Deep Borehole Field Test Site Characterization

Kristopher L. Kuhlman
Sandia National Laboratories

U.S. Nuclear Waste Technical Review Board Briefing

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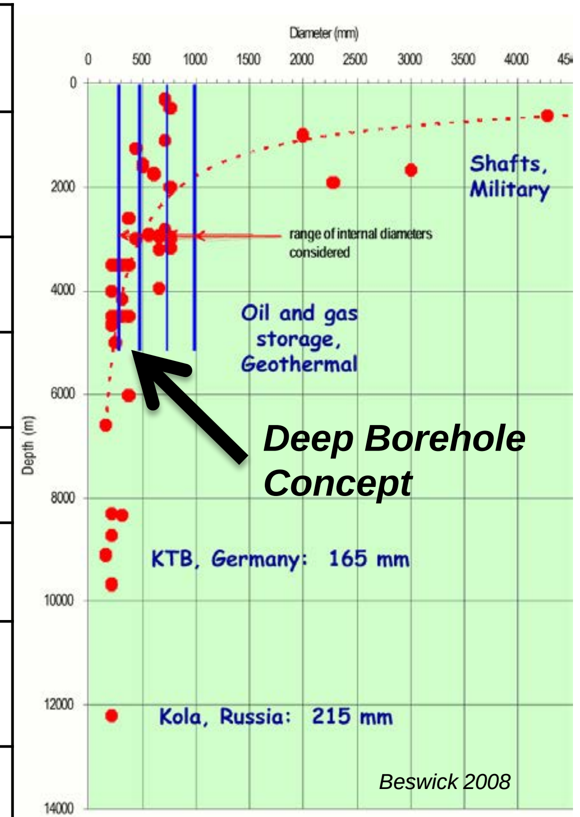
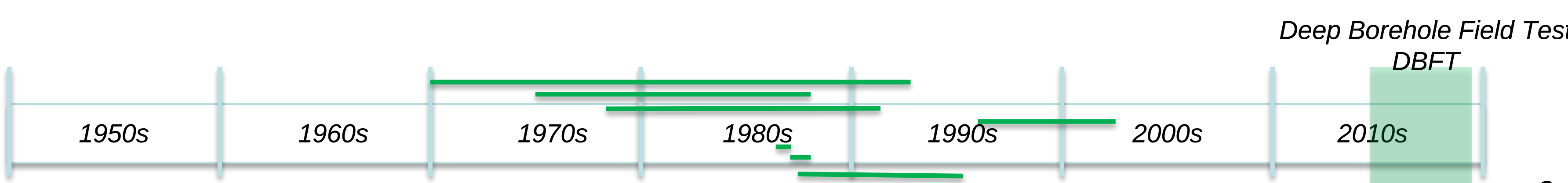
Deep Crystalline Drilling

Name	Location	Years	Depth [km]	Diam. [in]	Purpose
Kola SG-3	NW USSR	1970-1992	12.2	8½	Geologic Exploration + Technology Development
Fenton Hill (3)	New Mexico	1975-1987	3, 4.2, 4.6	8¾, 9⅞	Enhanced Geothermal
Urach-3	SW Germany	1978-1992	4.4	5½	Enhanced Geothermal
Gravberg	Central Sweden	1986-1987	6.6	6½	Gas Wildcat in Siljan Impact Structure
Cajon Pass	California	1987-1988	3.5	6¼	Geomechanics near San Andreas Fault
KTB (2)	SE Germany	1987-1994	4, 9.1	6, 6½	Geologic Exploration + Technology Development
Soultz-sous-Forêts GPK (3)	NE France	1995-2003	5.1, 5.1, 5.3	9⅝	Enhanced Geothermal





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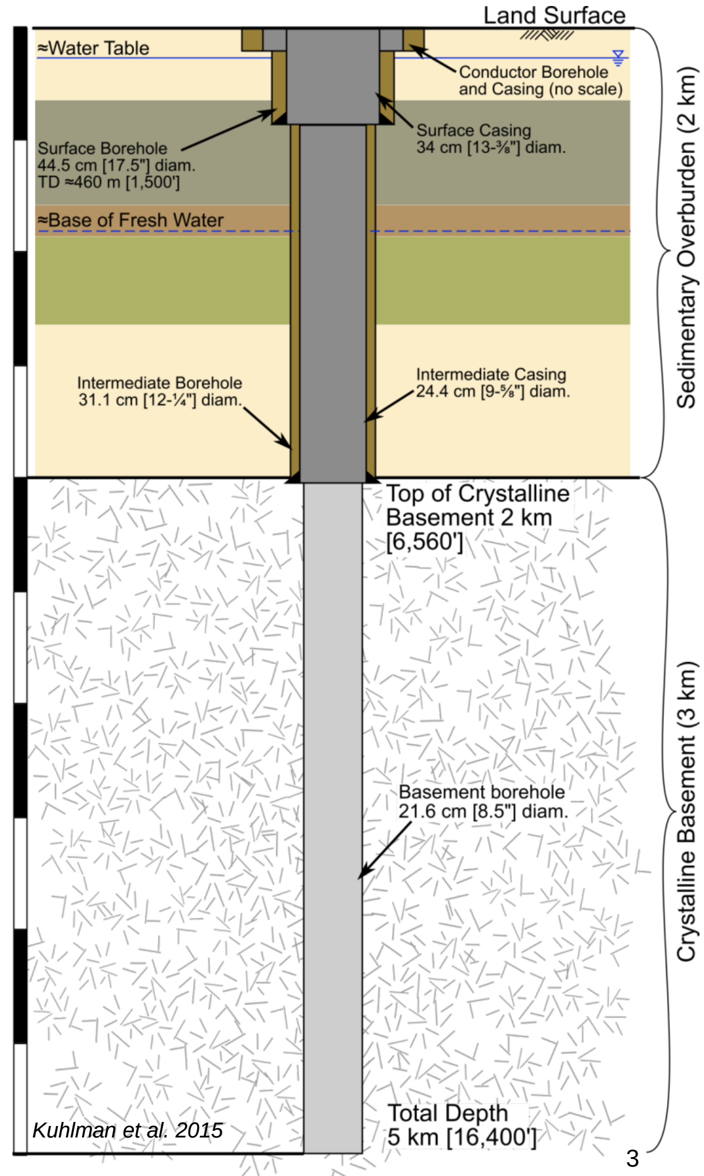
Characterization Borehole

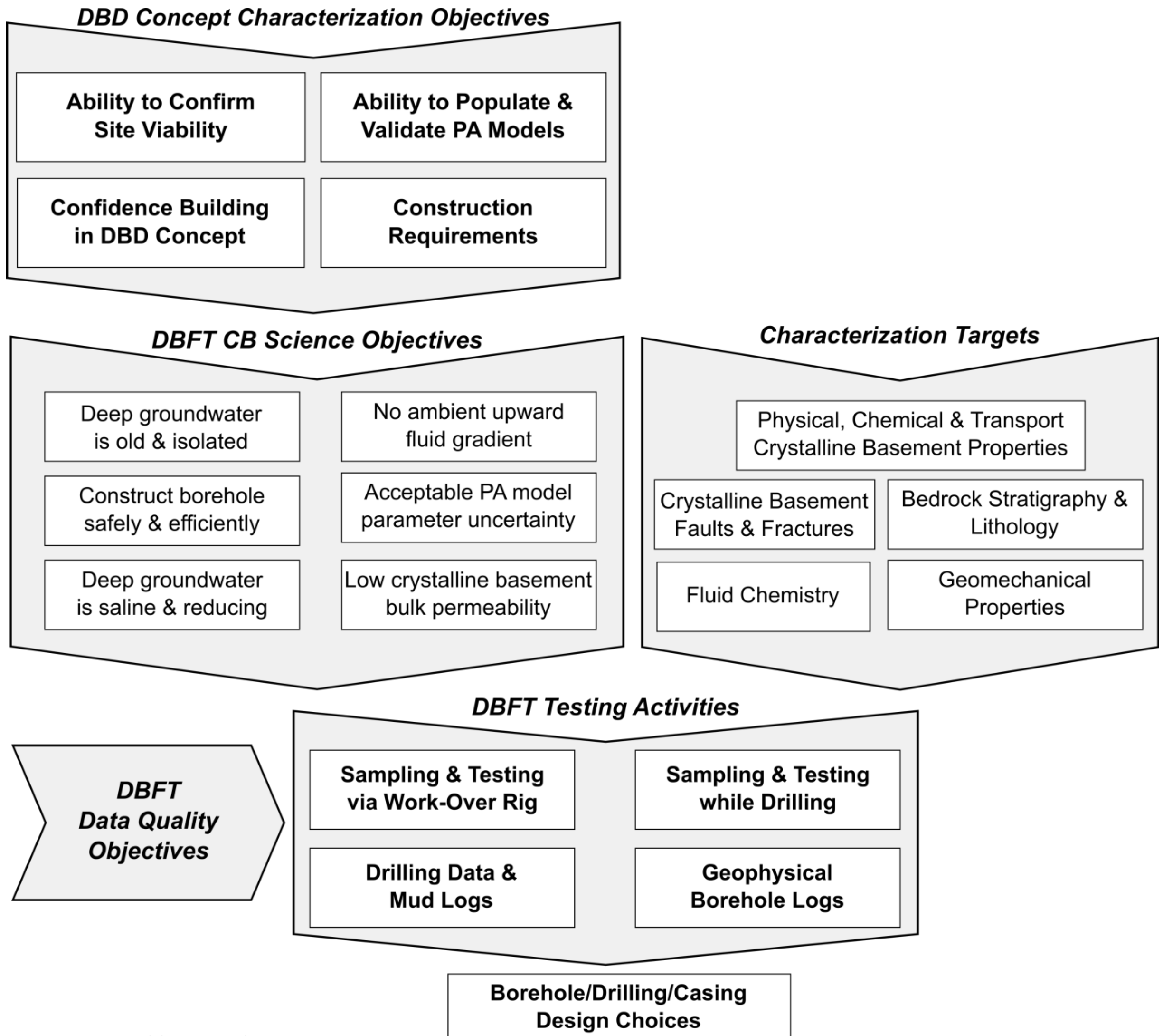
- **Drill/case sedimentary section**
  - **Minimal testing (not DBFT focus)**
- **Drill crystalline basement section**
  - **Core 150 m over 3 km (5%)**
  - **Hydrofracture stress tests**
  - **Borehole geophysics**
  - **Basement production log**
  - **Pore/fracture water samples**
- **Packer tool via work-over rig**
  - **Shut-in pressure tests**
  - **Packer pumping/slug tests**
  - **Tracer and heater tests**

Borehole designed to maximize likelihood of good samples



Characterization Targets/Methods

- **Field Test Drivers**
  - Why?
- **Science Objectives**
  - What are goals?
- **Char. Targets**
  - What to measure?
- **Field Activities**
  - What will we do?
- **Borehole Design**



Kuhlman et al. 2015

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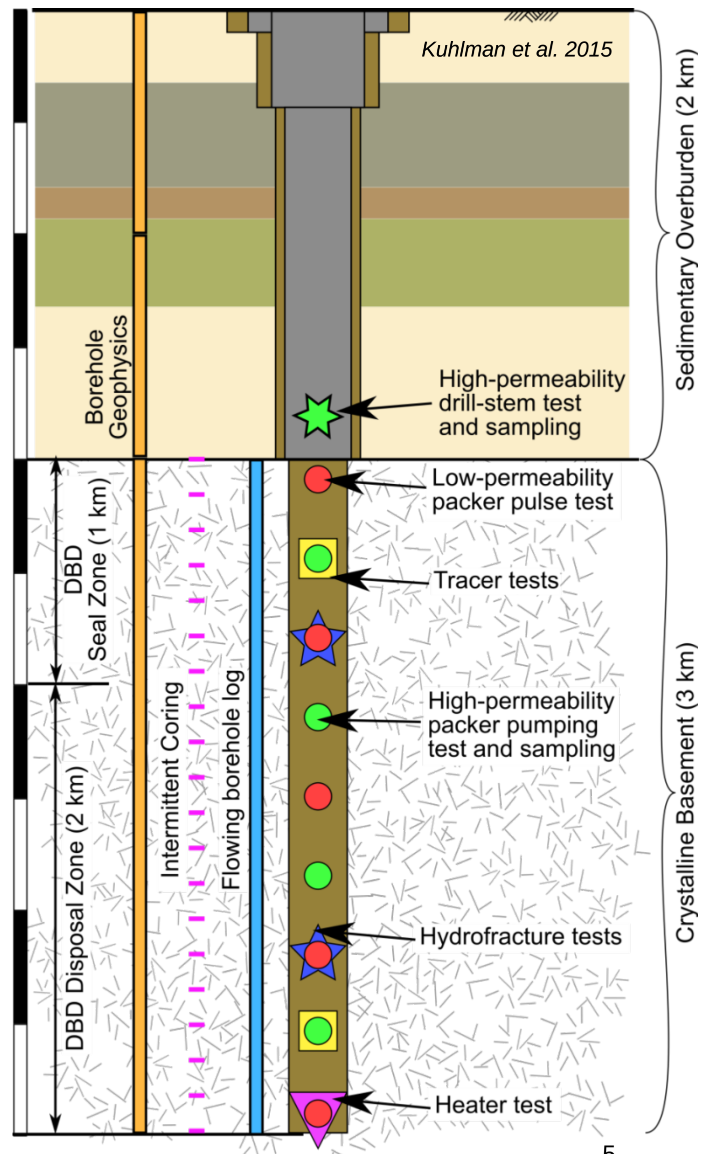
CB: Profiles

- **Borehole Geophysics**
- **Coring/Cuttings/Rock Flour**
- **Sample-based Profiles**
  - **Fluid density/temperature/major ions**
  - **Pumped samples from high-*k* regions**
  - **Samples from cores in low-*k* regions**
- **Drilling Parameters Logging**
  - **Mud fluids/solids/dissolved gases**
  - **Torque, weight-on-bit, etc.**
- **Testing-Based Profiles**
  - **Static formation pressure**
  - **Formation hydraulic/transport properties**
  - ***In situ* stress (hydrofrac + breakouts)**

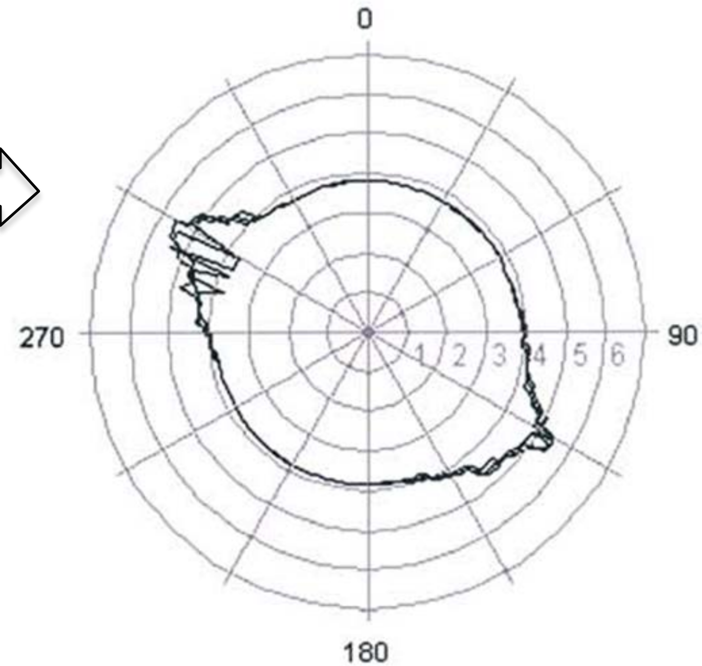


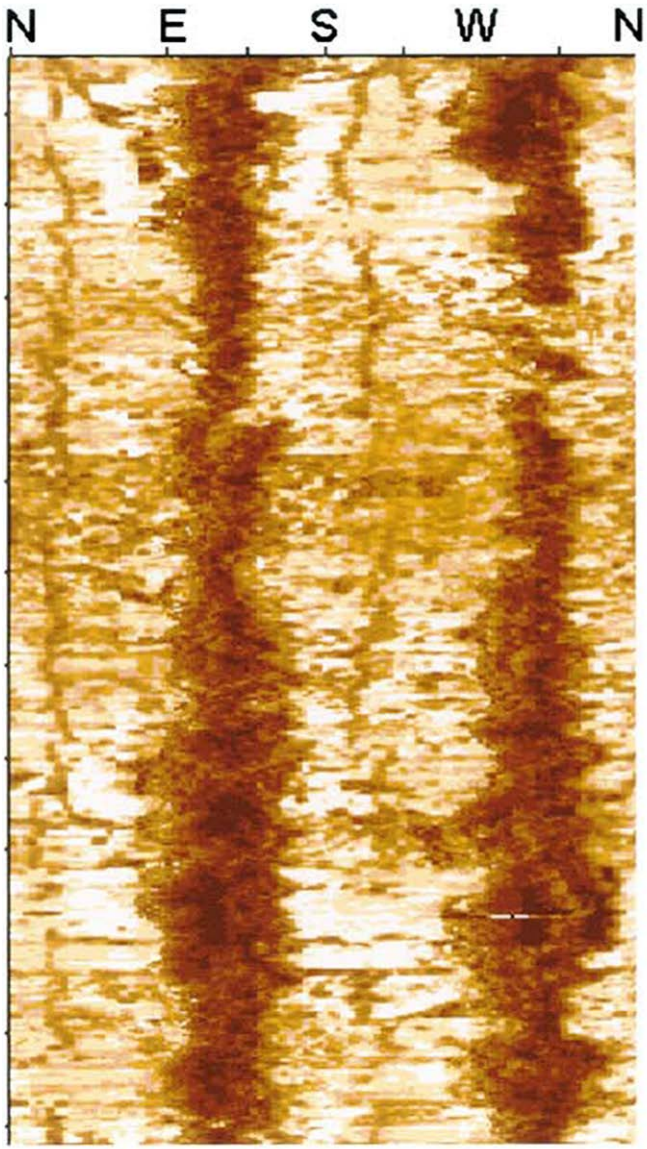
Borehole Breakouts: Historical

- Leeman (1964) was the first to consider breakouts on a mine wall as being the result of stress concentration
- Cox (1970), a Schlumberger field engineer, first noted their regional persistence
- Bell and Gough (1979) noted that the breakouts were aligned with the regional stresses
- Zoback et al. (1985) theoretically related far-field stresses to breakout size characteristics
- Laboratory experiments (Haimson and Herrick 1986) supported the suppositions of Bell and Gough and Zoback et al.

Wellbore Breakout Images

Wellbore cross-sections from digital processing of the televiewer signal

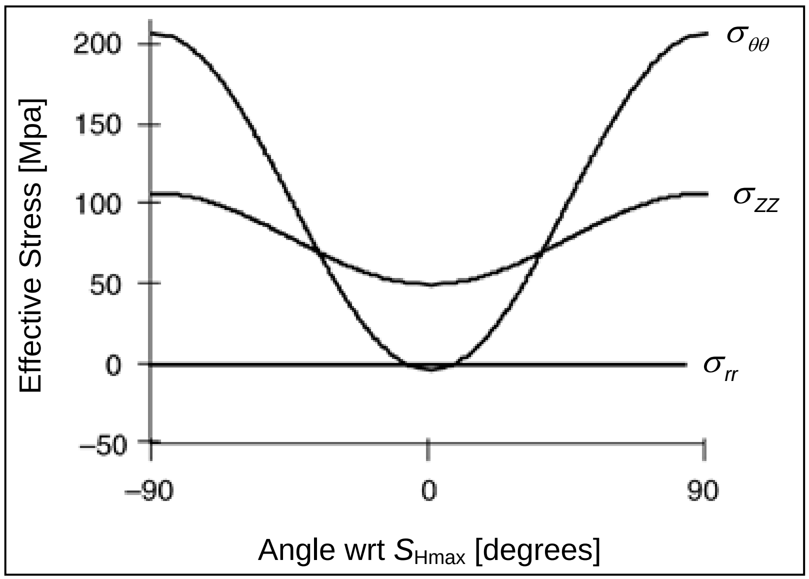




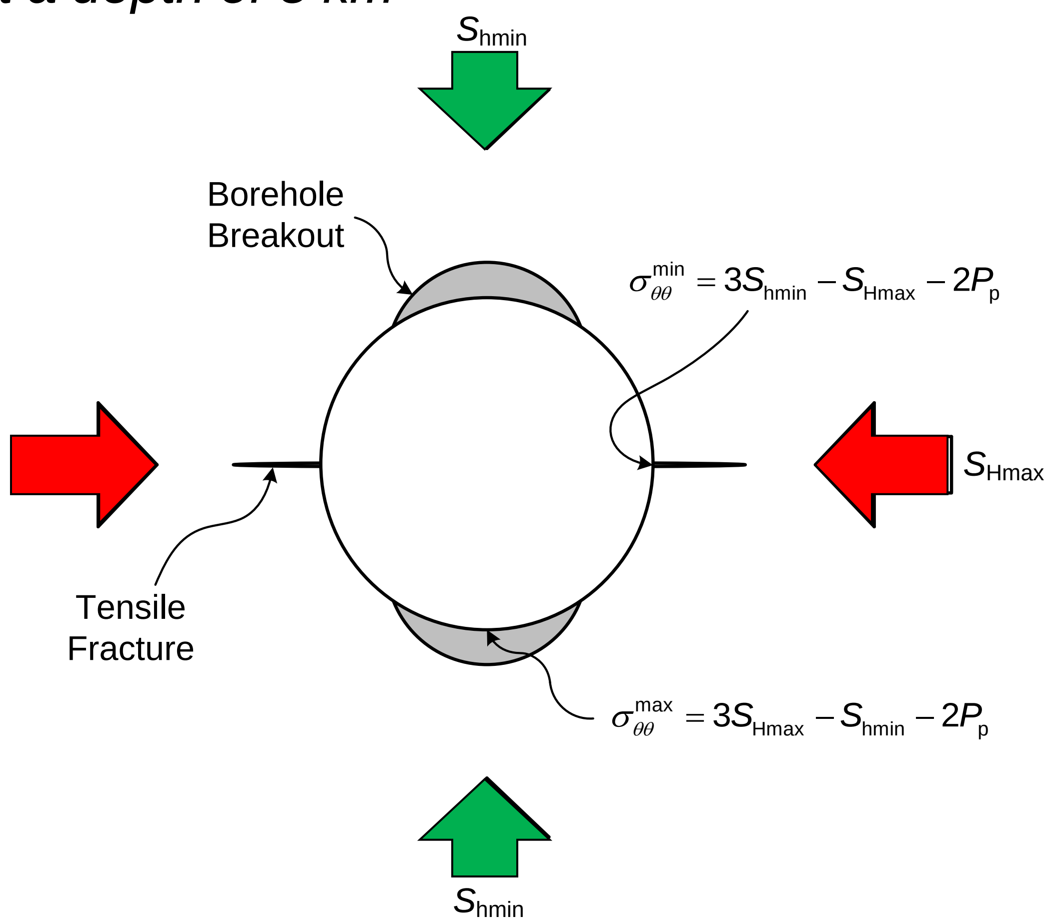
Unwrapped image from an ultrasonic borehole televiewer. Breakouts appear as dark bands of low reflectance on opposite sides of the wellbore. (Zoback et al. 2003)

Stresses Around Wellbore

Variation of effective principal stresses around a borehole with respect to S_{Hmax} for a hypothetical strike-slip/normal faulting stress state ($S_{Hmax} \approx S_v > S_{hmin}$) at a depth of 5 km



200 MPa = 29,000 psi



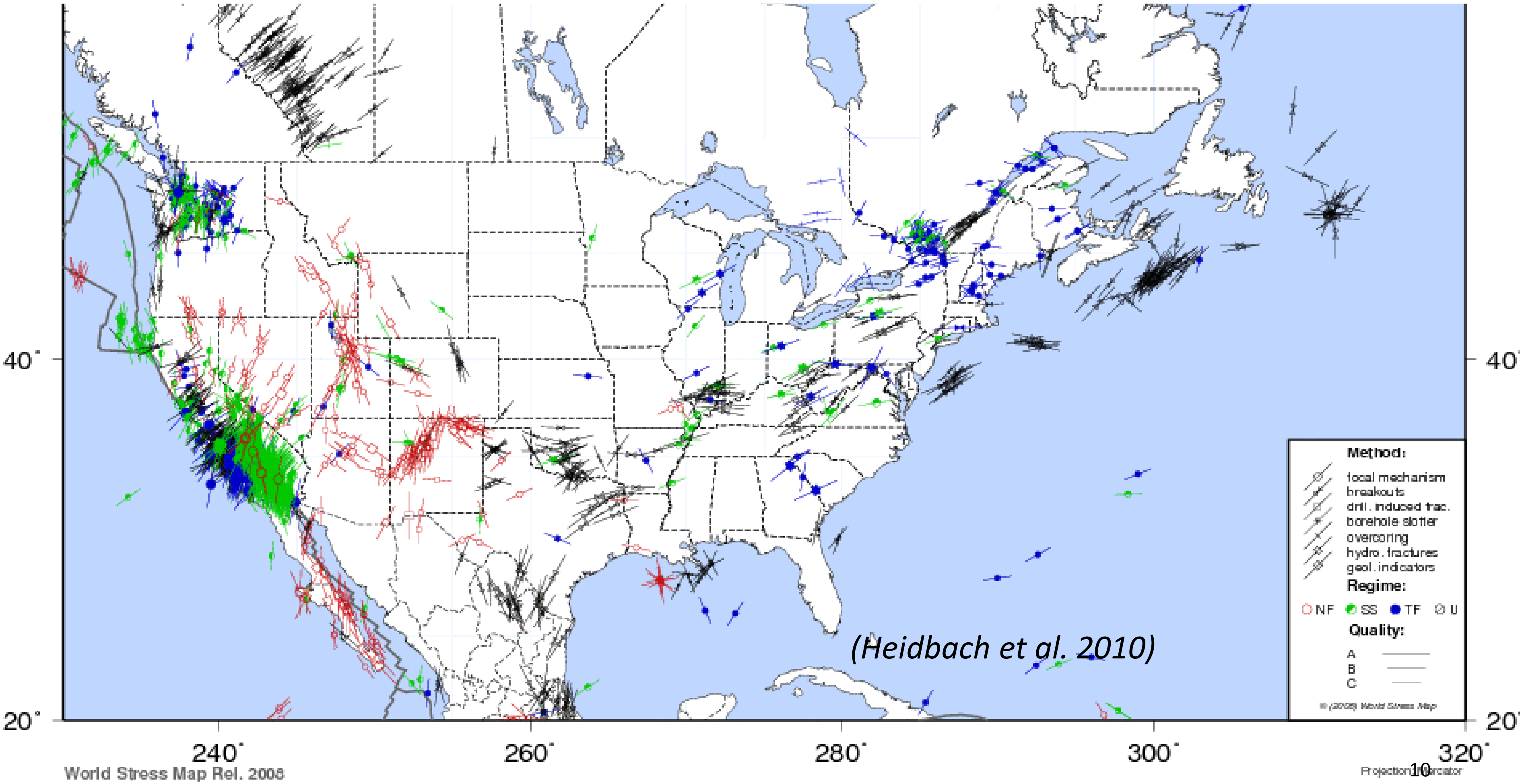
Modified from Moos (2006)

Breakouts in Deep Boreholes

- **San Andreas Fault Observatory at Depth – 3.1 km**
  - Breakouts from 0.8 to 2.2 km (pilot hole total depth, Hickman and Zoback 2004)
- **Cajon Pass (Baumgärtner et al. 1991; Shamir and Zoback 1992)**
  - Breakouts from 1.7- 3.5 km (to total depth)
- **KTB (Mastin et al. 1991; Brudy et al. 1997) – 9.1 km total depth**
  - Breakouts used for stress orientation below 3 km
    [VB (pilot hole) – 3 to 4 km; HB (main hole) – 3 to 8.6 km]
- **Kola Superdeep Borehole – 12.2 km total depth**
  - Breakouts start at 0.5 km (Kozlovsky 1984; Zoback et al. 1986)
- **Blanche-1 (S. Australian HDR geothermal well)**
  - Breakouts from 1.1- 1.4 km (1.9 km total depth) (Klee et al. 2011)

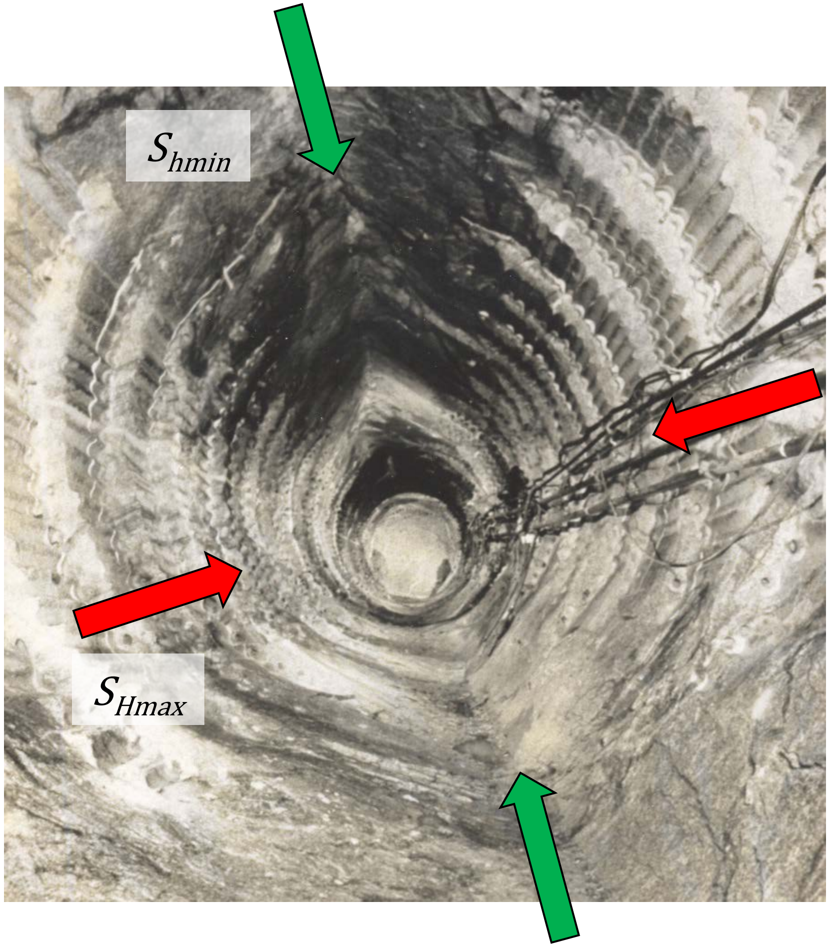
Predicting Breakouts

- **World Stress Map**
  - based on fault plane solutions and breakout orientations



Breakouts in Granitic Rock

- **Dog-ear breakout shape is stable**
  - modeling (Zheng et al. 1989, Herrick and Haimson 1994; Shen et al. 2002);
  - laboratory experiments (Haimson 2007)
- **Breakouts in granitic rock are generally shallow (Zang and Stephansson 2010)**



AECL underground research lab in Pinawa, Manitoba Lee & Haimson (1993).

Addressing Breakouts in DBFT

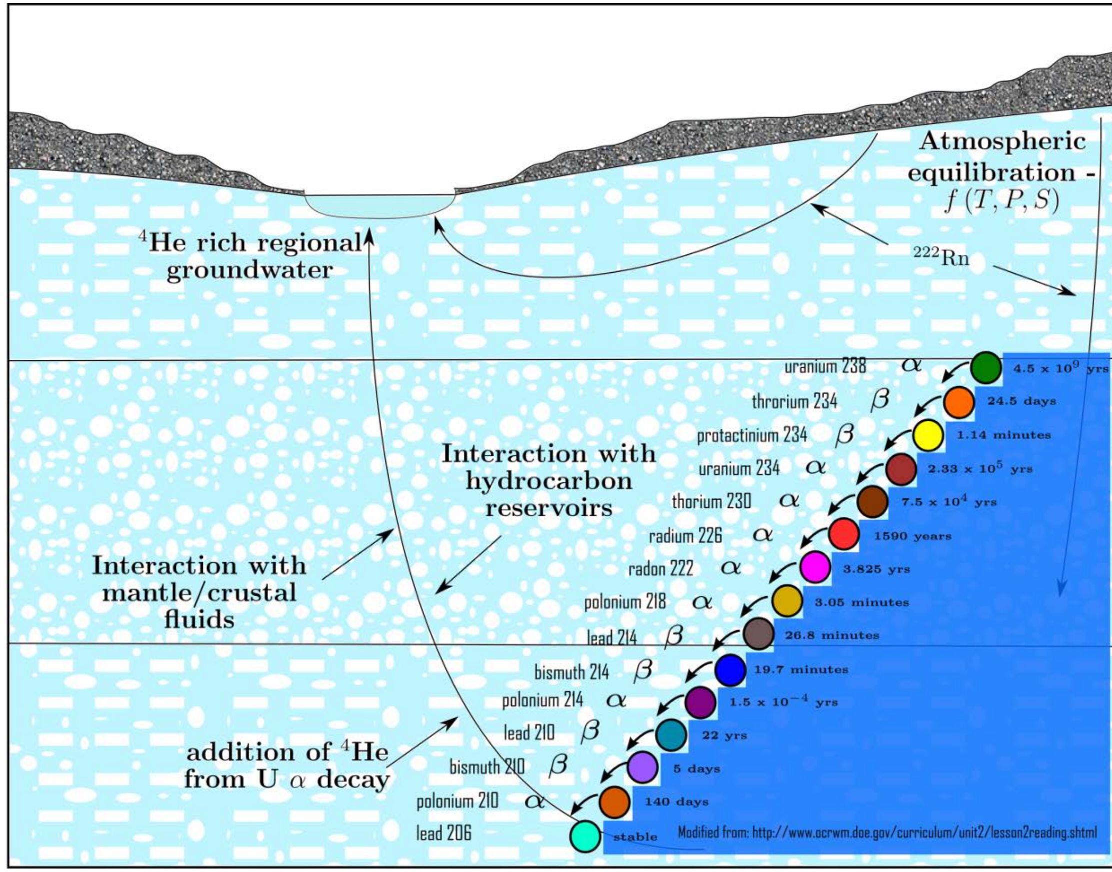
- **Controlling breakout formation**
  - Site selection
  - Maintain excess fluid pressure (ΔP) in the wellbore via mud weight
  - Clean/ream borehole to remove broken rock

- **Canister design**
  - Bevel edges to reduce chance getting caught on extruding rock
  - Make smaller OD canister
    - *Canister filled with incompressible material for same ID*
    - *Fill material bearing some of down-hole hydrostatic stress*

CB: Environmental Tracers

- **Vertical Profiles**
  - **Noble gases (He + Ne)**
  - **Stable water isotopes**
  - **Atmospheric radioisotope tracers (e.g., ^{81}Kr, ^{129}I, ^{36}Cl)**
  - **^{238}U/^{234}U ratios**
  - **^{87}Sr/^{86}Sr ratios**
- **Long-Term Data**
  - **Water provenance**
  - **Flow mechanisms**

Minerals → pores → fractures



Fluid Sample Quality + Quantity will be Very Important!

Repeatability between DST, packer & core samples?

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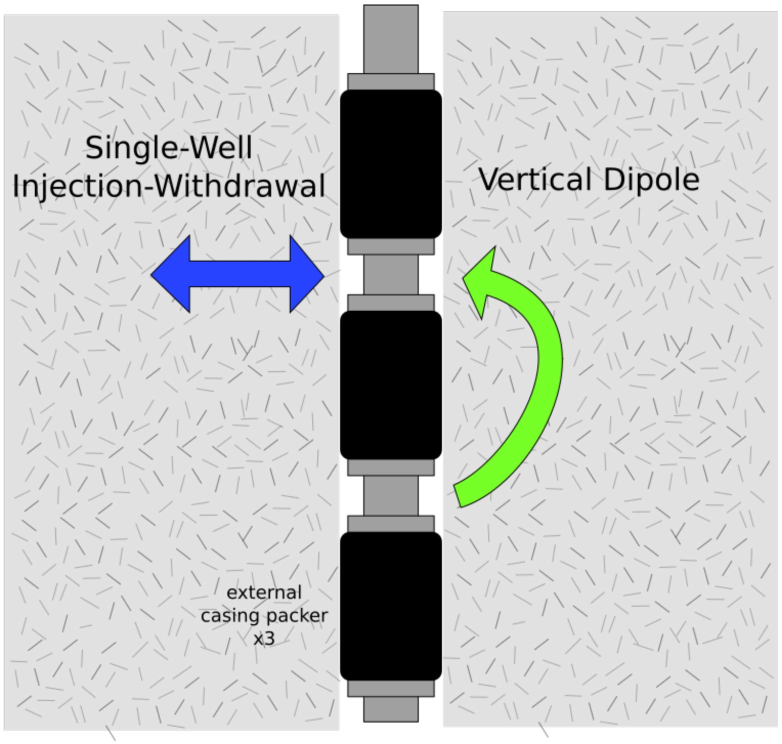
CB: Hydrogeologic Testing

- **Hydrologic Property Profiles**
  - **Static formation pressure**
  - **Permeability / compressibility**
    - ***Pumping/sampling in high K***
    - ***Pulse testing in low K***
- **Borehole Tracer Tests**
  - **Single-well injection-withdrawal**
  - **Vertical dipole**
  - **Understand transport pathways**
- **Hydraulic Fracturing Tests**
  - **σ_h magnitude**
- **Borehole Heater Test**
  - **Surrogate canister with heater**



Deep Borehole Field Test

- **Characterization & siting are *<u>different from</u>*:**
  - **Mined waste repositories**
    - ***More geologic isolation – less "site mapping"***
    - ***Single-phase fluid flow***
    - ***Less steep pressure gradients***
  - **Oil/gas or mineral exploration**
    - ***Crystalline basement vs sedimentary rocks***
    - ***Low-permeability***
    - ***Avoid mineralization***
    - ***Avoid overpressure***
  - **Geothermal exploration**
    - ***Low geothermal gradient***

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