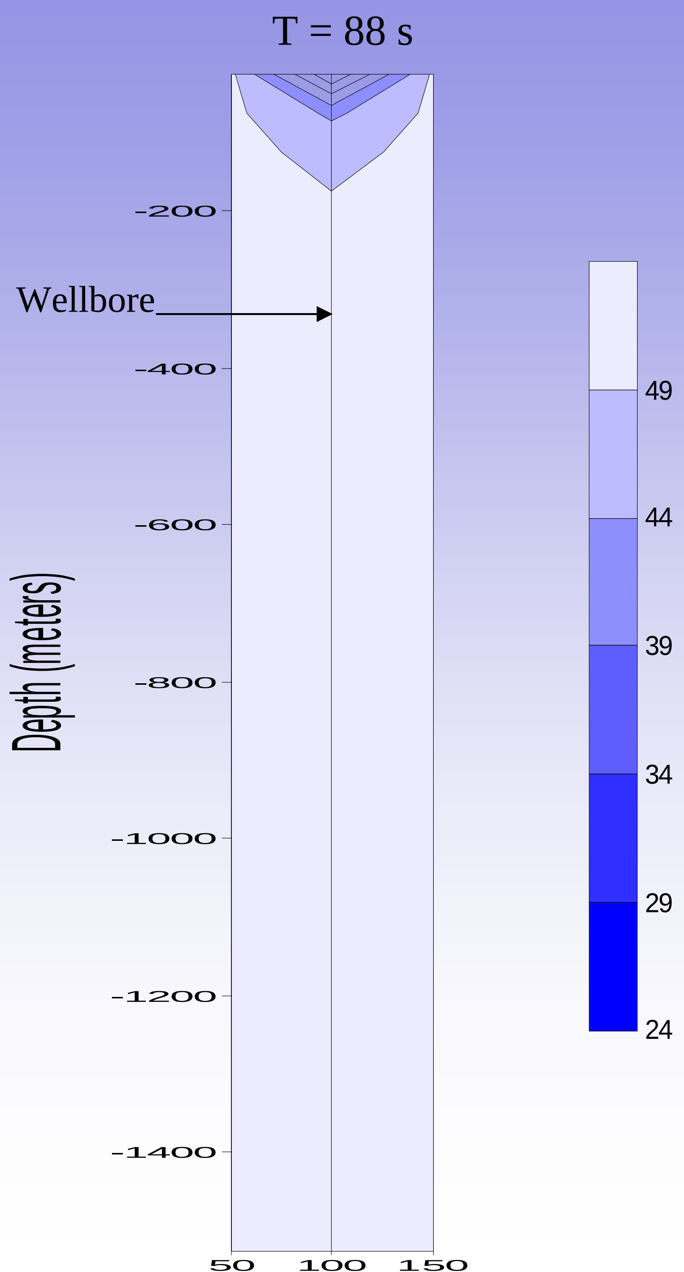
- Poor Well Completion
- * Mud zone
- * Mechanical Stress
- * Corrosion

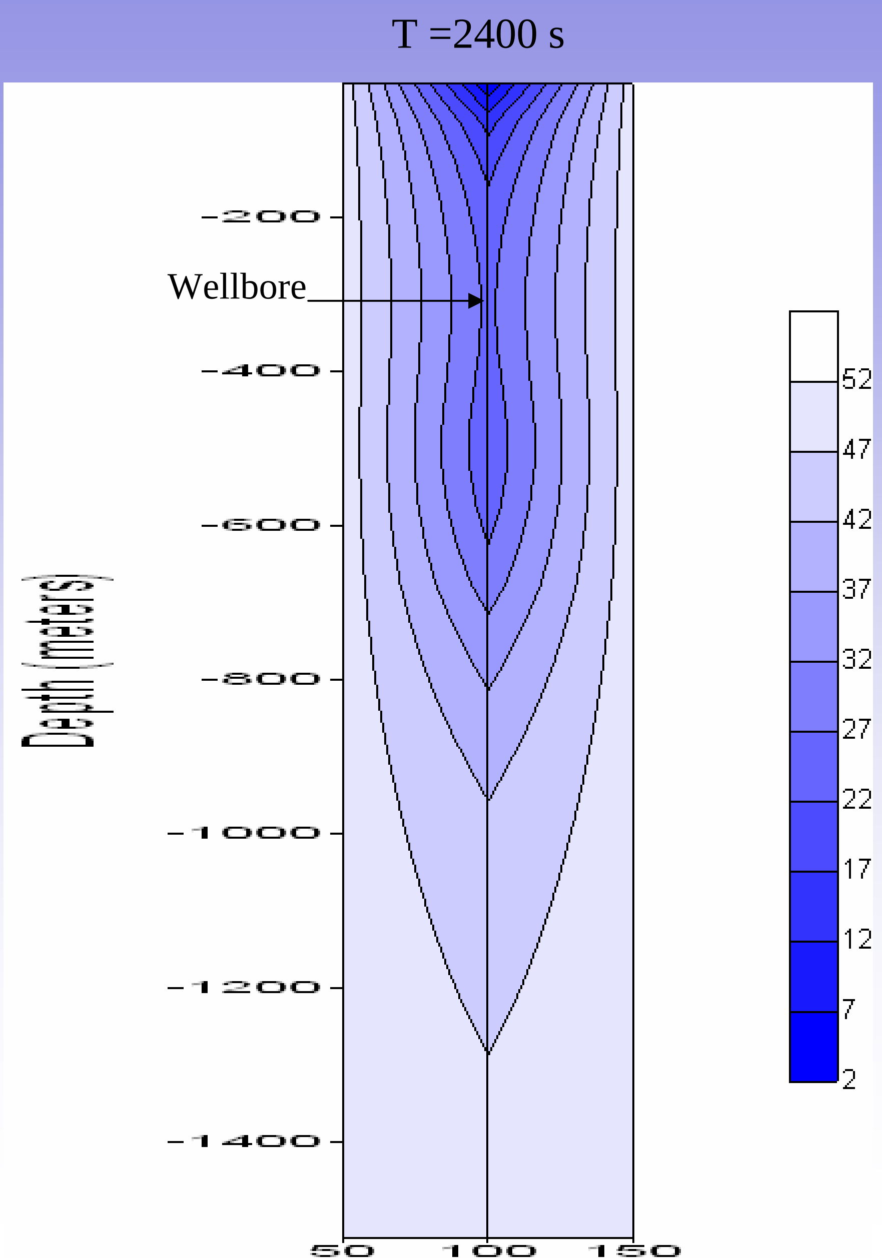


*SACROC field site, experiment and modeling studies address these

Nordbotten, J, M. Celia, S. Bachu, A. Dahle, Env. Science and Technology, pp. 602-611, 2005.

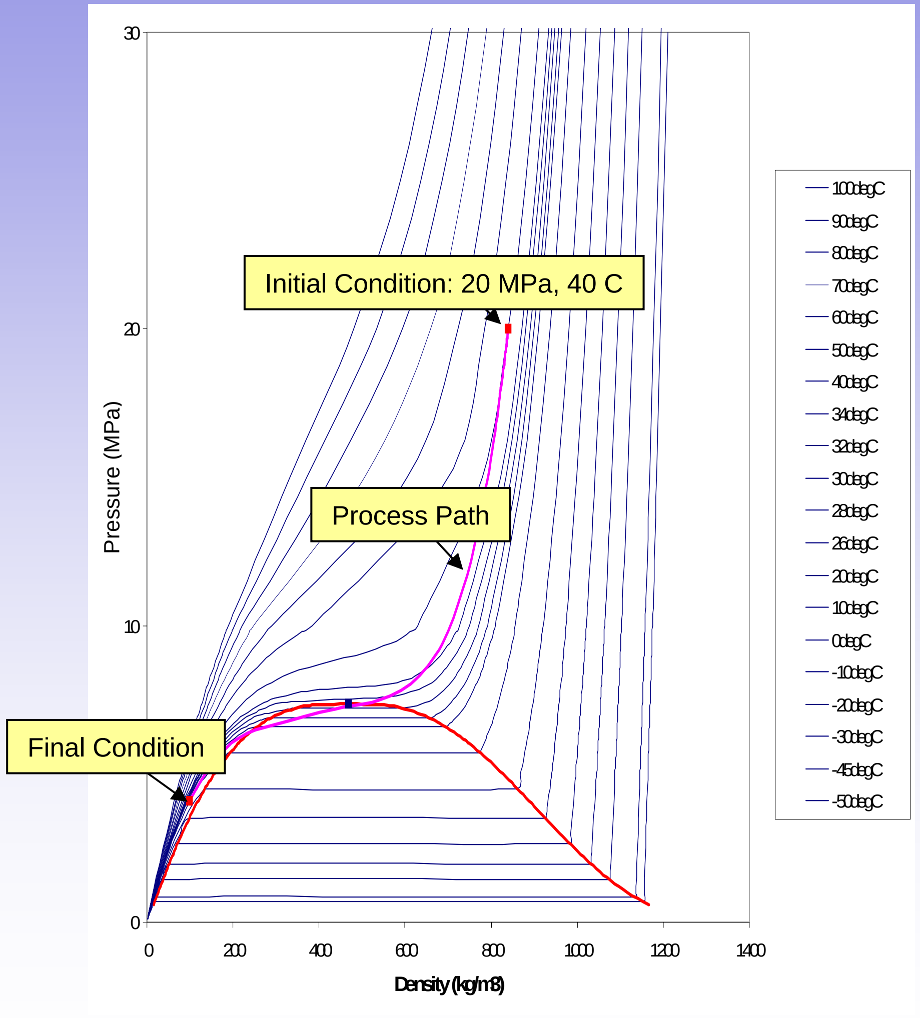
Temperature distribution in the reservoir





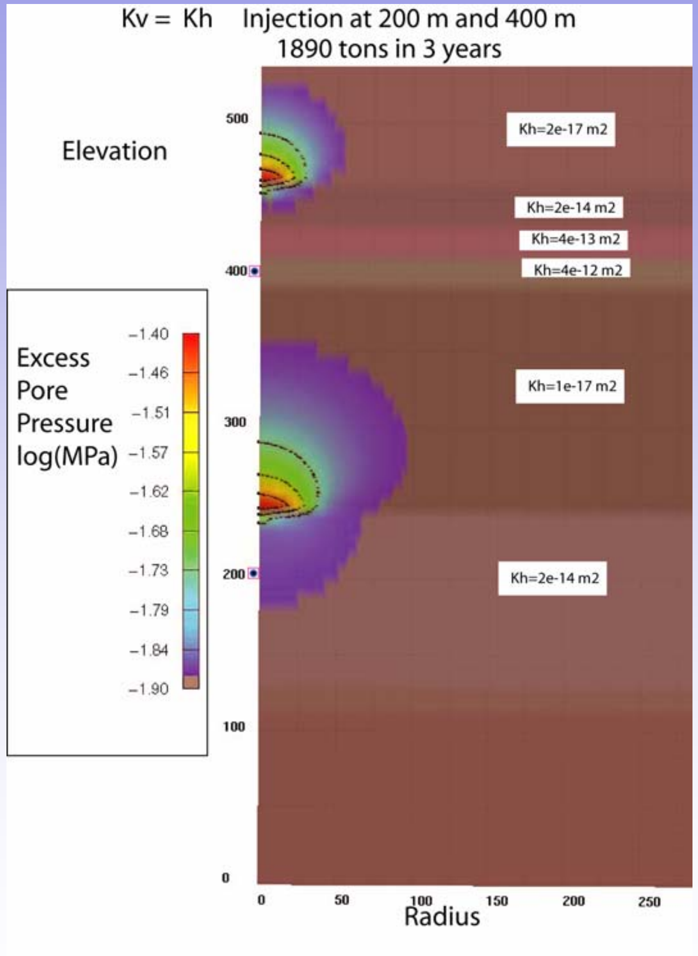
Wellbore processes

- Possible flow in wellbore and annulus
- Non-darcy multi-phase fluid behavior
- Coupled with formation heat and mass transfer
- Coupled with geochemical reactions
- Coupled with stress models



Range of environment for Geologic Sequestration

- Rocks
  - Carbonate, Basalt, Sandstone, Coal
- Fluids
  - Water, Brine, Gas, Hydrocarbons(?)
- Temperature
  - 10-100 C
- State of Stress
  - Lithostatic + Shear (1-20 Mpa)



Background on Coupled Fluid Stress Codes

- Technology used by
  - Oil Industry (North Sea)
  - Geothermal
  - Hot Dry Rock
- Finite Element Based Codes
  - Good for Stress
  - Poor for flow (nonlinear)
- Explicit (Sequential Coupling)
  - Coupling is very strong between equations
  - Restricted to small time steps
- Joint or aperture behavior
  - Barton and Bandis (1983-1985)
  - Olsson and Barton (2001)
- Account for changes in:
  - Permeability
  - Fluid Storage
- Explicit fracture representation is common
- Linear Elasticity

A Large Computational Effort

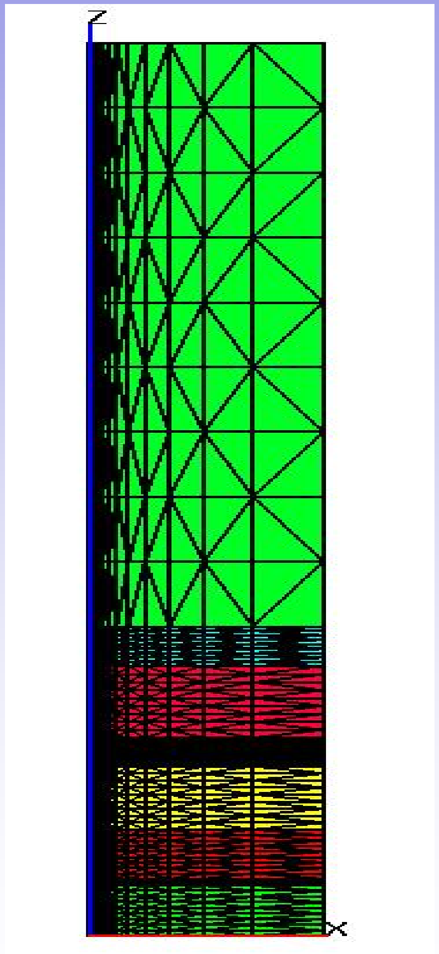
- Conservation Equations
  - Conservation of Water (brine would add another Eq)
  - Conservation of CO_2
  - Conservation of Energy
  - Stress Equations (3)
- Coupled reactive transport
- Material type
  - Continuum representation
  - Fracture networks

Puzzle Pieces

- Generalized Double Porosity
  - Sub-grid scale behavior on large grids
  - 1-D decomposition algorithms make this fast
  - “Generalization” means spatially dependent resolution
- Combined Control Volume Finite Element and Finite Element
- Reduced Degree of Freedom Algorithms (RDOF)

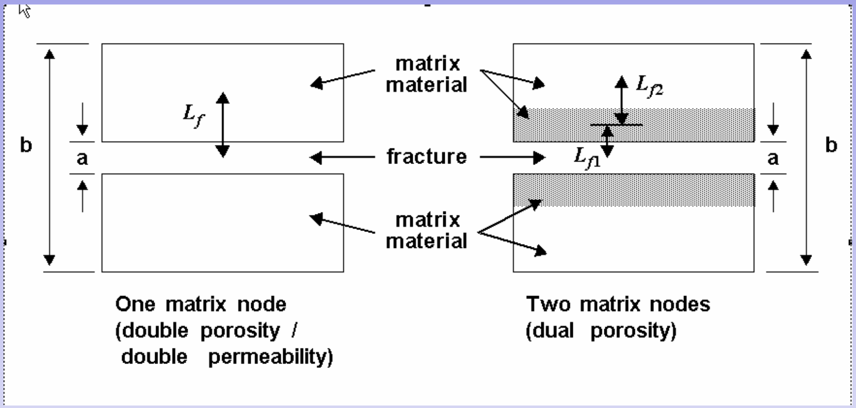
Finite Volume and Finite Elements

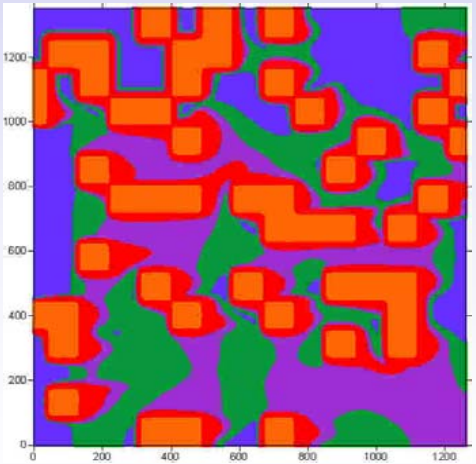
- Finite Volume for Flow and Reactive Transport
  - Works well for nonlinear problems (separation of fluid and geometric properties, upwinding)
- Finite Elements for Stress Equations
  - FE shape functions allow for xy terms and shear stress
- FEHM grid technology (can generate both FV and FE coefficients)



Generalized Double Porosity

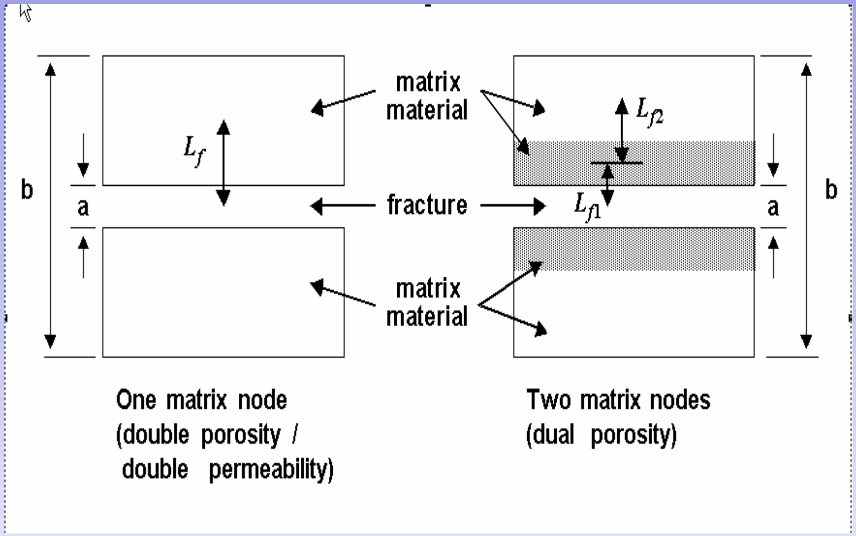
- Global connection through fracture or primary nodes
- Local communication and storage thought matrix material
- Multiple nodes are necessary in matrix to model gradients





Stress and GDPM

- Stress equations operate on the full continuum block
- Stress-fracture aperture-permeability data from the laboratory work is used to modify the double porosity parameters
- Block sizes are large (no explicit fractures)



Reduced degree of freedom

- Motivation
  - In coupled process simulations, one process, usually flow, dominates. Other processes, such as heat transfer occur at slower time scales
  - Nonlinear phenomena, such as phase changes, are often local by nature, comprising only a small percentage of the total gridblocks.
- Computations
  - Eliminate ‘passive’ degrees of freedom
  - Reorder linear system based on convergence of nonlinear problem

	Fully Implicit	RDOF-Solver	RDOF-NR
	Equivalent Continuum		
ILU(1)[1]	9 x NC x N¶	NC x N	NC x N
ILU(2)[2]	9 x 1.4 x NC x N†	1.4 x NC x N	1.4 x NC x N
GMRES	3 x (NR + 1) x N‡	3 x (NR + 1) x N	(NR + 1) x N
	Dual-Permeability		
ILU(1)	36 x NC x N¶	4 x NC x N	4 x NC x N
ILU(2)	36 x 1.4 x NC x N†	4 x 1.4 x NC x N	4 x 1.4 x NC x N
GMRES	6 x (NR + 1) x N‡	6 x (NR + 1) x N	2 x (NR + 1) x N

Note:

•Same equations are solved as in the fully implicit method

•Simplification is in the solver

The Approach

- Generate all conservation equations (Newton-Raphson
- Generate the GDPM equations (spatially variable)
- Pre-solve the GDPM equations
- Reduce the degree of freedom (RDOF)
- Solve the linear system of equations (Preconditioned Krylov space methods
- Back-solve the RDOF equations
- Back-solve the GDPM equations

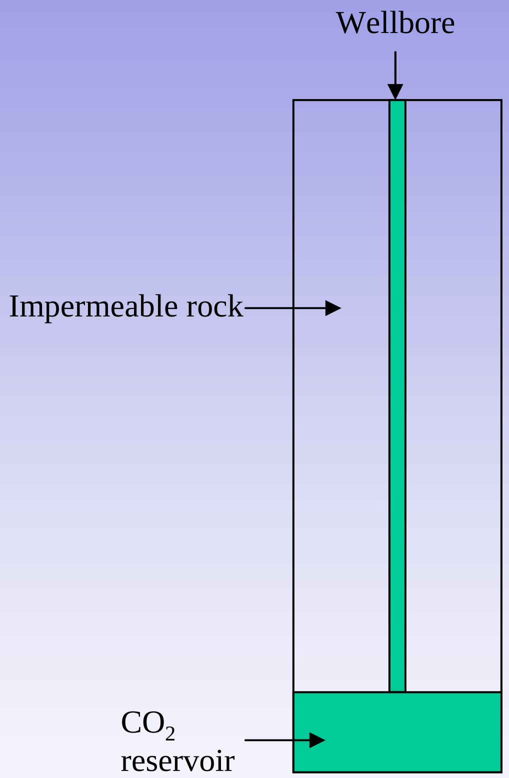
Advantages

- GDPM, RDOF can be space and time dependent
- Same grid for flow, transport, stress simulations
- Easy testing of different pore pressure models
- Simple incorporation into the GoldSim framework

LANL Approach THM

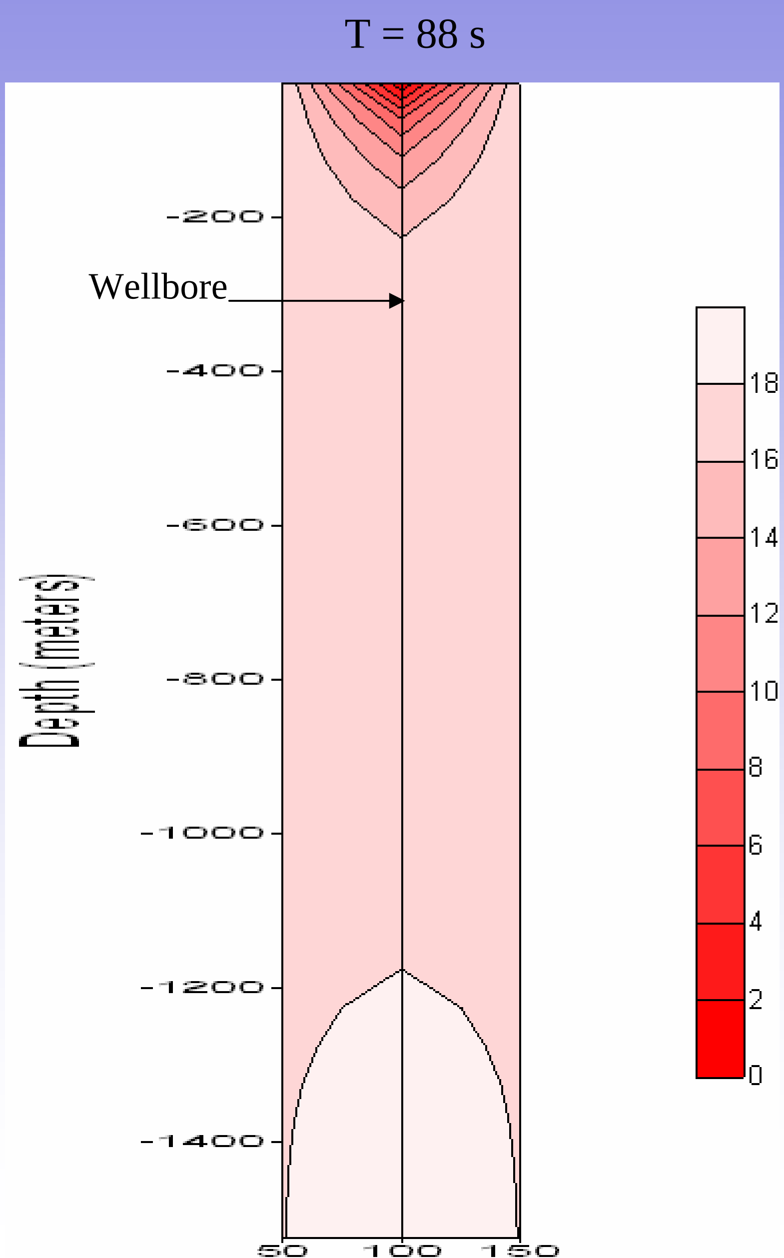
- Tseng, P. H., and **G. A. Zyvoloski**, A Reduced Degree of Freedom Method for Simulating Non-isothermal Multi-phase Flow in Porous Medium, *Advances in Water Resources*, Vol. 23, pp 731-745, 2000.
- Bower, K. M., and **G. Zyvoloski**, A Numerical Model for Thermo-Hydro-mechanical Coupling in Fractured Rock, *Int. J. Rock Mech. Min. Sci.*, Vol. 34, No. 8., pp. 1201-1211, 1997.

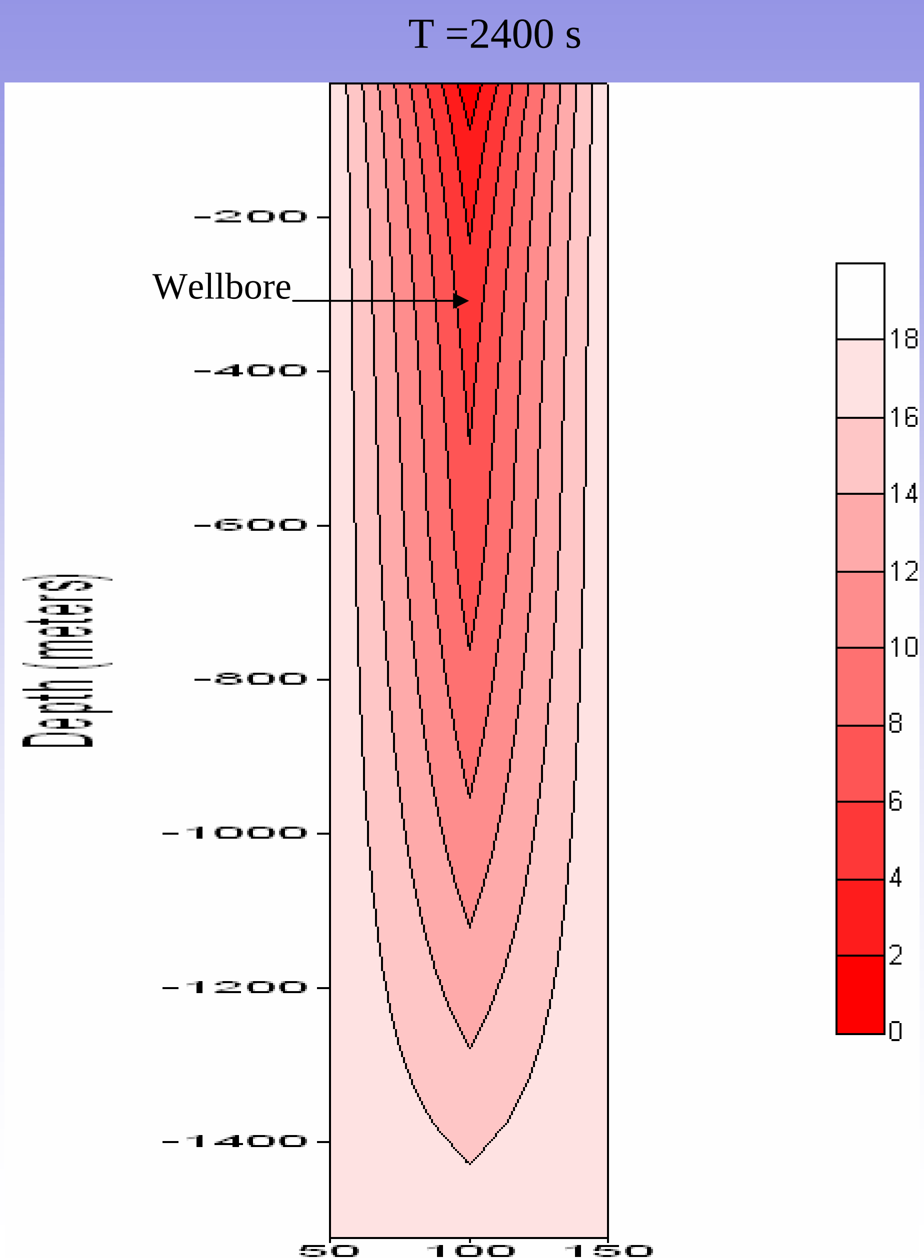
Leakage through wellbore



Two-dimensional grid 3 x 1 x31 (x,y,z)
Well bore blocks : 0.1 m x 0.1 m x 50 m (x, y, z)
Impermeable rock: 100 m x 0.1 m x 50 m (x, y, z)
Reservoir rock: 100 m x 0.1 m x 50 m (x, y, z)
Well bore porosity : 0.4
Reservoir rock porosity : 0.2
Impermeable rock porosity : 0.0
Well bore permeability : 10^{-9} m^2
Reservoir rock permeability : 10^{-12} m^2
Initial Pressure : 17 MPa
Initial Temperature : 50 °C

Pressure distribution in the reservoir





CO_2 Phases in the wellbore