Poroelastic Models of Stress Diffusion and Fault Re-Activation in Underground Injection

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Outline

Relation of hydrogeology to stress, deformation, and failure

The "solid" earth exhibits a poroelastic response.

Underground injection: the petition process and modeling

Flow and containment
Chemical fate
Mechanical integrity
Modeling plays a central role in the regulatory process.

Induced earthquakes

Traditional methods to predict are conservative, inaccurate.

COMSOL poroelastic models: set-up and results

Stress diffusion models
Implications for onset of failure
In some scenarios, poroelastic response decreases the perturbation pressure which would trigger seismicity.

Conclusions

Poroelastic models provide a more accurate prediction of the onset of seismicity.
These predictions can differ significantly from the traditional methods.
COMSOL provides an effective poroelastic modeling capability.

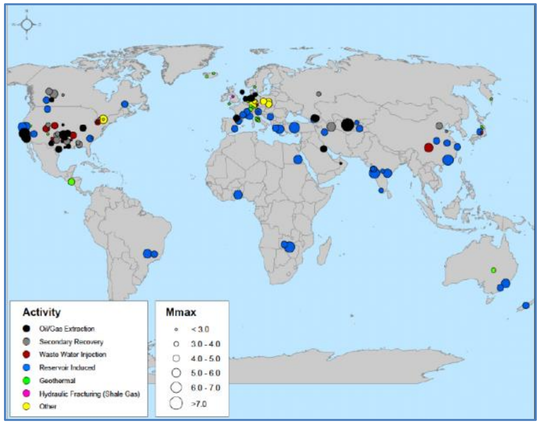
Groundwater has been known to be influenced by external forces – including earthquakes -- since Roman times. [1]

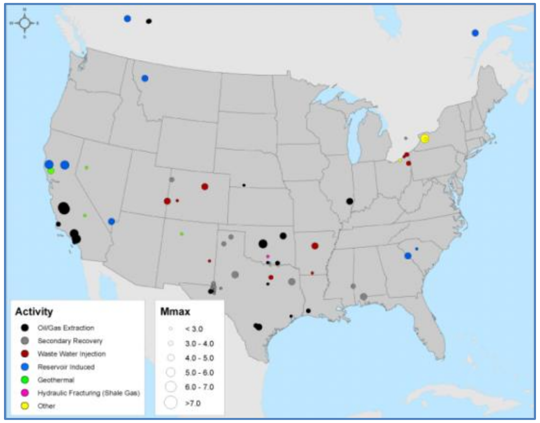
General
Water level in wells correlate with ocean tides
Water level changes as trains pass
Water level rise in wells near a pumping well
Land subsidence following oil/gas extraction

Earthquake-related
Water levels in wells
Lake Mead filling triggers earthquakes
Streamflow and spring discharge
changes following earthquake
Changes in mud volcanoes and geysers
Liquefaction

Earthquakes related to human activity are quite widespread.

Associated technology [2]
Oil/gas extraction
Secondary recovery
Waste water injection
Reservoir-induced
Geothermal
Hydraulic fracturing





The two-way coupling between rock matrix and pore fluids (poroelastic response) accounts for the connection between stress and deformation.

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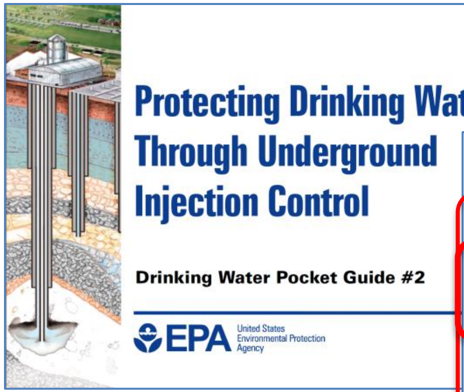
[1] e.g., H. F. Wang [2000]; Wang and Manga [2010].

[2] from Hitzman [2012]

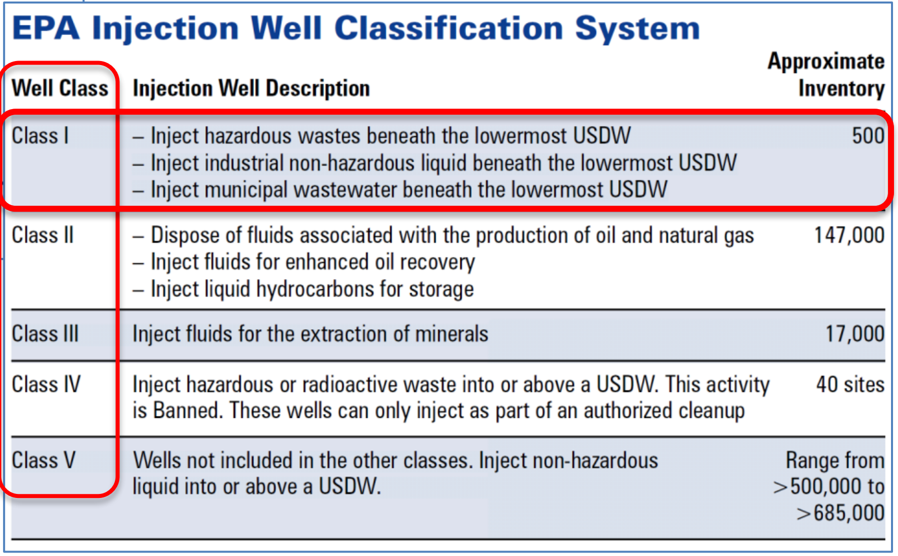
Siting, construction, and operation of injection wells are regulated by USEPA and by state and local authorities.



Protecting Drinking Water Through Underground Injection Control

Drinking Water Pocket Guide #2

EPA United States Environmental Protection Agency



EPA Injection Well Classification System

Well Class	Injection Well Description	Approximate Inventory
Class I	– Inject hazardous wastes beneath the lowermost USDW – Inject industrial non-hazardous liquid beneath the lowermost USDW – Inject municipal wastewater beneath the lowermost USDW	500
Class II	– Dispose of fluids associated with the production of oil and natural gas – Inject fluids for enhanced oil recovery – Inject liquid hydrocarbons for storage	147,000
Class III	Inject fluids for the extraction of minerals	17,000
Class IV	Inject hazardous or radioactive waste into or above a USDW. This activity is Banned. These wells can only inject as part of an authorized cleanup	40 sites
Class V	Wells not included in the other classes. Inject non-hazardous liquid into or above a USDW.	Range from >500,000 to >685,000

“not just a hole in the ground”

Highly engineered structure

Multiple layers of protection

Injectate is separated from USDW by multiple confining layers

USDW

confining

confining

confining

confining

confining

injection

For Class I wells, the petition process requires modeling to demonstrate, using accepted methodology and to a reasonable degree of certitude, that injection can be carried out in a manner “protective of human health and the environment.“

Flow and containment

Injectate shall remain confined to the permitted zone for 10,000 years

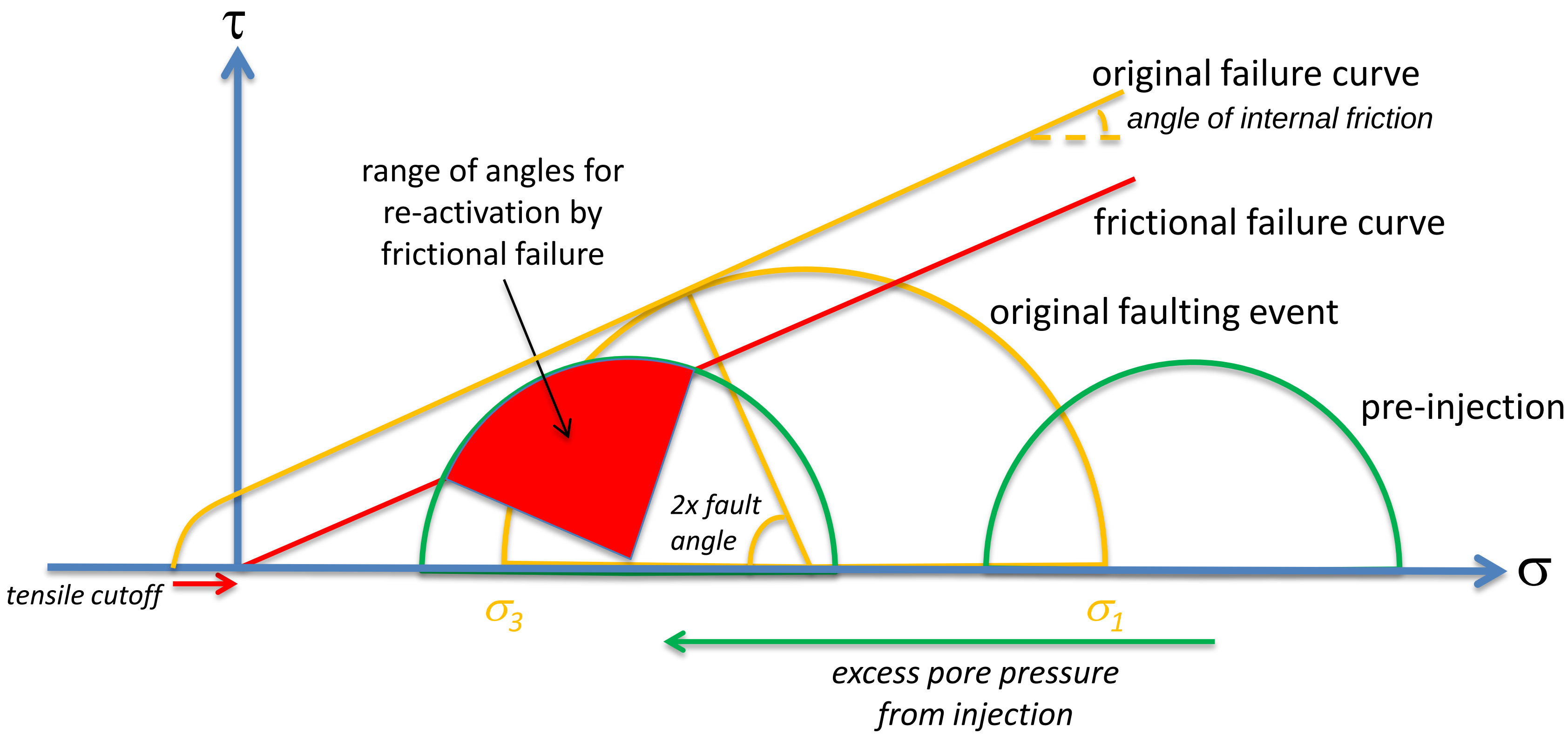
Chemical fate (alternate demonstration)

Interaction of the injectate with the native fluids in the rock shall render it non-hazardous

Mechanical integrity

Wellbore shall remain mechanically intact
Earthquakes due to failure of pre-existing faults shall not be induced as a result of injection operations
Any other features (solution cavities, …) shall remain stable against collapse

Failure criteria may be mapped into normal stress-shear stress (σ–τ) space. A two-dimensional state of stress appears as a circle in this space.



Predicting the state of stress during and following injection is critical to a reliable seismicity prediction.

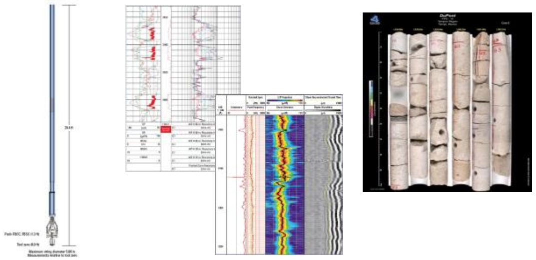
The structural integrity analysis for seismicity is composed conceptually of three models.

Darcy's Law

reservoir model

pressure buildup

rock hydrological properties
fluid properties

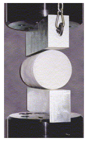


(poro)elastic Hooke's Law

rock mechanics model

rock stresses

rock mechanical properties

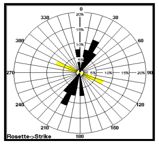


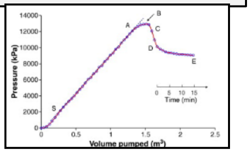
(Mohr-)Coulomb failure

frictional failure model

failure prediction: Y/N

rock failure properties
background stresses

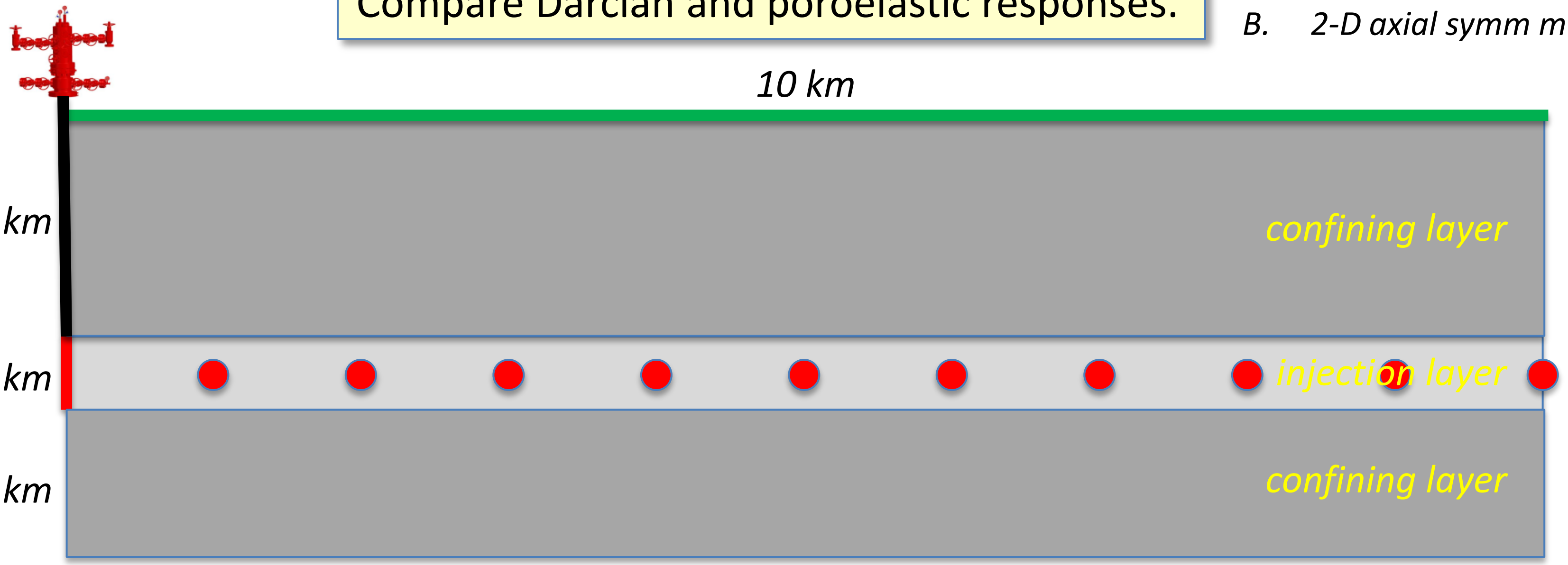




Model demonstration: inject water into a massive limestone formation at 1500 m depth

Compare Darcian and poroelastic responses.

A. 2-D planar symm model
B. 2-D axial symm model



Physical properties:

	confining layers	injection layer	
density	2750	2750	kg/m3
porosity	0.25	0.25	..
permeability	1.18E-14	2.90E-11	m2
Young's modulus	800	80	MPa
Poisson's ratio	0.25	0.25	..
Biot-Willis coefficient	1	1	..

Injection schedule: inject @ 1000 psi from day 7 to day 14

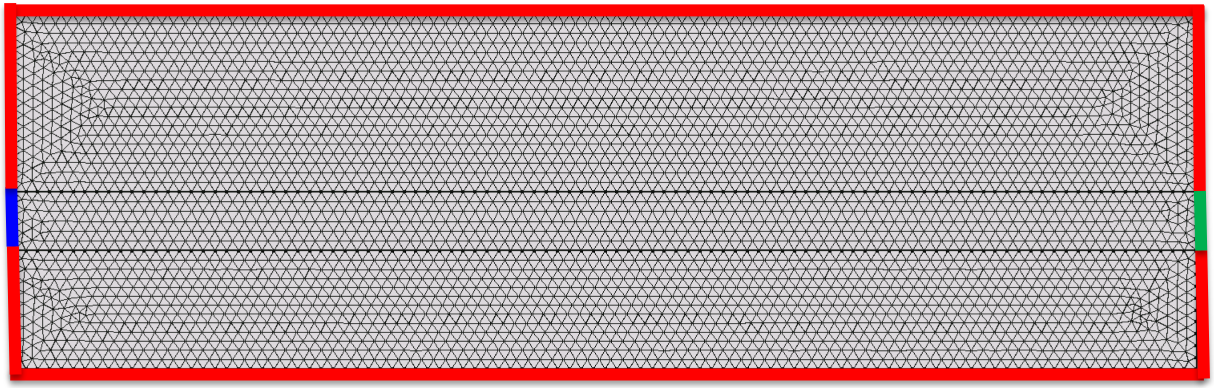
$$p = 1000*(flc2hs((t-7*86400),3600) - flc2hs((t-14*86400),3600))[psi]$$

We observe for 60 days at ● *observation points*

Mesh and boundary conditions

2-D model, *15541 DoF*

flow boundary conditions



no flow

no flow

pressure pulse

no flow

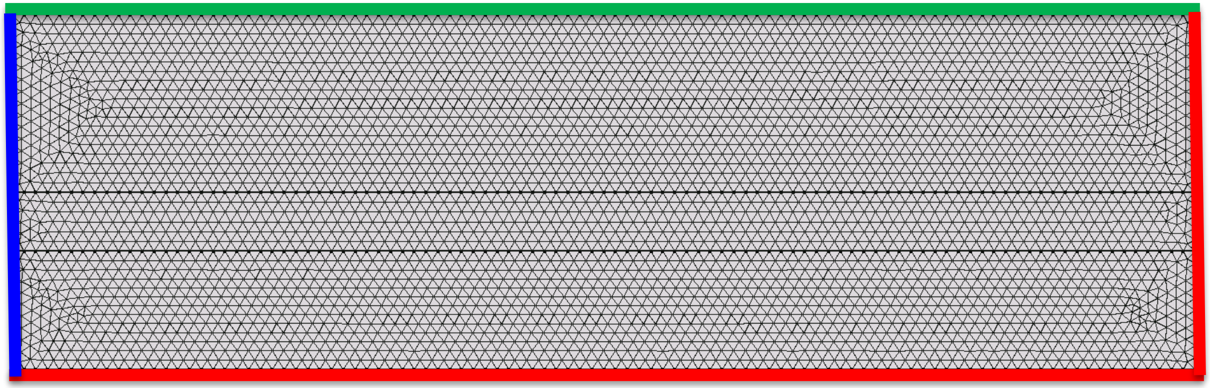
no flow

pressure = 0

no flow

no flow

mechanical boundary conditions



free surface

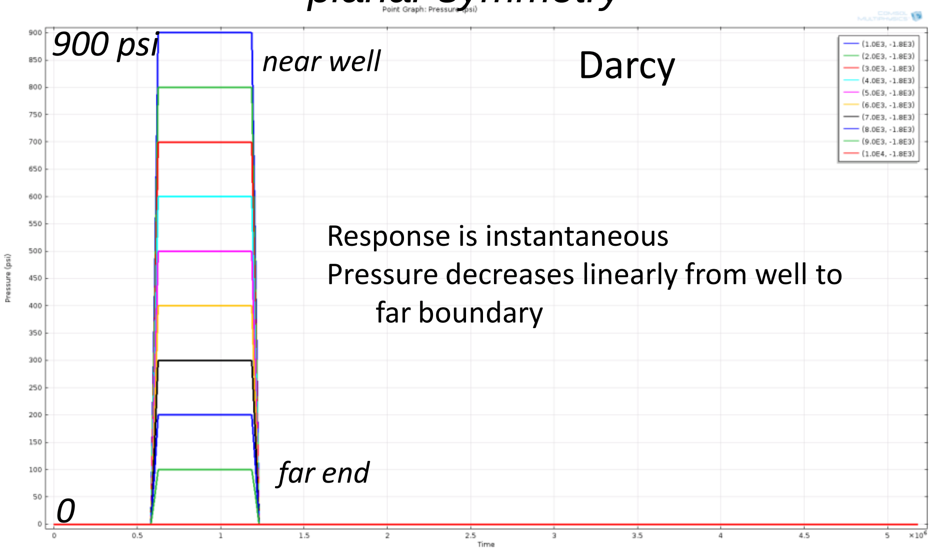
roller

fixed

fixed

Fluid pressure at injection depth vs time

planar symmetry



900 psi

near well

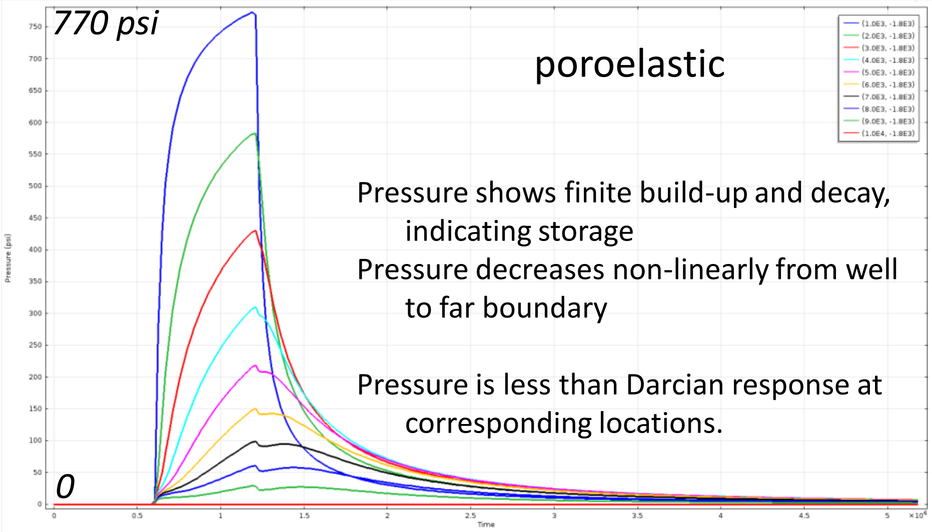
Darcy

Response is instantaneous

Pressure decreases linearly from well to far boundary

far end

0



770 psi

poroelastic

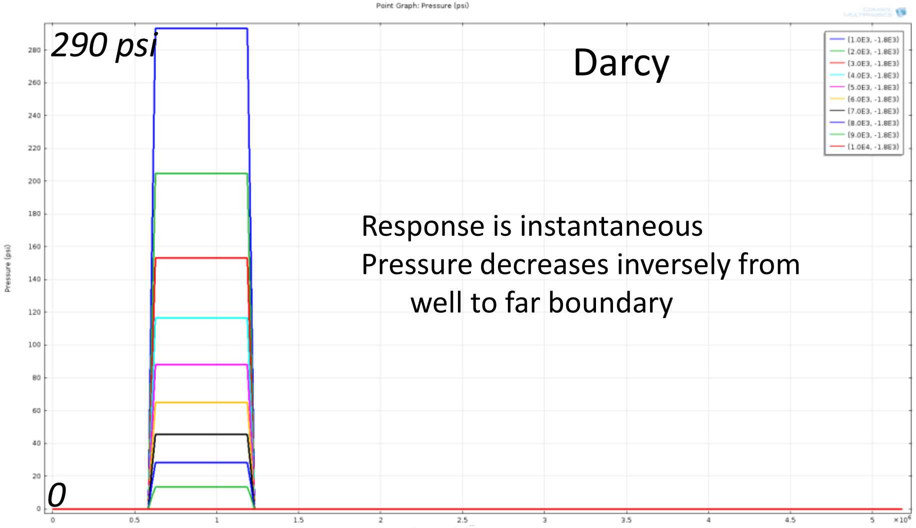
Pressure shows finite build-up and decay, indicating storage

Pressure decreases non-linearly from well to far boundary

Pressure is less than Darcian response at corresponding locations.

0

axial symmetry



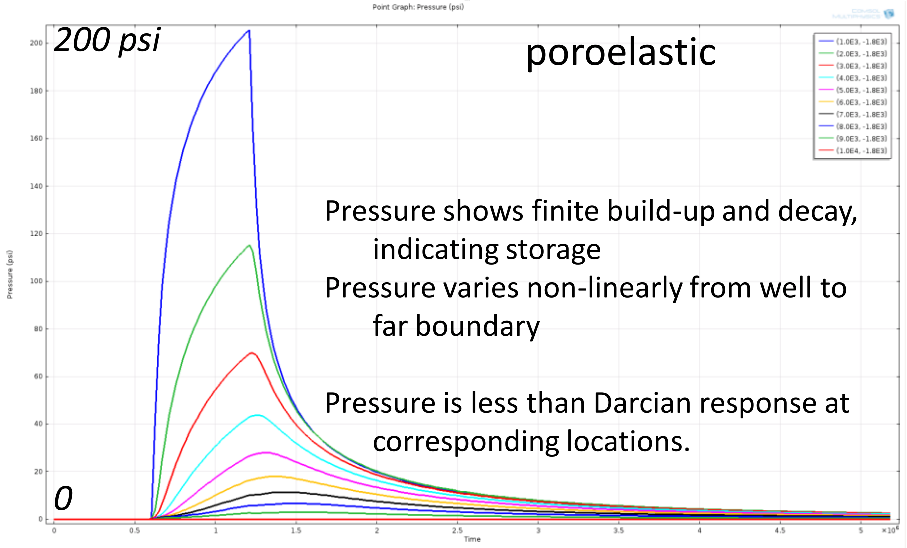
290 psi

Darcy

Response is instantaneous

Pressure decreases inversely from well to far boundary

0



200 psi

poroelastic

Pressure shows finite build-up and decay, indicating storage

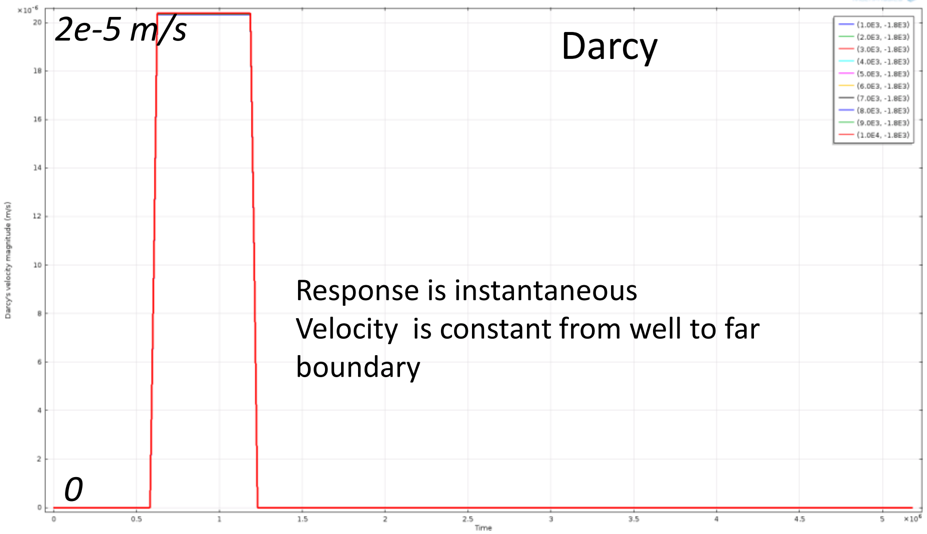
Pressure varies non-linearly from well to far boundary

Pressure is less than Darcian response at corresponding locations.

0

Horizontal fluid velocity at injection depth vs time

planar symmetry



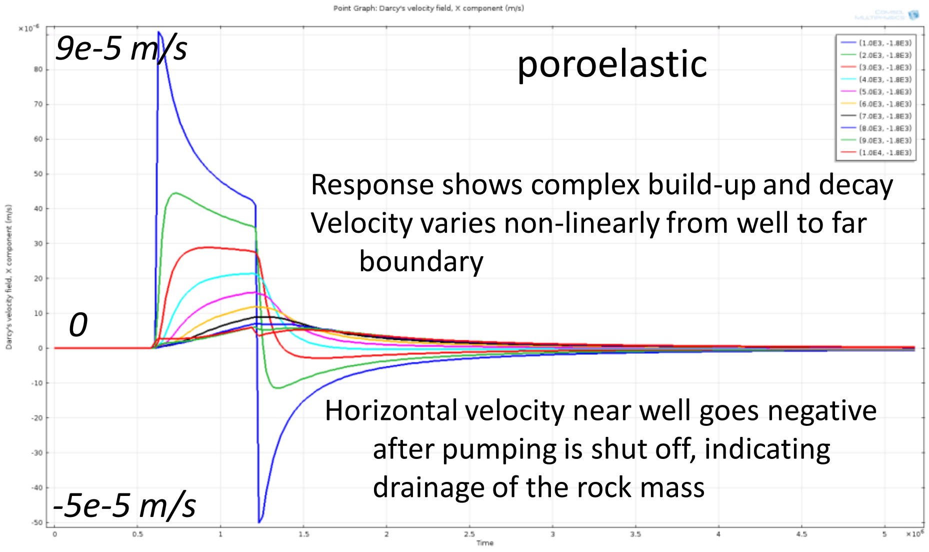
2e-5 m/s

Darcy

0

Response is instantaneous

Velocity is constant from well to far boundary



9e-5 m/s

poroelastic

0

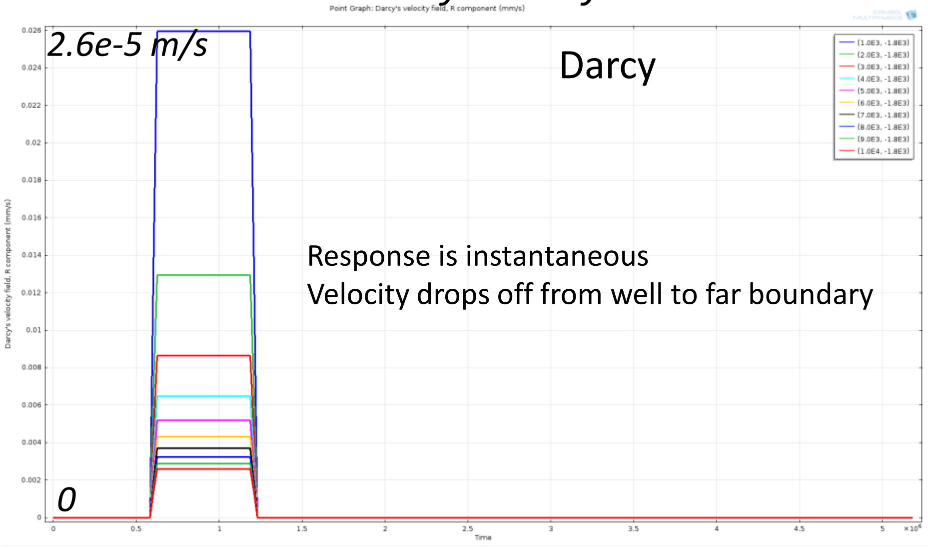
-5e-5 m/s

Response shows complex build-up and decay

Velocity varies non-linearly from well to far boundary

Horizontal velocity near well goes negative after pumping is shut off, indicating drainage of the rock mass

axial symmetry



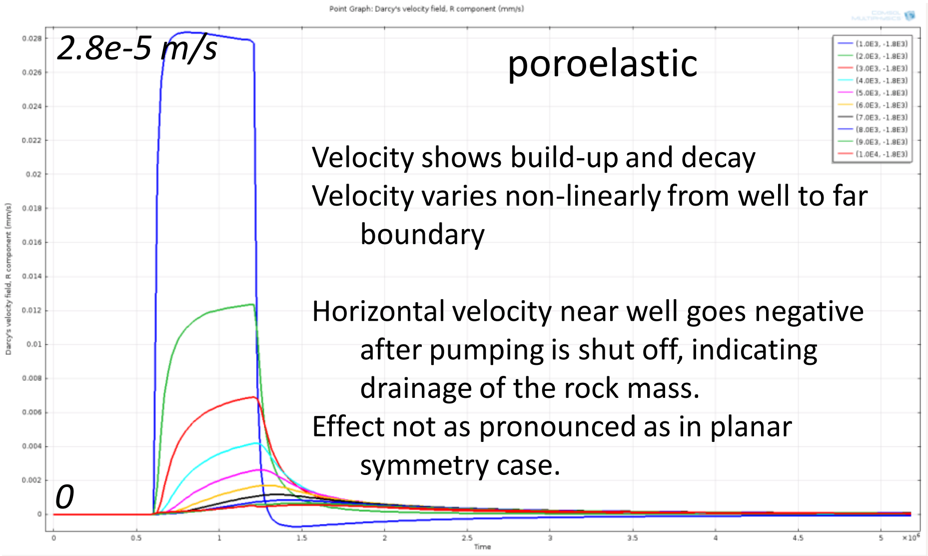
2.6e-5 m/s

Darcy

0

Response is instantaneous

Velocity drops off from well to far boundary



2.8e-5 m/s

poroelastic

0

Velocity shows build-up and decay

Velocity varies non-linearly from well to far boundary

Horizontal velocity near well goes negative after pumping is shut off, indicating drainage of the rock mass.

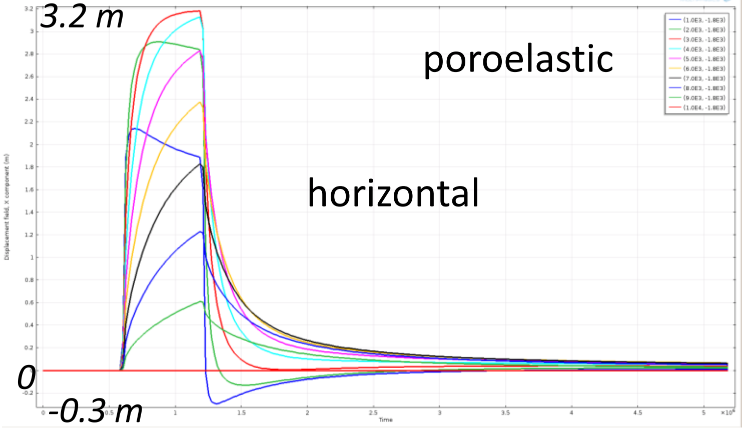
Effect not as pronounced as in planar symmetry case.

Deformation at injection depth vs time (planar symmetry)

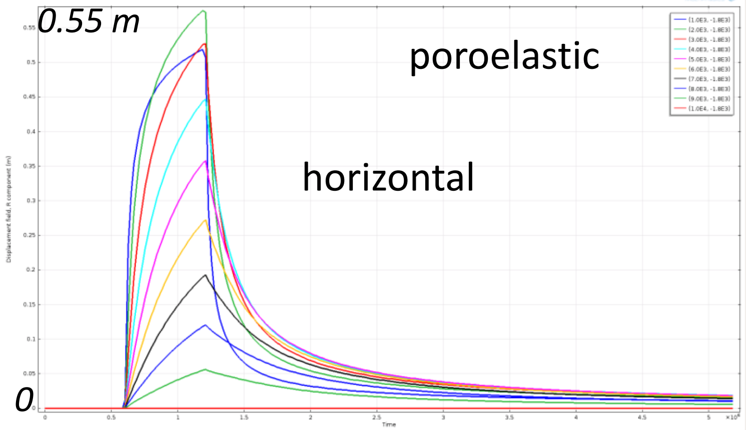
No deformation in Darcy model

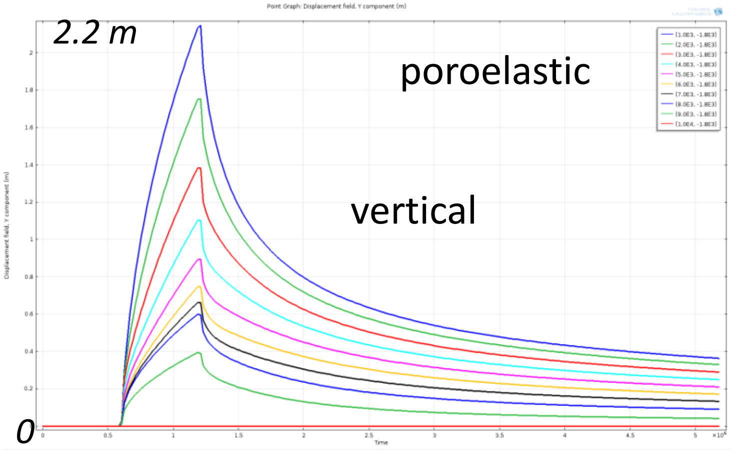
Response shows complex build-up and decay
Deformation varies non-linearly from well to far boundary
Horizontal and vertical deformations are about the same
Horizontal deformation near well goes negative for a while
after pumping is shut off as water drains

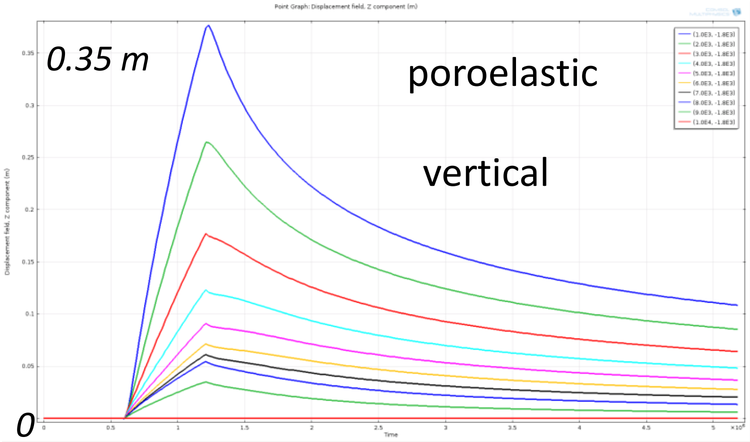
planar symmetry



axial symmetry







Deformation vs time during injection period in poroelastic model (planar symmetry)

Injection starts on day 7

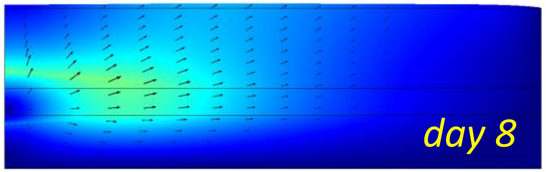
Injection ends after day 14

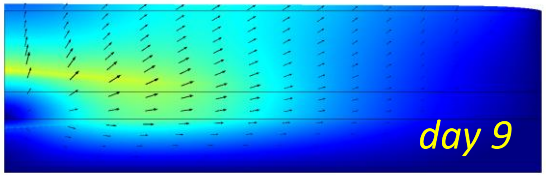
Earth deforms during injection

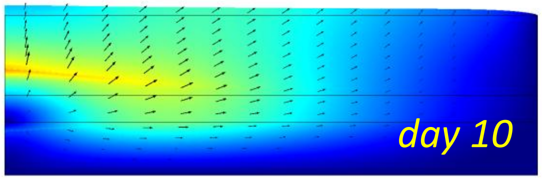
Max deformation occurs at depth and is a few meters in both horizontal and vertical

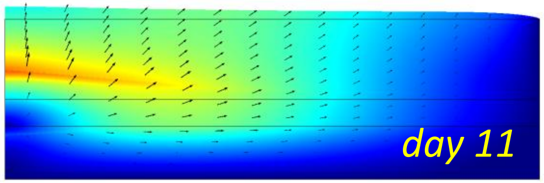
Post-injection, earth deflates

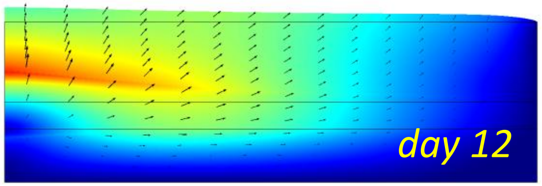
Some inflation persists even after 60 days

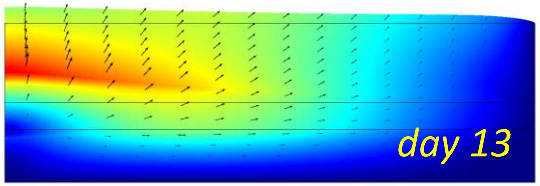


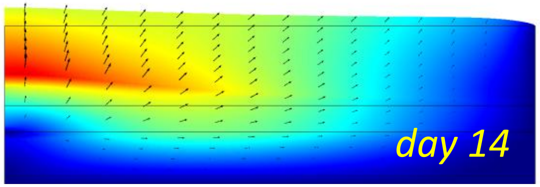


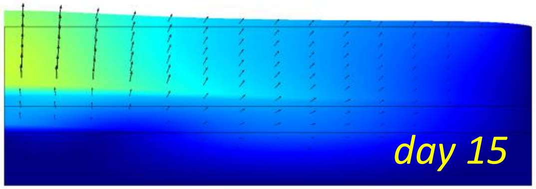


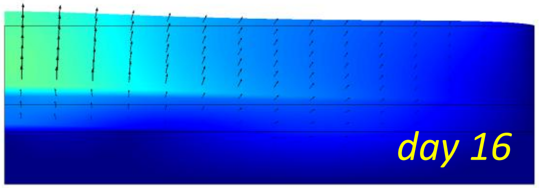


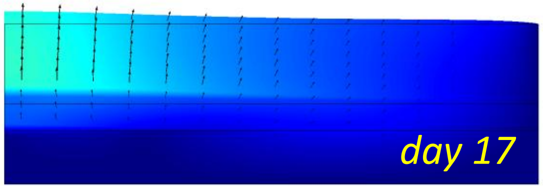










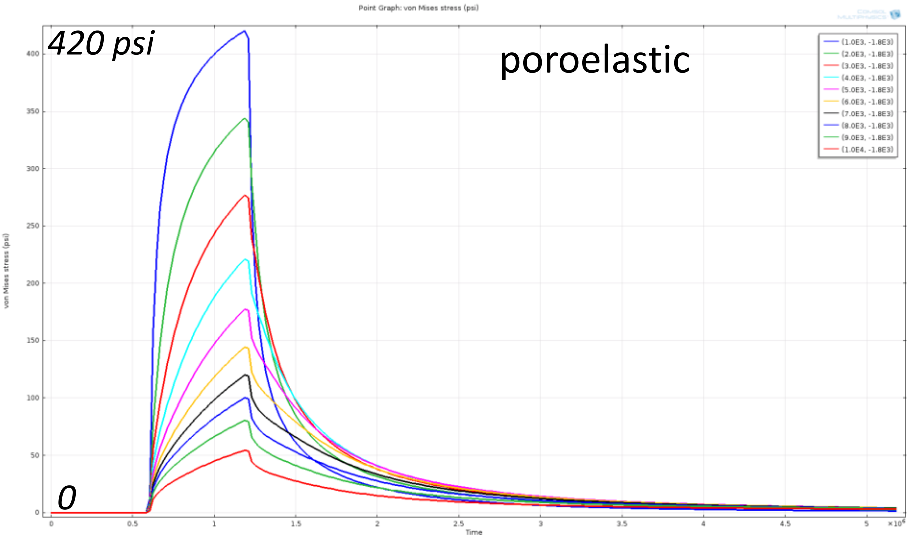


von Mises stress at injection depth vs time (planar symmetry)

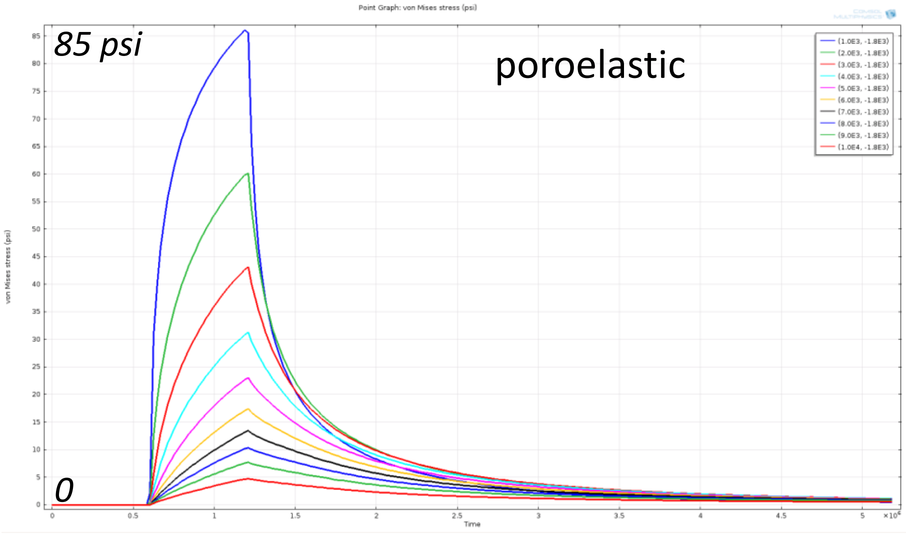
No solid framework to stress in Darcy model

Stress shows finite build-up and decay, indicating storage in injection interval
Stress varies non-linearly from well to far boundary

planar symmetry



axial symmetry



Key Points

The “solid” earth exhibits a poroelastic response relating pore pressure, stress, deformation, and failure.

Since models play a central role in the regulatory process governing underground injection, the poroelastic response of reservoir rocks should be included in models for onset of seismicity.

Models using a poroelastic reservoir show that, at least in some scenarios, the perturbation pressure is reduced from that found by traditional methods.

- This would allow higher injection pressures before onset of seismicity.

COMSOL provides an effective poroelastic modeling capability.

Further validation is needed before this approach can be incorporated into regulations.

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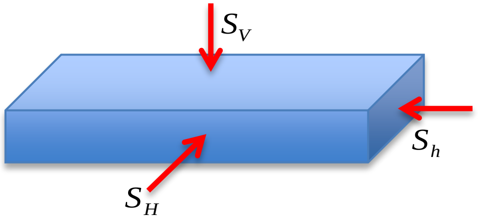
Extra Slides

Prior studies of injection-induced seismicity suffer from one or more deficiencies -- all related to stresses in the rock mass.[1]

Used flowing downhole pressure buildup at the well as an indicator of observed critical pressure.

Used “USGS Unaltered Stress Assumption” rather than properly formulated poroelastic model to calculate rock stresses.

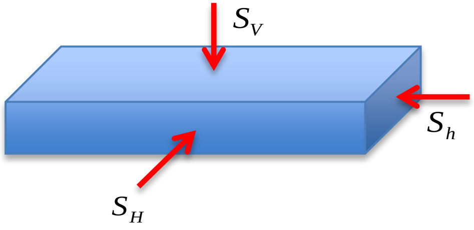
Used Mohr-Coulomb Criterion, rather than the more general Coulomb Criterion, to establish the predicted critical pressure.



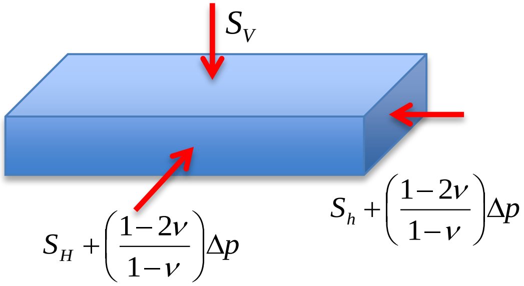
uniform layer,
stressed S_V, S_H, S_h

perturbation pressure
due to injection Δp

USGS Unaltered Stress Assumption



poroelastic stress model



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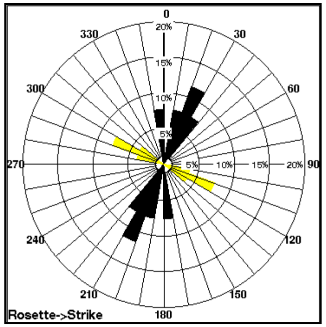
[1] Miller et al. [2010]

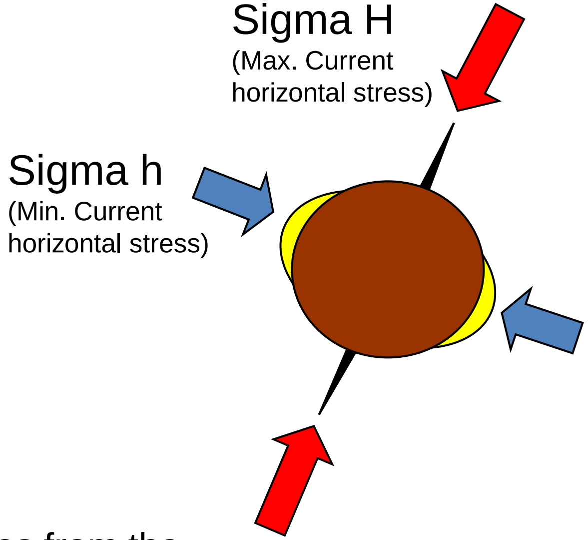
Orientation and magnitude of the background stresses come from well tests.

Breakouts and drilling-induced fractures observed in well logs indicate local stress field orientation.

Schlumberger FMI log



A hydrofrac test provides the best available estimate of the least horizontal stress.



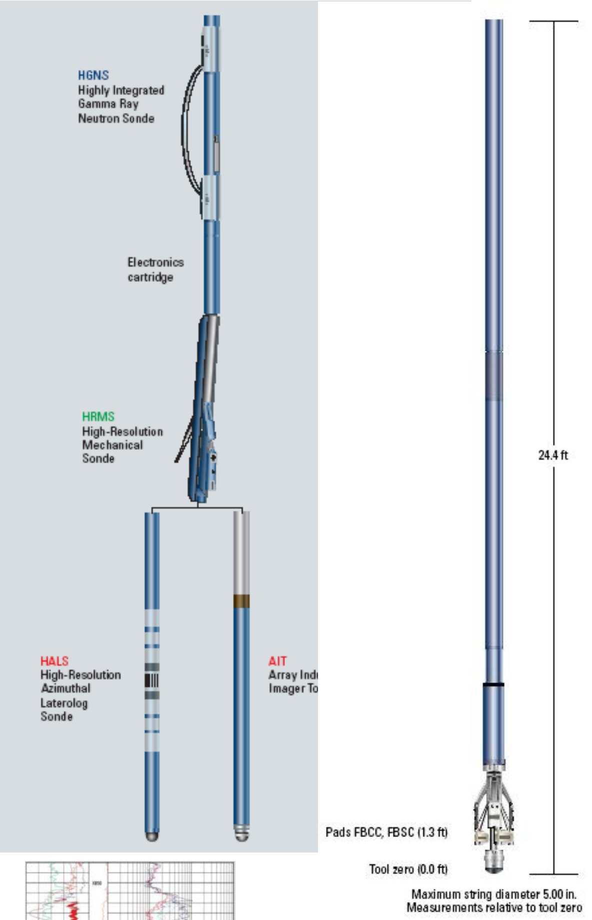
Sigma H
(Max. Current horizontal stress)

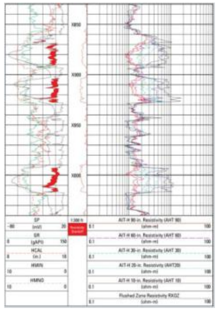
Sigma h
(Min. Current horizontal stress)

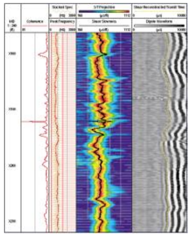
From Schlumberger's DSI log, we infer greatest horizontal stress.

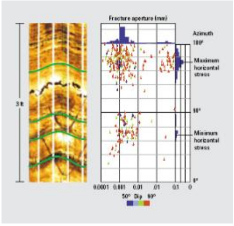
From the density log, we estimate the vertical stress, which comes from the "overburden" (gravity acting on mass density).

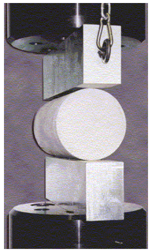
Rock mechanical data come from specialized wireline well logs, calibrated by lab measurements on selected rock cores…











… to provide a continuous record of rock mechanical properties down the well.