ical-Numerical Sharp-Interface Model of CO2 Sequestration & Application to Illinois Basin: DE-FOA0000023-02

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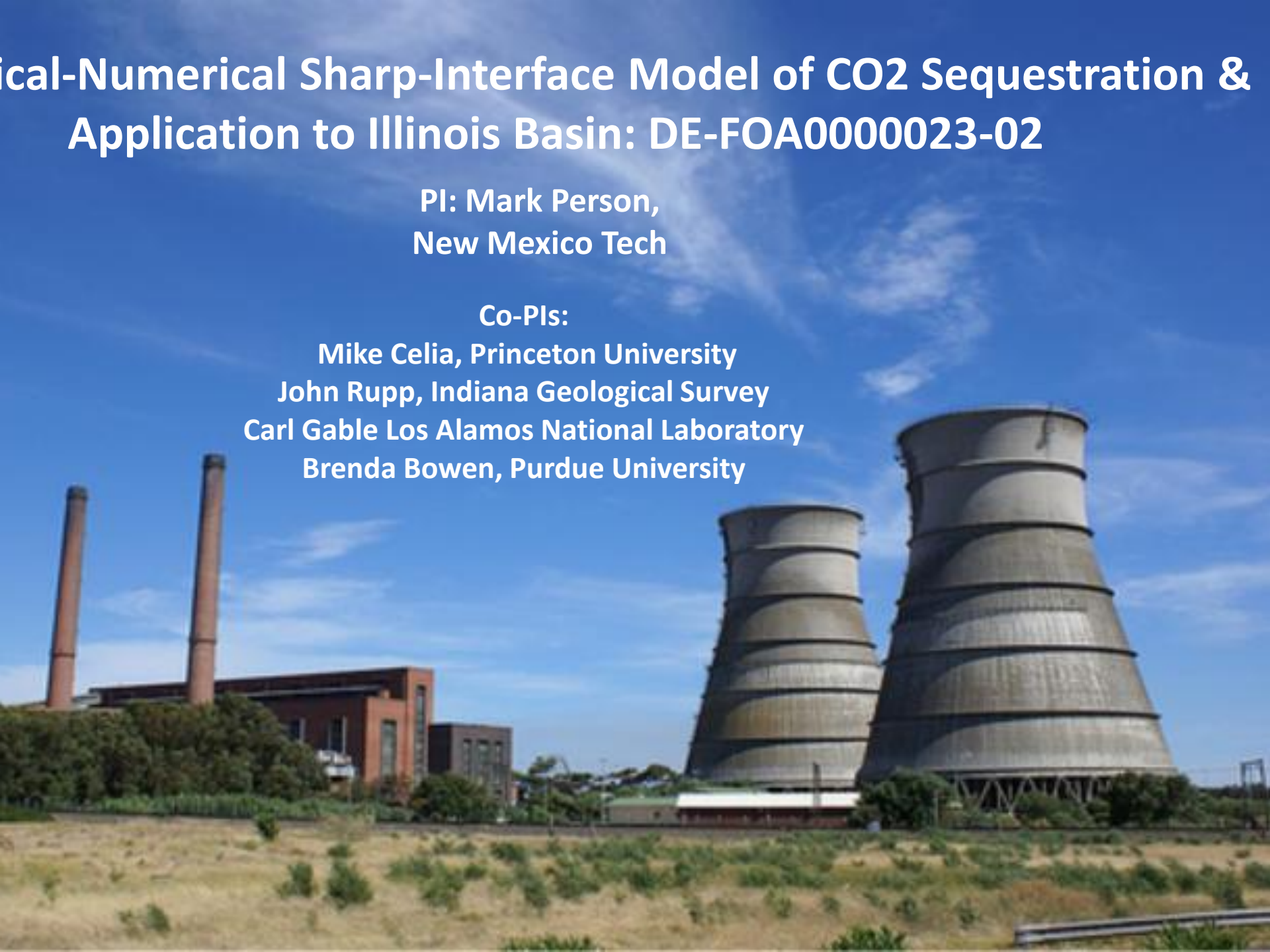


Project Questions:

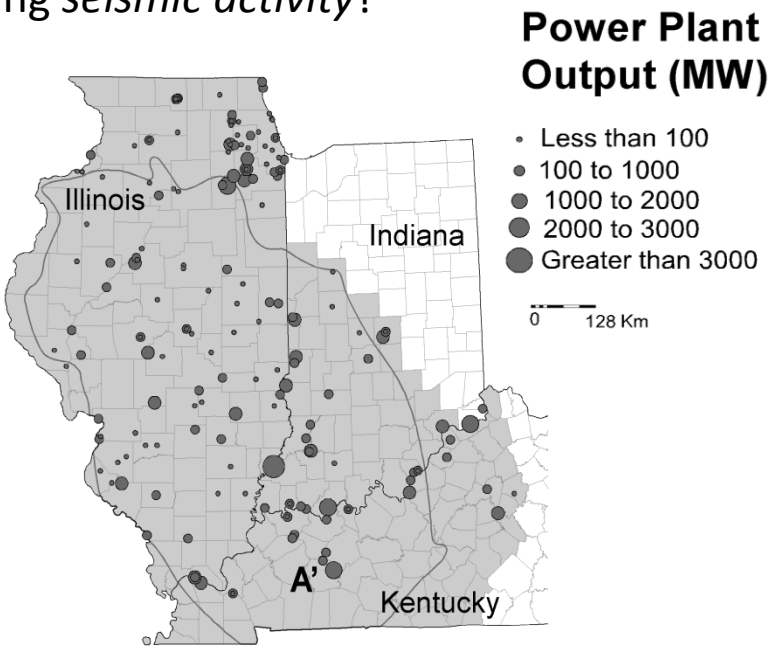
What are *the hydrologic consequences* of injecting 80 million metric tons of CO_2 back into the Illinois Basin annually?

Will large *pressure anomalies* associated with CO_2 injection propagate across the Illinois basin?

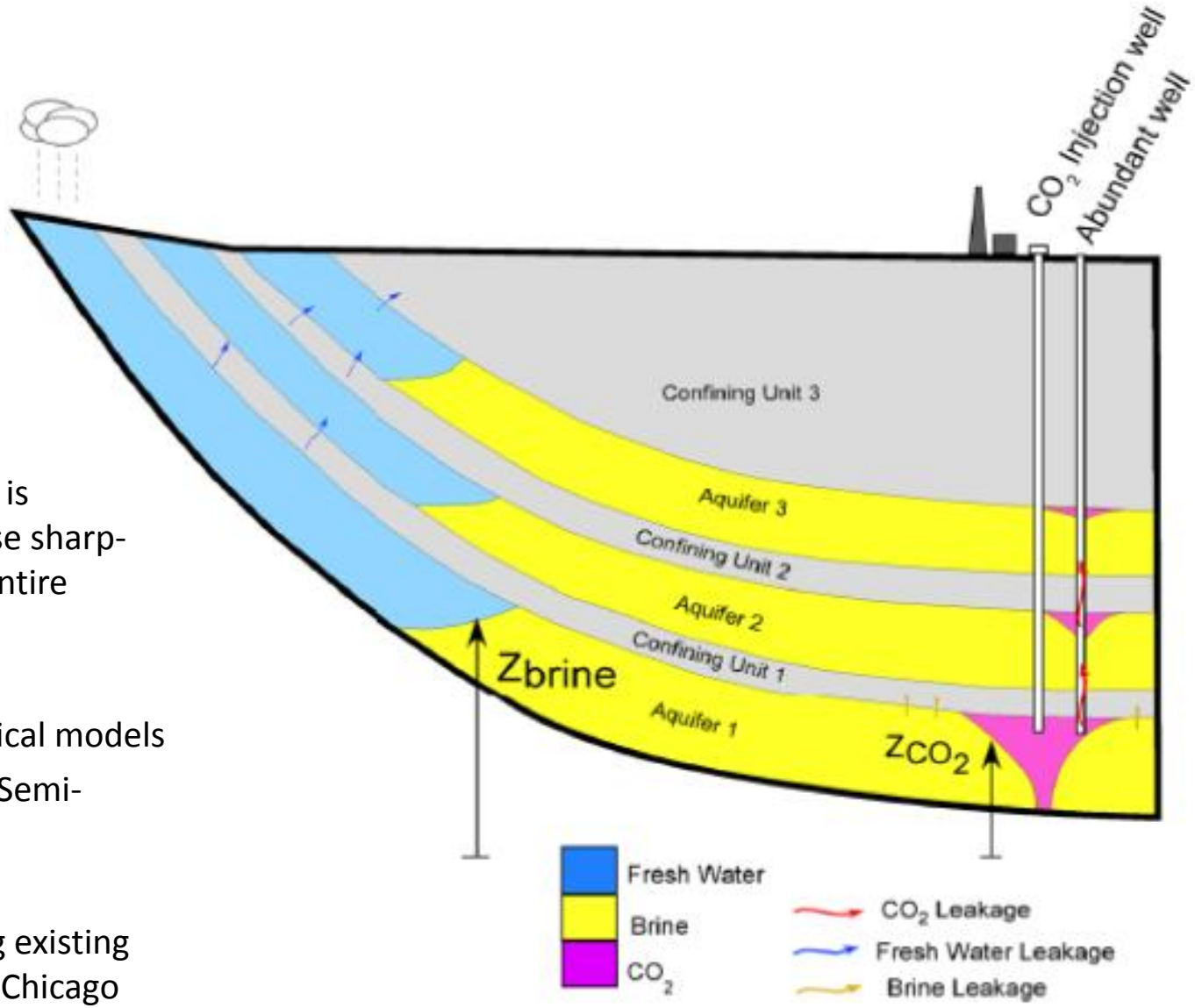
Will significant *well-well interference* occur within- or between- injection well centers?

Are there *optimal regions* of the basin that would likely *minimize pore pressure generation* and the potential for generating *seismic activity*?

Does CO_2 injection result in *significant displacement of brines* towards the margins of the basin to the North where the Mt Simon is exploited as a water resource?



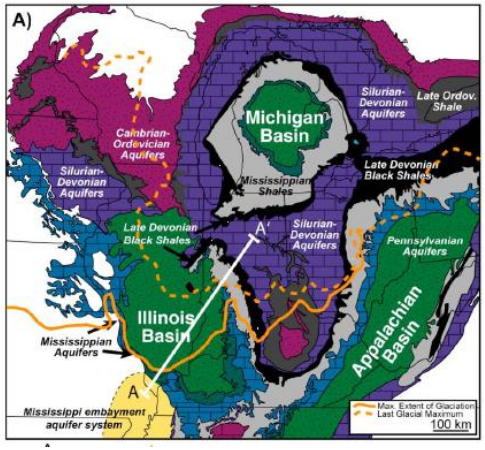
Basin-Scale, Three-Dimensional, Hybrid, Sharp-Interface Model

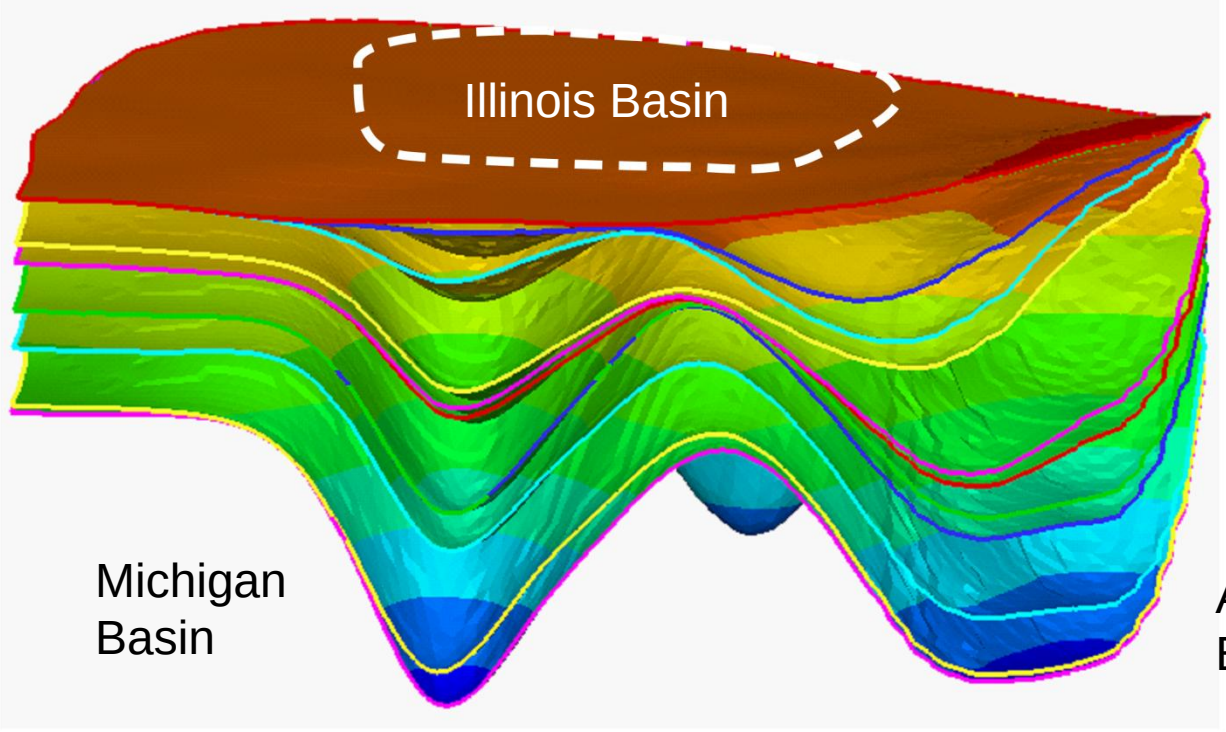


- Mike Celia (Princeton) is Developing 3D, 3-phase sharp-interface models for entire Illinois Basin
- Mt. Simon: full numerical models
  Overlying Reservoirs: Semi-analytical
- Calibrate models using existing head patterns around Chicago and salinity conditions

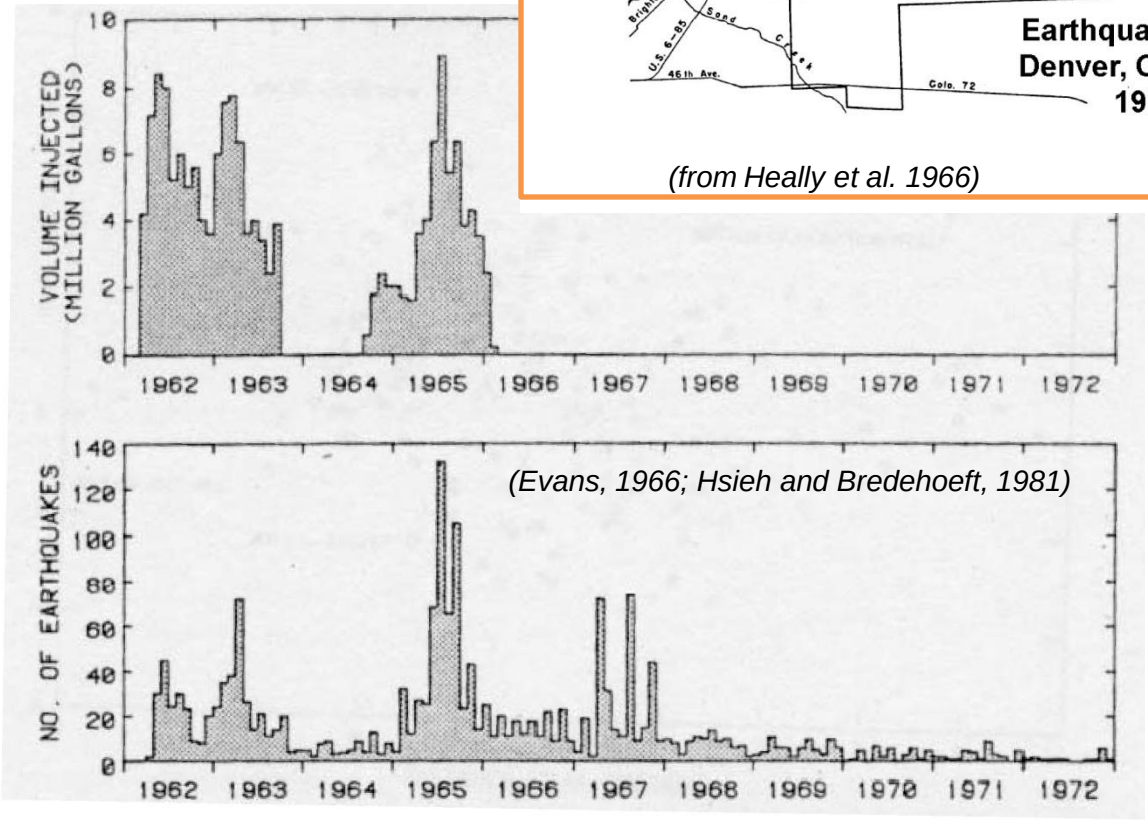
Illinois Basin Hydrostratigraphy

Stratigraphic units
Pennsylvanian
Upper Mississippian
Lower Mississippian
Upper Devonian
Middle Devonian
Upper Silurian
Lower Silurian
Upper Ordovician
Lower Ordovician
Eau Claire
Mt. Simon

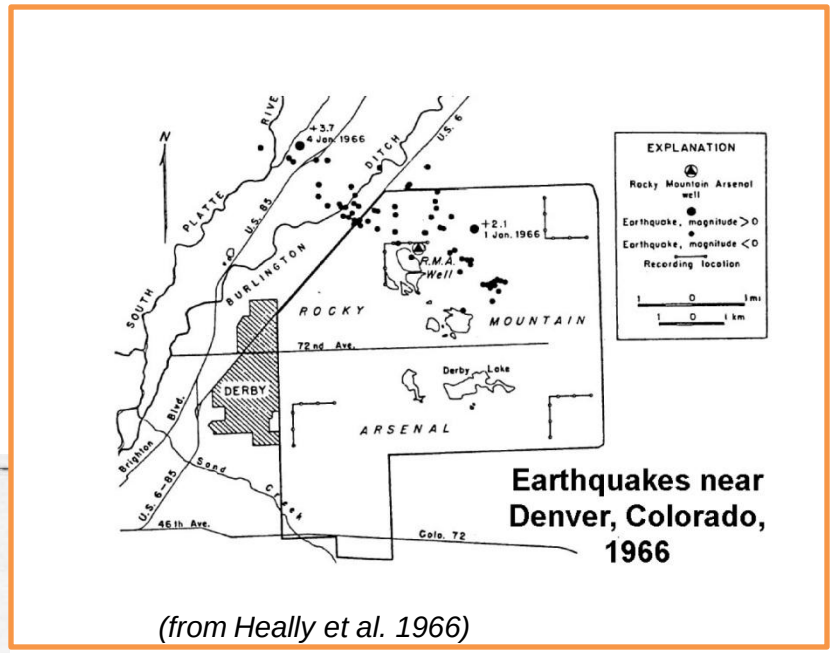




Induced Seismicity from Hazardous Waste Injection Denver Colorado, 1966

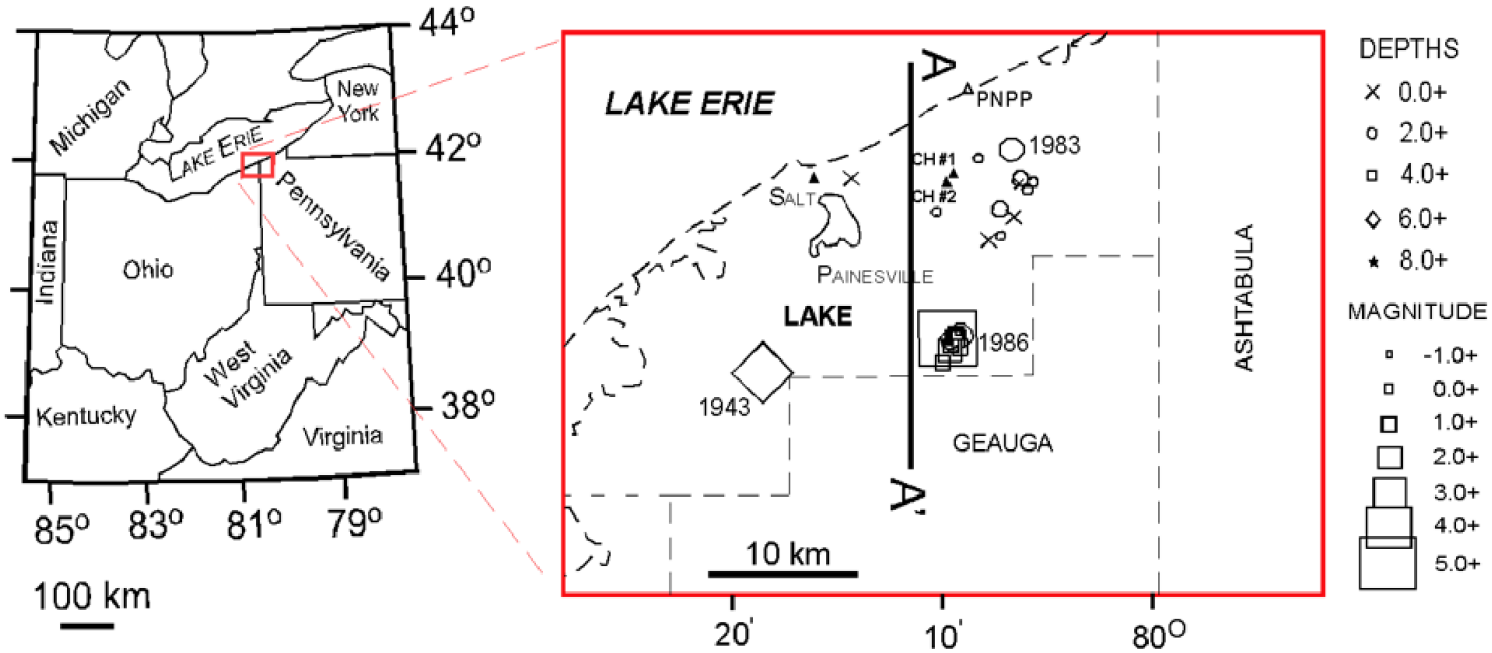


(Evans, 1966; Hsieh and Bredehoeft, 1981)

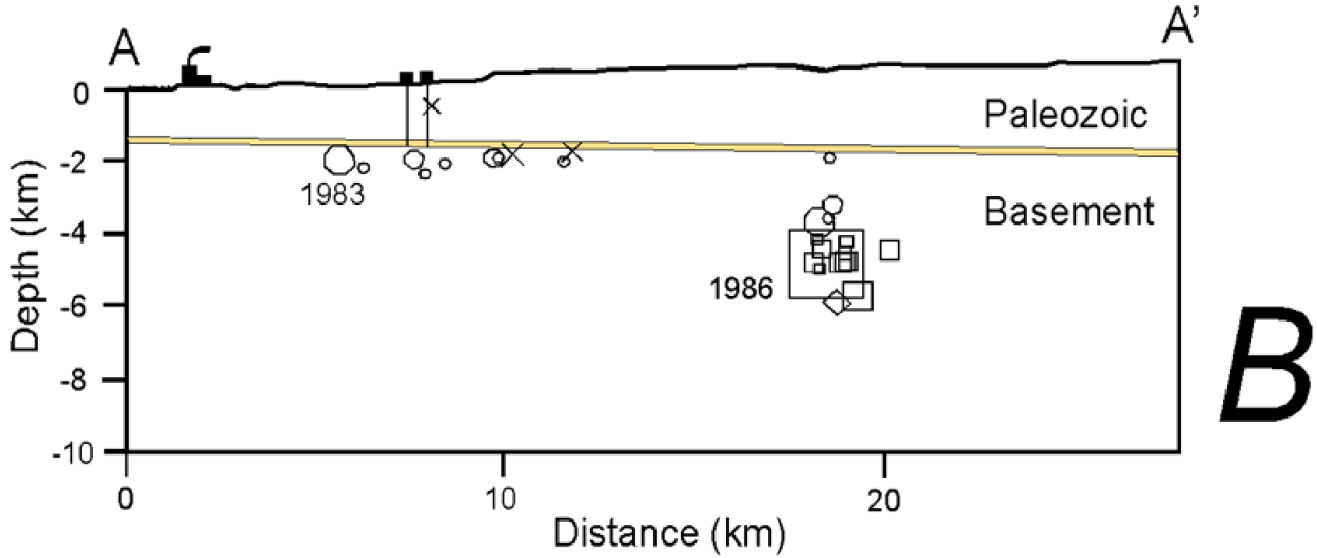


(from Heally et al. 1966)

Induced Seismicity from Hazardous Waste Injection, Asthabula, Ohio, 1980's



Nicholson and Wesson (1990)



Geothermal (EGS) Induced Seismicity

Geothermal quake risks must be faced

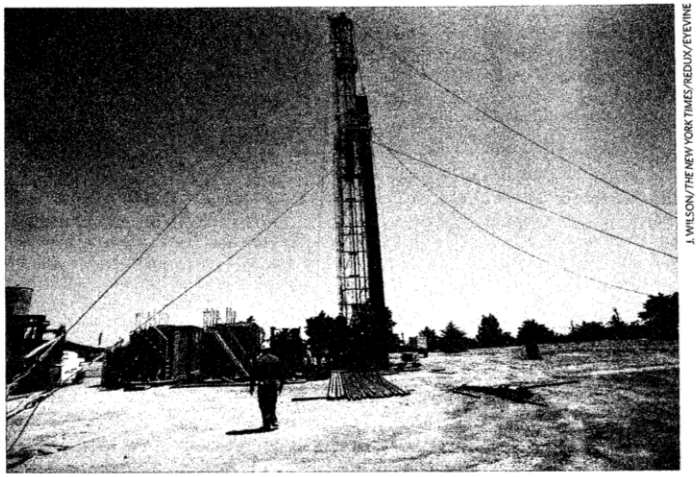
Discussion needs to be open about how exploitation of Earth's internal heat can produce earthquakes, says **Domenico Giardini**, so that the alternative-energy technology can be properly utilized.

Deep geothermal energy is increasingly being explored as an attractive alternative energy source. Conventional hydrothermal resources, such as hot springs in geothermal areas, have been effectively exploited in the past century, but their distribution and potential for supplying electricity is somewhat limited. Tapping deep geothermal energy offers new prospects.

An enhanced geothermal system (EGS), originally called a 'hot dry rock' system, involves drilling a hole at least 3 kilometres deep into a layer of non-porous rock where temperatures are higher than 100 °C. Fluids are pumped under high pressure into the rock (a process called stimulation), which induces it to fracture, generating micro-earthquakes, thereby increasing its permeability and creating a reservoir for the fluid. The ruptures generate elastic waves that are detectable by sensitive seismic networks. Once a reservoir of permeable rock larger than a cubic kilometre has been formed, additional holes are drilled to extract heat from the rock mass by circulating fluids through the fracture network.

The brute-force approach of EGS is attractively simple. And it has, theoretically, the capacity to generate large amounts of alternative energy by tapping a virtually unlimited source — the heat stored deep inside Earth. An expert panel convened at the Massachusetts Institute of Technology in Cambridge in 2006 estimated that EGS could provide up to 100,000 megawatts of electricity in the United States by 2050, or about 10% of the current national capacity — a very large proportion for an alternative energy source. In October, the United States announced that up to US$132.9 million from the recovery act would be directed at EGS demonstration projects, and big names including Google have invested in the technology.

The drawback is that such enhanced geothermal systems can induce earthquakes. The initial stimulation creates micro-earthquakes that might be felt at the surface or even produce damage. And the pressurized water forced into the rock could interact with existing deep faults, generating potentially large quakes. The probability of this happening is not large, but needs to be considered. In addition, geothermal energy is more profitable if it generates electricity and heating at the same time. That means that customers have to be close to the energy source, so it is attractive for operators to develop geothermal-energy sites in urban areas, where earthquakes are more problematic.



J. WILSON/THE NEW YORK TIMES/REDUX/EYEVINE

Enhanced geothermal systems, such as this planned one in California, must undergo quake risk analysis.

Thousands of deep geothermal sites will have to be developed for geothermal energy to supply a sizeable component of the global energy need. If a significant fraction of these induce seismic action under dense urban areas that is felt or is damaging, this will exceed the natural rate of activity in stable continental areas. Man-made rather than natural earthquakes are already the dominant component of seismicity in mining districts in countries such as Poland and the Czech Republic, but is society across Europe and elsewhere ready to accept this threat in urban areas?

In a recent case in California, a planned EGS site at the Geysers, a geothermal power field about 100 kilometres north of San Francisco, met with public resistance and fell under review by the Department of Energy (even though the company involved had completed an appropriate seismicity review). In September, that project was suspended because of technical difficulties.

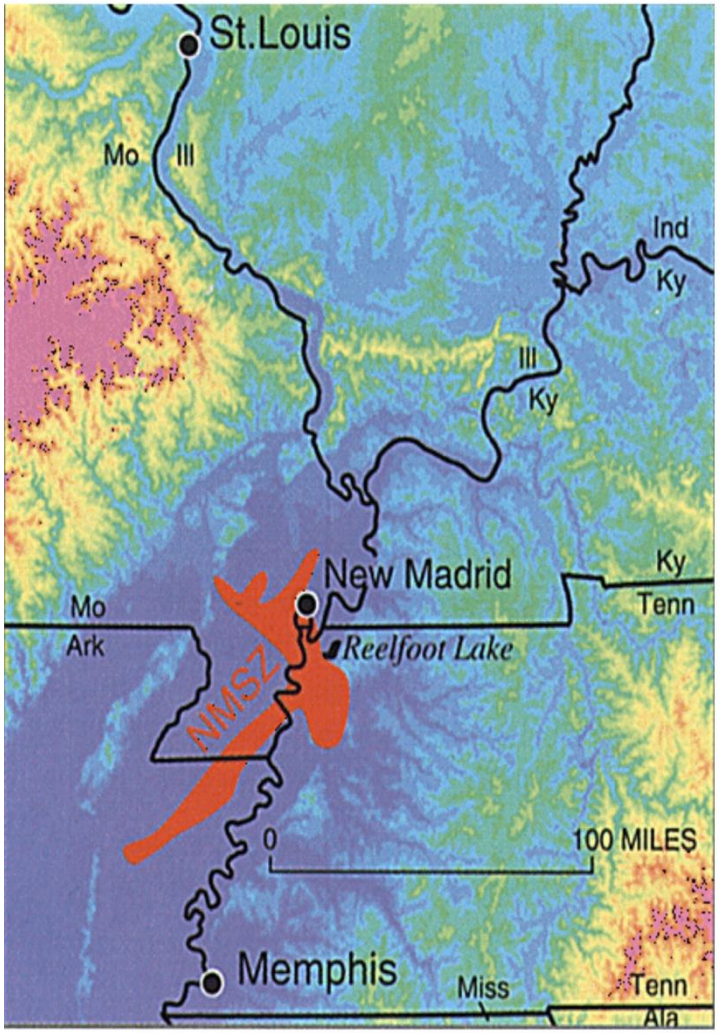
For an enhanced geothermal system located near a city or in an area already hit by past large earthquakes, the increased seismic risk requires developing mitigation strategies, such as restricting the pressure or location of pumped fluids. Open and comprehensive information and education needs to be provided to the public and to authorities before, during and after the project. The risks must be openly recognized and assessed, and thought needs to be given to how to insure against damage caused by the projects. Discussion is needed with all stakeholders — including scientists, politicians and the public — to decide what level of risk is acceptable. Otherwise society risks a public backlash that could unnecessarily quash a promising alternative-energy technology.

The Basel story

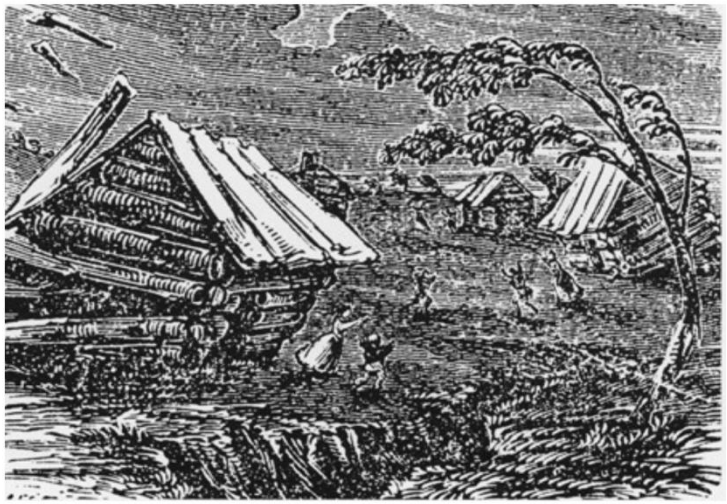
One of the first purely commercially oriented EGS projects — the Deep Heat Mining project — was initiated in Basel, Switzerland, in 1996 by the Geopower Basel (GPB) consortium. In my view, what started as a promising green-energy initiative turned into a messy affair. It is a textbook example of how the failure to come to terms fully with the possibility of producing earthquakes in an urban area (by everyone involved — including the public) became in itself the largest risk to the whole

Nature (2009)

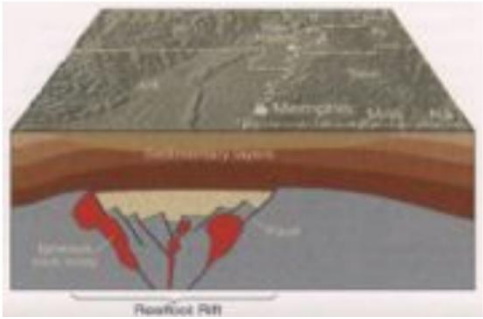
Natural Seismicity, New Madrid Earthquake, 1811



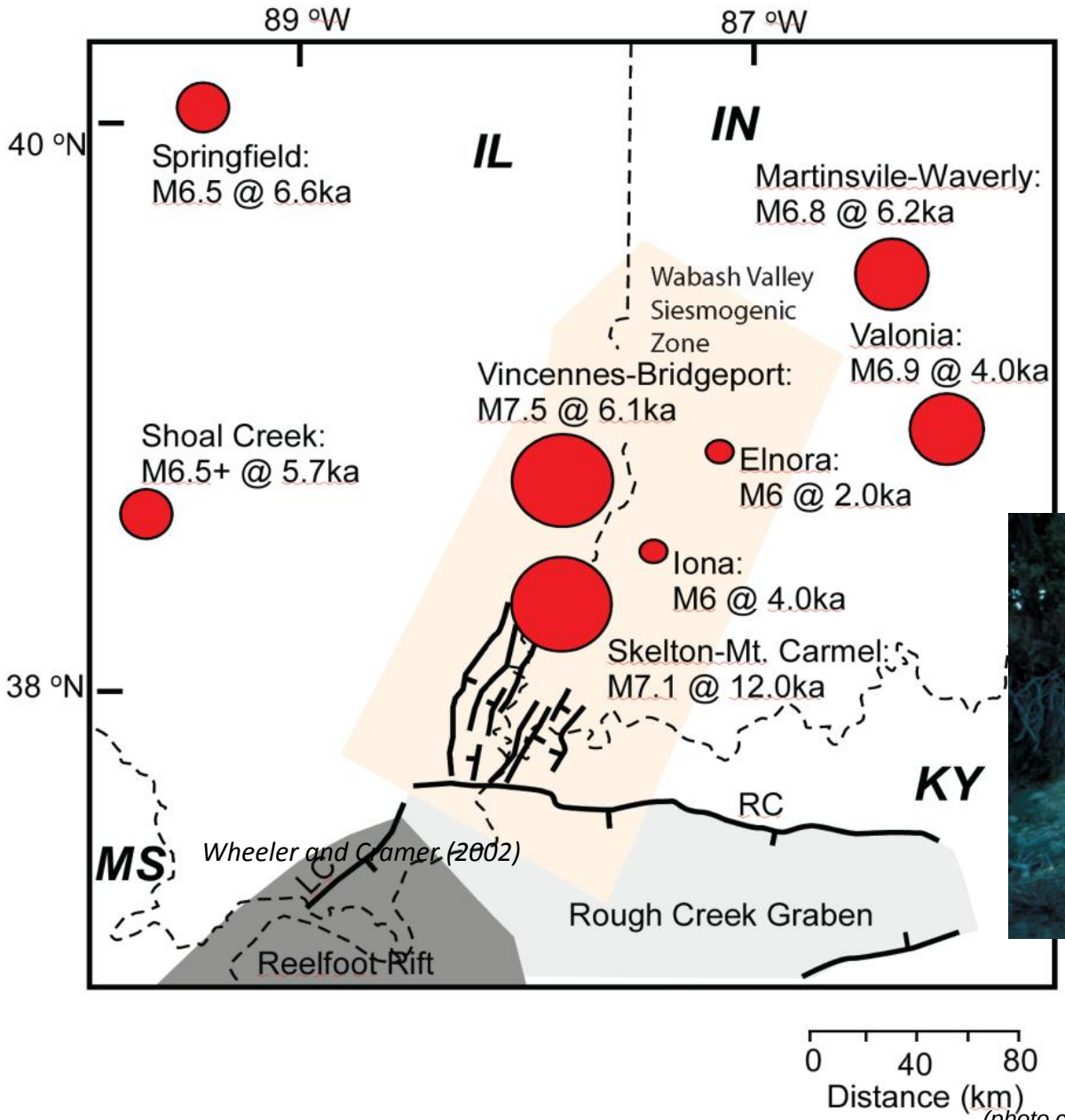
Earthquake Damage



Reelfoot Rift Zone



Paleo-Siemiscity Data From Southern Illinois Basin



Wheeler and Cramer (2002)

Holocene Sand Dike

(photo courtesy of M. Hamburger)

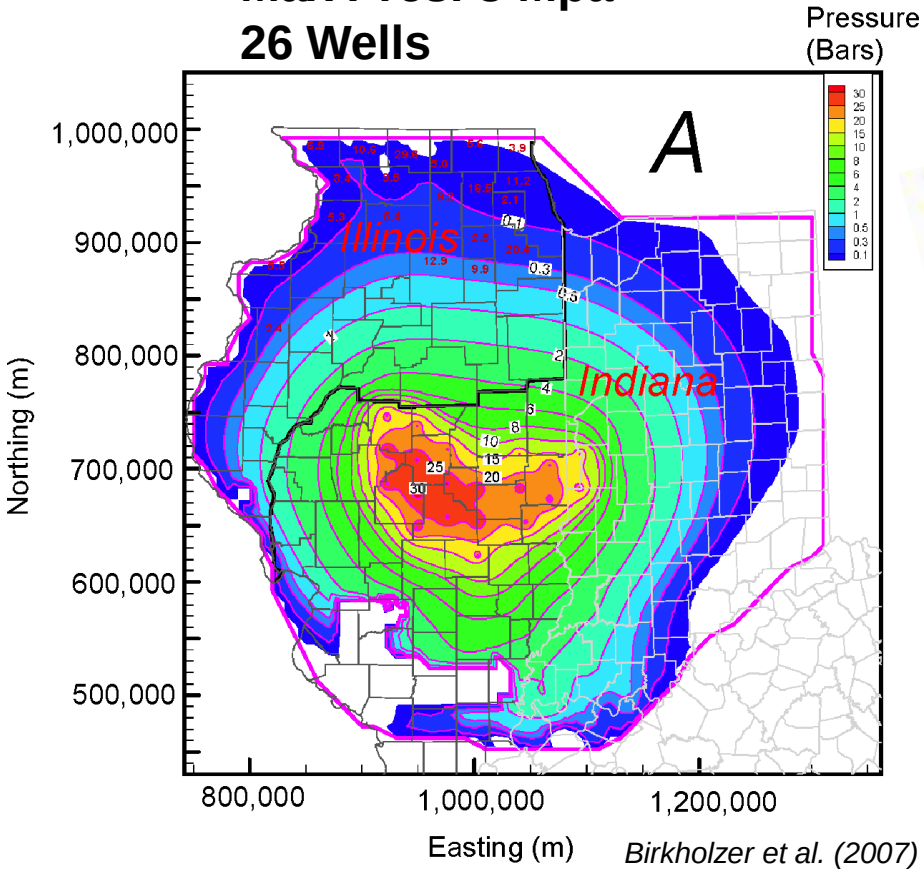
Contrasting Pressure Predictions

Dealing with Parameter Uncertainty:
Two Mt. Simon CO_2 Injection Scenarios

Max Pressure
12 MPa
728 Wells

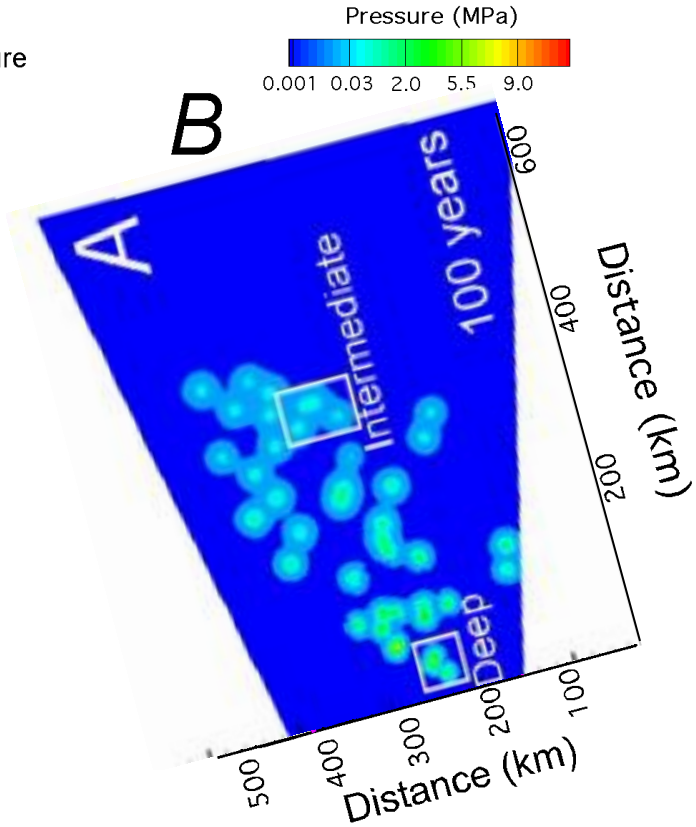
TOUGH2

Max Pres. 3 Mpa
26 Wells



Birkholzer et al. (2007)

SharpCO$_2$



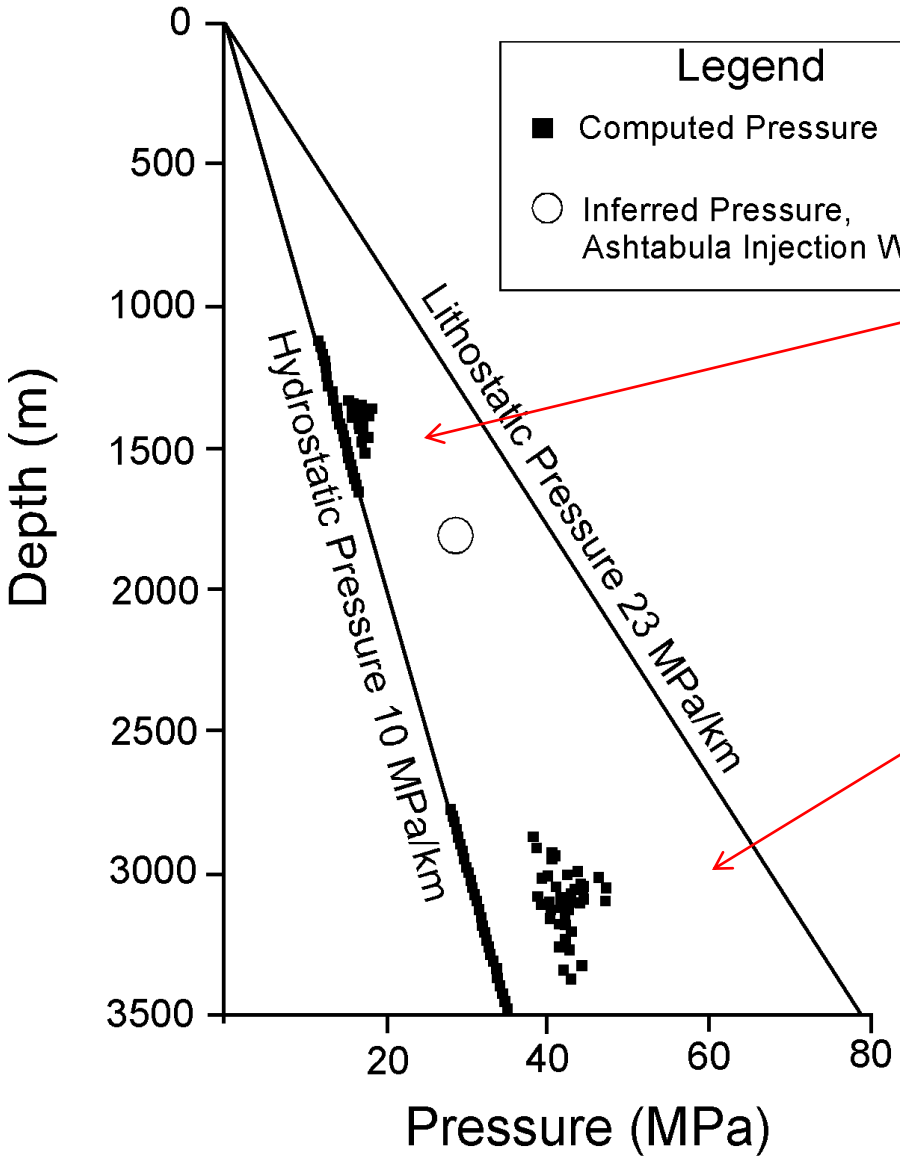
Person et al. (2010, accepted)

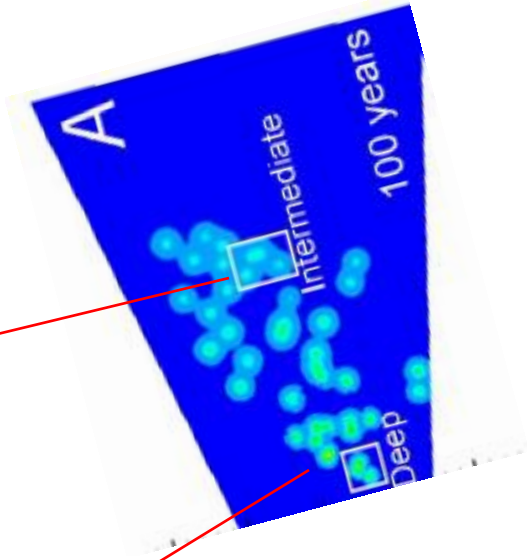
Permeability Assumptions:

1000 mD → 10^{-12} m^2
Constant

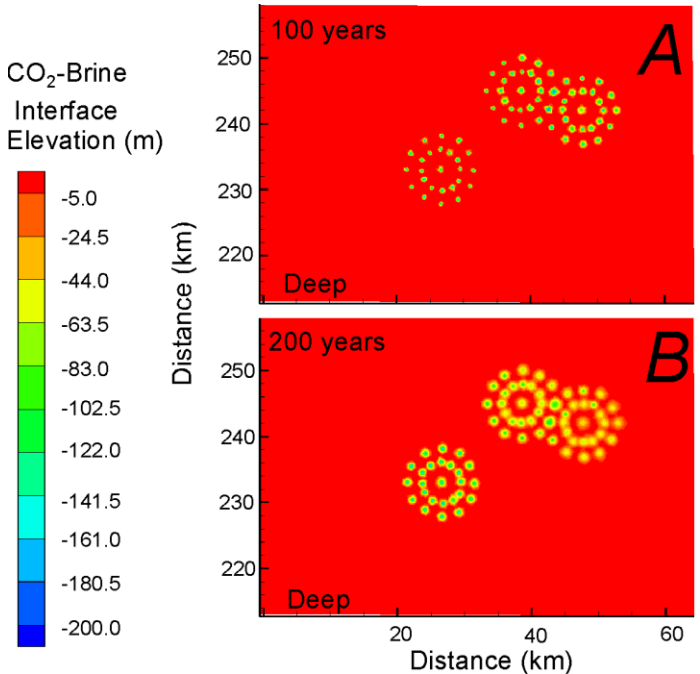
5-100 mD → 5×10^{-14} - 10^{-13} m^2
Varies with Depth

Pressure – Depth Plot

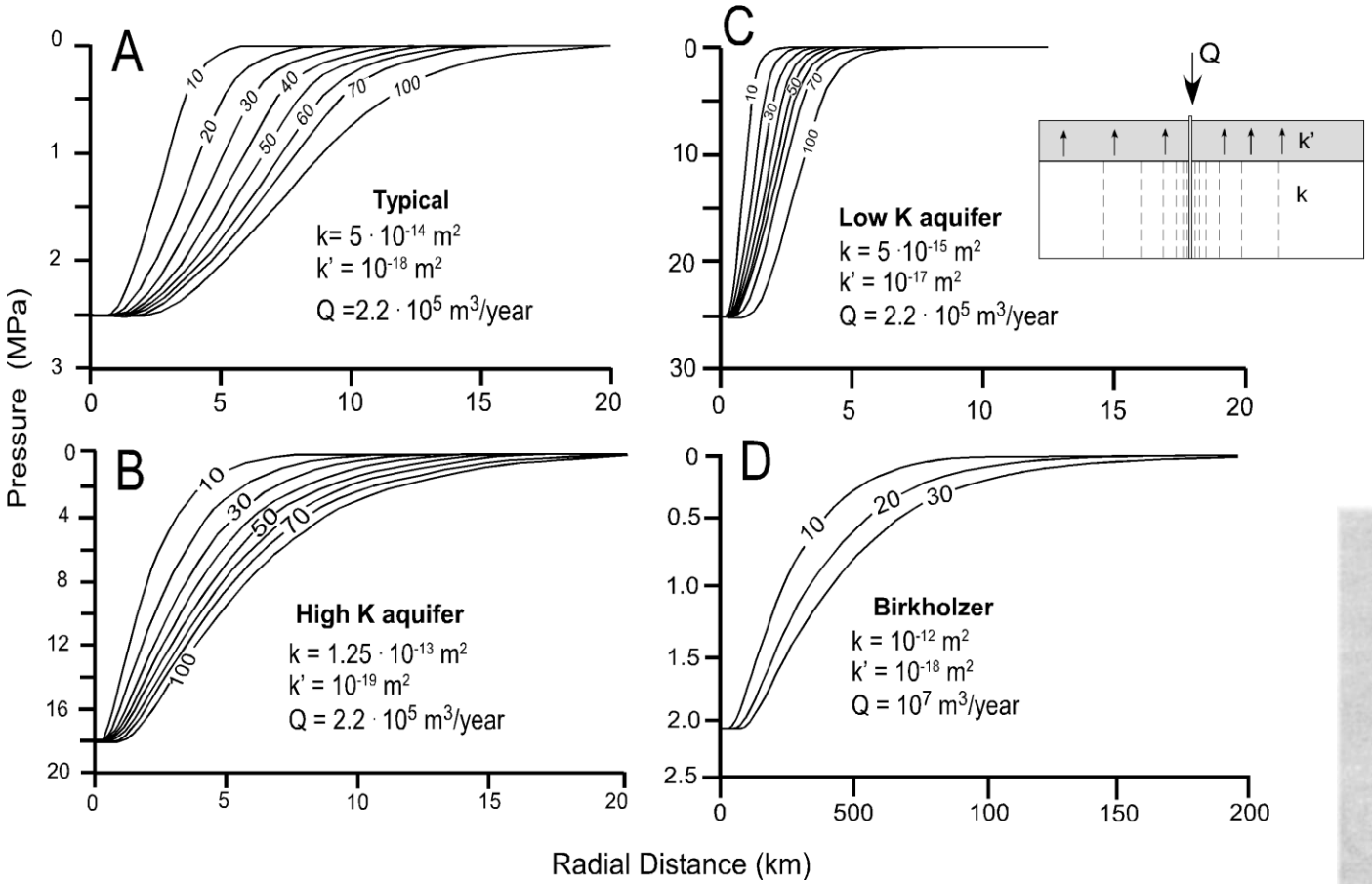




CO_2 Lens Thickness Intermediate Depth



Single-Phase Analytical Calculations



Madi Hantush
Founder NM Tech
Hydrology Program

Governing Equation

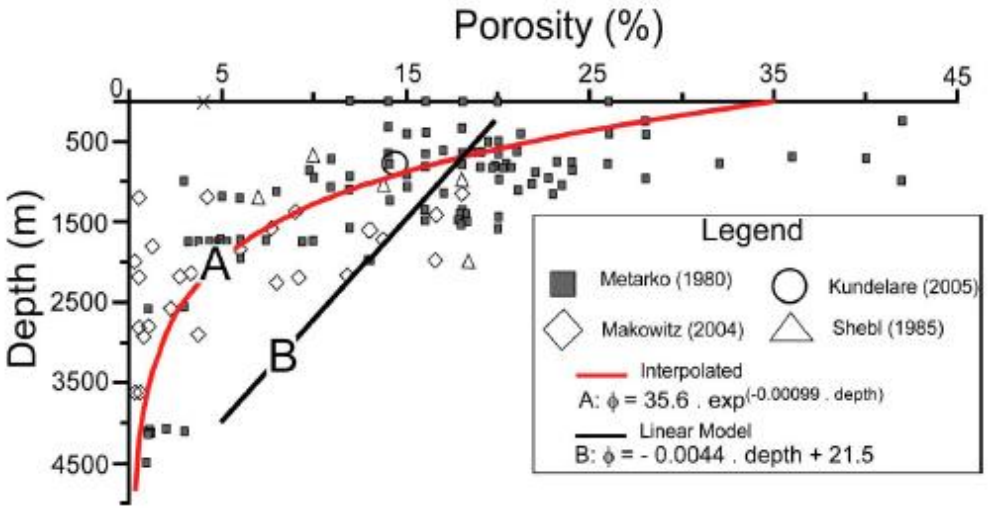
$$\frac{S}{T}\frac{\partial s}{\partial t} = \frac{1}{r}\frac{\partial s}{\partial r} + \frac{\partial^2 s}{\partial r^2} - \frac{K'}{Tb'}s$$

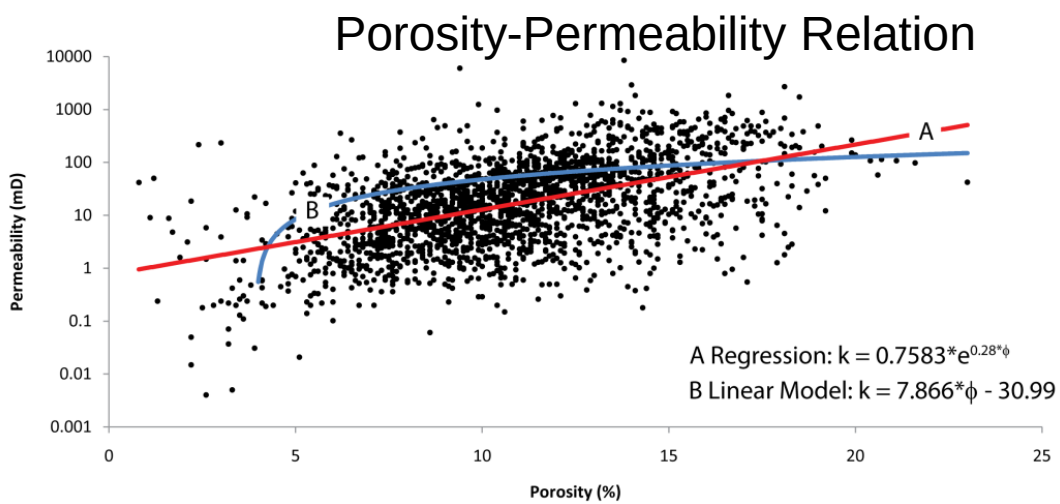
Hantush and Jacob (1955)

Analytical Solution

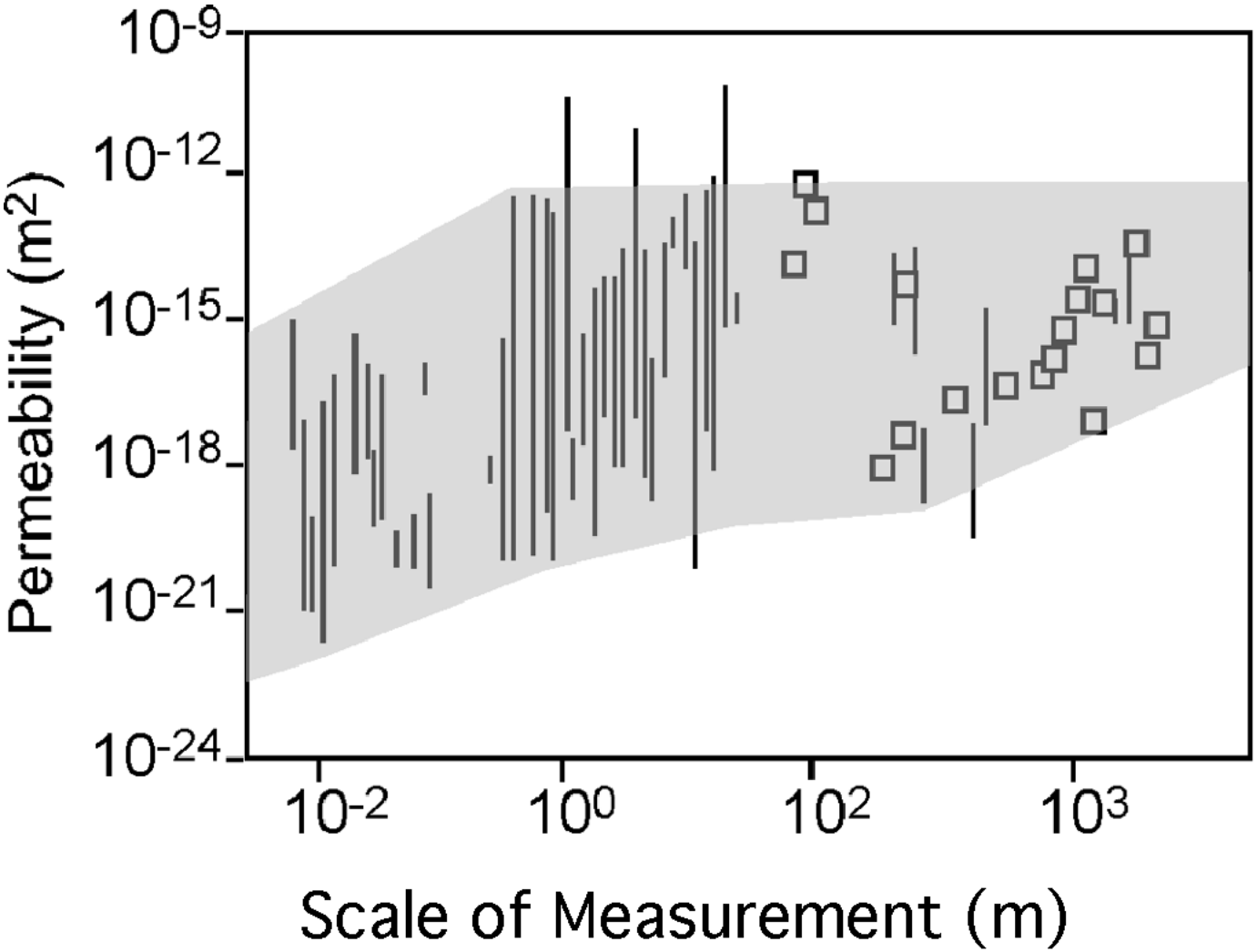
$$s = \frac{Q}{4\pi T}L(u,v)$$

Mount Simon – Eau Claire Petrophysics





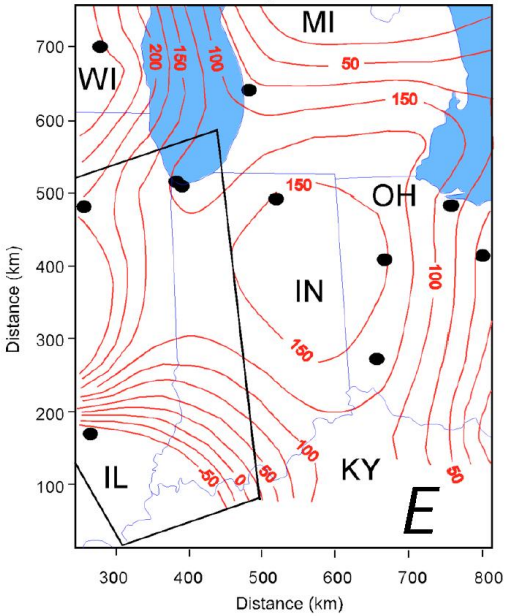
Scale Effects



Clauser (1999)

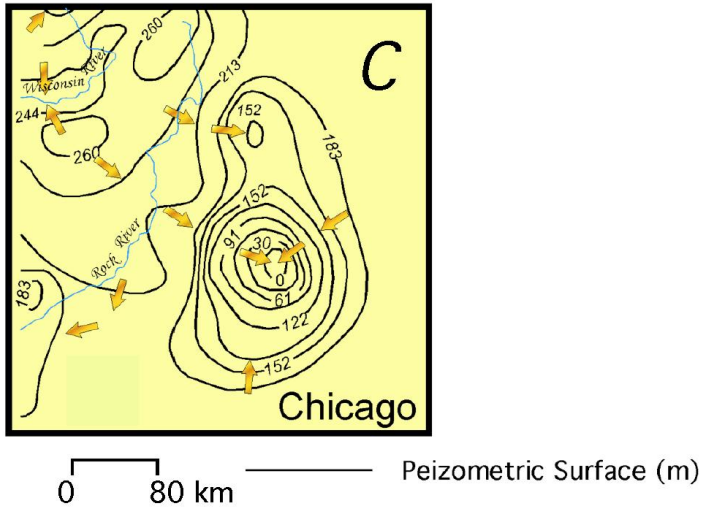
Model Calibration; Head & Pumping Data

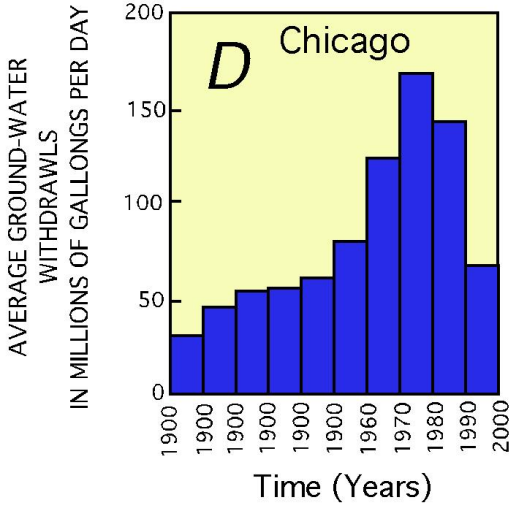
Pre-Development Heads



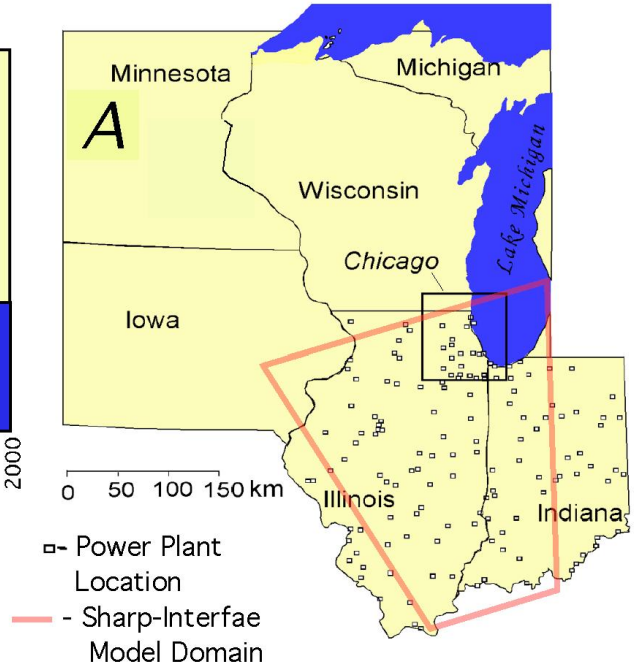
(Gupta and Bair, 1997)

Post-Development Drawdown





(Lloyd and Lyke, 1995)

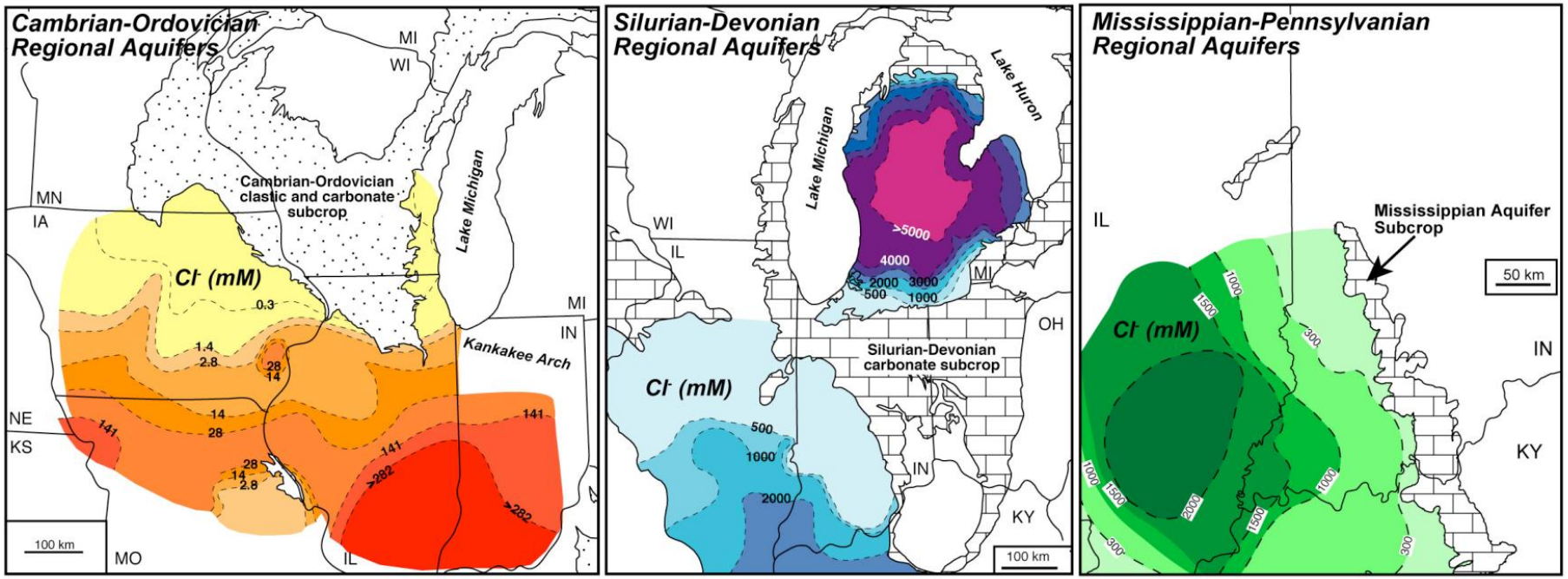


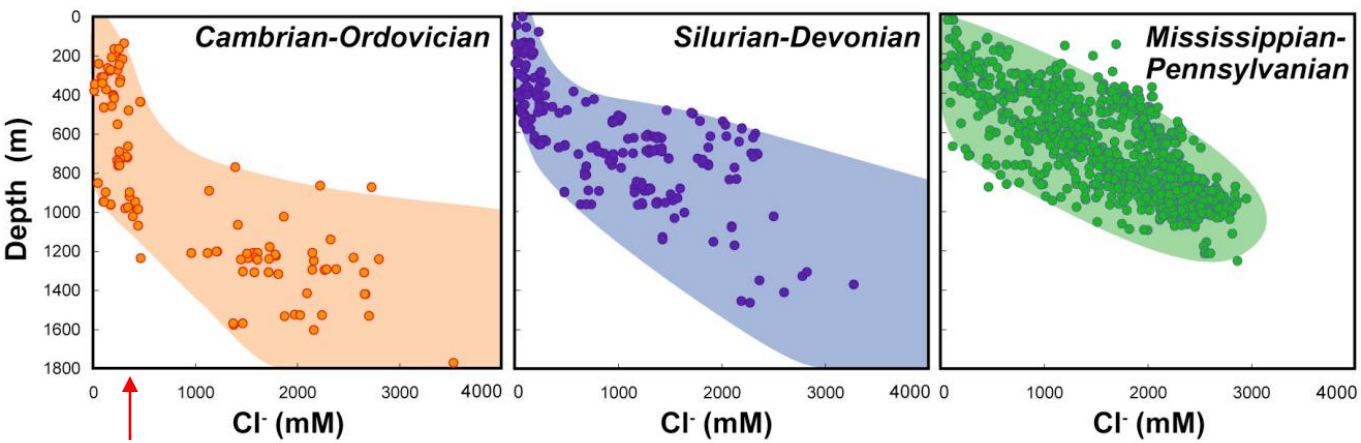
Chicago Water Withdraws:

150 x 10^6 gpd = 235 MT/yr H_2O

600 ft drawdown = 1.8 MPa

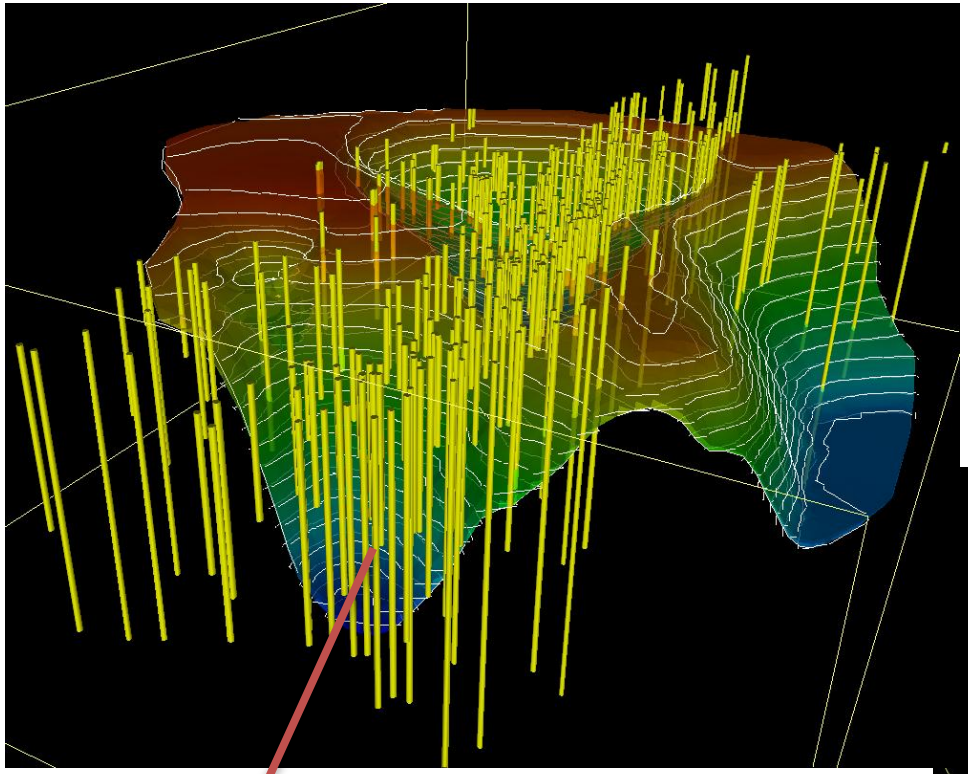
Model Calibration: Illinois Basin Salinity Data

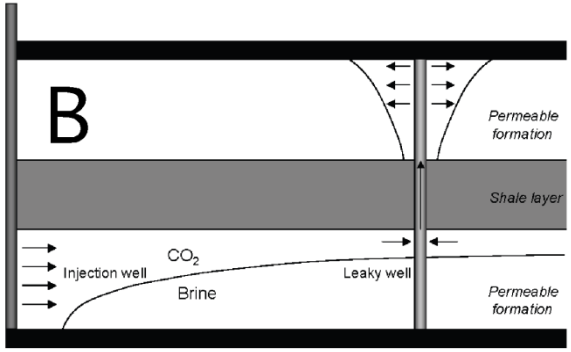


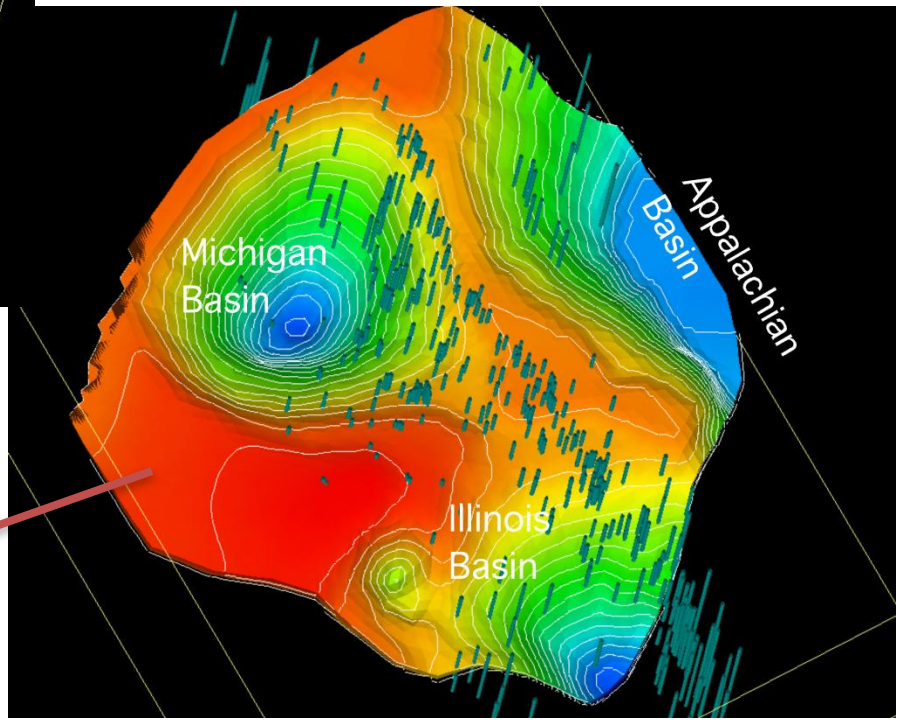


Seawater

CO_2 leakage across Abandoned Oil Wells in Illinois Basin



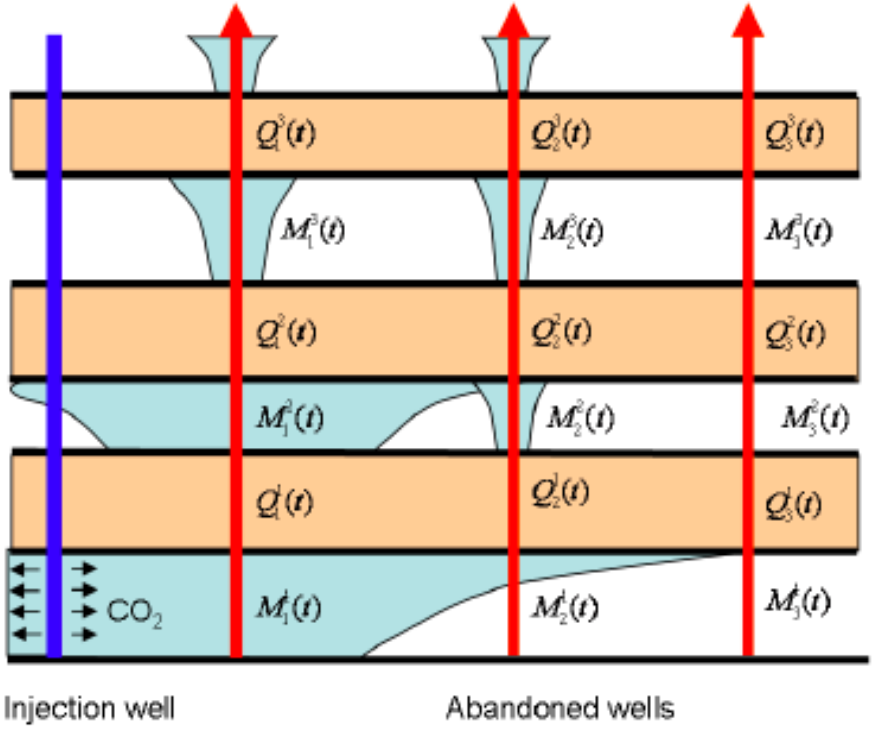




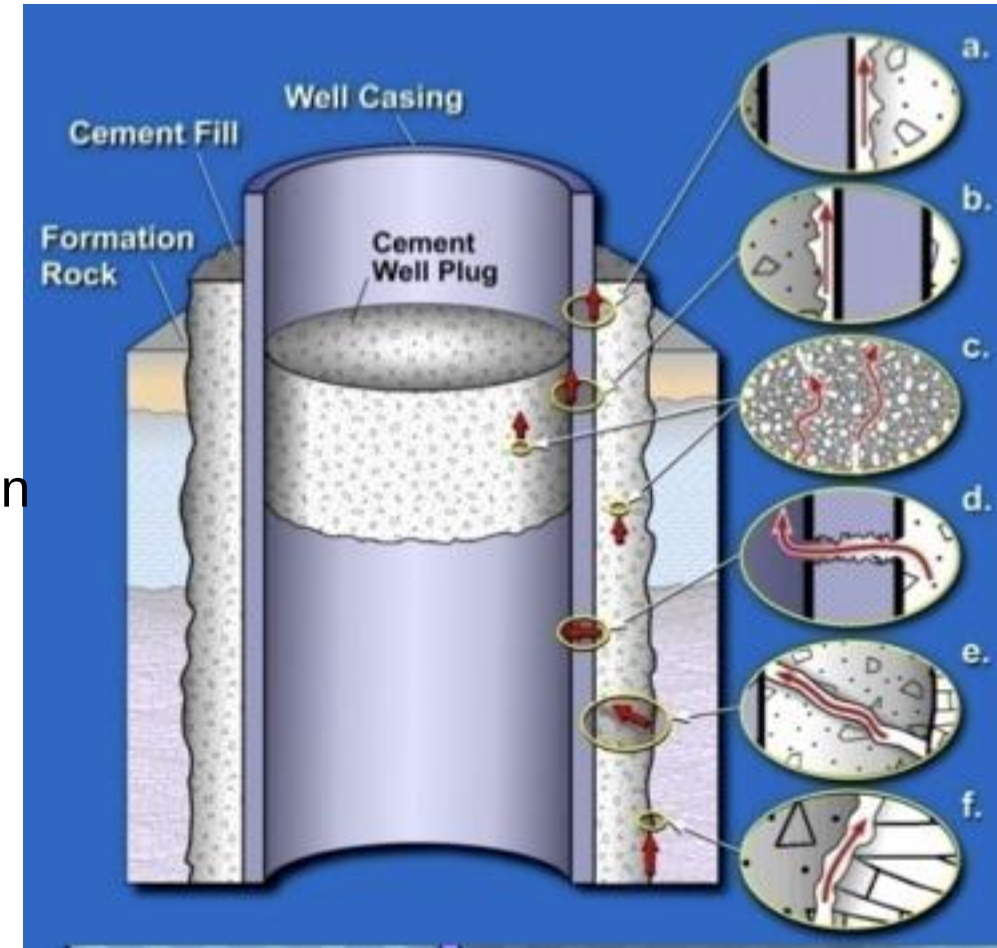
Oil and gas wells

Mt. Simon top

ABANDONED WELL LEAKAGE PATHWAYS



a. Degraded cement seal with casing
b. Degraded cement seal with facies
c. Diffusion/Seepage through Cement well-plug



d. Fractures/intentional blow-through in casing
e. Fractures in cement annulus seal
f. Seepage through cement-facies seal

(Nordbotten *et al.*, 2009)