Fluid Flow and Permeability in the Upper Crust

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Nuclear Waste Technical Review Board
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USGS
science for a changing world

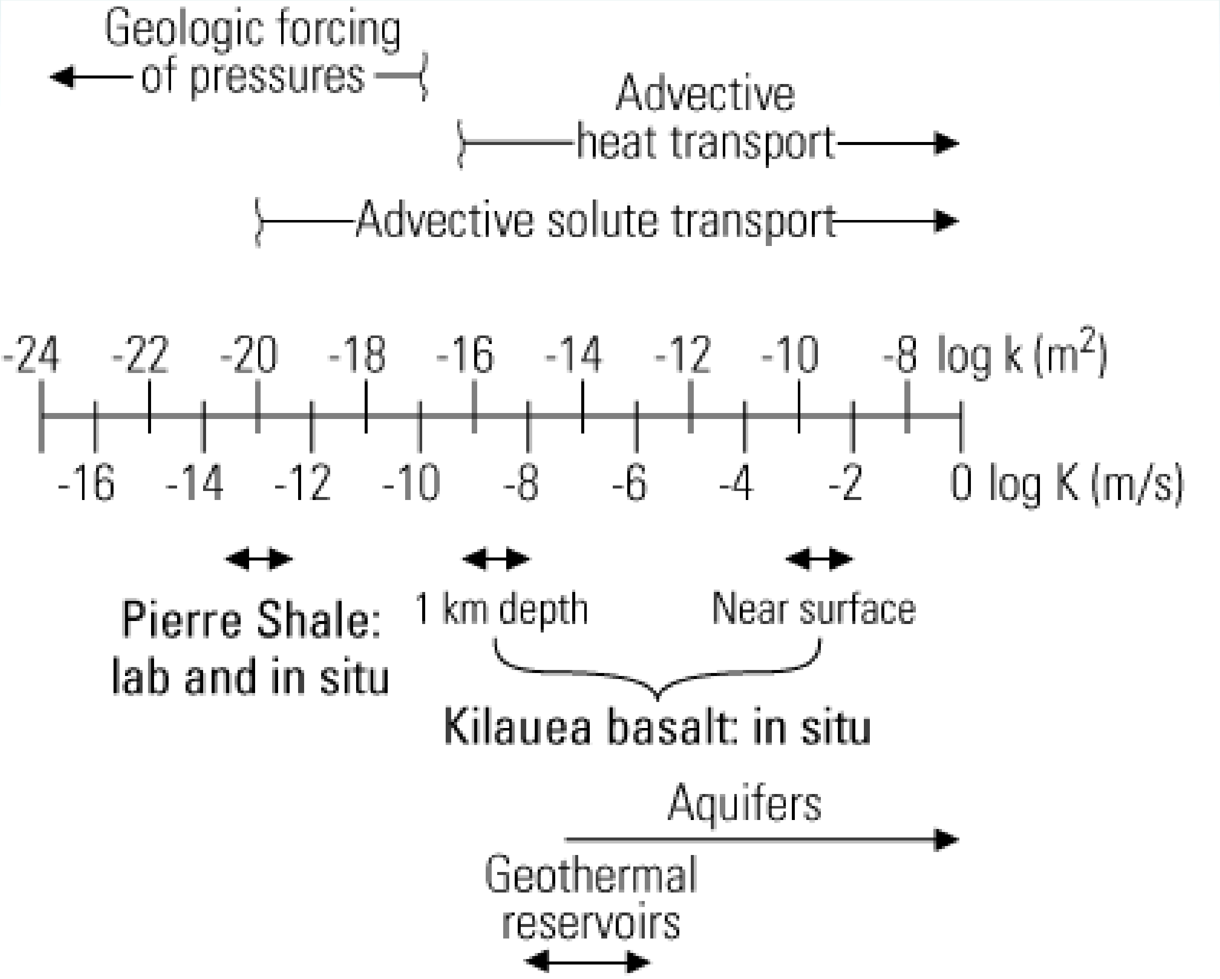
Permeability of the continental crust and its transient variation

Depth of circulation of meteoric water

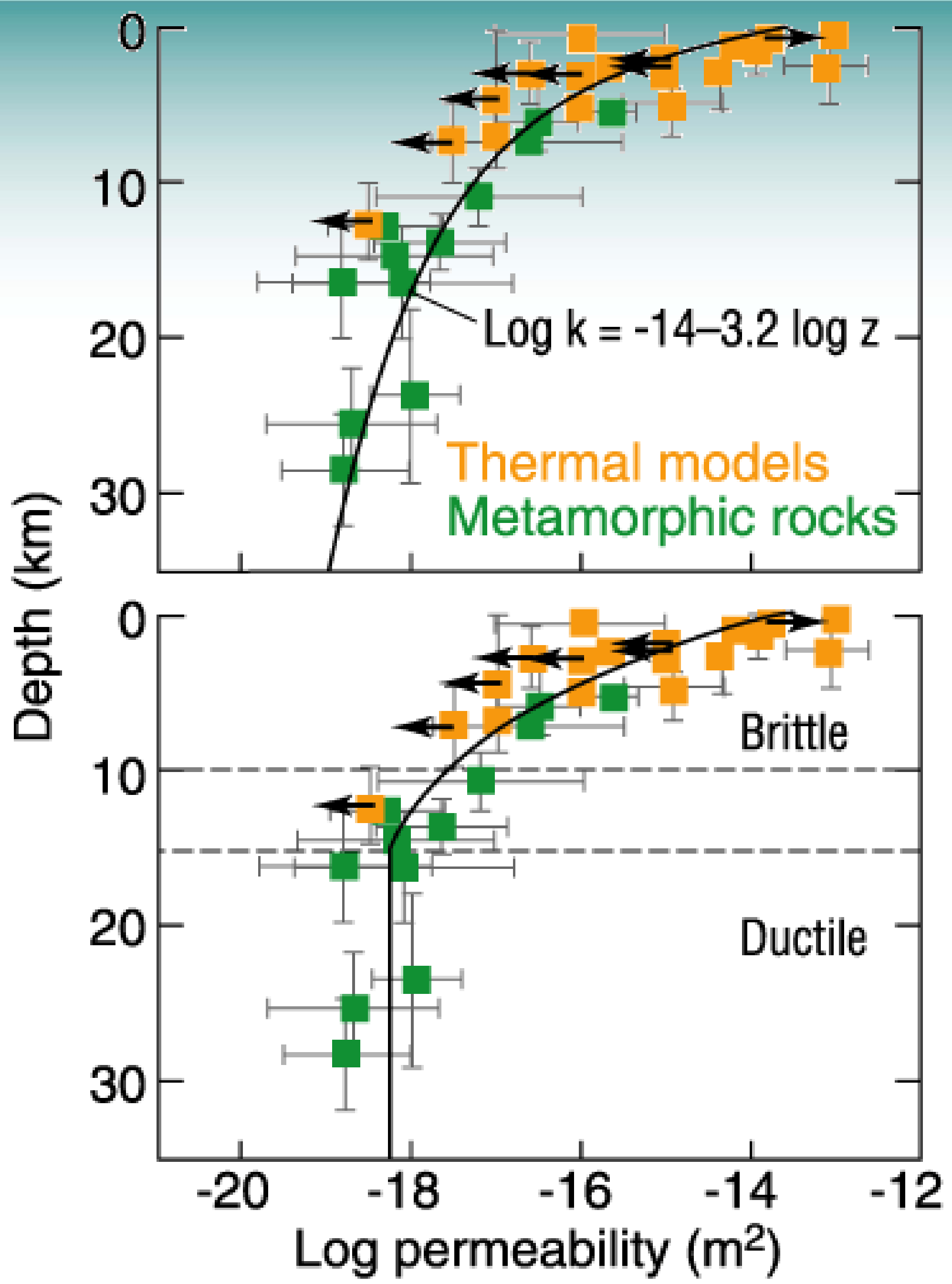
Fluid injection, seismicity, and permeability enhancement

Real and “virtual” fluid sources and their effects on fluid pressure

Permeability

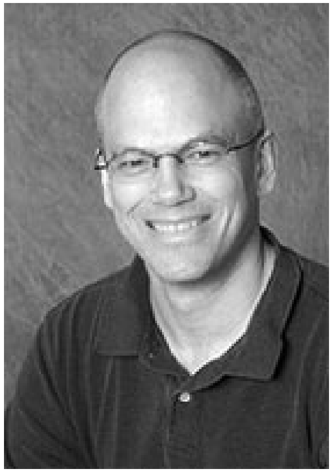


Ingebritsen *et al*., *Groundwater in Geologic Processes*, 2006



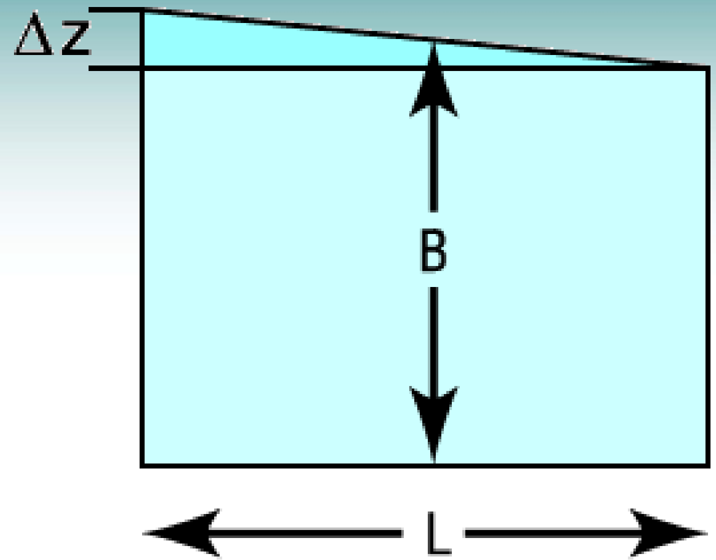
USGS

Permeability of the continental crust based on geothermal and metamorphic data



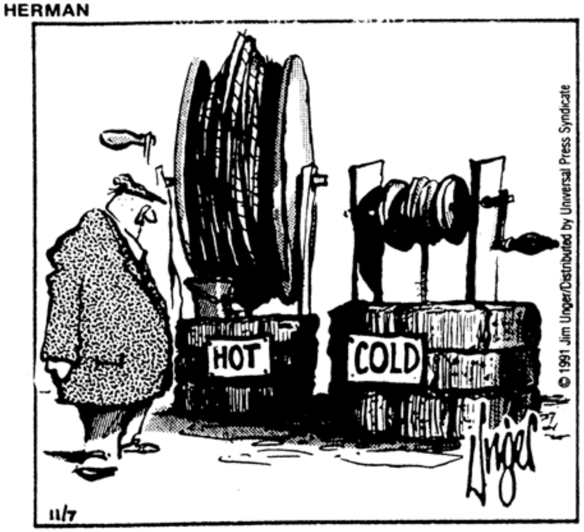
Craig Manning

Manning and Ingebritsen, *RoG*, 1999; Ingebritsen and Manning, *Geology*, 1999; *PNAS*, 2002



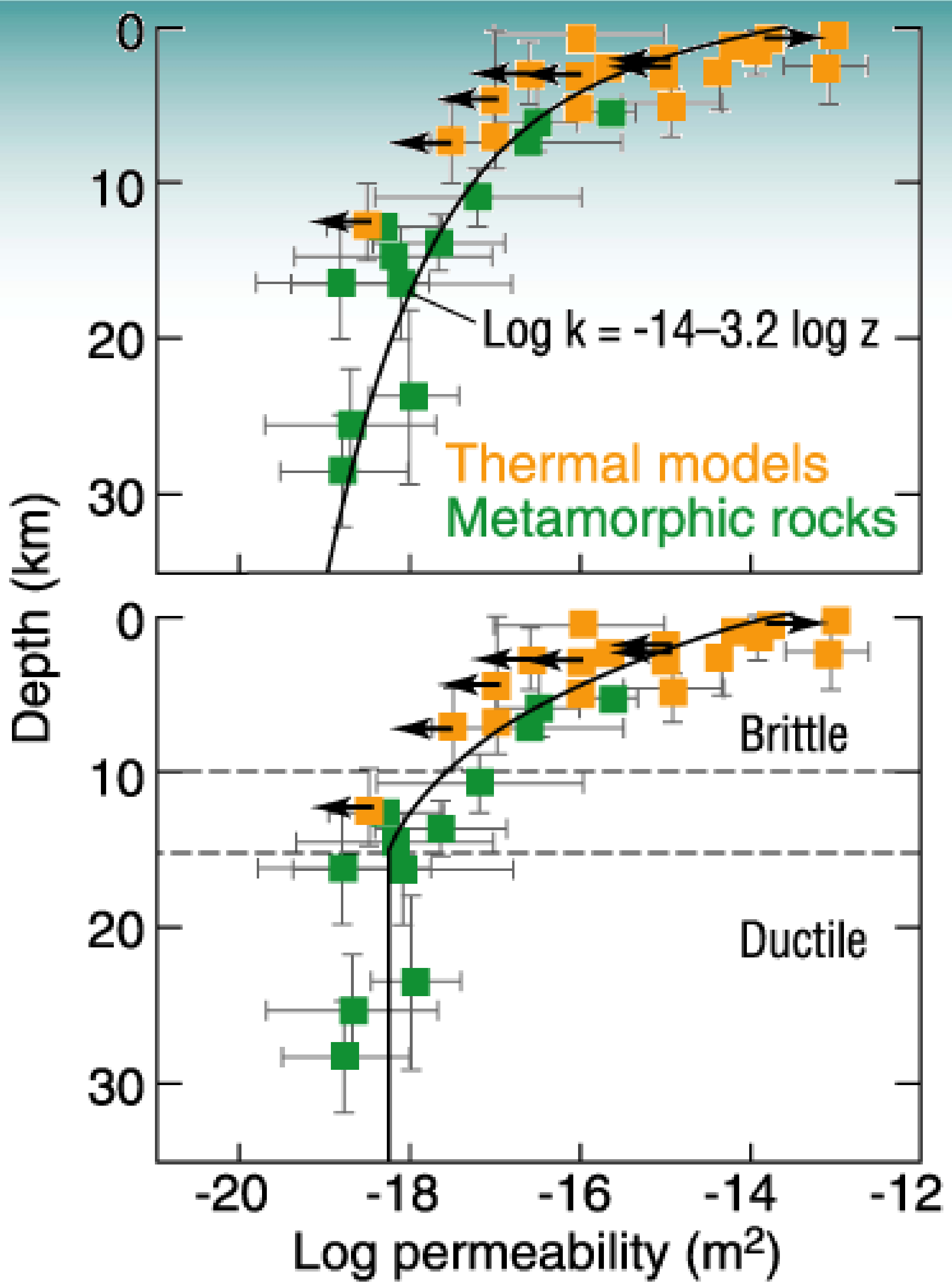
$$Pe = \frac{k \rho_w^2 g c_w B \Delta z}{\mu_w K_m L}$$

Domenico and Palciauskas (1973)



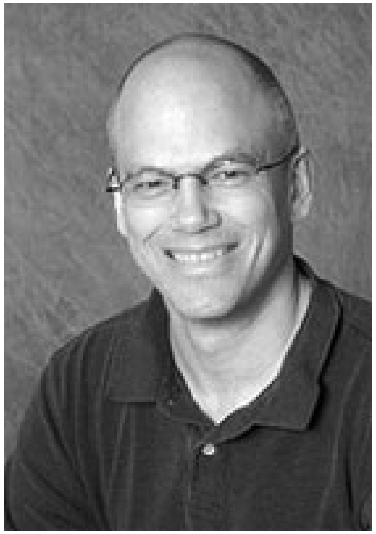
Dr. Steven E. Ingebritsen, pondering a
fundamental geologic relationship

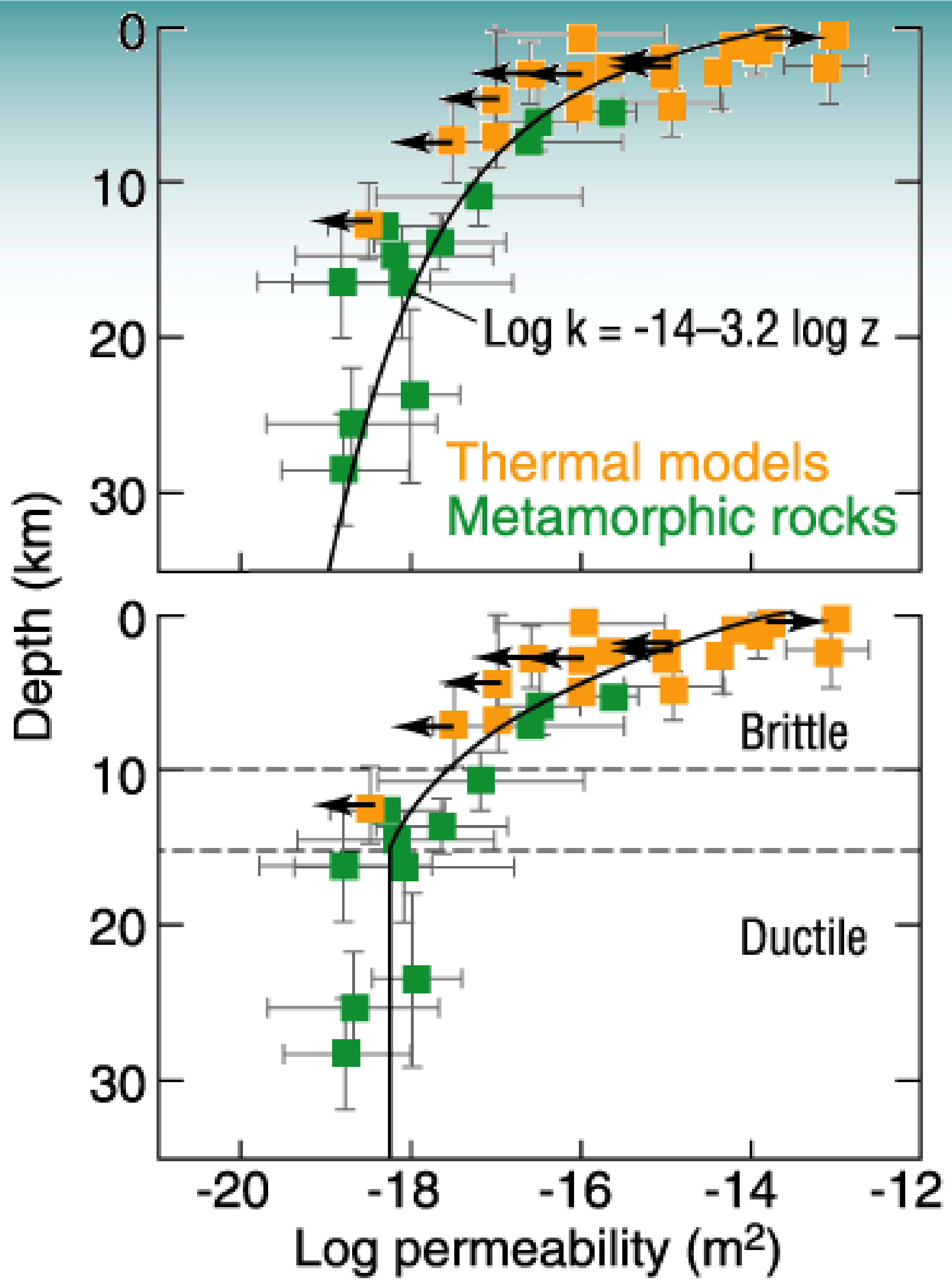
Permeability of the continental crust based on geothermal and metamorphic data



Manning and Ingebritsen, *RoG*, 1999; Ingebritsen and Manning, *Geology*, 1999; *PNAS*, 2002

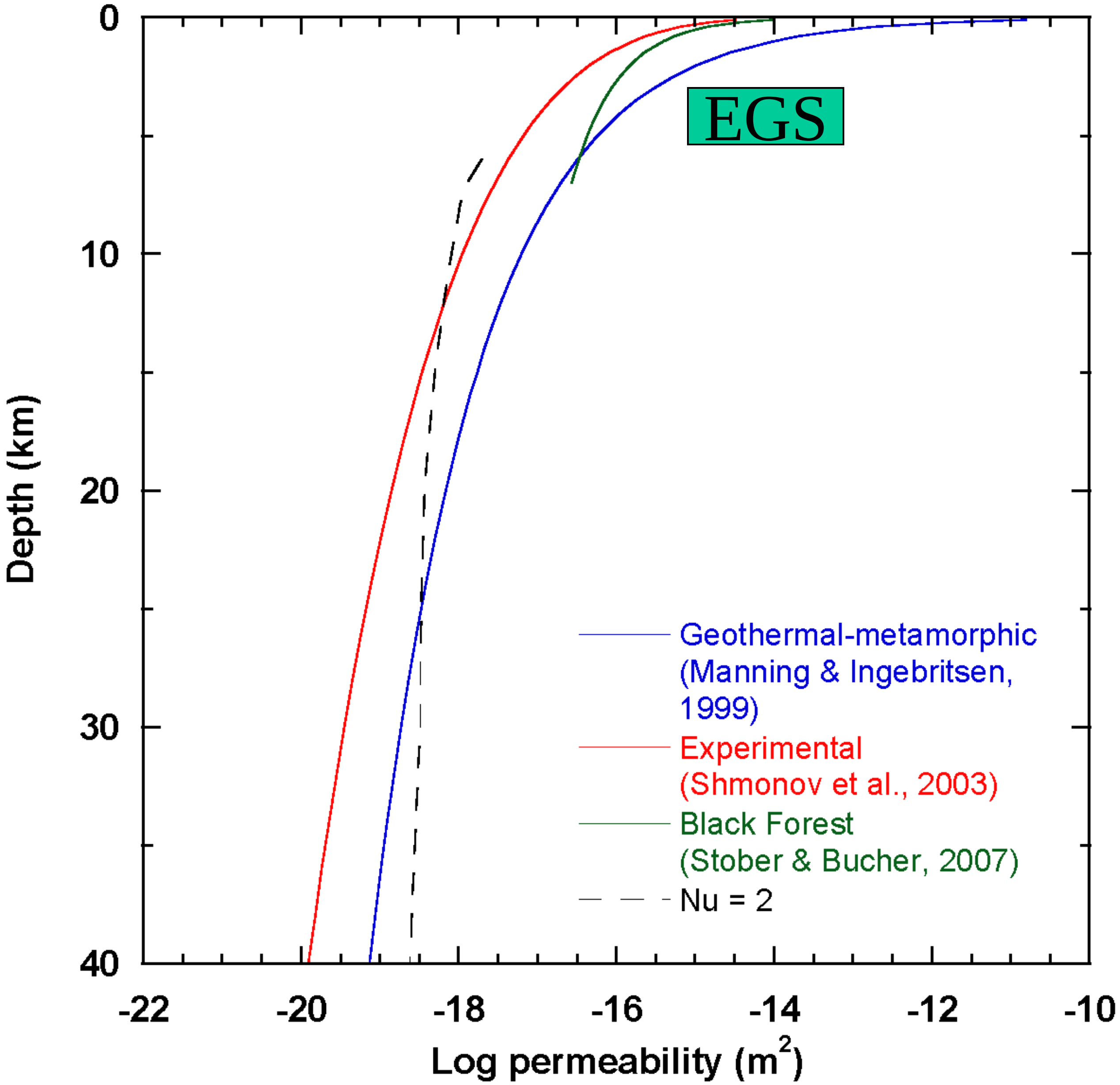
$$k = \left[\frac{Q\mu}{\Delta t \left(\partial \left(P + \rho g z \right) / \ \partial x \right)} \right]$$



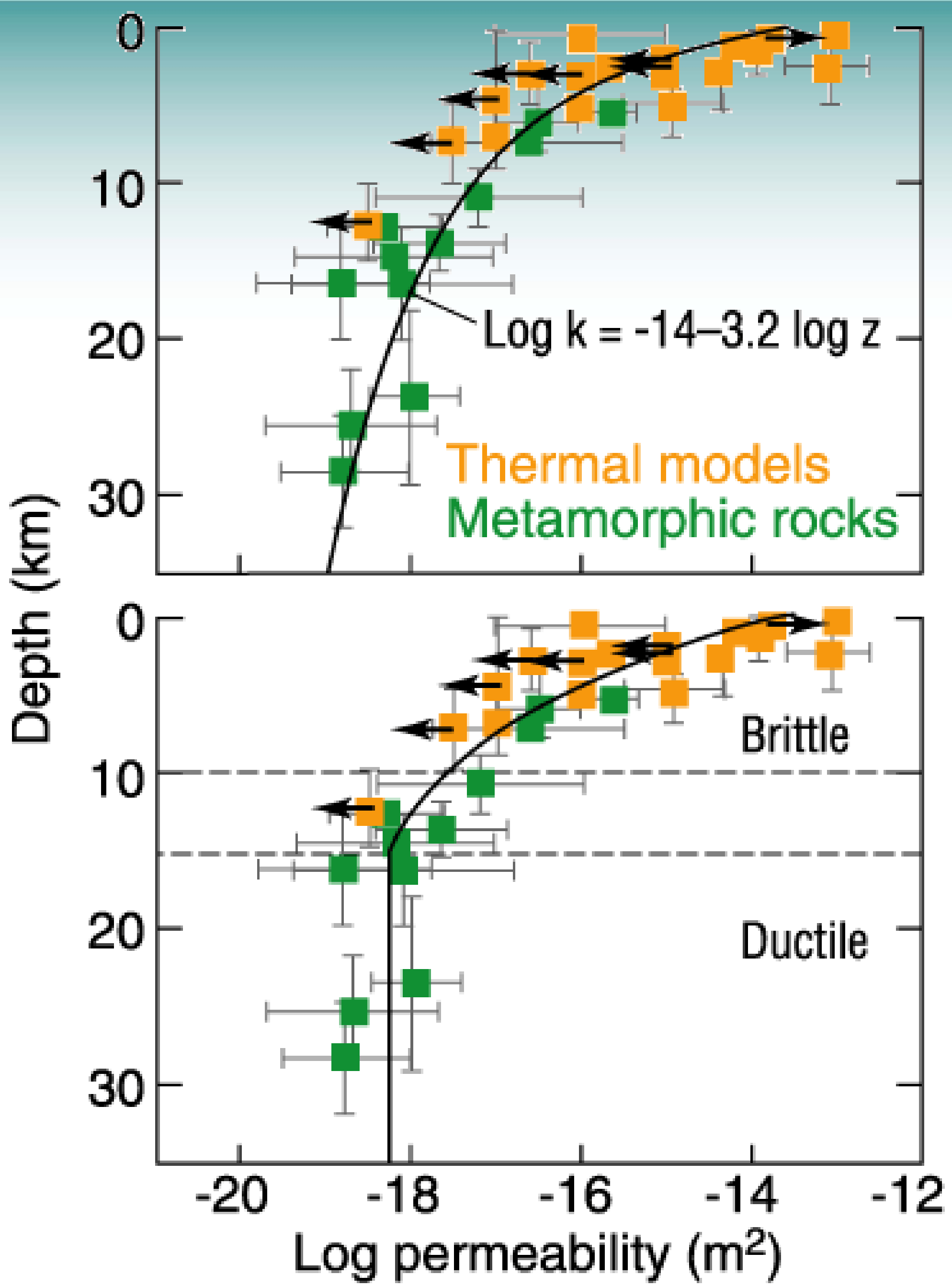


Permeability of the continental crust based on geothermal and metamorphic data

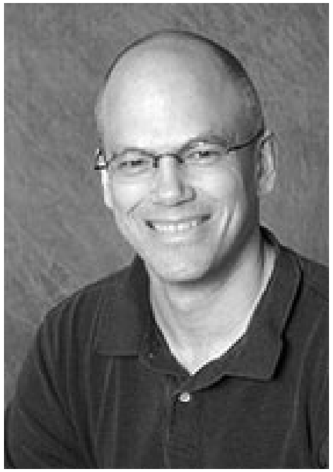
Manning and Ingebritsen, *RoG*, 1999; Ingebritsen and Manning, *Geology*, 1999; *PNAS*, 2002


0
10
20
30
40
Depth (km)
-22
-20
-18
-16
-14
-12
-10
Log permeability (m^2)
EGS
Geothermal-metamorphic (Manning & Ingebritsen, 1999)
Experimental (Shmonov et al., 2003)
Black Forest (Stober & Bucher, 2007)
Nu = 2

Permeability of the continental crust based on geothermal and metamorphic data



USGS



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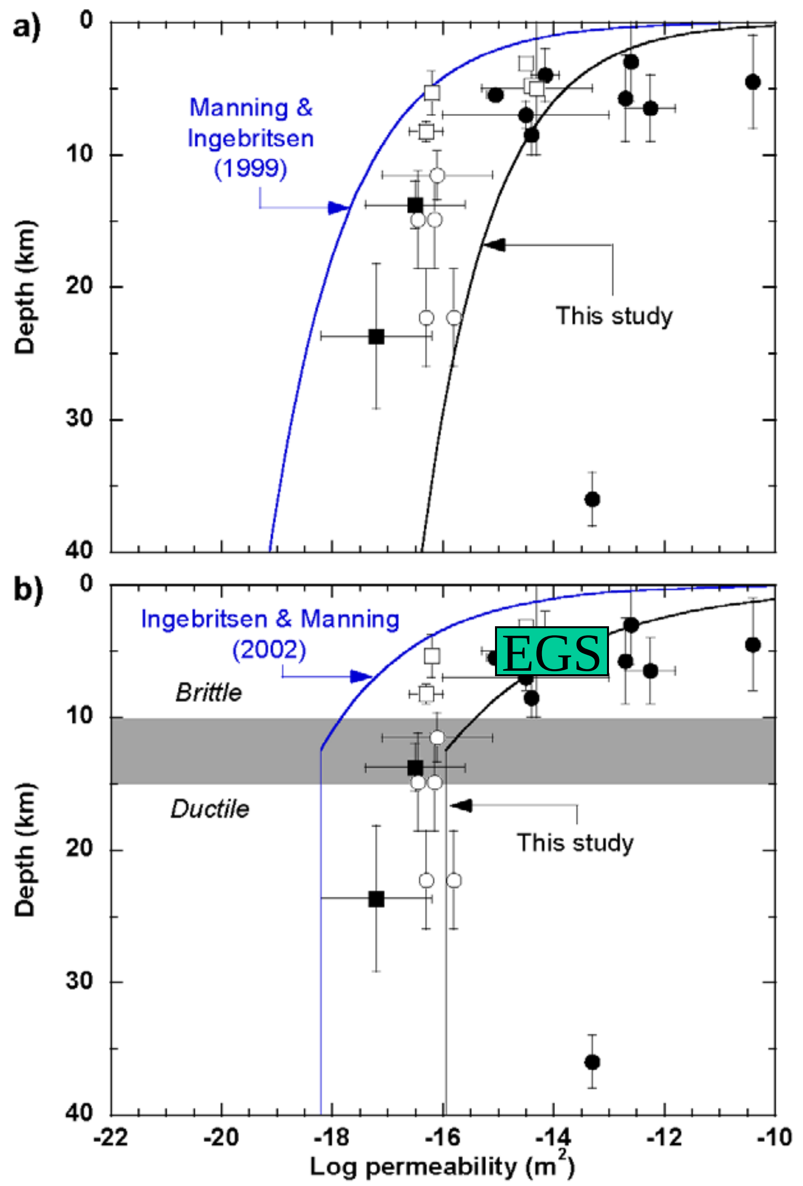
Evidence for “high” permeabilities



Hypocenter migration

FZ metamorphism

Focused heating

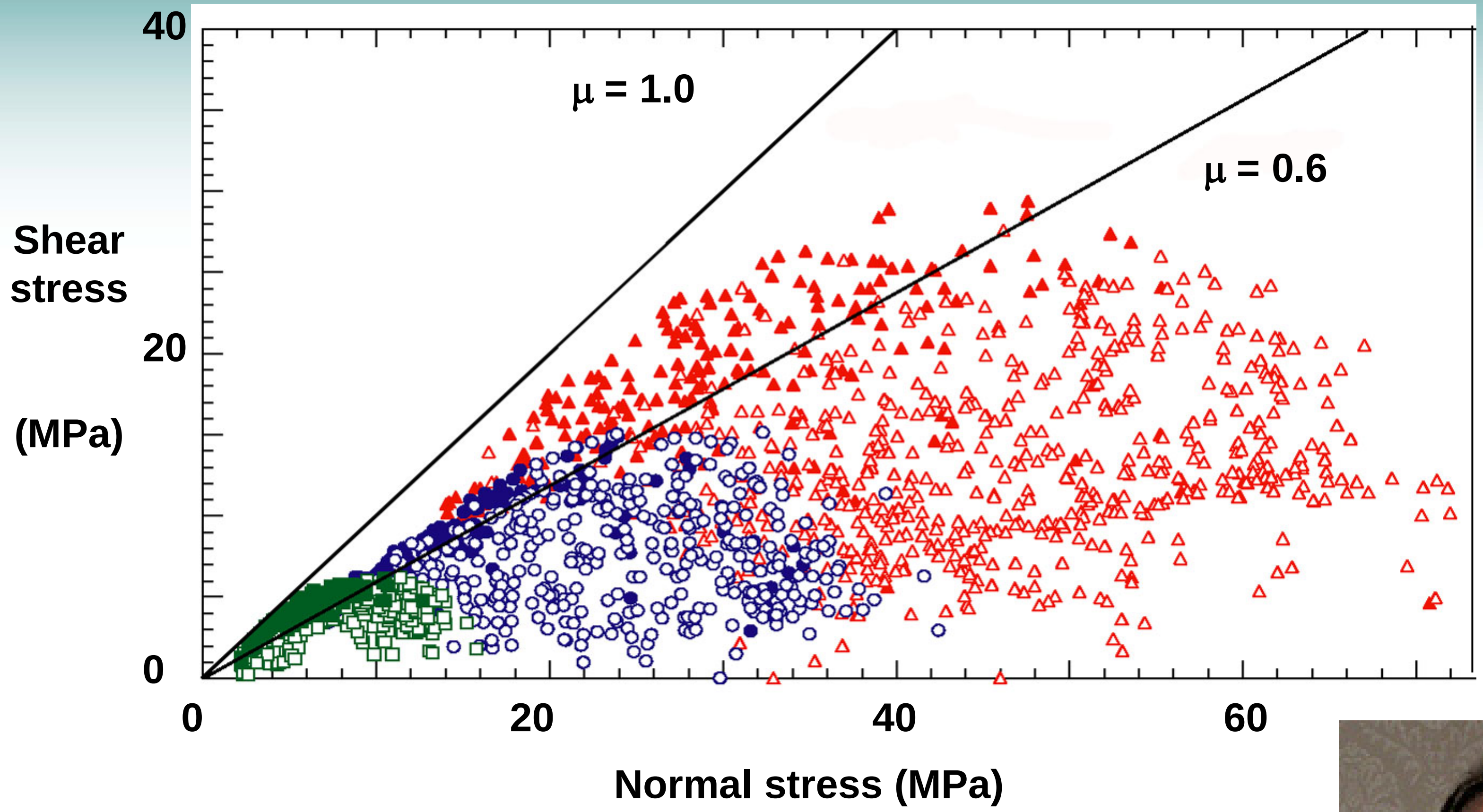
Anthropogenic permeability

Ingebritsen & Manning, *Geofluids*, 2010

Dynamic coupling between

fluid pressure, seismicity, permeability,

(and high-temperature reactive transport)

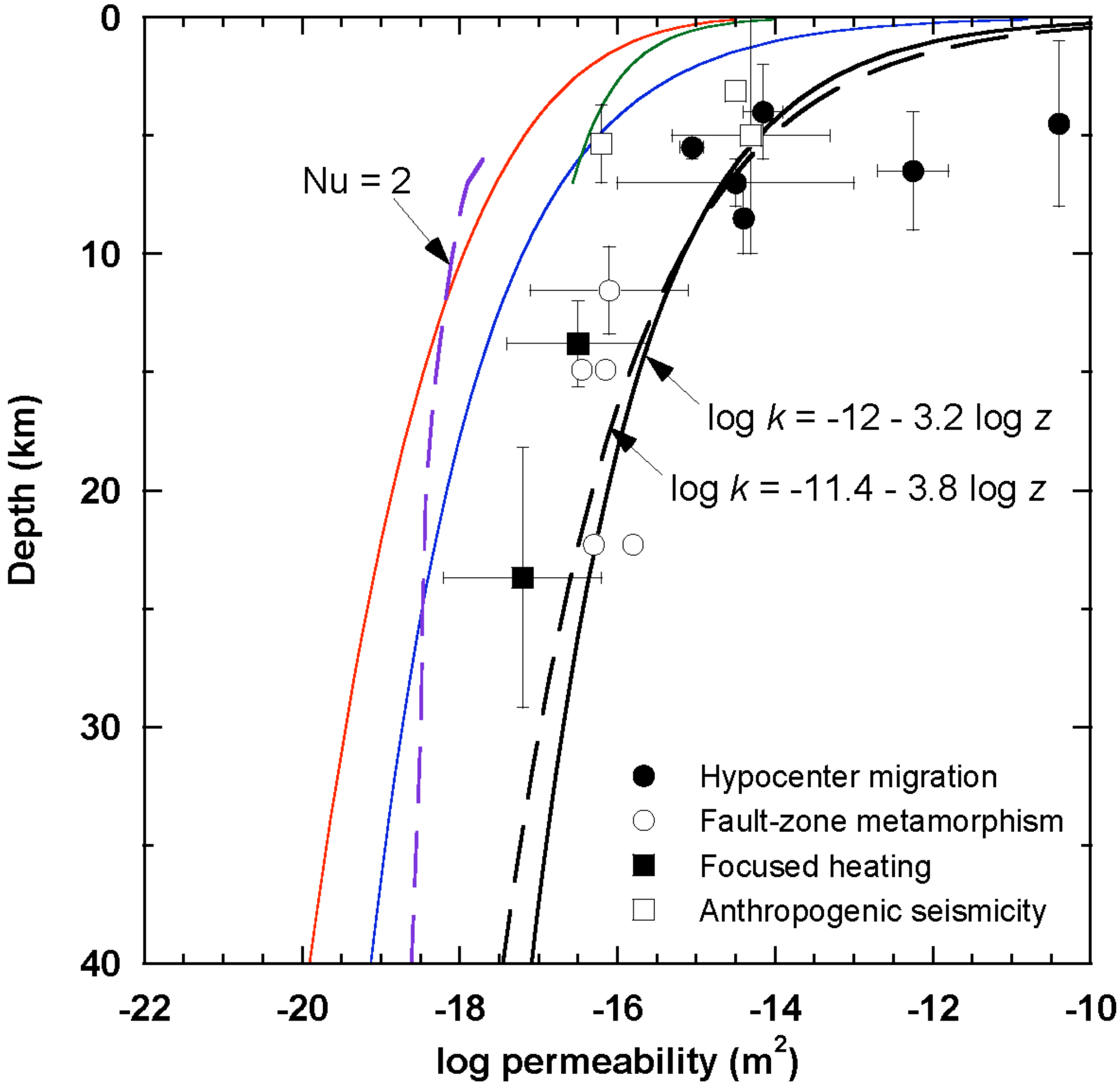


Filled symbols – hydraulically conductive fractures
Open symbols – non-conductive fractures

Townend & Zoback, ***Geology*****, 2000**

Colleen Barton

Permeability decay?



Ingebritsen & Manning, *Geofluids*, 2010

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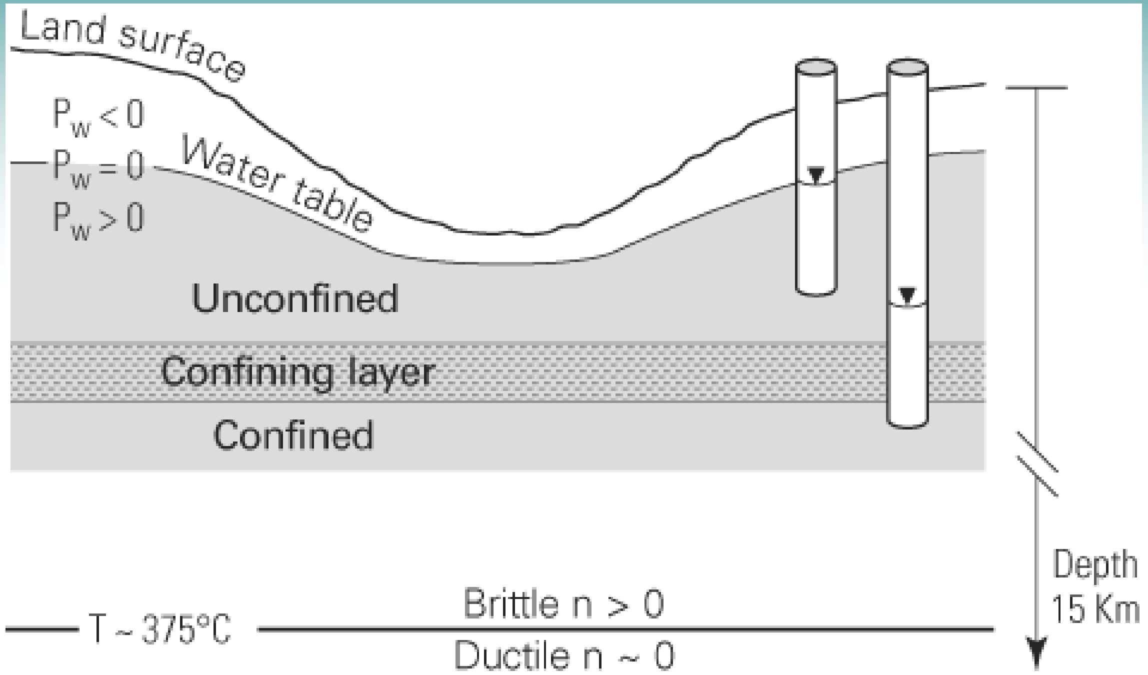
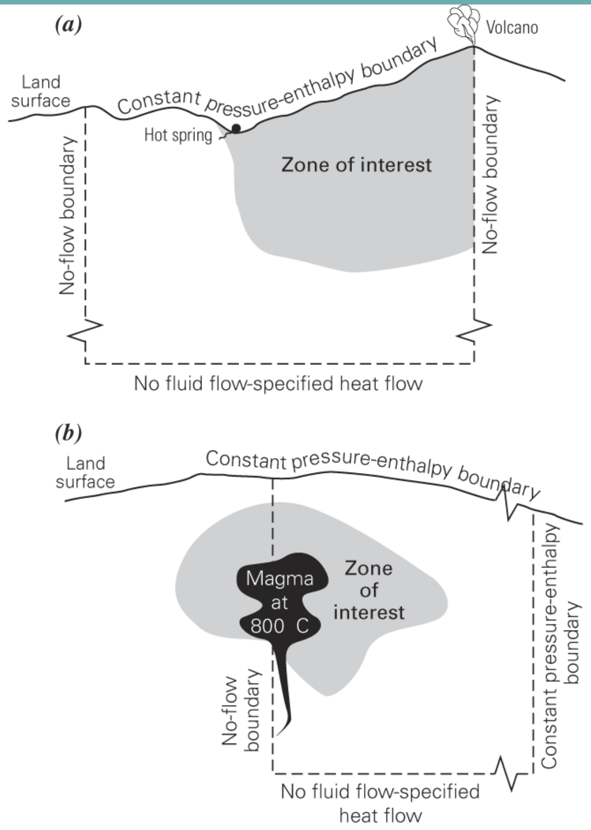


Meteoric water circulation to ~10 km depth in crystalline crust demonstrated by:

o oxygen-isotope composition of hydrothermally altered rock (*e.g*. Taylor *in Role of Fluids in Crustal Processes*, 1990)

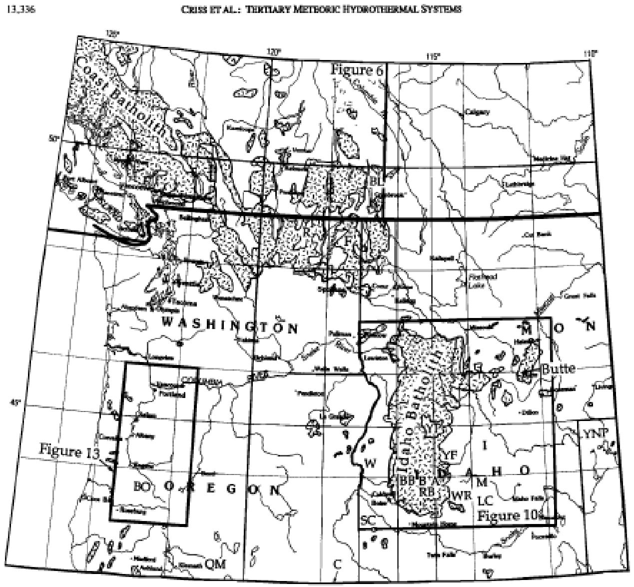
o near-hydrostatic pressures in deep research drillholes (Huenges *et al*., *JGR*, 1997)

The ultimate limit may be the brittle-ductile transition…..



The driving effect of topography decrease with depth, but magmatism introduces a driving force for deep flow…..

…so that Tertiary meteoric hydrothermal systems altered the rocks exposed over ~5% of the NW United States and SW Canada:



Criss *et al.*, *JGR*, 1991

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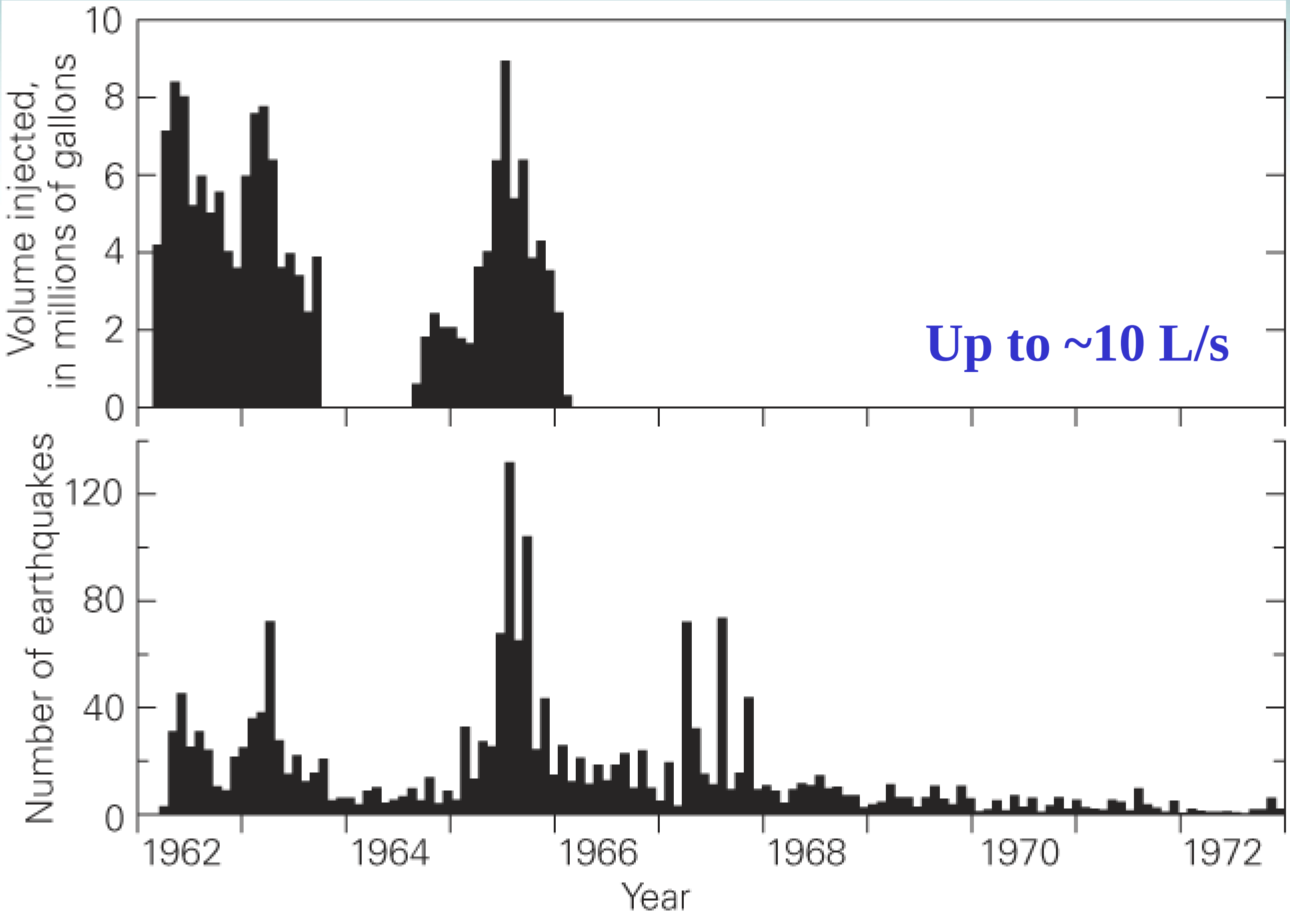
Induced seismicity first documented at Rocky Mountain Arsenal



Up to ~10 L/s

John Bredehoeft

At the RMA, failure occurred under subhydrostatic conditions

	z_{fail}	P_{fail}	dP/dz
RMA:	**$\geq$3.6 km**	**302 b**	**<83 b/km**
Rangely:	**$\geq$2.0 km**	**257 b**	**<130 b/km (lithostatic ~ 250 b/km)**

Hsieh & Bredehoeft, *JGR*, 1981

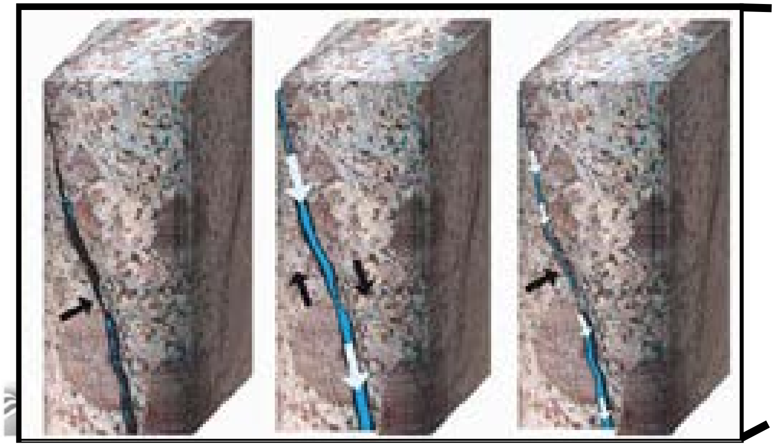
Implications of RMA, reservoir-induced seismicity, and “seasonal” seismicity…:

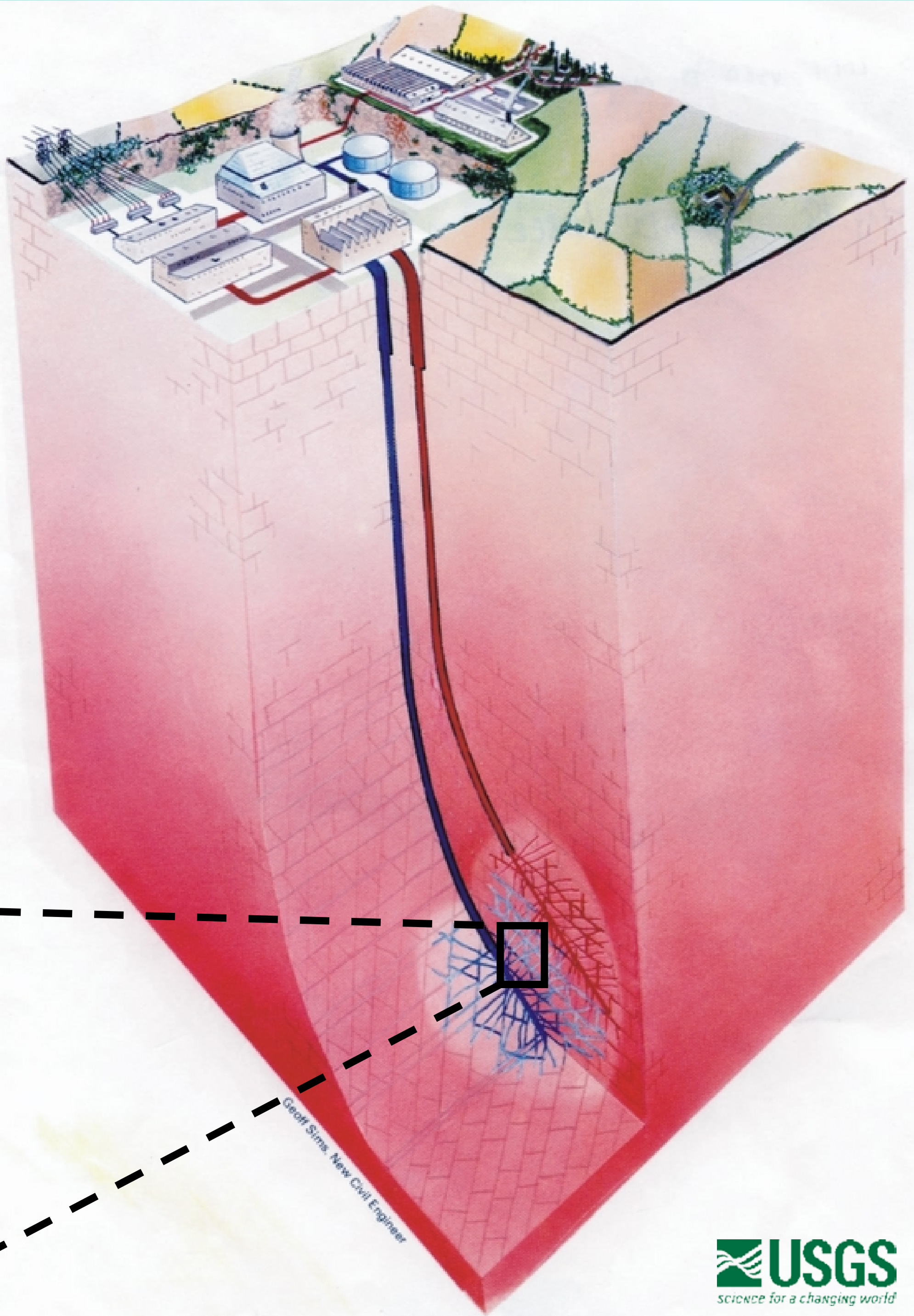
Western Canada – Wolf *et al*., *BSSA*, 1997
Philippine sea plate – Ohtake and Nakahara, *Pageoph*, 1999
Northeast Japan – Heki, *EPSL*, 2003
Mount Hood – Saar and Manga, *EPSL*, 2003
Western US volcanoes – Christiansen *et al*., *EPSL*, 2005
Bavaria – Hainzl *et al*., *GRL*, 2007
Parkfield, California – Christiansen *et al*., *GRL*, 2005
Himalaya – Bollinger *et al*., *GRL*, 2007; Bettinelli *et al*., *EPSL*, 2008

Many instances of RIS – Talwani *et al*., *JGR*, 2007

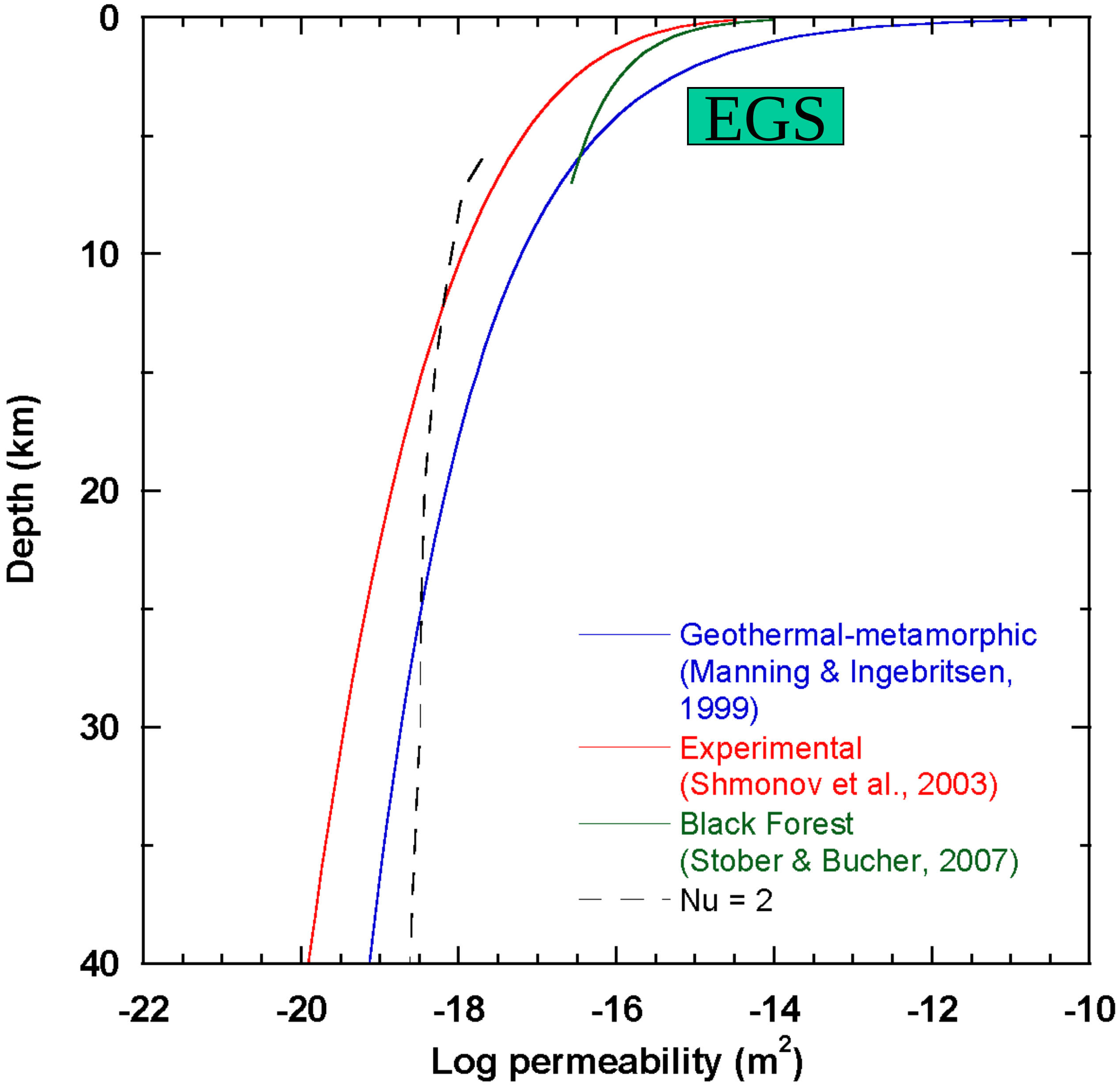
Enhanced Geothermal Systems (EGS)

Enhance permeability by causing existing fractures to slip and propagate or creating new tensile cracks by raising fluid pressure





Geoff Sims, New Civil Engineer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Log permeability (m^2)
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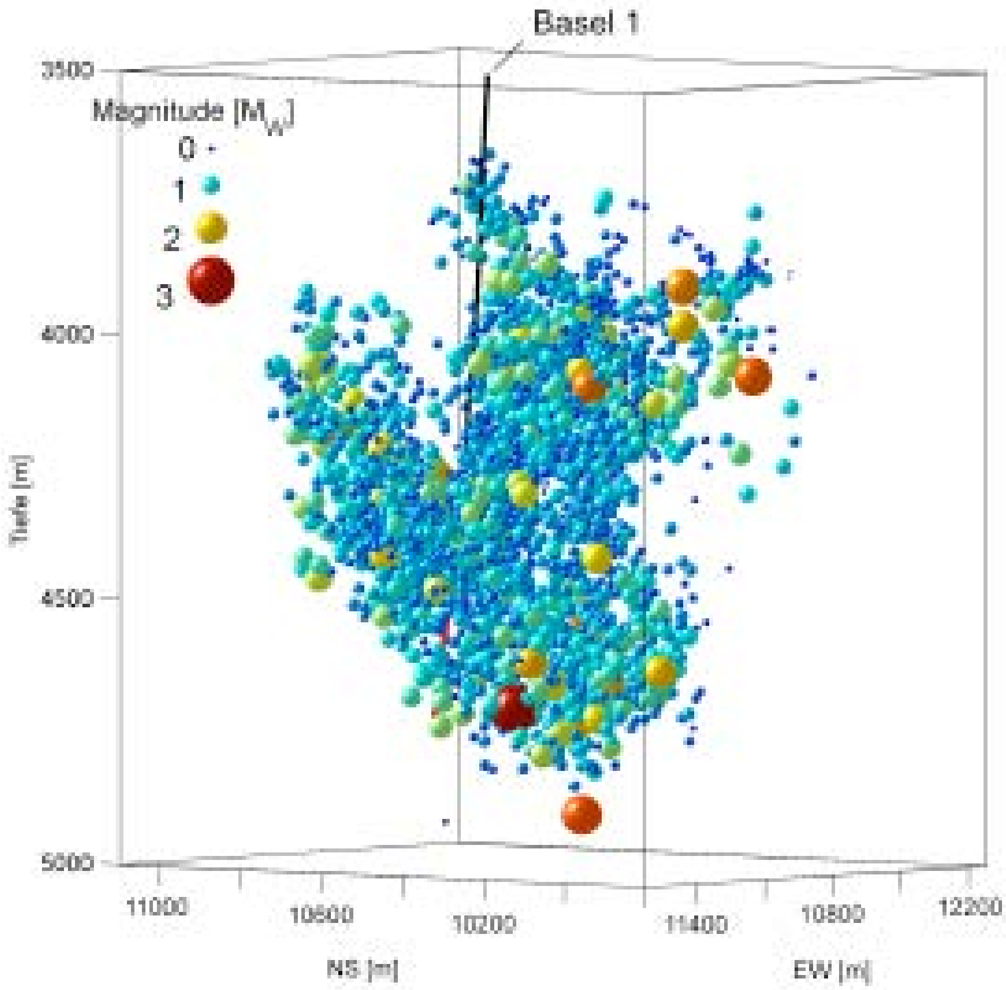
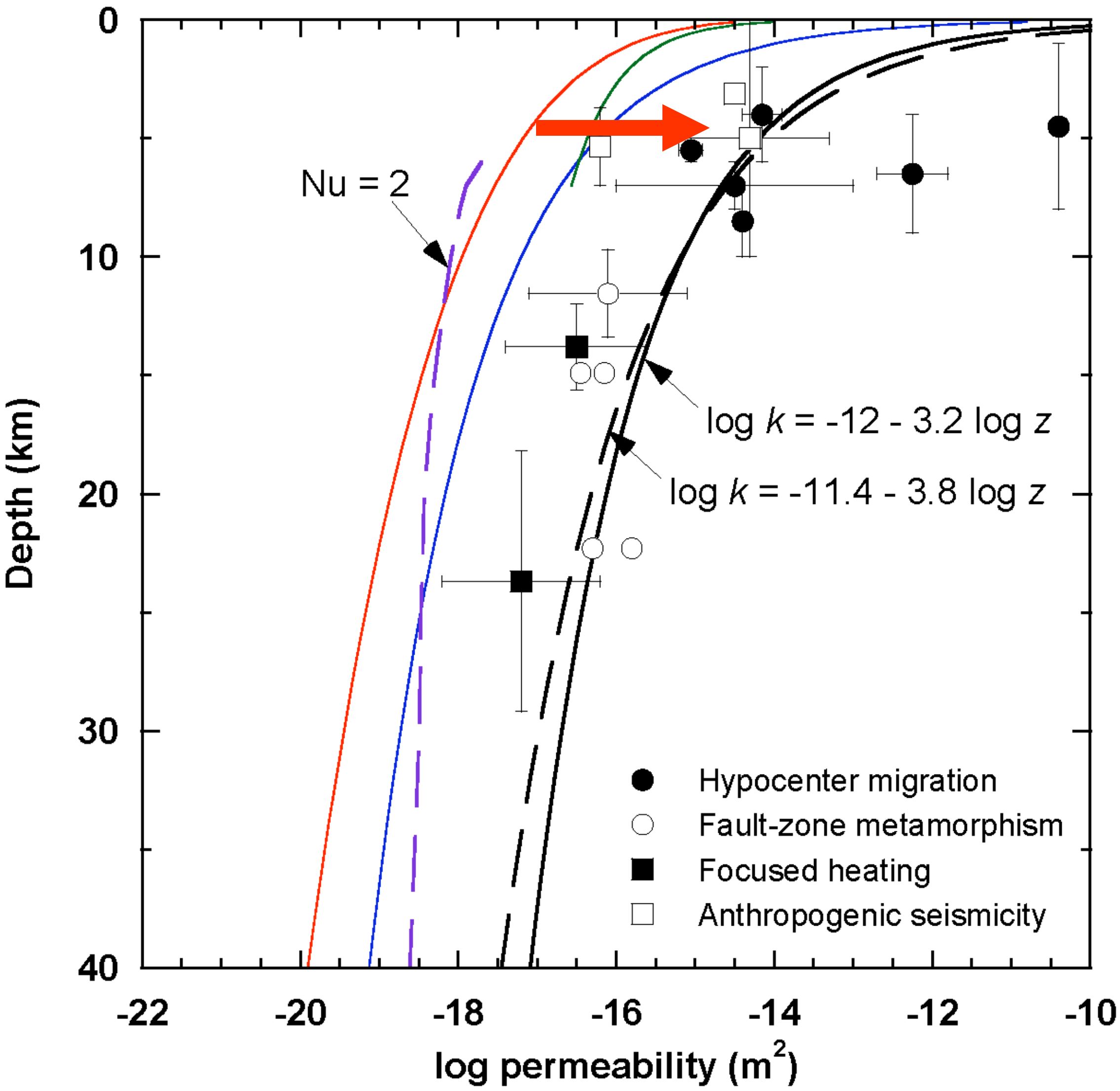
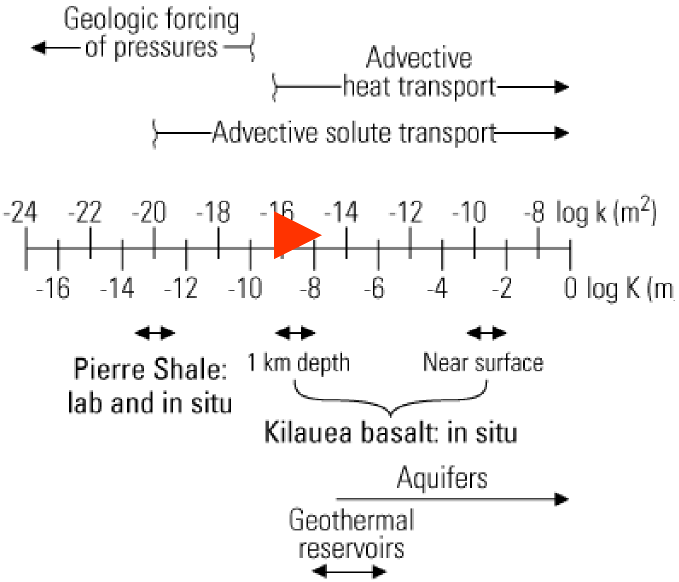
Basel seismicity, December 2006



Haring & others, http://www.geothermal.ch/fileadmin/docs/downloads/dhm_egc300507.pdf

Approximate Basel and Soultz permeabilities – before and after

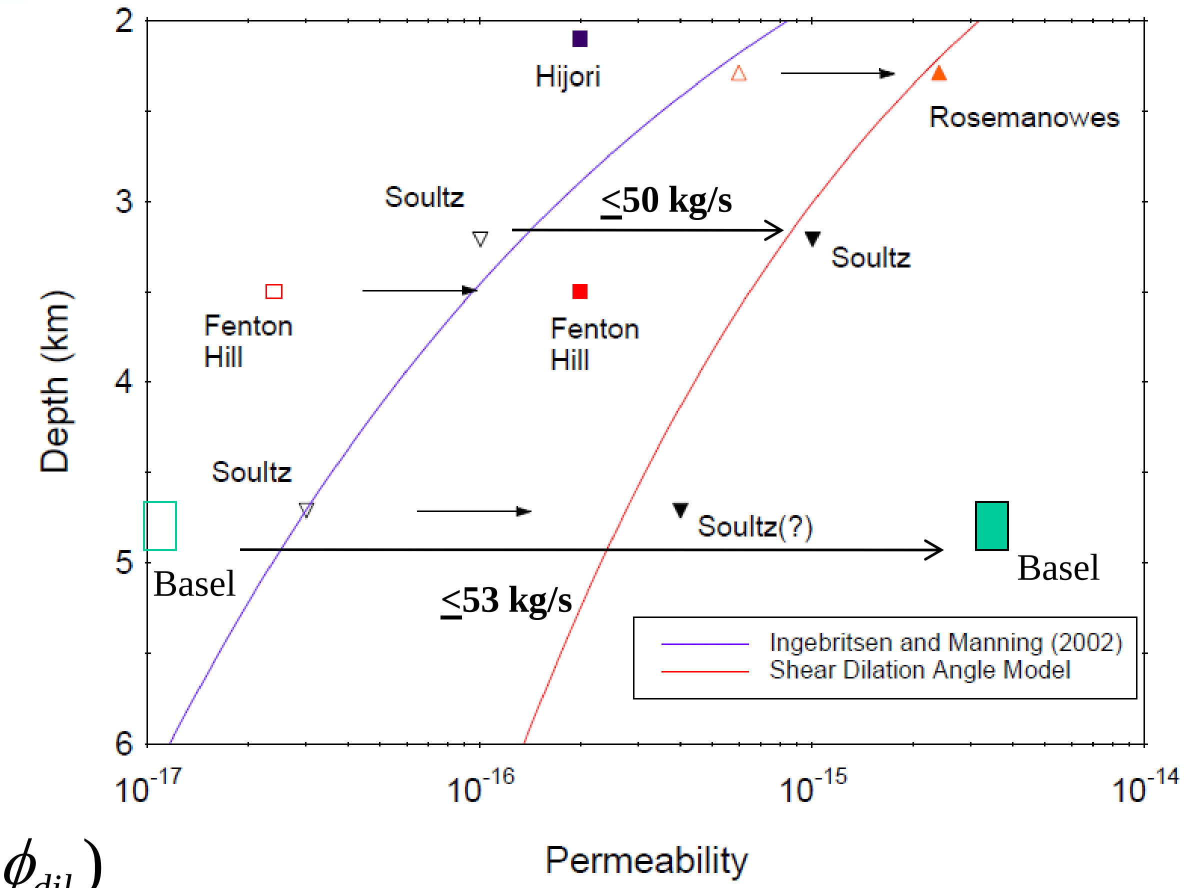




Basel *k* values from Haring & others, *Geothermics*, 2008

Inferred Variations in Permeability with Depth

Observations from EGS projects, all conducted in regions characterized by extensional or strike-slip stress regimes, indicate that both pre-stimulation and post-stimulation permeabilities differ by approximately 1 to 2 orders of magnitude and decrease with depth.



$$\left(k\right)^{1/3} \propto a = \frac{a_0 + U \tan(\phi_{dil})}{1 + 9\sigma' / \sigma'_{nref}}$$

Colin Williams, GSA Annual Meeting, 2010

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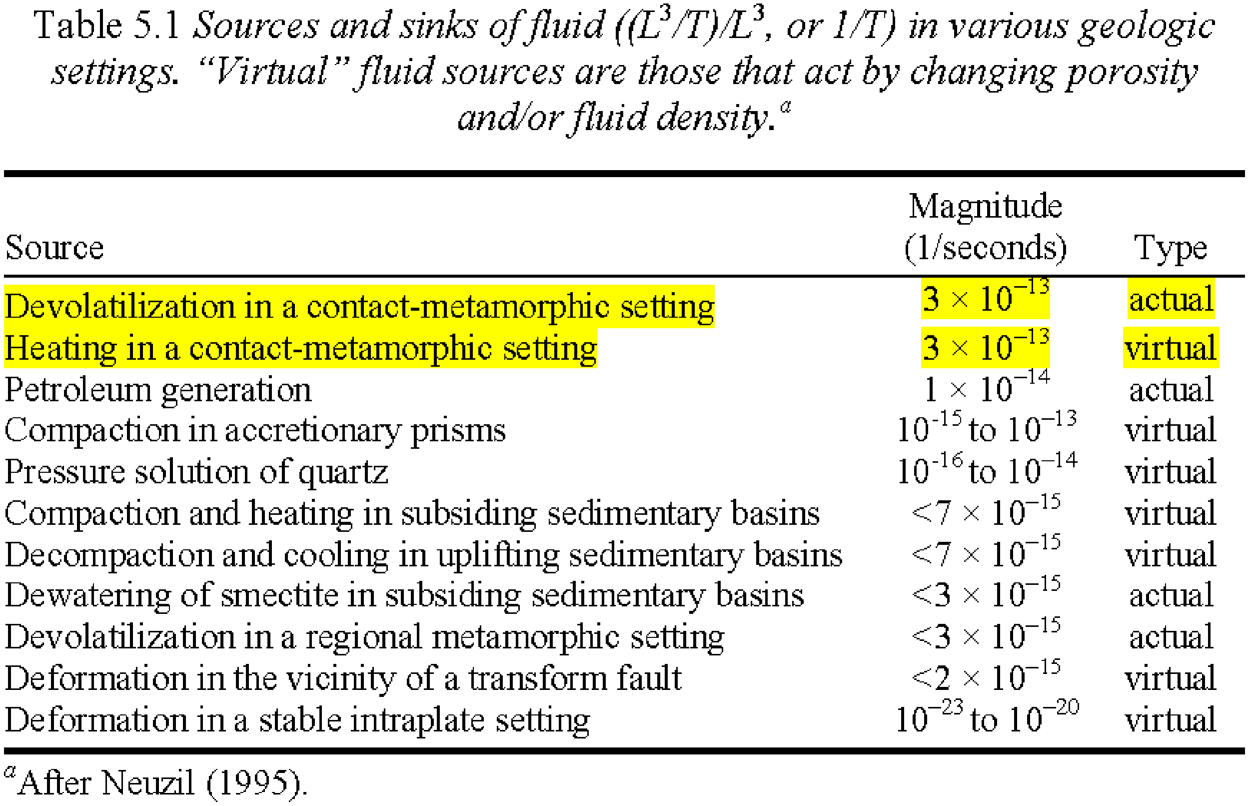


Table 5.1 *Sources and sinks of fluid* (($L^3/T)/L^3$, *or* $1/T$) *in various geologic settings. "Virtual" fluid sources are those that act by changing porosity and/or fluid density.*[a]

Source	Magnitude (1/seconds)	Type
Devolatilization in a contact-metamorphic setting	3×10^{-13}	actual
Heating in a contact-metamorphic setting	3×10^{-13}	virtual
Petroleum generation	1×10^{-14}	actual
Compaction in accretionary prisms	10^{-15} to 10^{-13}	virtual
Pressure solution of quartz	10^{-16} to 10^{-14}	virtual
Compaction and heating in subsiding sedimentary basins	$<7 \times 10^{-15}$	virtual
Decompaction and cooling in uplifting sedimentary basins	$<7 \times 10^{-15}$	virtual
Dewatering of smectite in subsiding sedimentary basins	$<3 \times 10^{-15}$	actual
Devolatilization in a regional metamorphic setting	$<3 \times 10^{-15}$	actual
Deformation in the vicinity of a transform fault	$<2 \times 10^{-15}$	virtual
Deformation in a stable intraplate setting	10^{-23} to 10^{-20}	virtual

[a] After Neuzil (1995).

Chris Neuzil

Ingebritsen *et al.*, *Groundwater in Geologic Processes* (2nd), Cambridge U.P., 2006

A dimensionless form of the groundwater flow equation for a homogeneous, isotropic hydraulic-conductivity field:

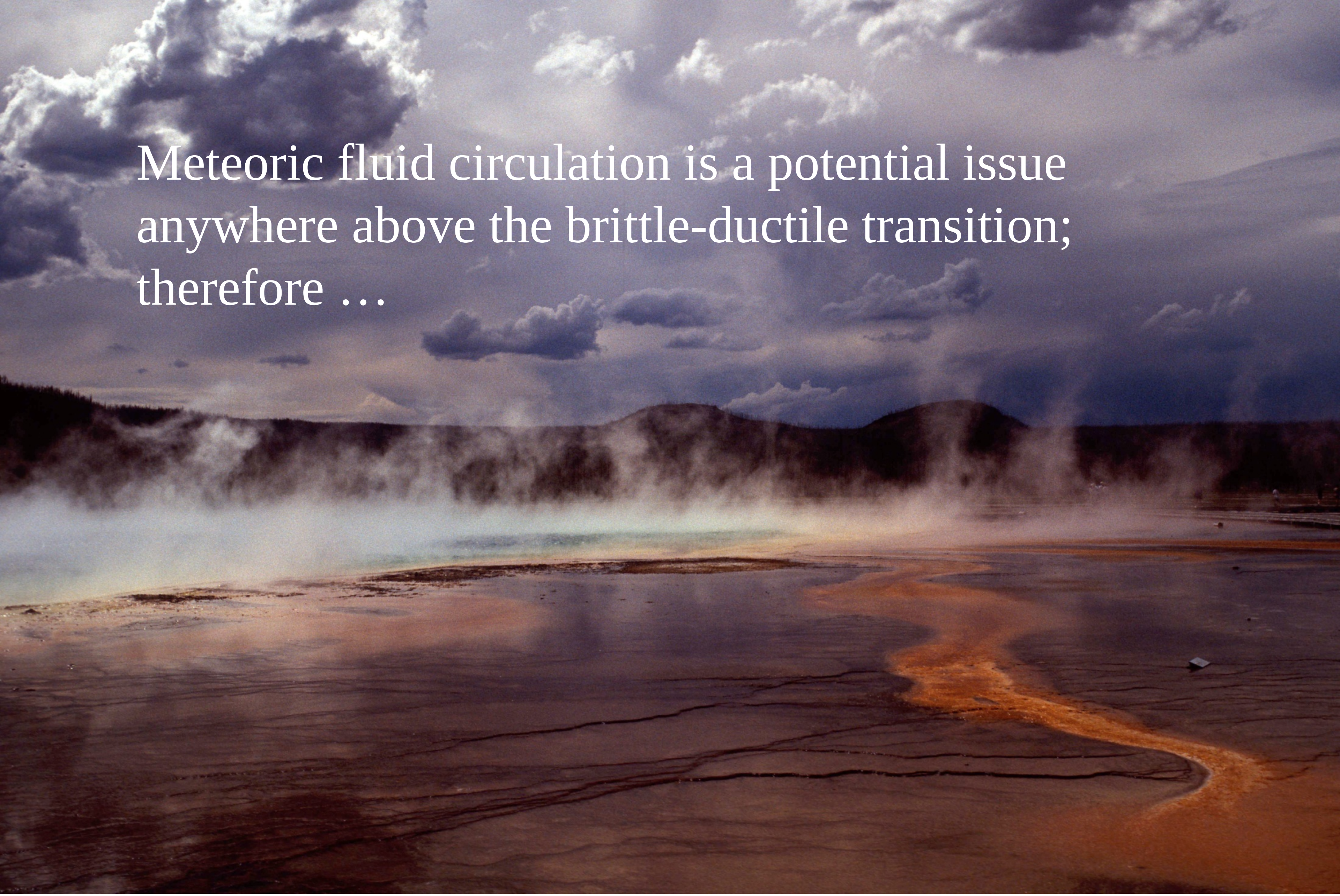
$$\frac{\partial h_{\mathrm{d}}}{\partial t_{\mathrm{d}}} = \nabla^2 h_{\mathrm{d}} + \Gamma_{\mathrm{d}},$$

Elevated fluid pressures expected if $\Gamma_{\mathrm{d}} > 1$,

where $\Gamma_{\mathrm{d}} = \Gamma L/K$

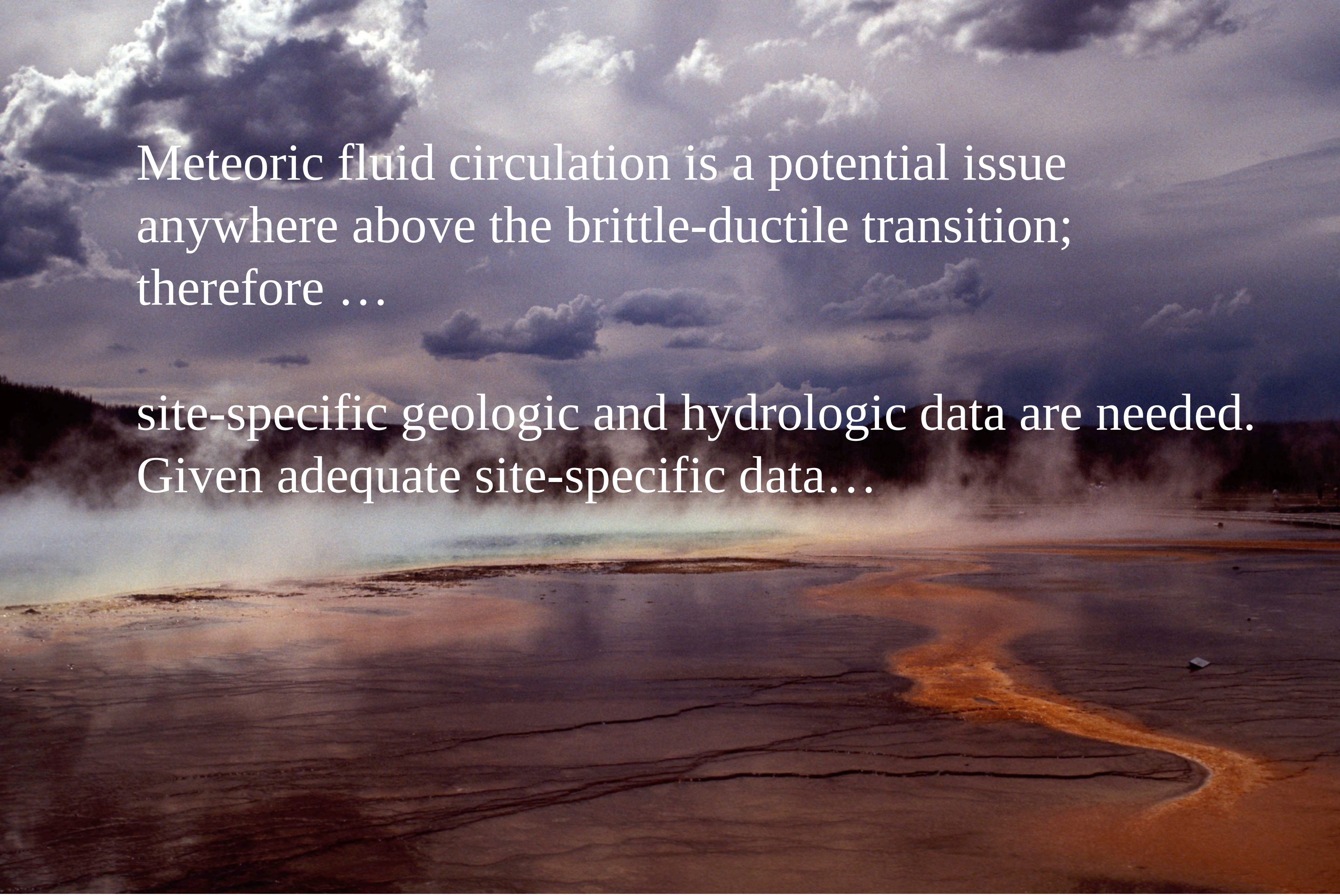
A convenient way to estimate whether actual or "virtual" fluid sources of magnitude Γ (1/s) are likely to effect the fluid-pressure field (Neuzil, *AJS*, 1995)

Photo by R.O. Fournier



Meteoric fluid circulation is a potential issue anywhere above the brittle-ductile transition; therefore …

Photo by R.O. Fournier



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site-specific geologic and hydrologic data are needed. Given adequate site-specific data…

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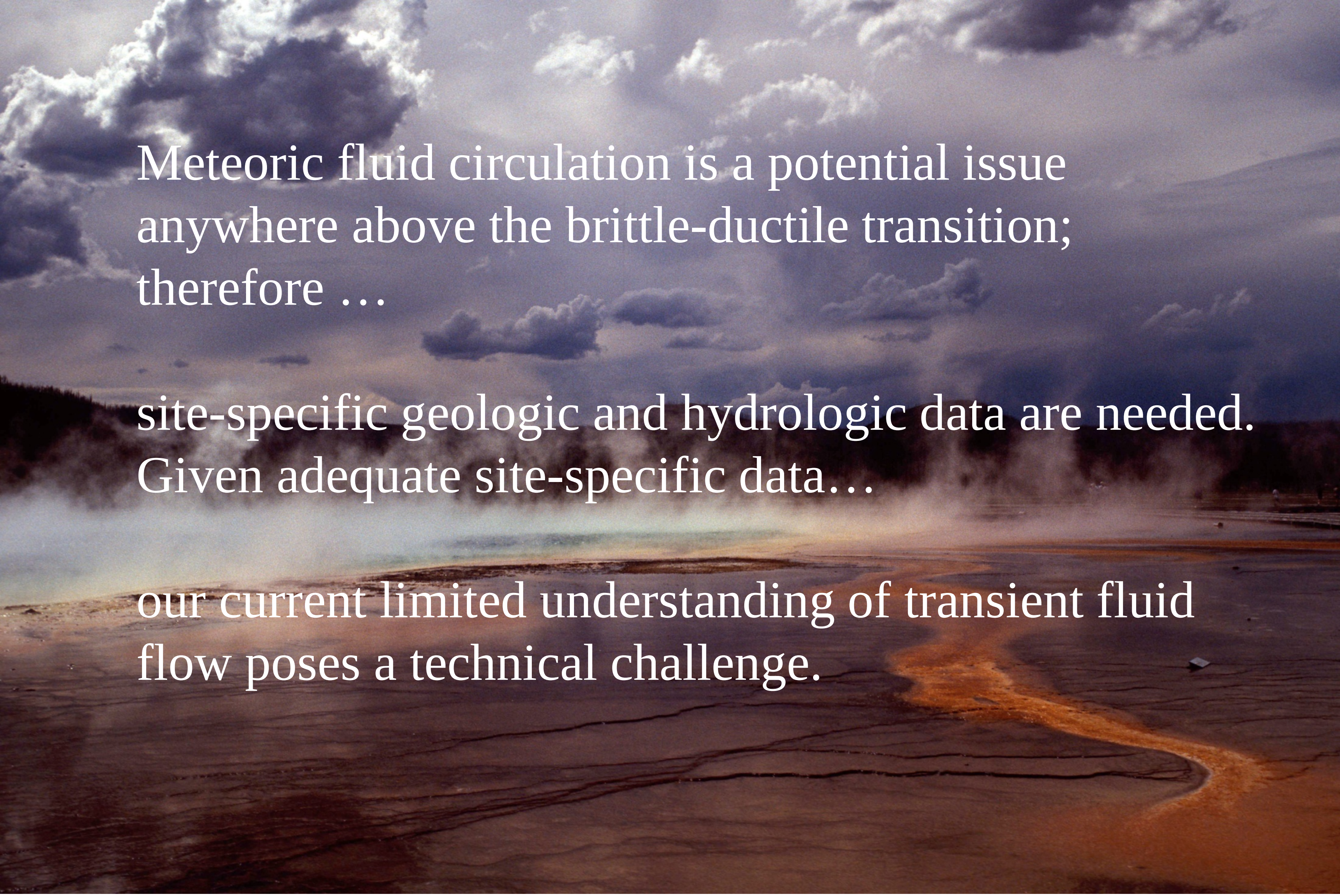


Meteoric fluid circulation is a potential issue anywhere above the brittle-ductile transition; therefore …

site-specific geologic and hydrologic data are needed. Given adequate site-specific data…

our current limited understanding of transient fluid flow poses a technical challenge.

Photo by R.O. Fournier

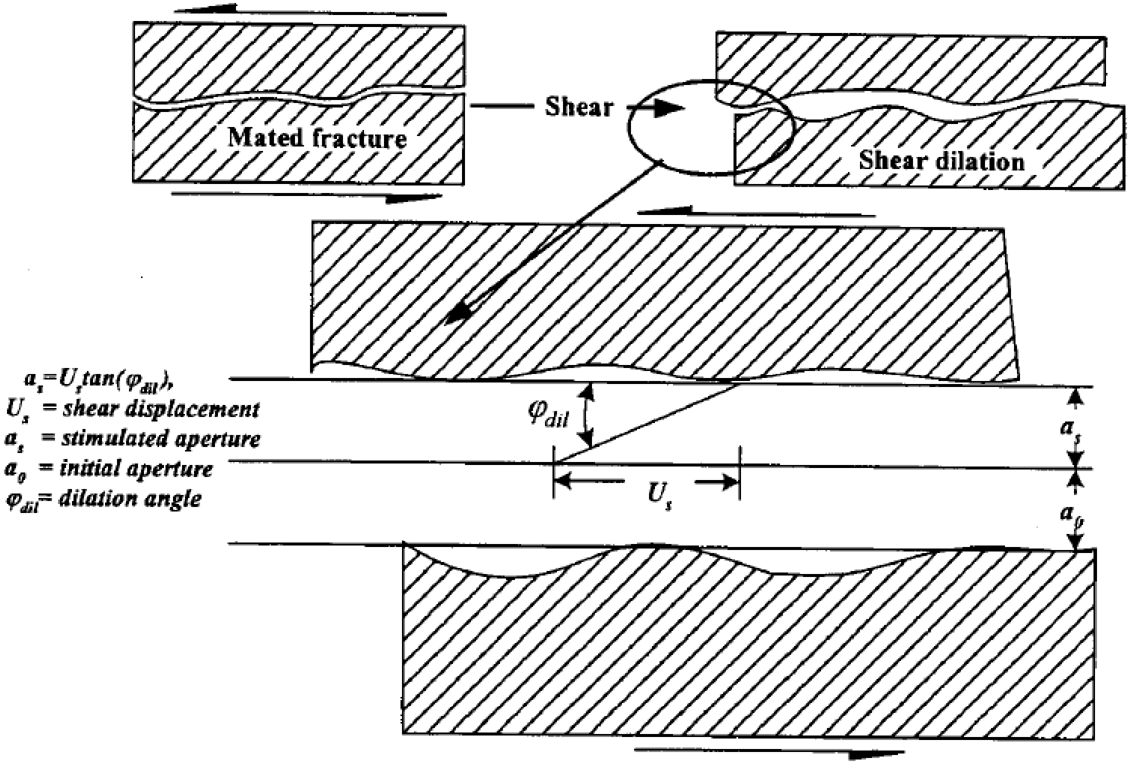
Shear-dilation model for slip-induced permeability

$$(k)^{1/3} \propto a = \frac{a_0 + U\tan(\phi_{dil})}{1+9\sigma'/\sigma'_{nref}}$$

a_0 is *in situ* fracture property. U, φ_{dil} and σ'_{nref} are functions of elastic moduli. σ´ depends on the tectonic state of stress and fluid pressure

Most of these factors are poorly constrained. Model validation limited

Observations from field experiments to follow….

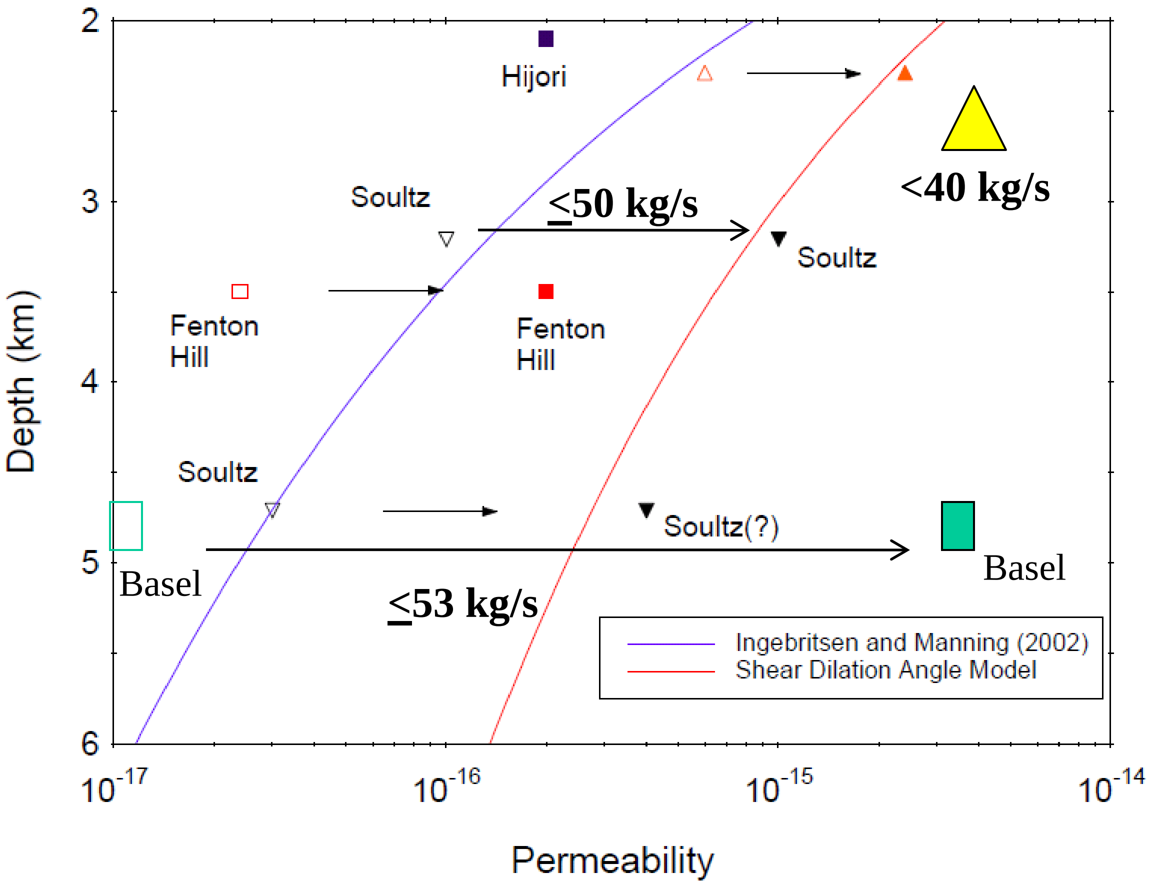


Hydrogeologic/geomechanical simulation: CO_2 injection into the Rose Run Sandstone, eastern Ohio

(Lucier and Zoback, *IJGGC*, 2008)

Depth	**~2.4 km**
Permeability	**4-5 x 10^{-15} m^2 (mean of multigaussion distribution)**
Porosity	**4%**
Bottomhole pressure constraint	**32-42 Mpa (< caprock fracture pressure)**
Injectivity	**0.1-1.2 Mt CO_2/yr ($\leq$40 kg/s)**

Rose Run Sandstone GCS model in context of EGS



▲ Rose Run Sandstone, Eastern Ohio (Lucier and Zoback, *IJGGC*, 2008)