Stress, Fracturing and Borehole Integrity: Implications for Drilling, Completion and Disposal of Radioactive Waste at 3-5 km Depth in Crystalline Rock

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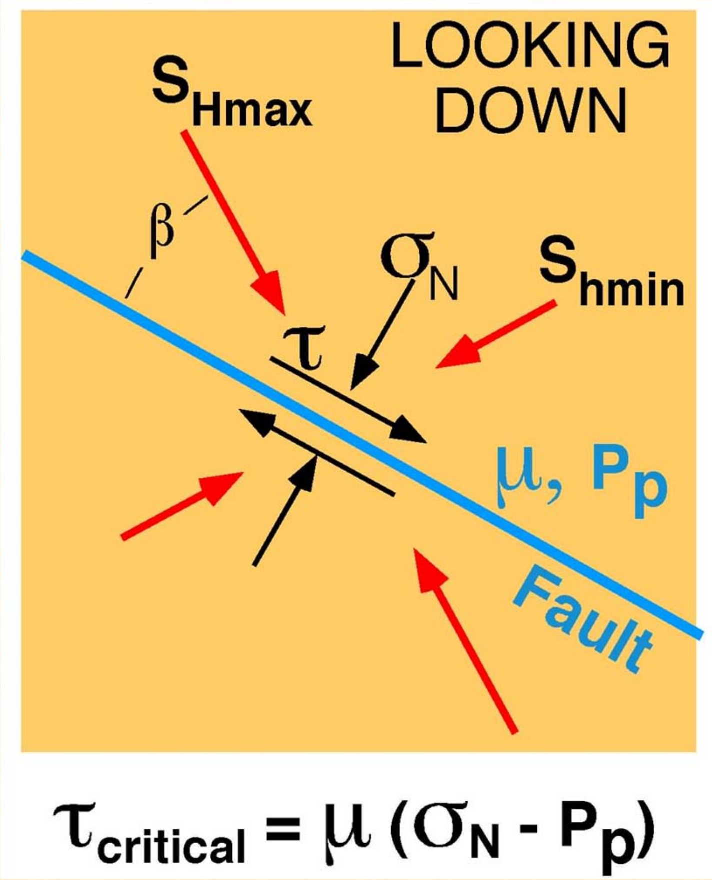
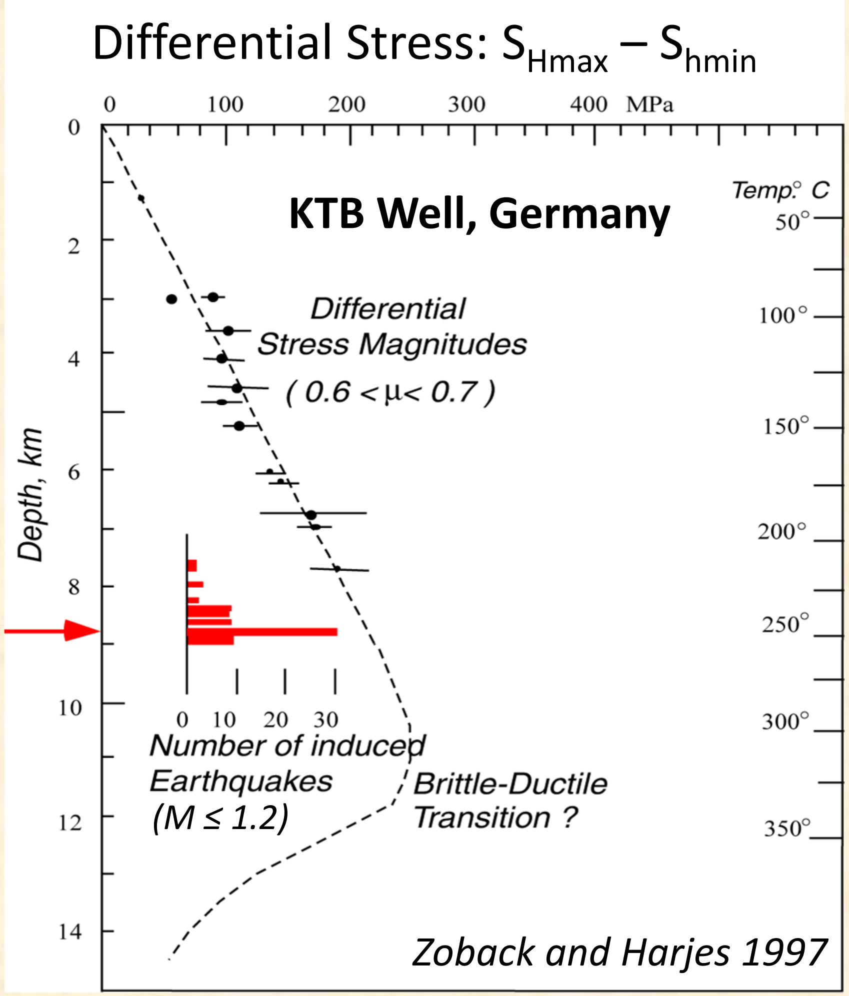
science for a changing world

State of Stress in the Earth's Crust: High Stress Differences Reflect Incipient Frictional Failure



Borehole stress measurements show that much of the Earth's crust is critically stressed: μ = 0.6 – 1.0 (Byerlee's Law)

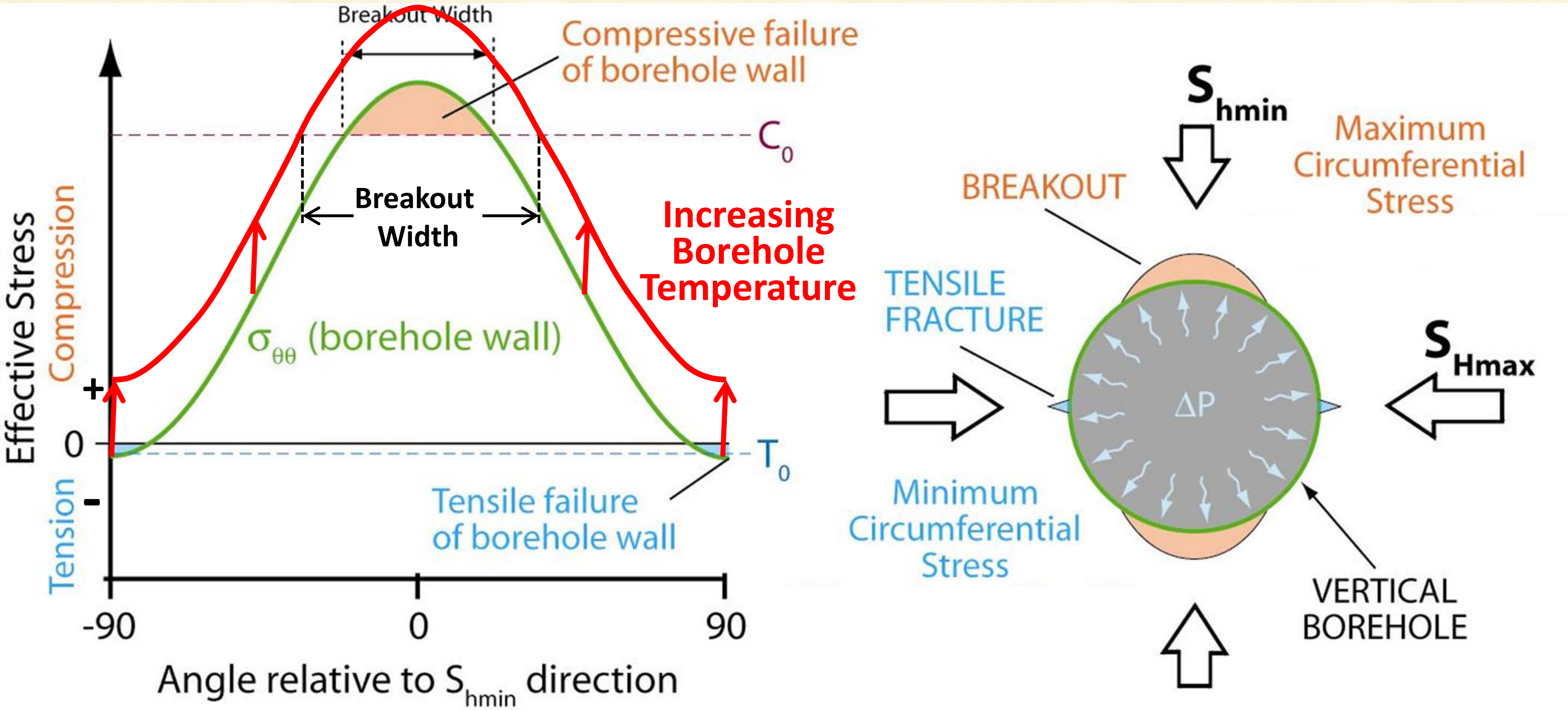
In low porosity crystalline rocks, fault slip increases permeability: basis for creation of *Enhanced Geothermal Systems*



Modeling shows these MEQs can be induced by ΔP_p < 1 MPa (c.a. 1% above ambient hydrostatic P_p)

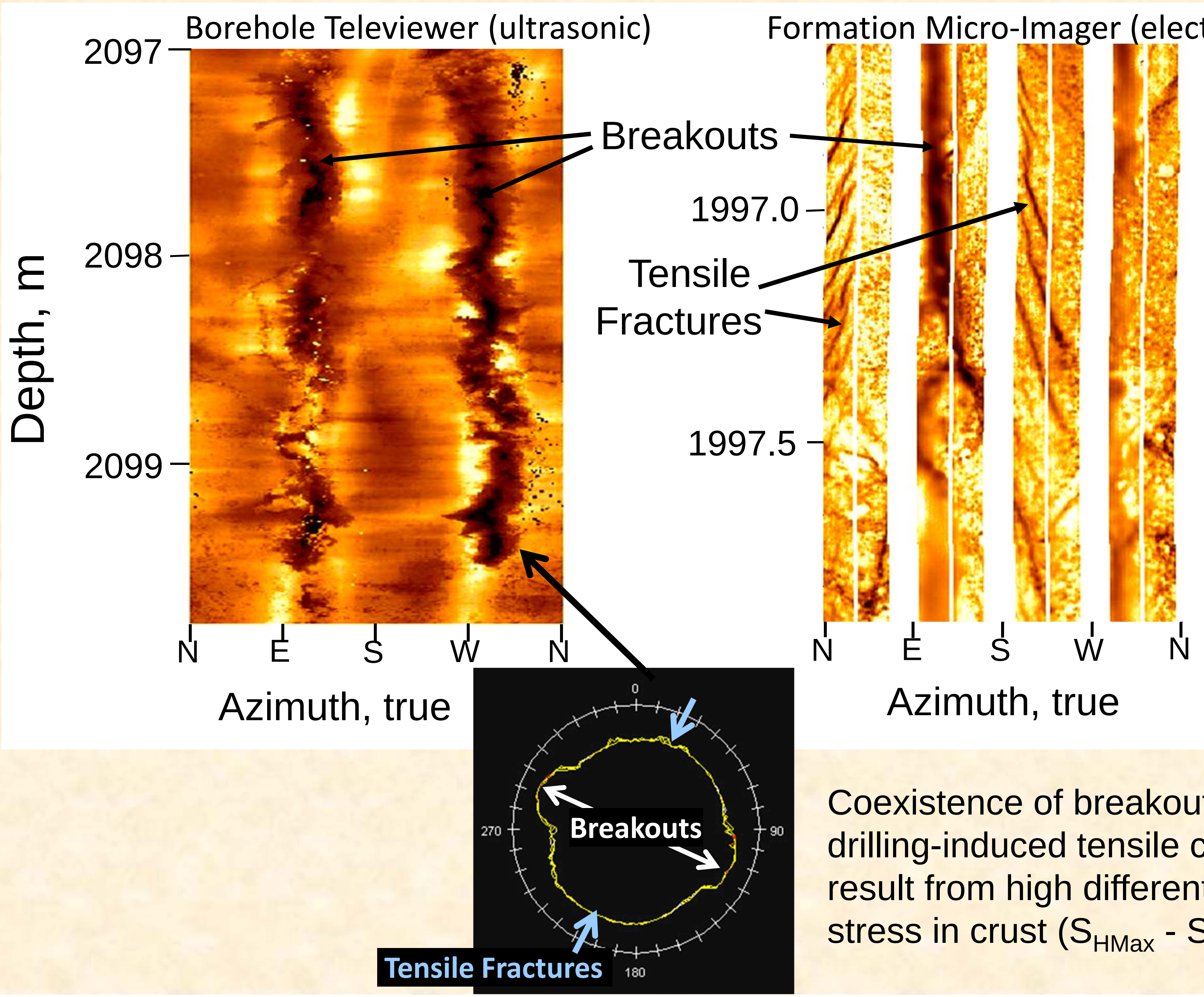
Relationship between Horizontal Principal Stresses and Drilling-Induced Failure

Elastic Stress Concentration Around a Vertical Well



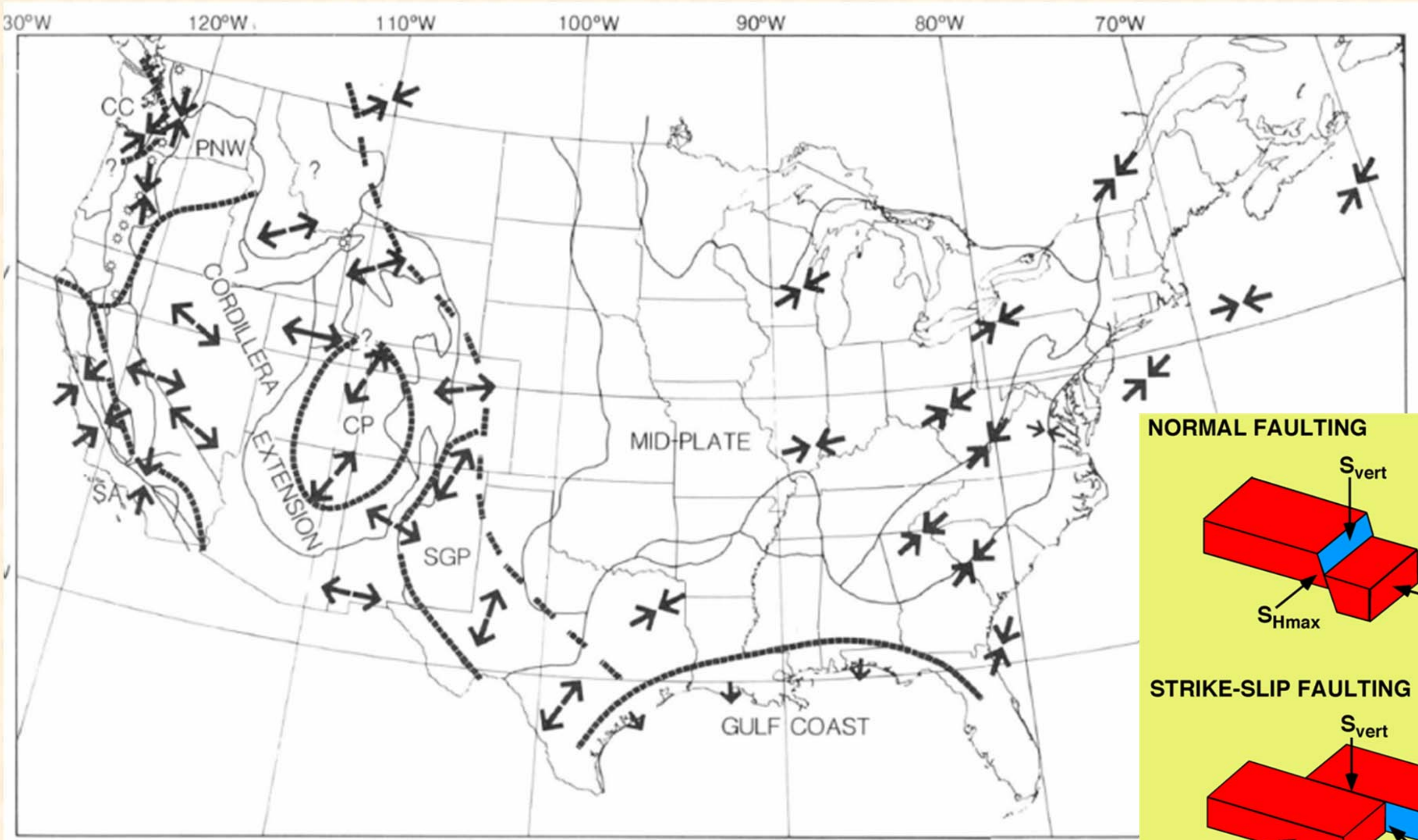
Principal stress magnitudes and orientations from observations of breakout and tensile fracture geometry, mini-hydraulic fracturing tests, geophysical well logs and lab tests on core.

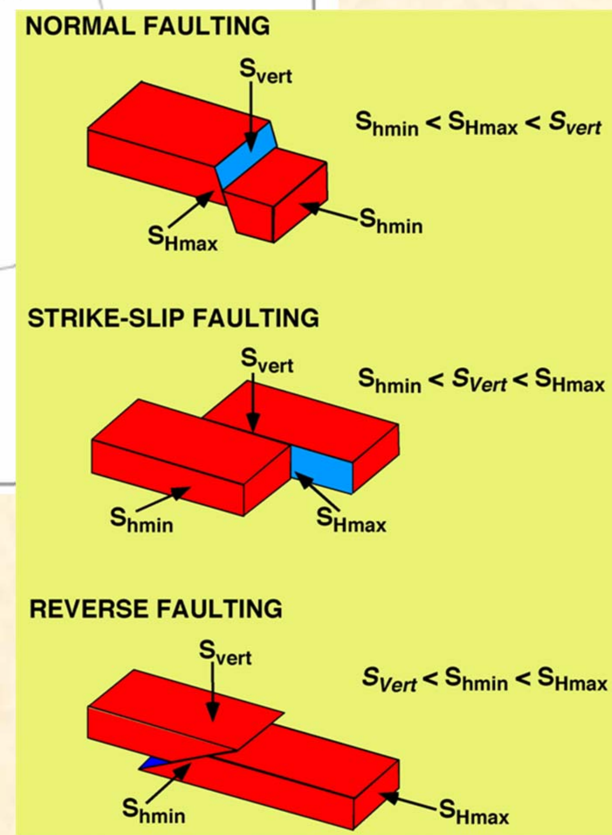
Drilling-Induced Borehole Failure: SAFOD Pilot Hole (granite)



Coexistence of breakouts and drilling-induced tensile cracks result from high differential stress in crust (S_{HMax} - S_{hmin})

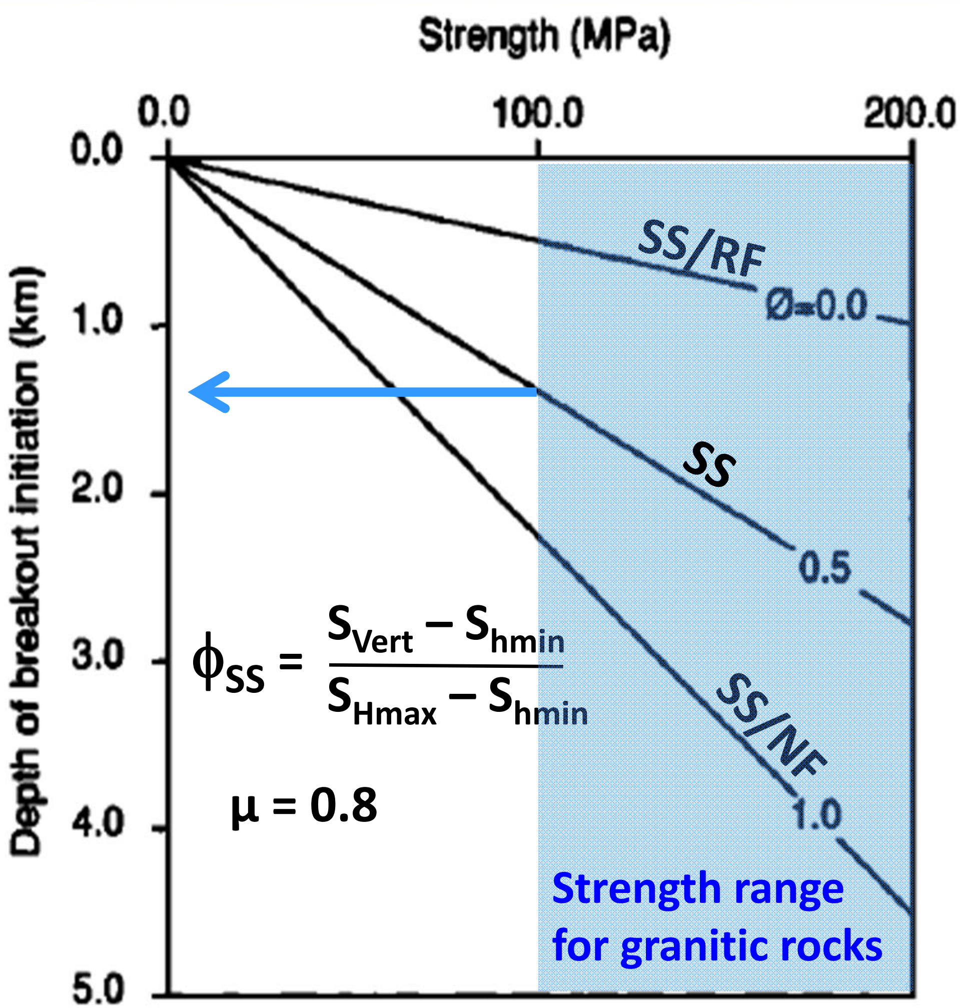
Most of the U.S. is Under a Compressional Stress Regime





Zoback and Zoback, 1989
(see also *World Stress Map*)

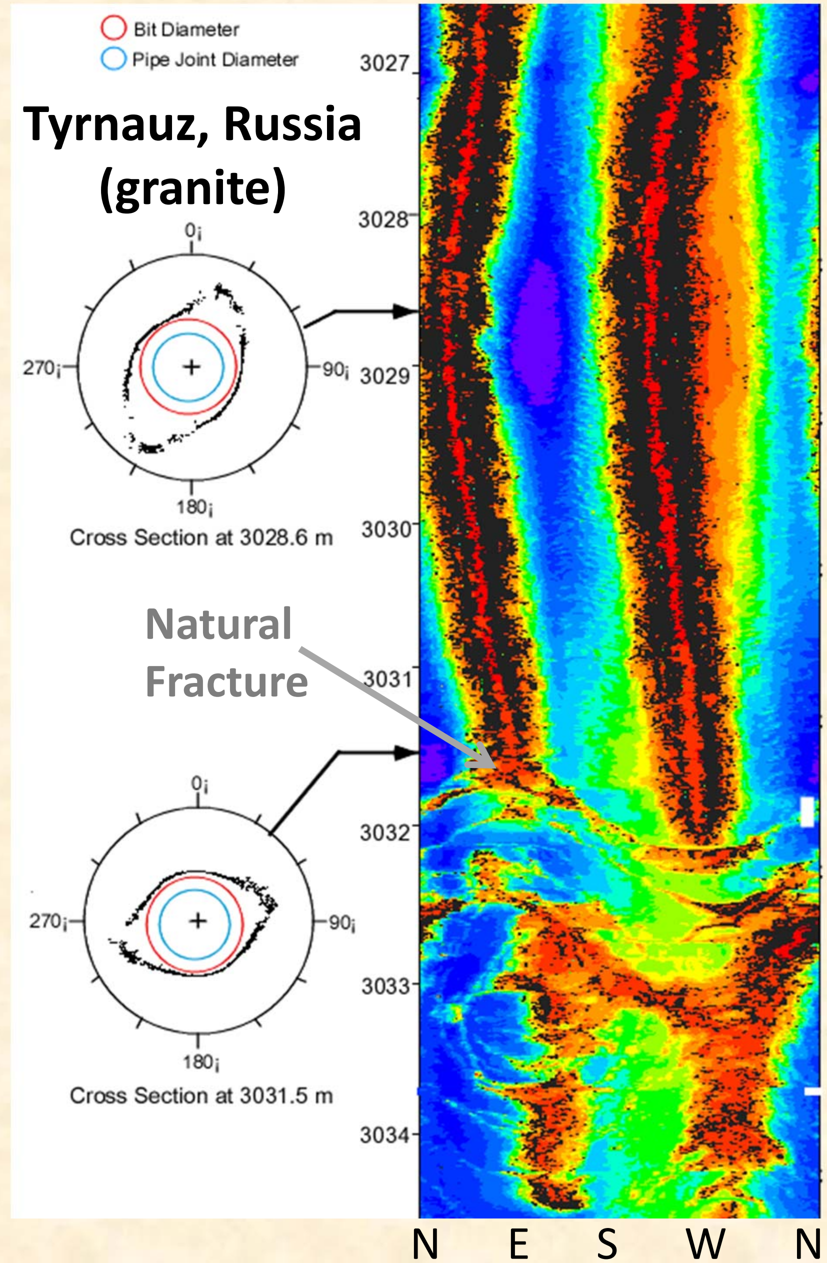
Depth to Breakout Initiation



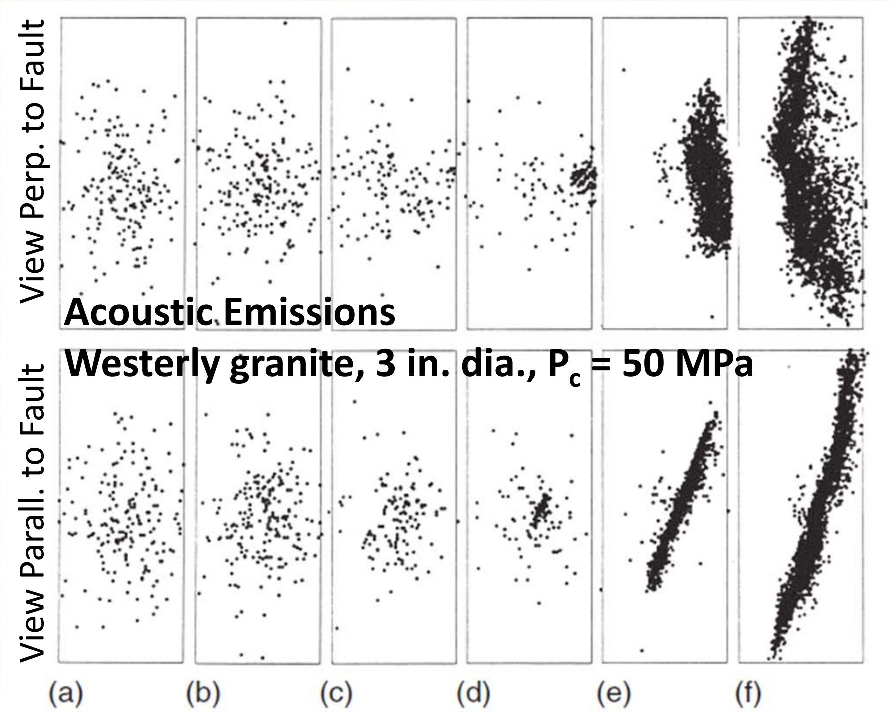
Shown for pure strike-slip faulting regime (ϕ = 0.5) plus transitional SS to reverse and normal faulting regimes

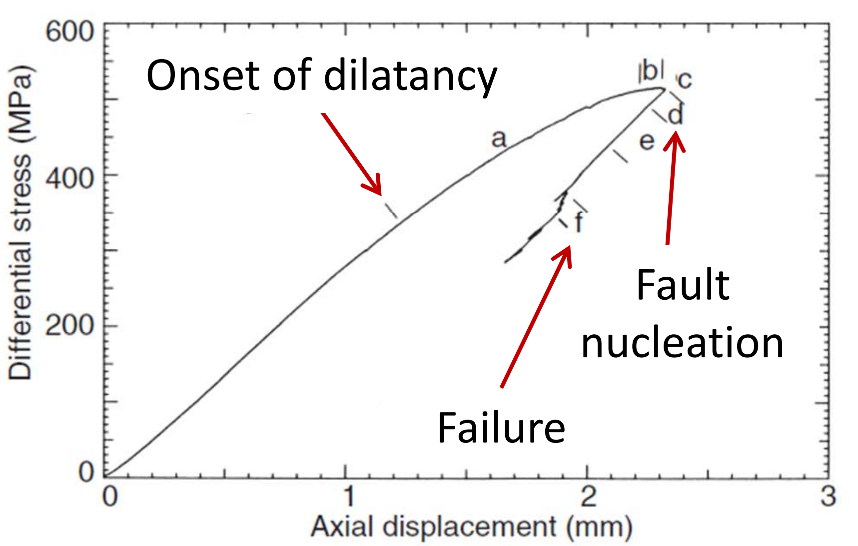
Moos and Zoback, 1990

Breakouts Can Be Huge in SS/RF Regimes at Depth ≥ 3 km

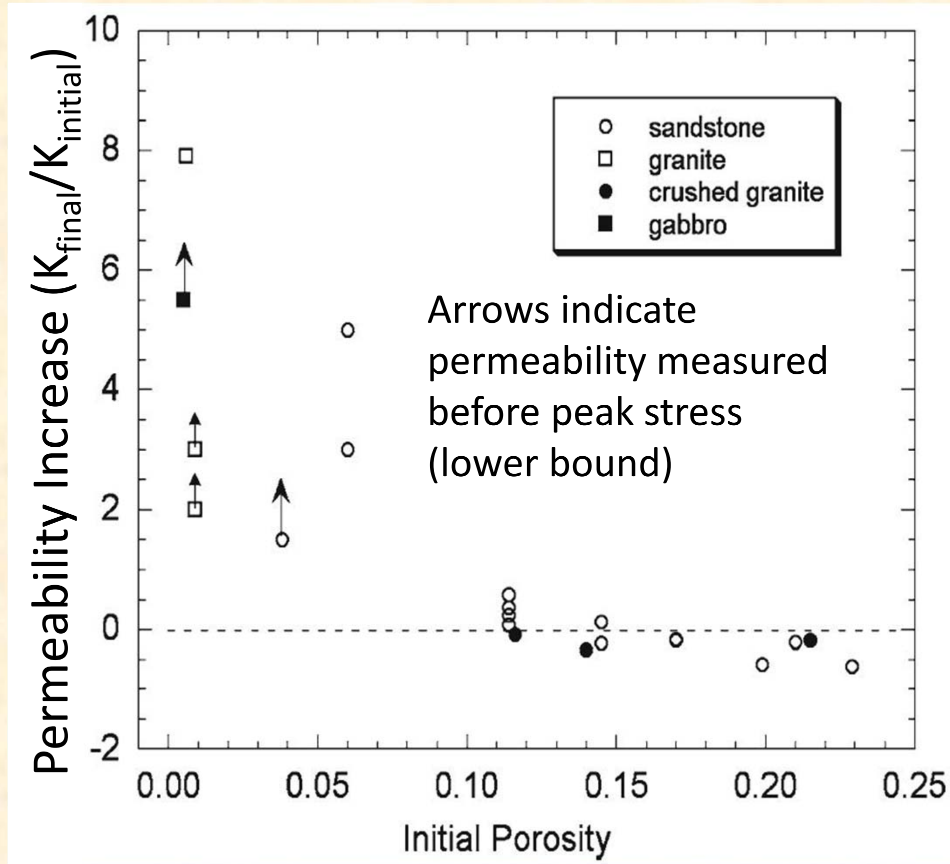


High Permeability Damage Zones Associated with Breakouts Could Provide Vertical Fluid Pathways Outside of Seals





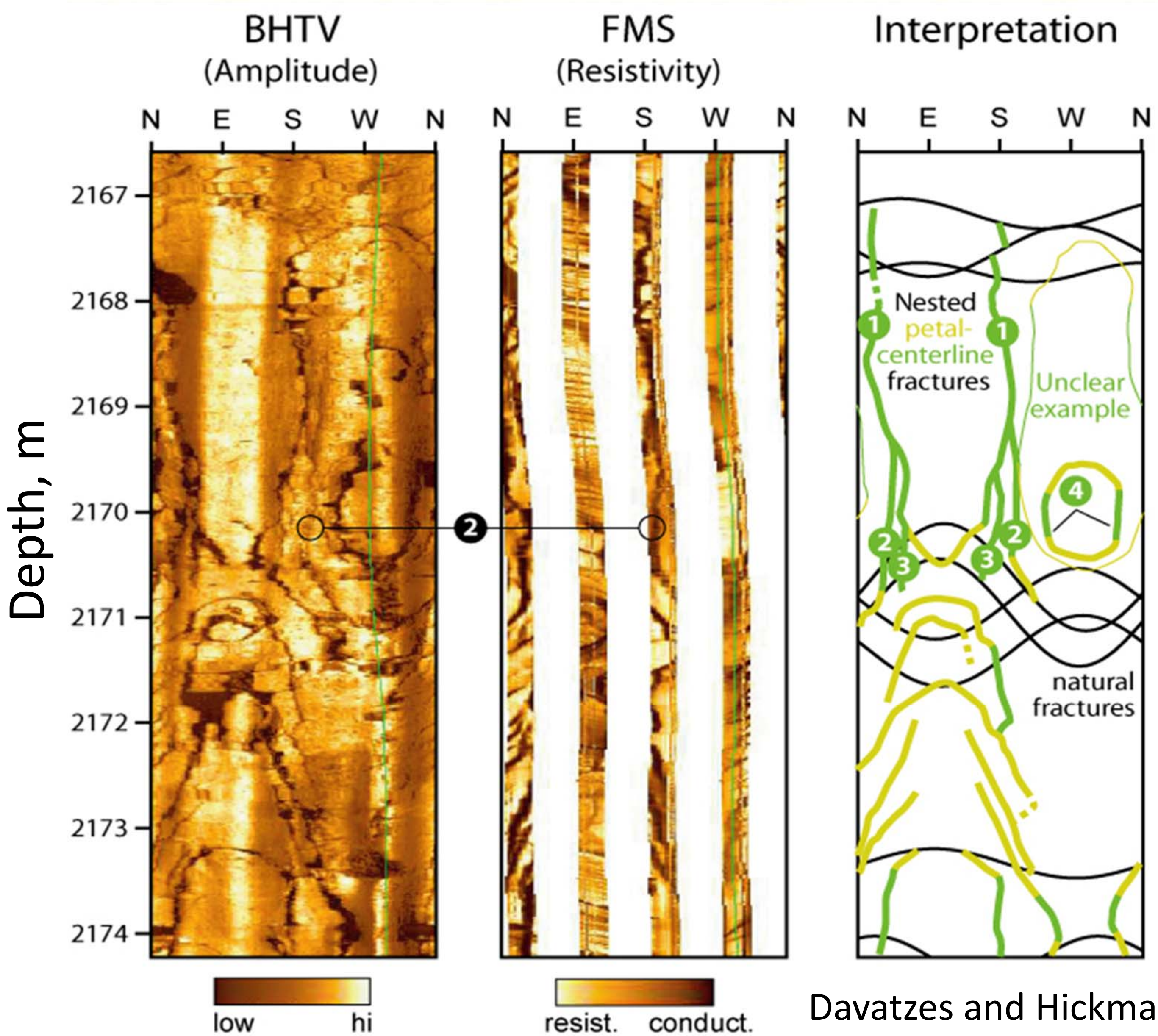
Increase in Permeability from Onset of Dilatancy to Peak Differential Stress (*pre-failure*)



Wong and Zhu, 1999

Lockner et al., 1991, 1992

Drilling Induced Tensile Fractures Can Be Extensive and Interact in Complex Ways with Natural Fracture Systems



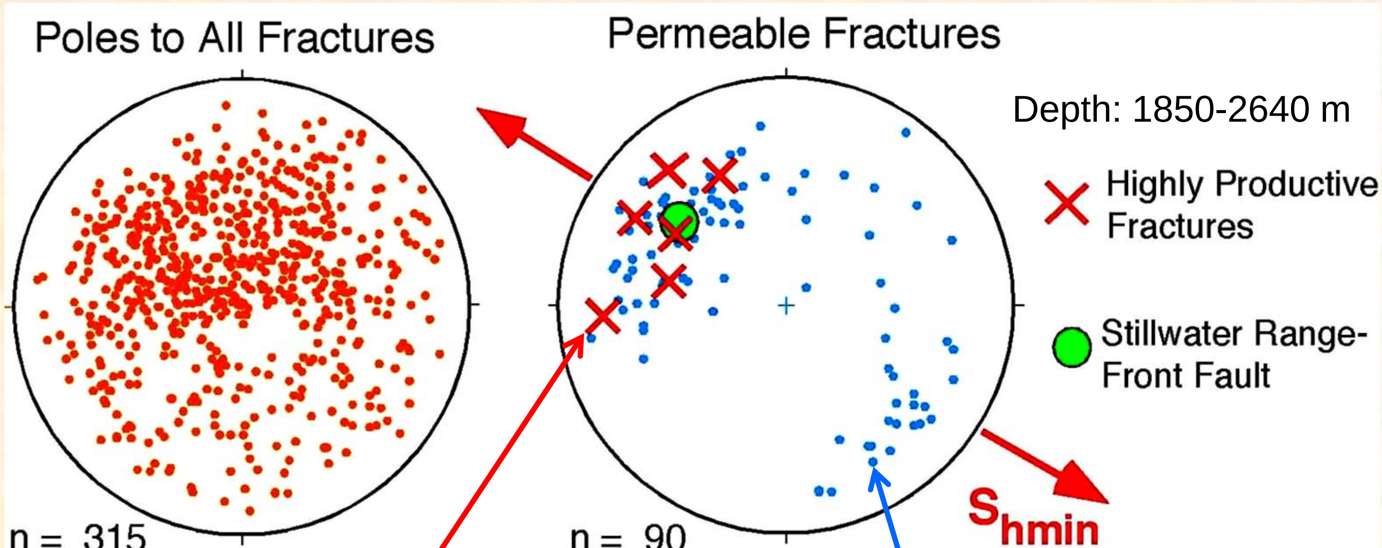
Can create multiple pathways for fluid bypass around seals, especially if natural fractures reactivated (dilated) due to drilling-induced stress or fluid pressure disturbances.

Coso Geothermal Field, CA (granitic rocks)

Davatzes and Hickman, 2010

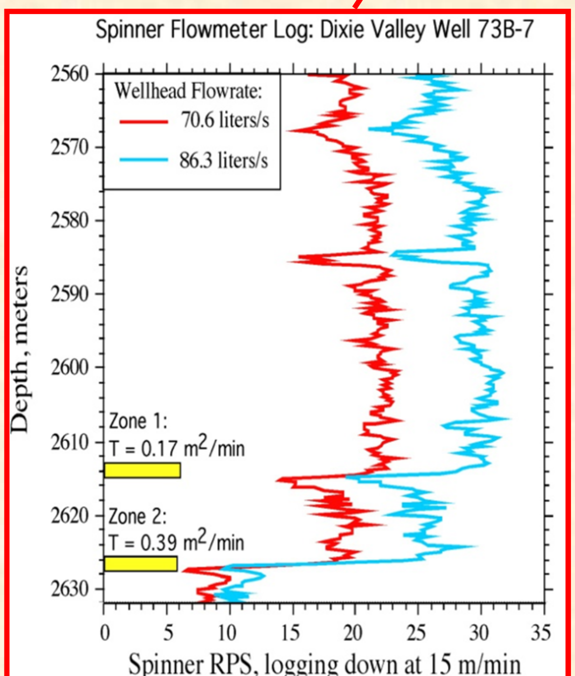
Permeability in Low-Porosity Geothermal Systems Often Dominated by a Few Fractures

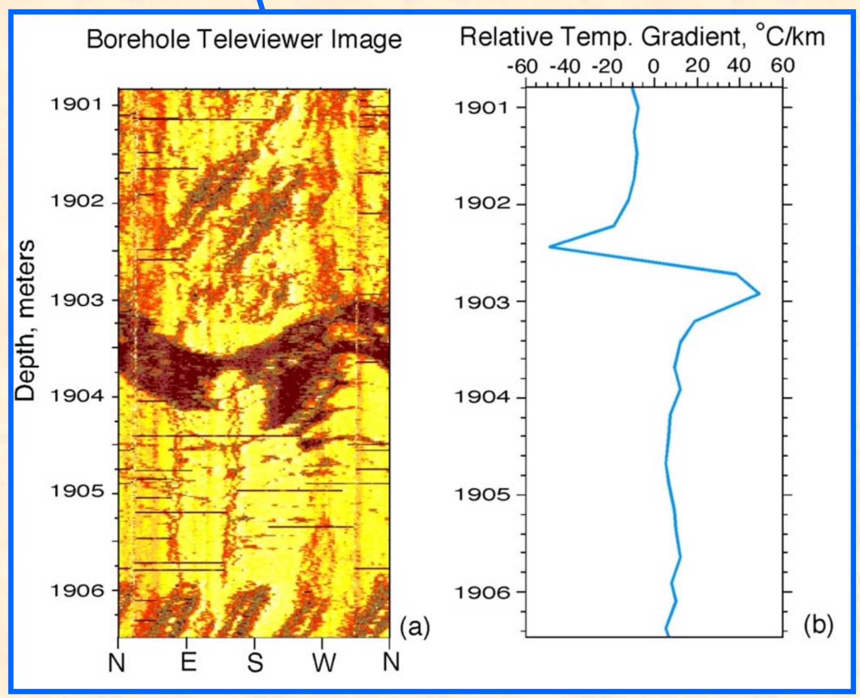
Dixie Valley Geothermal Field, NV, Production Well 73B-7



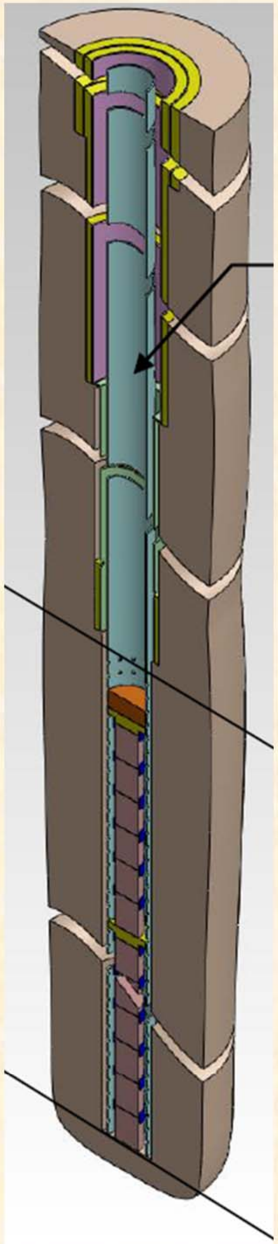
lower hemisphere stereographic projections

Gabbro and anorthosite





Hickman et al., 1998; Barton et al., 1998



After waste in place, but before removing casing (Arnold et al., 2011)

Summary: Borehole Integrity Issues

- Extensive wellbore failure will complicate drilling, completion and seal installation and could compromise ***long-term*** integrity of seals:
  - Breakouts become more severe with depth, and can even lead to complete circumferential borehole failure (esp. in RF stress regime). Severe breakouts pose major challenges to drilling and completion.
  - Breakouts could pose operational challenges when cementing casing and setting multiple seals in long open-hole interval above canisters.
  - High-permeability damage zones produced by breakouts, drilling-induced tensile fractures and dilated natural fractures could provide “short-circuit” pathways around seals.
- Increasing temperature after canister emplacement could lead to:
  - Increase in compressive hoop stress ($\sigma_{\theta\theta}$), promoting continued breakout growth and borehole enlargement/collapse.
  - Thermal pressurization of borehole fluids, reactivating nearby faults (esp. if slightly permeable) and significantly increasing fracture permeability.
  - Establishment of hydrothermal convection system, with unknown impact on permeability evolution and contaminant transport.
  - Microcracking due to differential thermal expansion (esp. quartz-rich rocks), increasing matrix permeability and decreasing rock strength.
- Geothermal drilling experience shows that a few fractures can dominate permeability in crystalline rock, allowing heat and mass transport over large distances. *How can we be assured that these high-permeability fractures (or faults) will* ***not*** *be close enough to a borehole repository to compromise geologic containment?*