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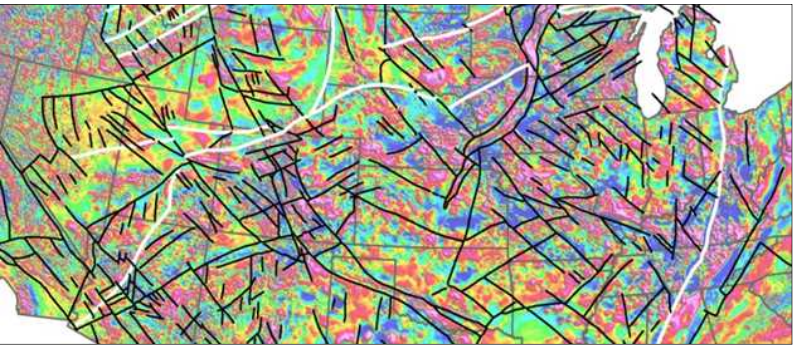

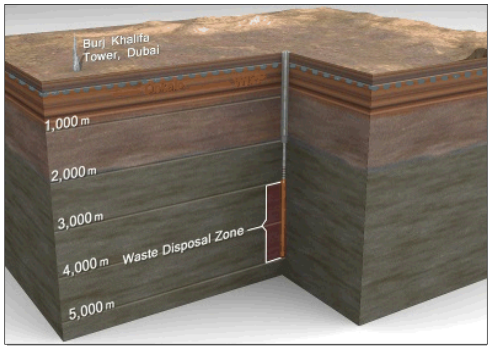

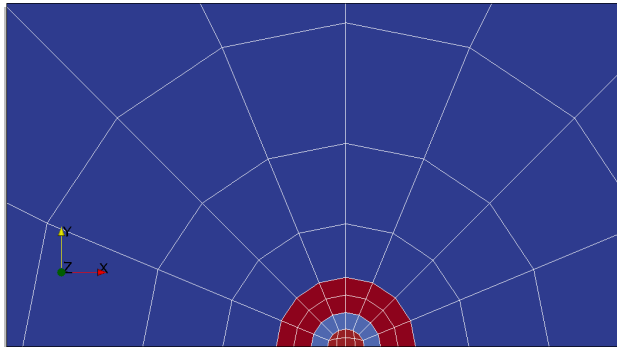

Deep Borehole Field Test Borehole Testing

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SFWST Working Group Meeting May 24, 2017

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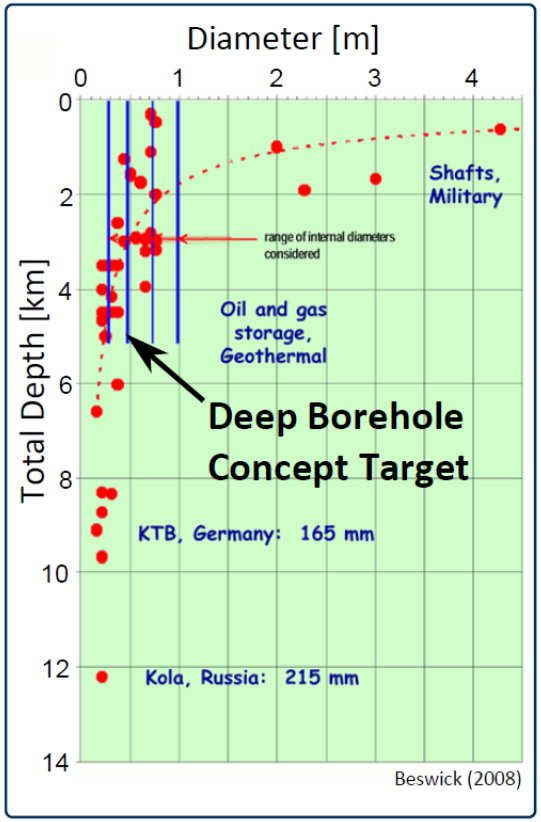
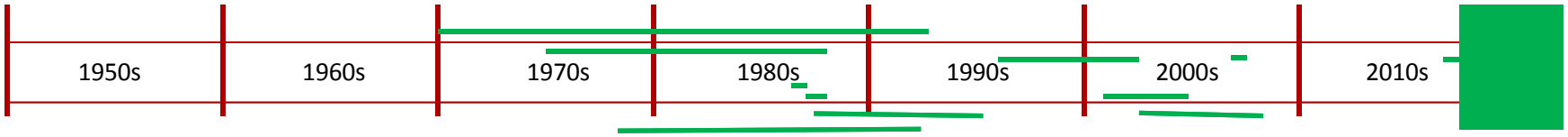
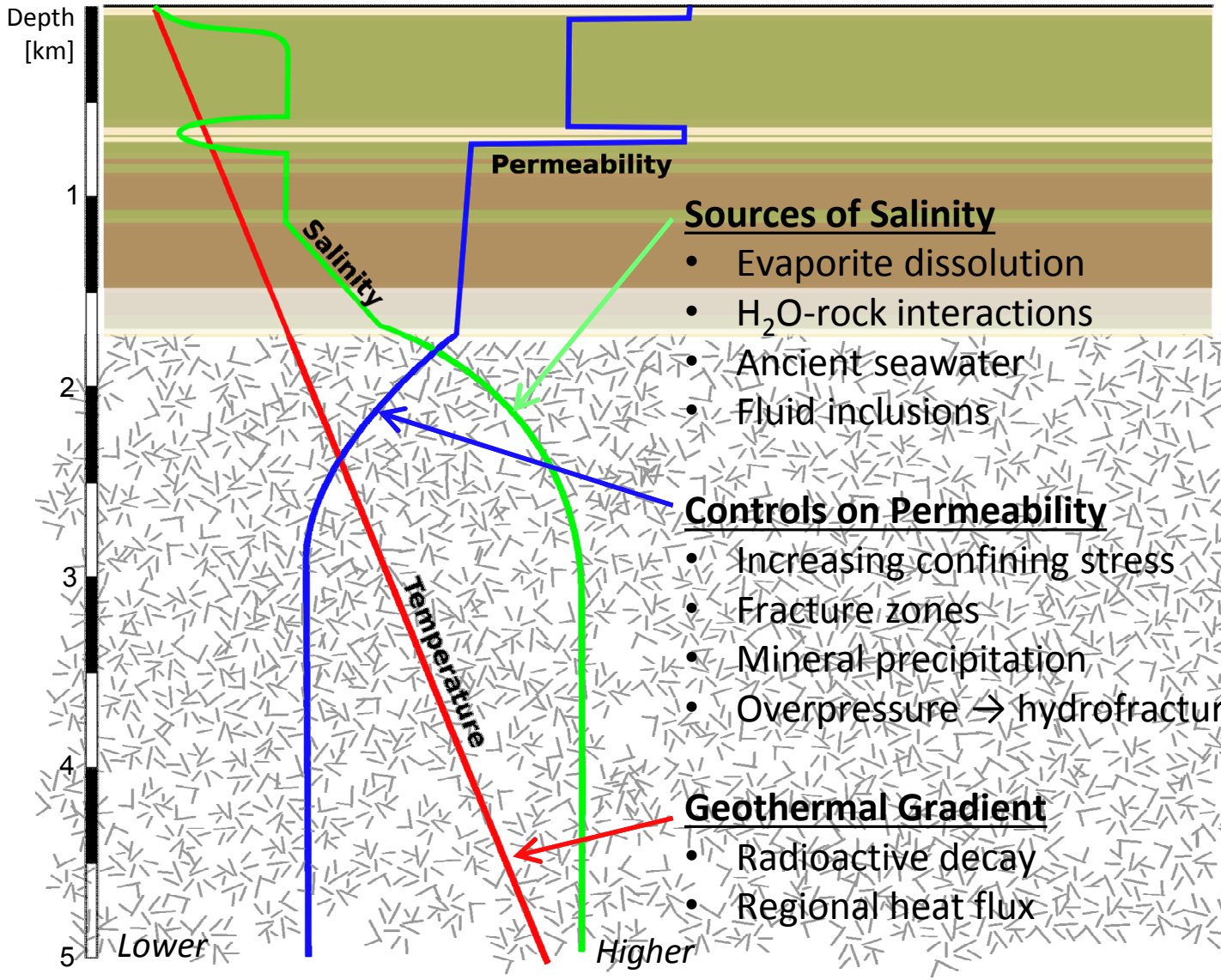
Deep Crystalline Drilling

Site	Location	Years	Depth to Crystalline [km]	Total Depth [km]	Diam. at TD [inch]
Kola	NW USSR	1970-1992	0	12.2	8½
Fenton Hill	New Mexico	1975-1987	0.7	2.9, 3.1, 4.0, 4.4	8¾, 9⅞
Urach	SW Germany	1978-1992	1.6	4.4	5½
Gravberg	Central Sweden	1986-1987	0	6.6	6½
Cajon Pass	Southern California	1987-1988	0.5	3.5	6¼
KTB	SE Germany	1987-1994	0	4, 9.1	6, 6½
Soultz	NE France	1995-2003	1.4	5.1, 5.1, 5.3	9⅝
CCSD	E China	2001-2005	0	2, 5.2	6
SAFOD	Central California	2002-2007	0.8	2.2, 4	8½, 8¾
Basel	Switzerland	2006	2.4	5	8½
IDDP-2	Iceland	2016-2017	0	4.7	6





Basement Conceptual Profiles



Sources of Salinity
- Evaporite dissolution
- H_2O-rock interactions
- Ancient seawater
- Fluid inclusions

Controls on Permeability
- Increasing confining stress
- Fracture zones
- Mineral precipitation
- Overpressure → hydrofracture

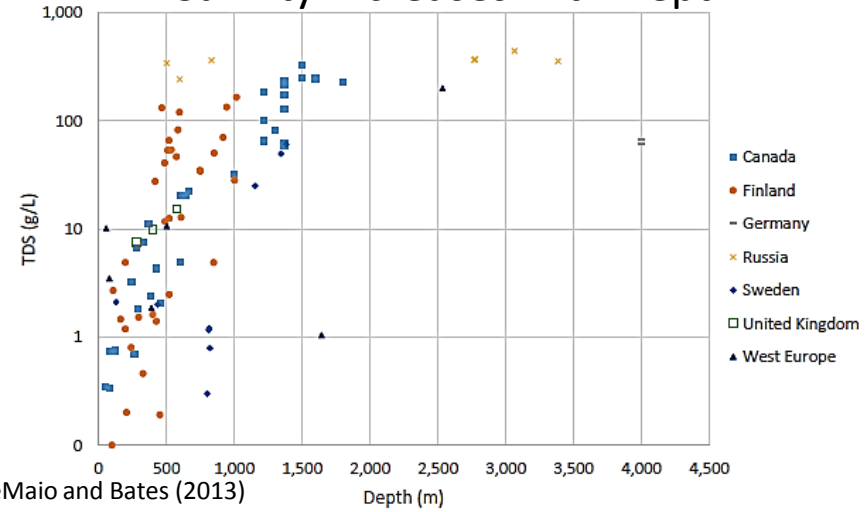
Geothermal Gradient
- Radioactive decay
- Regional heat flux

Sedimentary Overburden ≤ 2 km

Crystalline Basement ≥ 3 km

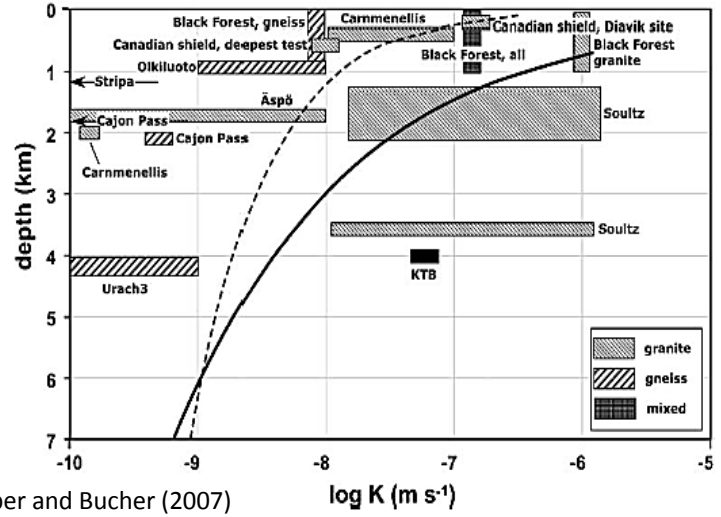
Observed Profiles

Salinity Increases with Depth



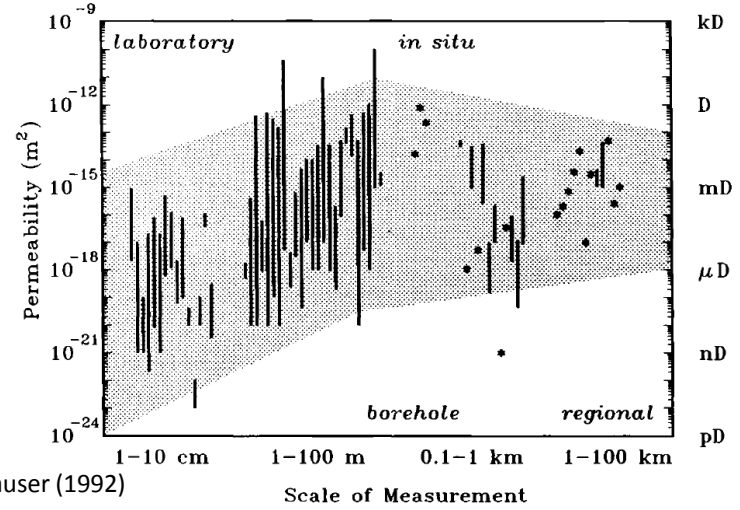
DeMaio and Bates (2013)

Bulk Permeability Decreases with Depth



Stober and Bucher (2007)

Bulk Permeability Increases with Scale

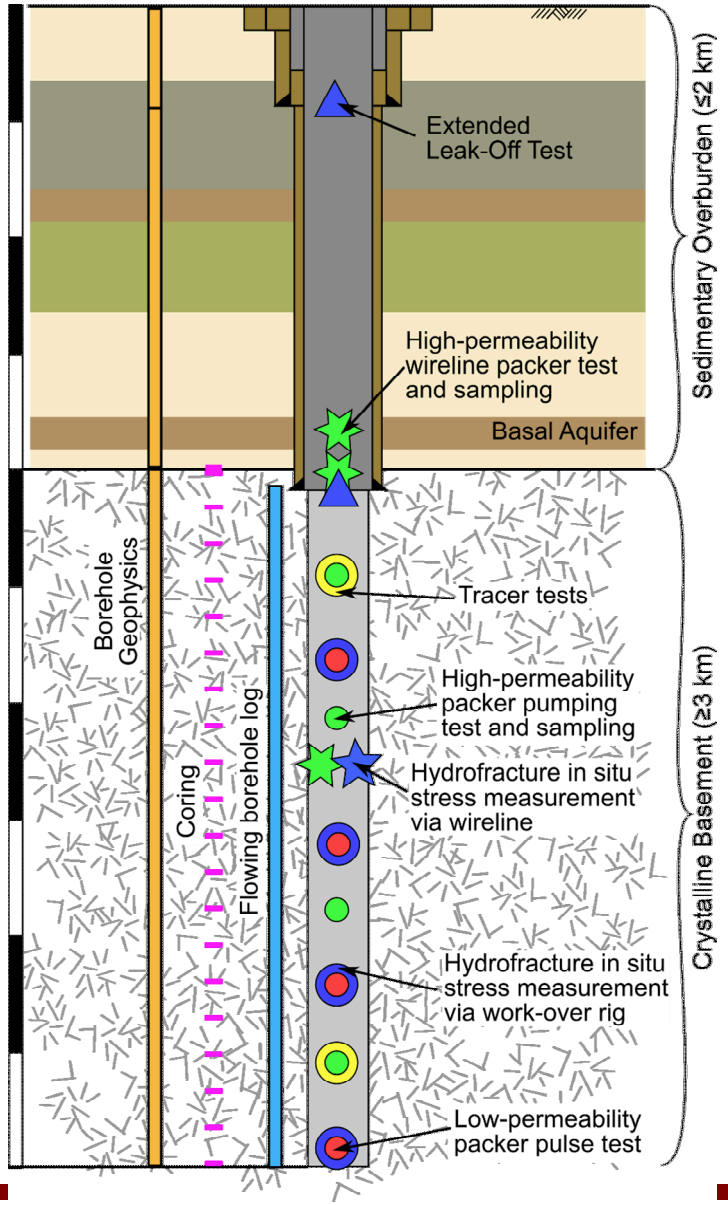


Clauser (1992)

Chemical evidence for isolation is less prone to scale-dependency than permeability

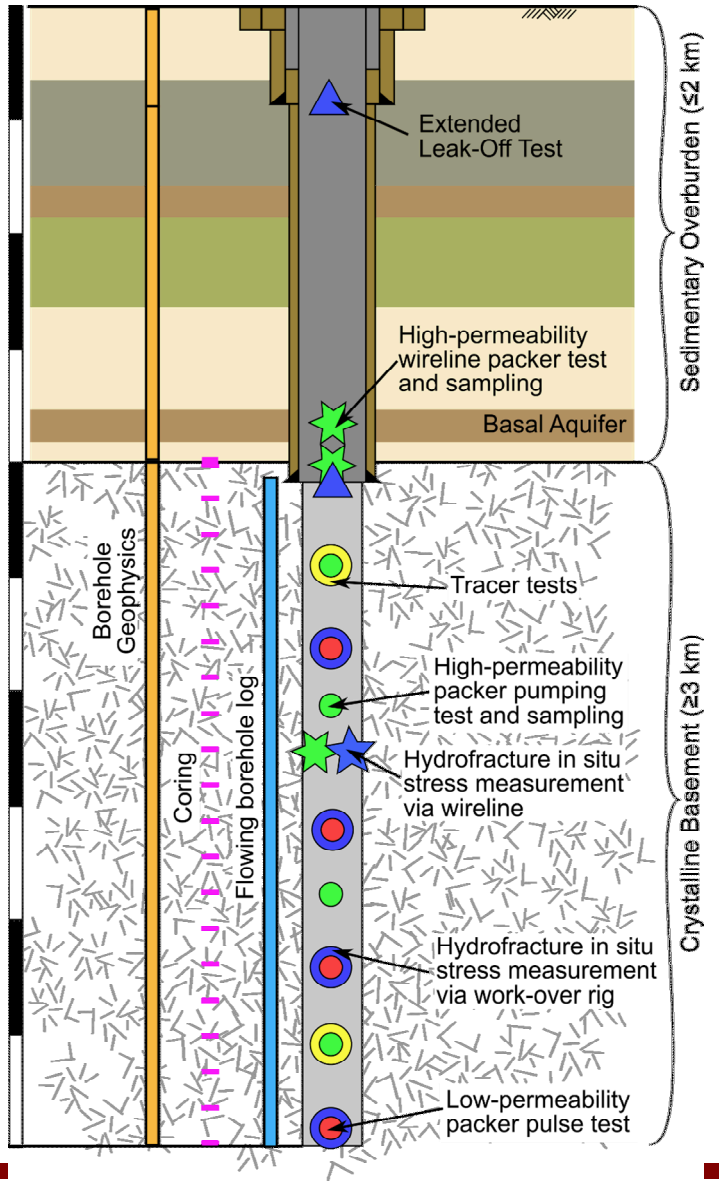
Characterization Borehole (CB)

- **Sampling During Drilling**
- **Borehole Geophysics**
- **Flowing Borehole Salinity Log**
- **Sample-based Profiles**
  - Fluid density/temperature/major ions
  - Compositional samples
- **In Situ Testing-based Profiles**
  - Formation hydraulic/transport properties
  - *In situ* stress (hydrofrac + breakouts)
- **Exploring TRL of Methods**
  - Not exhaustively testing a site for licensing
  - Workable at 50 Mpa / 150° C / 4 km tubing?
  - Compare methods under field conditions



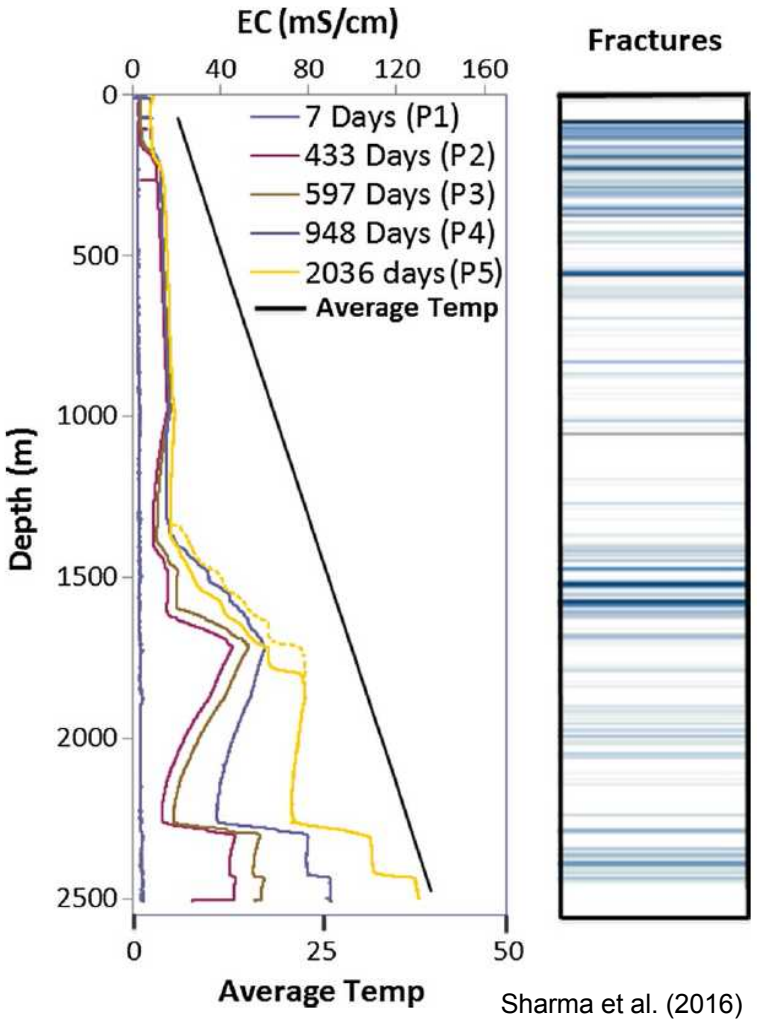
CB Characterization *During* Drilling

- **Mud logging (~continuous)**
  - Ion chromatograph (liquid)
  - Gas chromatograph (gas)
  - XRD/XRF rock flour (solids)
- **Fluid sampling (each ~30 m)**
  - Mud before & after circulation
  - Analytes
    - Drilling mud tracer (iodine, fluorescein)
    - C, S, N & stable water isotopes
    - Drilling mud additive
- **Advance Coring 5% (≈150 m)**
- **Drilling parameters:**
  - rate, WOB, rotation speed, deviation, drilling specific energy, etc.



CB Testing After Drilling

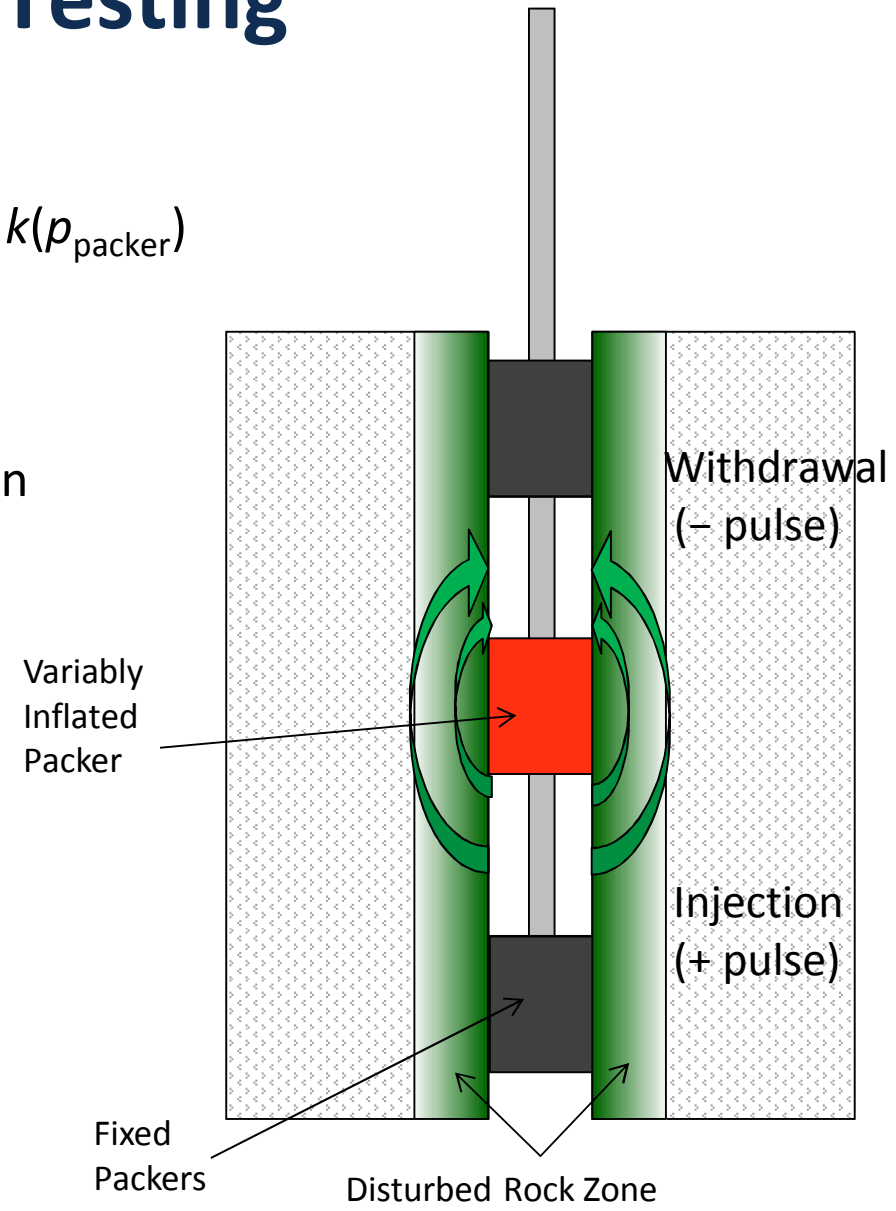
- **Flowing Fluid Elec. Cond. (FFEC) log**
- **FFEC to Locate:**
  - Permeable zones
  - Gaining zones
  - Losing zones
- **Focus in situ packer testing on:**
  - 5 permeable zones
    - Formation fluid samples collected at surface
    - Estimate hydraulic properties
  - 5 low-permeability zones
    - Estimate hydraulic properties
- **Spane & Thorne (PNNL)**



Sharma et al. (2016)

In Situ Packer-Based Testing

- **In Situ Packer Testing**
  - New hydromechanical dipole test: $k(p_{packer})$
- **Hydrologic Tests**
  - Static formation pressure
  - Permeability / compressibility / skin
  - Sampling in high *k* intervals
- **Tracer Tests**
  - Single-well injection-withdrawal
- **Hydraulic Fracturing Tests**
  - σ_h magnitude
  - Estimate stress tensor via existing fractures



Characterization Comparison

Method	KTB Reference	Soultz Reference
Laboratory Core Testing	Rauen, A. and Winter H., 1995, Petrophysical Properties, 1995, *in* Emmermann R., Althaus, E., Giese, P and Stockhert, B. Eds. KTB Report 95-2: Results of Geoscientific Investigation in the KTB Field Laboratory Final Report 0-9101 m. Kontiny et al., 1997, Formation of ore minerals in the metamorphic rocks of the German continental deep drilling site (KTB), J. Geophys. Res. 102, 18323-18336. Roeckhel, T., and Nateu O., 1995, , *in* Emmermann R., Althaus, E., Giese, P and Stockhert, B. Eds. KTB Report 95-2: Results of Geoscientific Investigation in the KTB Field Laboratory Final Report 0-9101 m.	Genter, A and Traineau, H., 1992. Borehole EPS1, Alsace, France: preliminary geological results from granite core analysis for Hot Dry Rock Research. Scient. Drill. 3, 205–214. Genter, A., and Traineau, H., 1996, Analysis of macroscopic fractures in granite in the HDR geothermal well EPS-I, Soultz-sous-Forets, France J. Volcanol. and Geotherm. Res. 72 121-141.
Borehole Imaging and Caliper Logs	Bram, K., et al., 1995, The KTB Borehole – Germany's Superdeep Telescope into the Earth's Crust. *Oilfield Review*, 7:4-22	Genter, A., et al., 1997. Comparative analysis of direct (core) and indirect (borehole imaging tools) collection of fracture data in the Hot Dry Rock Soultz reservoir (France). J. Geophys. Res. 102 (B7), 15,419–15,431. Genter, A., et al.,1991. Application of FMS and BHTV tools for evaluation of natural fractures in the Soultz geothermal borehole GPK1. Geotherm. Sci. Tech. 3, 69–82.
High and Low-k Packer Tests	Kessels, W. Objectives and execution of the hydraulic testing in the KTB-Oberfalz borehole within the long-term measurement and test programme, Scientific Drilling, 2, 287-298.	Jung, R., 1991, Hydraulic fracturing and hydraulic testing in the granitic section of borehole GPK-1 Soultz sous Forets. Geotherm. Sci. & Tech.3, 149-198.
Vertical Seismic Profile	Rabbel, W., et al., 2004, Superdeep vertical seismic profiling at the KTB deep drill hole (Germany): Seismic close-up view of a major thrust zone down to 8.5 km depth. J. Geophys. Res. 109, B09309, 20p. Luschen, E., K. et al., 1996, Nature of seismic reflections and velocities from VSP-experiments and borehole measurements at the KTB-deep drilling site in SE-Germany, Tectonophysics 2, 64, 309-326.	Sausse, J et al., 2010, 3D model of fracture zones at Soultz-sous-Forets based on geological data, image logs, induced microseismicity and vertical seismic profiles, C. R. Geoscience 342, 531–545.
Gamma Density Log	Pechnig et al., 1997, Integrated log interpretation in the German Continental Deep Drilling Program: lithology porosity and fracture zones. J. Geophys. Res., 102, 18363-18390.	Genter A. et al., 1997, Synthesis of geological and geophysical data at Soultz-sous-Foret (France). Rapport BRGM R 39440, 36 p.
Full-Waveform Sonic Log	Jones AG and Holliger K., 1997, Spectral analyses of the KTB sonic and density logs using robust nonparametric methods, J. Geophys. Res., 102, 18391-18403.	Genter A. et al., 1997, Synthesis of geological and geophysical data at Soultz-sous-Foret (France). Rapport BRGM R 39440, 36 p.
Spontaneous Potential Log	ELEKTB Group, 1997, KTB and the electrical conductivity of the crust, J. Geophys. Res., 102, 18289-18305.	Genter A. et al., 1997, Synthesis of geological and geophysical data at Soultz-sous-Foret (France). Rapport BRGM R 39440, 36 p.
Hi-Res Temperature Log	Clauser et al., 1997, The thermal regime of the crystalline continental crust: Implications from the KTB, J. Geophys. Res. 102, 18417-18441.	Genter A. and Tenzer, H., 1995, Geological Monitoring of the GPK-2 borehole 1420-3880 m (Soultz-sous-Forets, France), Rapport BRGM R 38629, 46p. Spichak V., et al., 2010, Deep temperature extrapolation in the Soultz-sous-Forets Area using magnetotelluric data. In Proceedings, Thirty-Fifth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 1-3, 2010.
Neutron Porosity Log	Pechnig et al., 1997, Integrated log interpretation in the German Continental Deep Drilling Program: lithology porosity and fracture zones. J. Geophys. Res., 102, 18363-18390.	Genter A. et al., 1997, Synthesis of geological and geophysical data at Soultz-sous-Foret (France). Rapport BRGM R 39440, 36 p.
Borehole Gravity Log	Bosum, W., et al., 1997, Three-dimensional interpretation of the KTB gravity and magnetic anomalies. J. Geophys. Res., 102, 18307-18321.	
Induced Polarization Log	Bram, K., et al., 1995, The KTB Borehole – Germany's Superdeep Telescope into the Earth's Crust. *Oilfield Review*, 7:4-22.	
Photoelectric Effect Log	Pechnig et al., 1997, Integrated log interpretation in the German Continental Deep Drilling Program: lithology porosity and fracture zones. J. Geophys. Res., 102, 18363-18390.	Genter A. et al., 1997, Synthesis of geological and geophysical data at Soultz-sous-Foret (France). Rapport BRGM R 39440, 36 p. Sausse, J., et al., 2006, Permeability and alteration within the Soultz granite inferred from geophysical and flow log analysis. Geothermics, 35, 544-560.
Fluid Density or Downhole Pressure Log	Huenges, et al., 1995, Formation pressure down to a depth of 8.7 km in the Kontinentale Tiefbohrung (KTB) Scientific Drilling, 5, 17-21. Huenges et al, 1997, The permeable crust: Geohydraulic properties down to 9101 m depth. J. Geophys. Res., 102, 18255-18265.	Megel, T., et al., 2005, Downhole Pressures Derived from Wellhead Measurements during Hydraulic Experiments. Proceedings World Geothermal Congress 2005 Antalya, Turkey, 24-29 April 2005.
Hydraulic Fracturing Tests	Zoback, M.D. and Harjes H.-P., 1997, Injection-induced earthquakes and crustal stress at 9 km depth at the KTB deep drilling site, Germany. J. Geophys. Res., 102, 18477-18491. Brudy, M. et al., 1997, Estimation of the complete stress tensor to 8 km depth in the KTB scientific drill holes: Implications for crustal strength. J. Geophys. Res., 102, 18453-18475. Shapiro, S., et al., 1997, Estimating the crust permeability from fluid-injection-induced seismic emission at the KTB site. Geophys. J. Int. 131, F15-FI8.	Rummel F. and Baumggrtner J. 1991, Hydraulic fracturing stress measurements in the GPK-1 borehole, Soultz-sous-Forets. *Geotherm. Sci. & Tech.* 3, 119-148. Klee, G., Rummel, F., 1993. Hydrofrac stress data for the European HDR research project site, Soultz-sous-Forets. Int. J. Rock Mech. Min. Sci. 30, 973–976.
Resistivity Log	ELEKTB Group, 1997, KTB and the electrical conductivity of the crust, J. Geophys. Res., 102, 18289-18305.	Genter A. et al., 1997, Synthesis of geological and geophysical data at Soultz-sous-Foret (France). Rapport BRGM R 39440, 36 p.
Open Borehole Dynamic Fluid Logging	Huenges et al., 1997, The permeable crust: Geohydraulic properties down to 9101 m depth. J. Geophys. Res., 102, 18,255-18,265	Aquilina, L. and Brach, M. 1995, Characterization of the Soultz hydrochemical system: WELCOM (well chemical on-line monitoring) appied to deepening of GPK-1borehole. Geochem. Sci. & Tech. 4, 239-251

Characterization Differences

- **DBFT Effort is Different from:**
  - Oil/gas or mineral exploration (low perm., low porosity rocks)
  - Geothermal exploration (low geothermal gradient)
  - Shallow drilling/testing (high p, high σ, deep, breakouts)
- **DBFT Characterization Approach**
  - Not exhaustive permeability characterization (scaling)
  - Seeking *geochemical* evidence of system isolation
- **DBFT Goals**
  - Drill straight large-diameter boreholes to 5 km depth
  - Demonstrate sample collection (cores + formation fluid)
    - Enough samples
    - Low enough contamination level
  - Demonstrate *in situ* testing at depth (3 to 5 km)


SAND2010-6048