Hydroseismicity and (hydro)geodetic monitoring for Southern African water and energy development

Chris Hartnady

Umvoto Africa (Pty) Ltd

Muizenberg, Cape Town

IGCP565 Final Workshop, Johannesburg, 29-30 October 2012

Outline

- Hydroseismicity: earthquakes triggered by fluid-pressure changes in a poro-elastic crust
- Crustal stress-strain provinces of Southern Africa and their hydroseismic potential
- Earthquakes induced by energy technologies
  - Fracking-related tremors
  - Waste-water disposal seismicity
- Role for hydrogeodetic monitoring

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Seismological Research Letters, Volume 58, No. 3, July - September, 1987

HYDROSEISMICITY: A HYPOTHESIS FOR THE ROLE OF WATER IN THE GENERATION OF INTRAPLATE SEISMICITY

John K. Costain, G. A. Bollinger, and J. Alexander Speer

Department of Geological Sciences
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061

Hydroseismicity

- Term introduced by Costain et al. (1987) to explain generation of *intraplate earthquakes*
- Based upon spatial correlation in SE USA between
  - crustal volumes of high seismicity
  - large gravity-driven river basins that can provide adequate supply of water to upper- and mid-crust
  - permeable crust that is tectonically stressed close to failure
- Combination of connected fractures and adequate groundwater transmits hydraulic-head transients to depths of 10-20 km, thereby triggering earthquakes

Fluid flow in deep crust

GEOFLUIDS
Geofluids (2010) 10, 193–205 doi: 10.1111/j.1468-8123.2010.00278.x

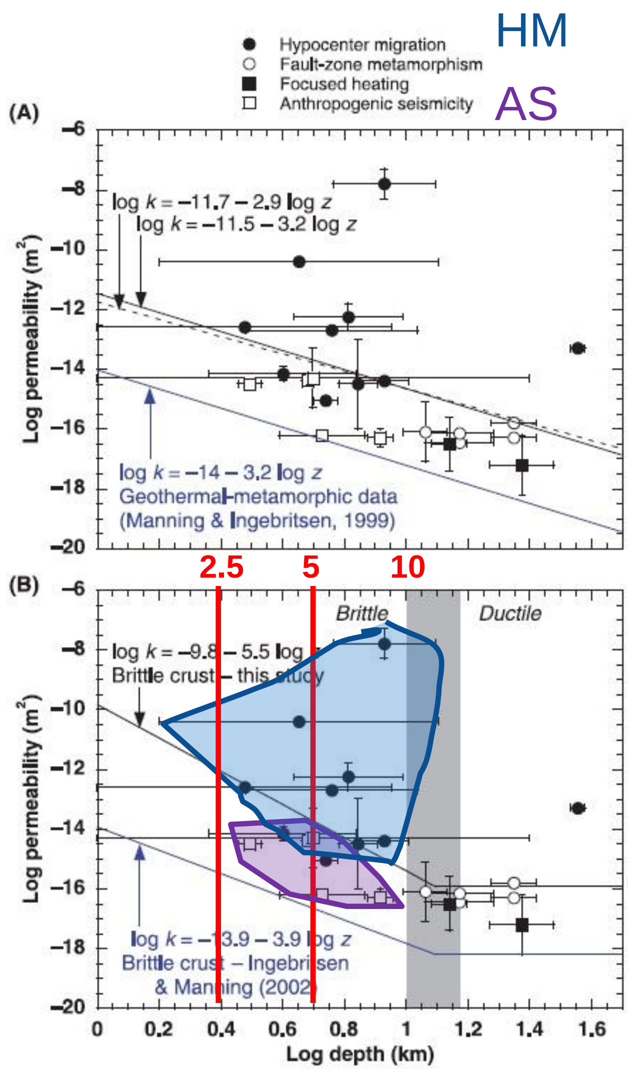
Permeability of the continental crust: dynamic variations inferred from seismicity and metamorphism

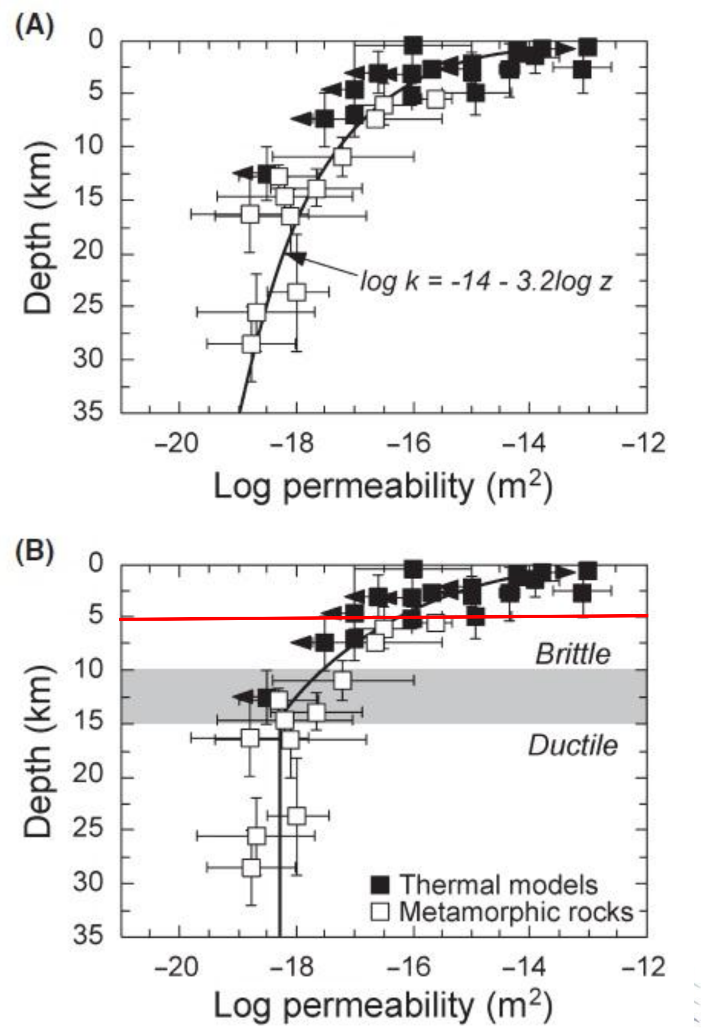
S. E. INGEBRITSEN[1] AND C. E. MANNING[2]
[1]US Geological Survey, Menlo Park, CA, USA; [2]Department of Earth and Space Sciences, UCLA, Los Angeles, CA, USA

Permeability k: measures how well porous medium transmits fluid, independent of fluid properties (unit = l^2)

Hydraulic conductivity K: measures how easily water moves through porous medium (unit = l/t)

Hydraulic diffusivity $D = K/S_s$, where (specific storage) $S_s = \rho_w(\beta_p + \eta . \beta_w)$ (D unit = l^2/t)





Crust at steady-state failure equilibrium

- "… The occurrence of widely distributed, low-level seismicity within stable continental regions …, the widespread phenomenon of induced seismicity and the in situ stress measurements in deep boreholes … consistently approximate to those predicted by Mohr-Coulomb frictional failure theory … all suggest that continental crust is typically critically stressed, and almost everywhere close to, or at, failure … or what Zoback et al. (2002) termed **steady-state failure equilibrium**. The associated rates of deformation are difficult to quantify, in part because recurrence intervals of the large earthquakes that are responsible for any accumulation of the strain on geological time-scales are much longer than historic seismic records. …" (Sandiford, 2010, p. 572)

Sandiford M. Why are the continents just so…?
J. metamorphic Geol., 2010, 28, 569–577 doi:10.1111/j.1525-1314.2010.00888.x

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Global plate tectonics

LW = Lwandle plate

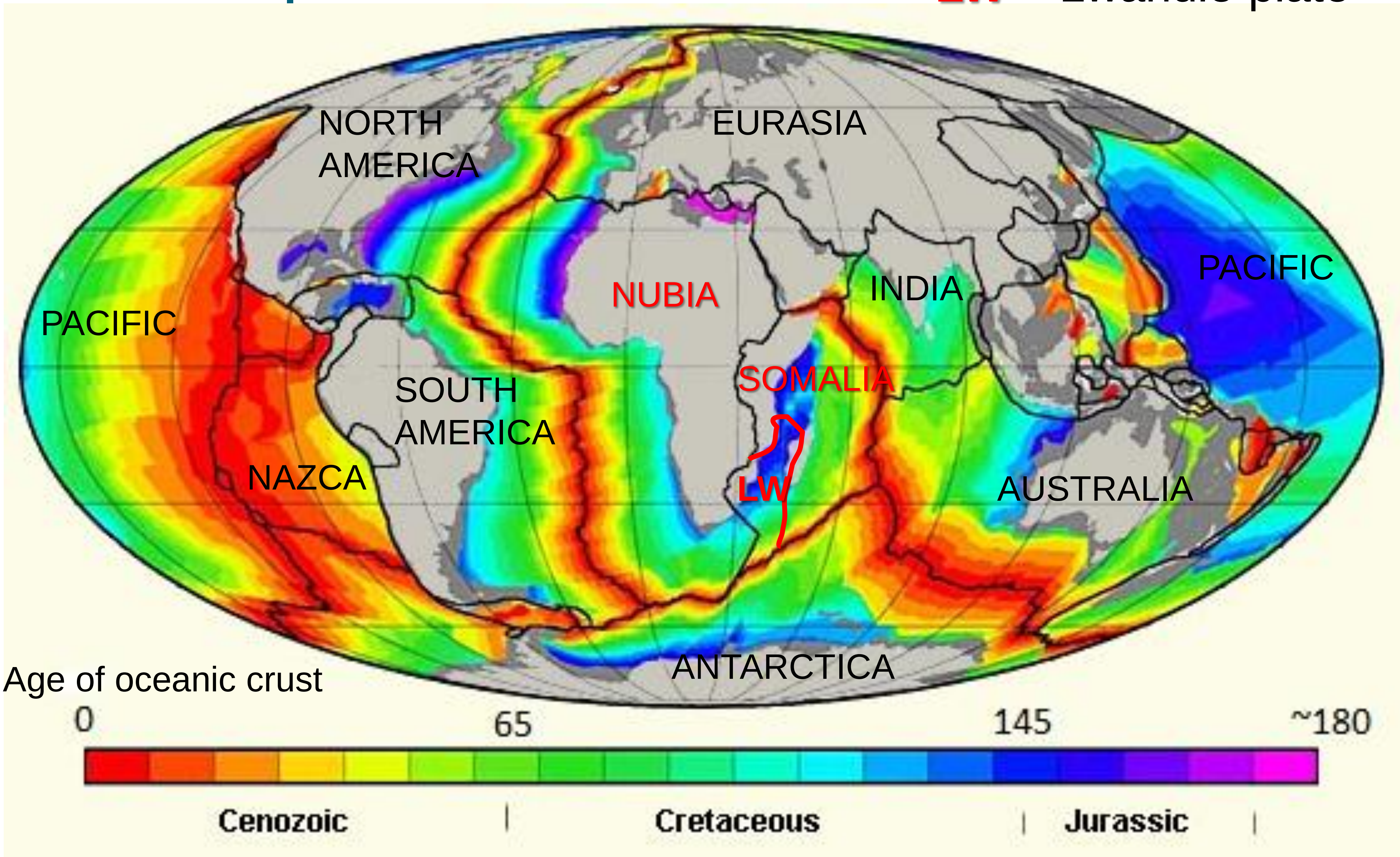
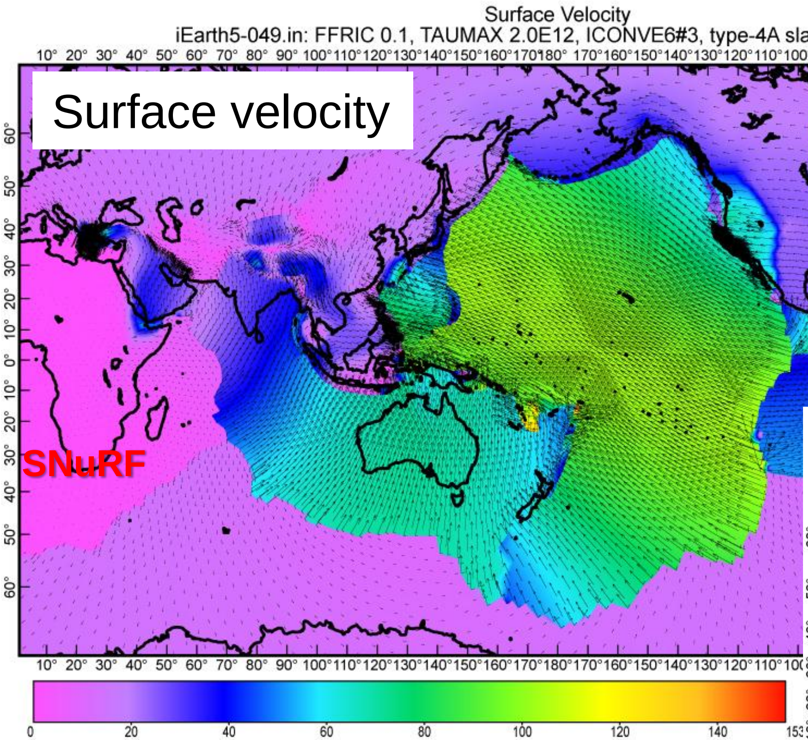
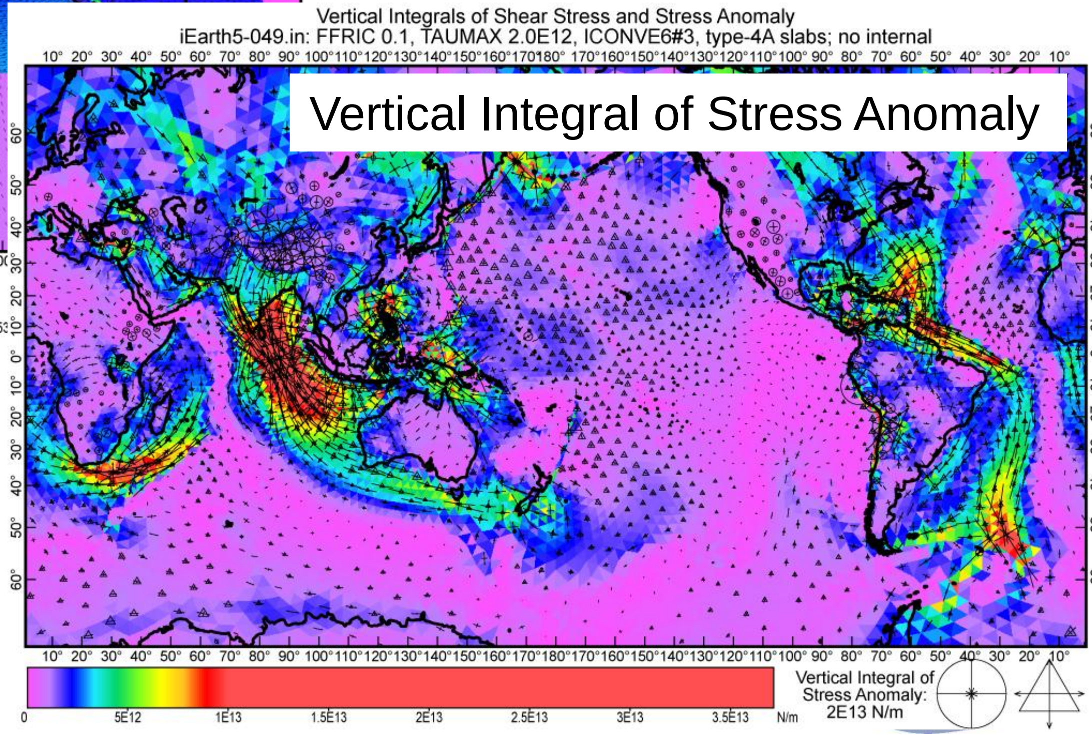


Plate motions and stresses

- from Bird, Liu & Rucker, 2008





African multi-plate model

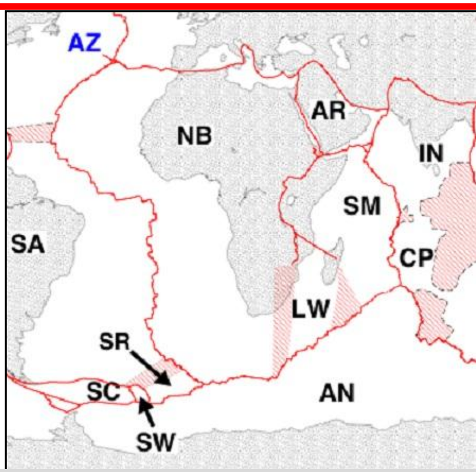
News & Views

South African Journal of Science 98, September/October 2002

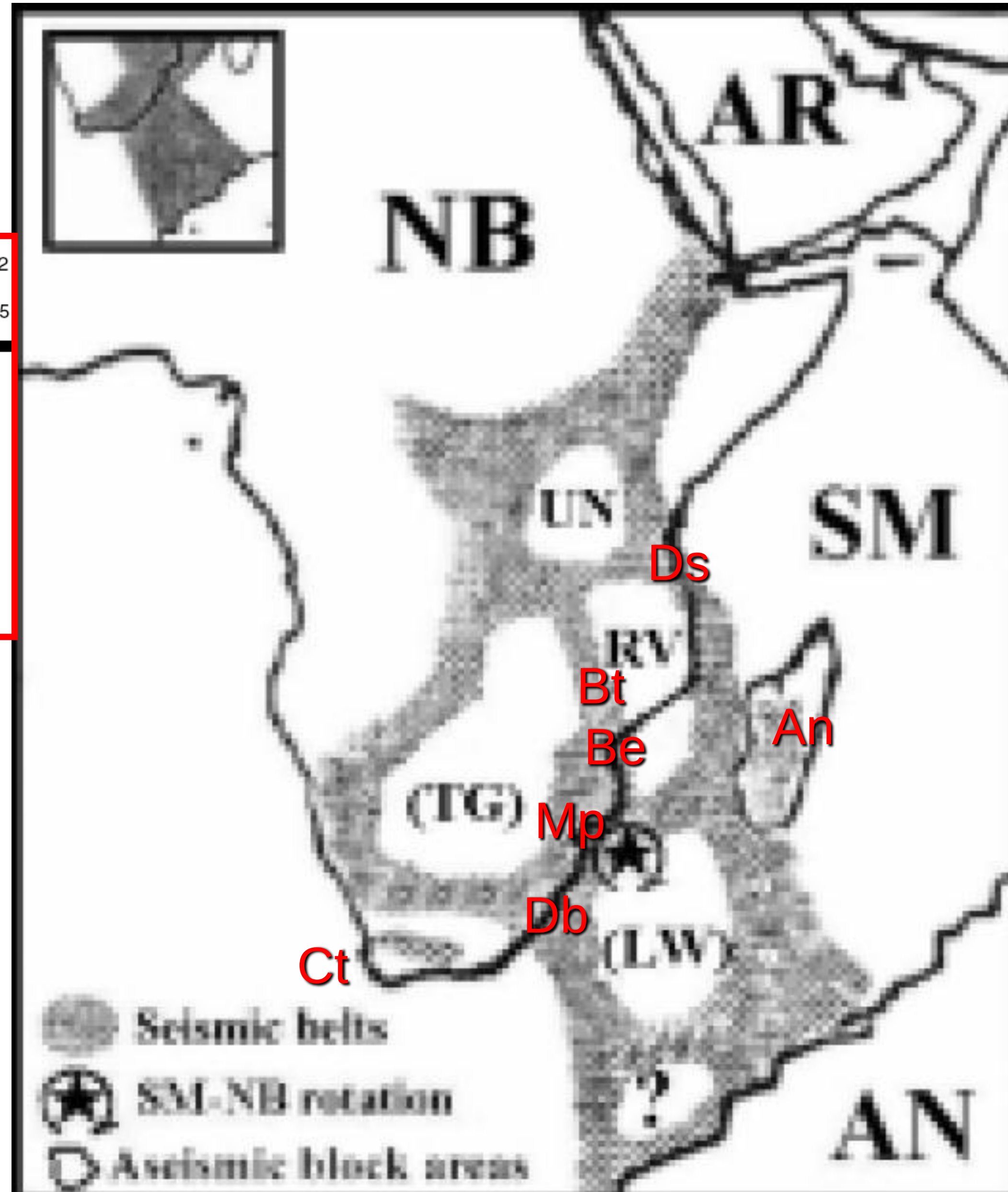
425

Earthquake hazard in Africa: perspectives on the Nubia–Somalia boundary

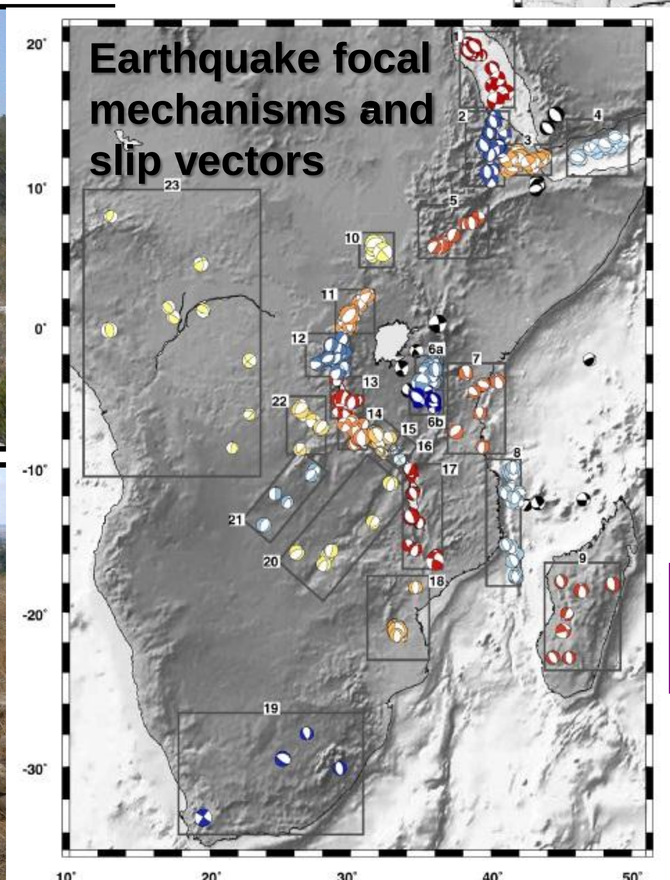
C.J.H. Hartnady*

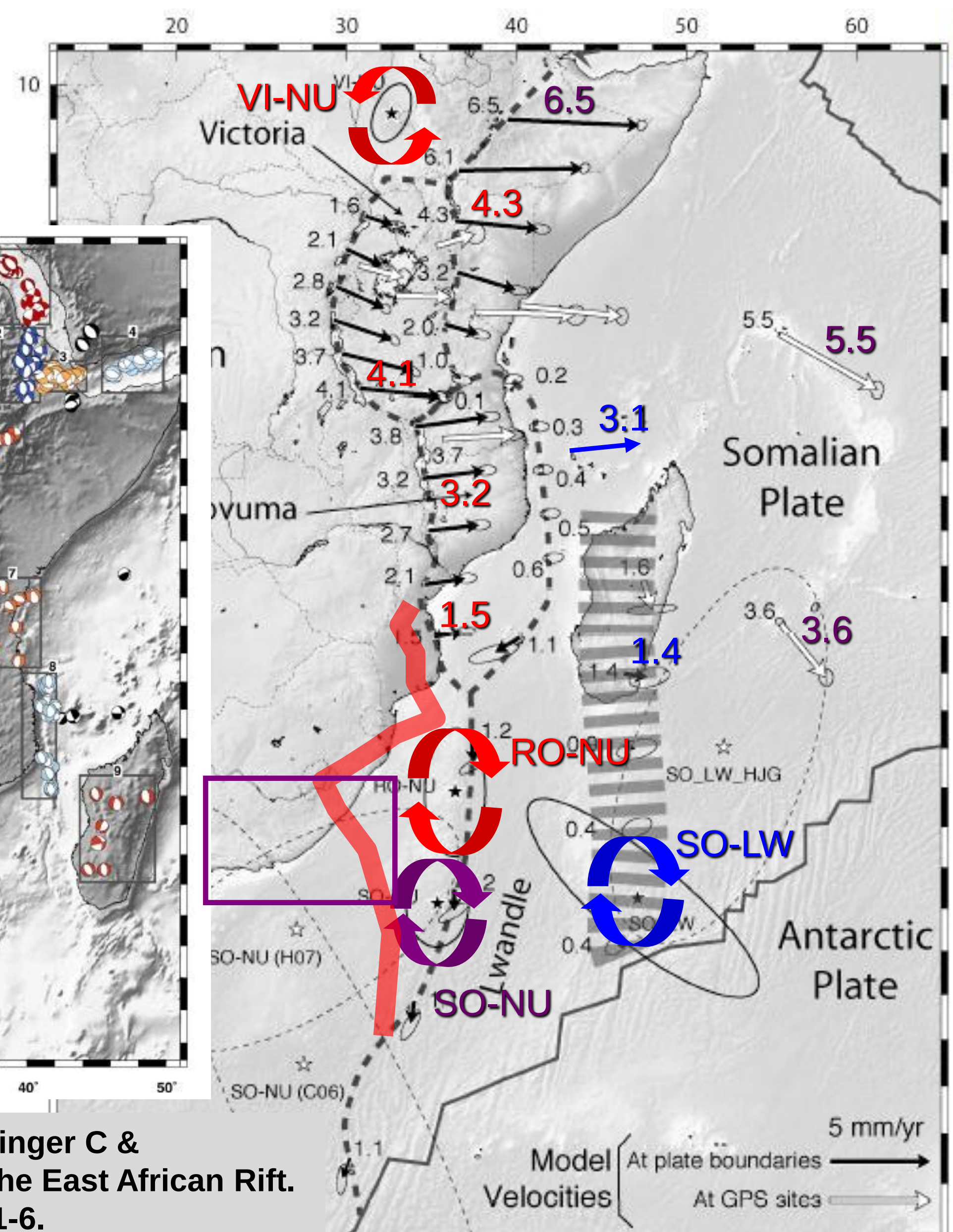


DeMets, C., Gordon, R., and Argus, D., 2010. Geologically current plate motions, Geophys. Jnl Internat., 181 (1), 1-80.



EARS: GPS and ESV kinematics

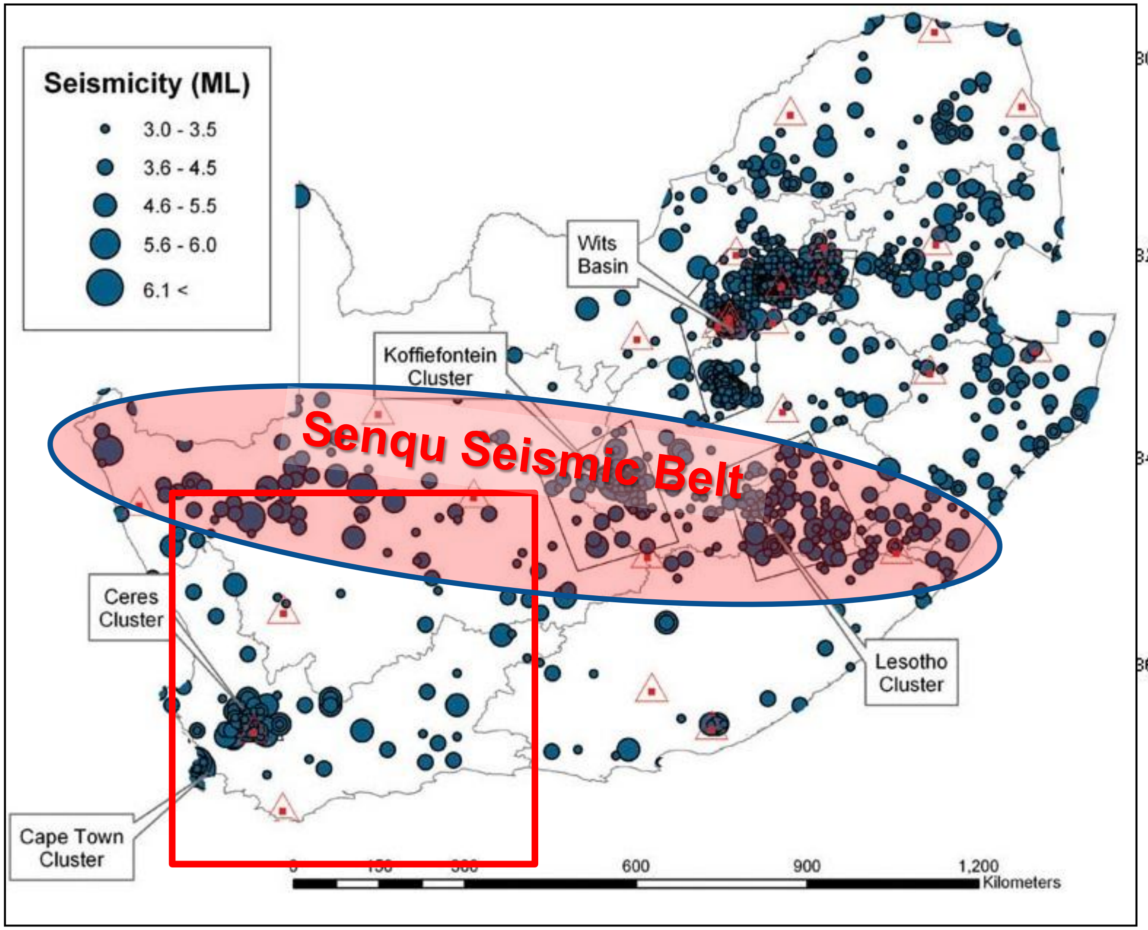




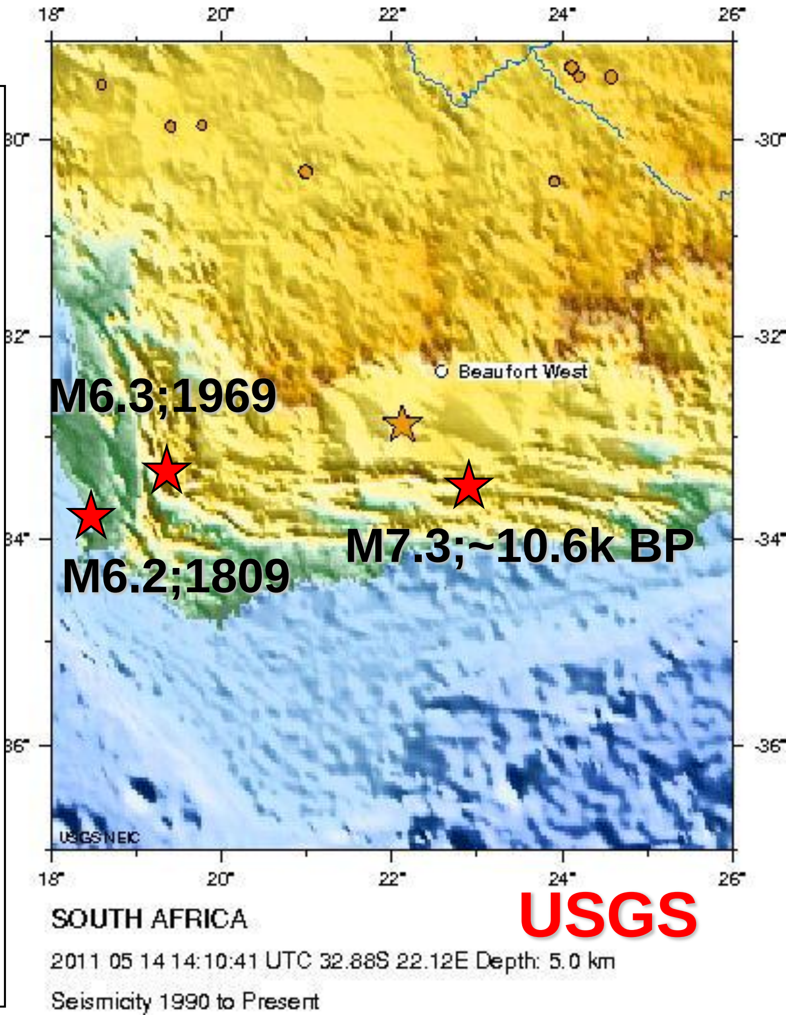
Stamps D, Calais E, Saria E, Hartnady C, Ebinger C & Fernandes R, 2008. A kinematic model for the East African Rift. Geophysical Research Letters, 35, L05304, 1-6.

SA and Karoo seismicity

- CGS earthquake database 1620-2009 (Singh et al., 2011)



Karoo earthquake 2011-05-14



Karoo basin structure

- SW-NE Geological Profile

Figure X-9. Map Showing Operator Permits in the Karoo Basin, South Africa[3,16]

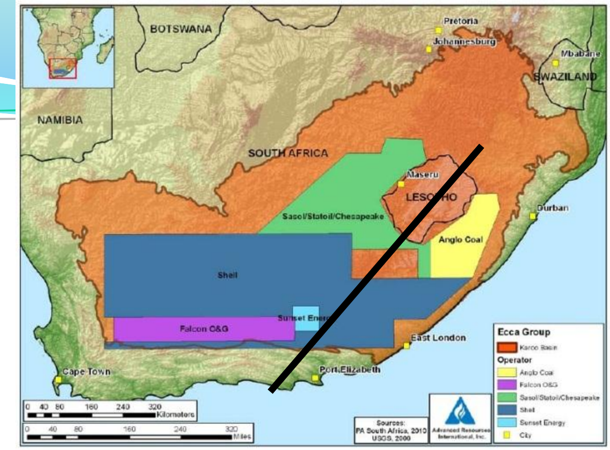
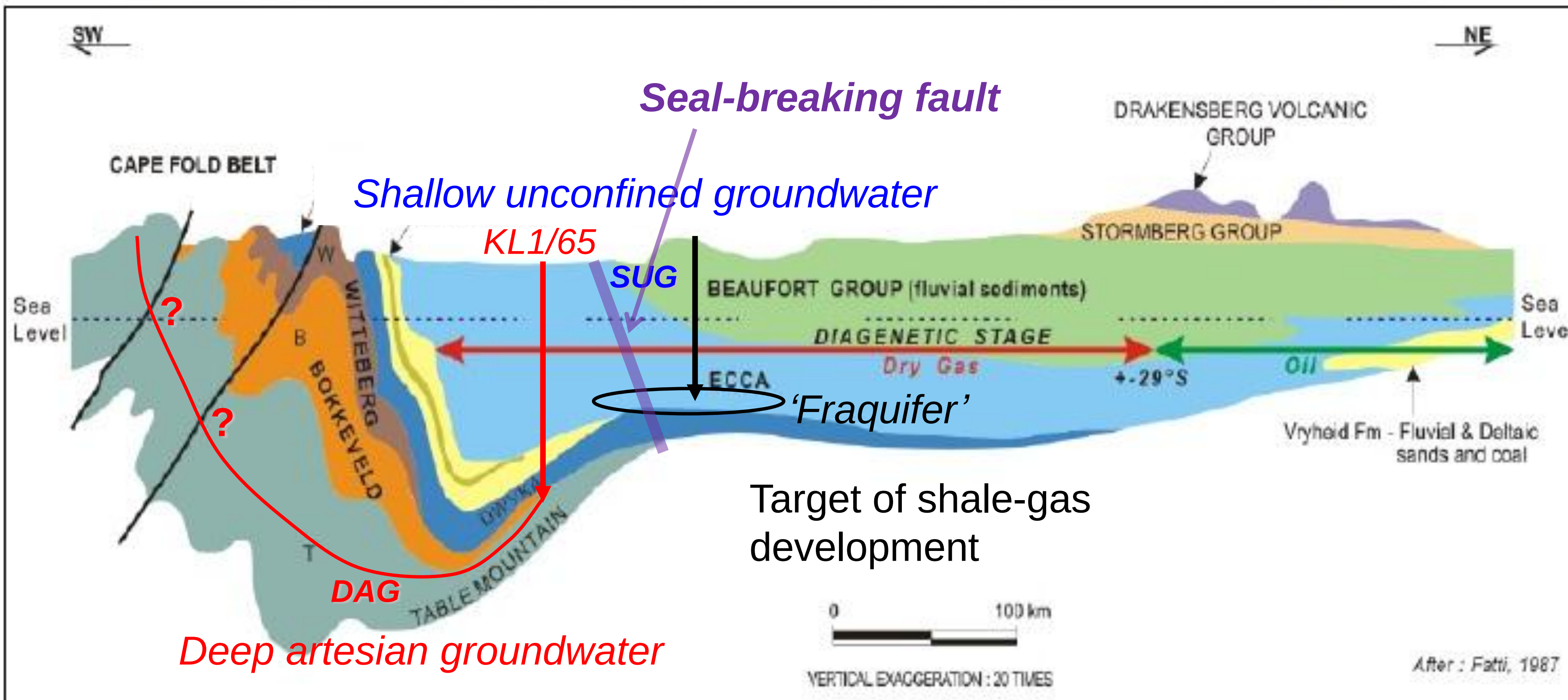
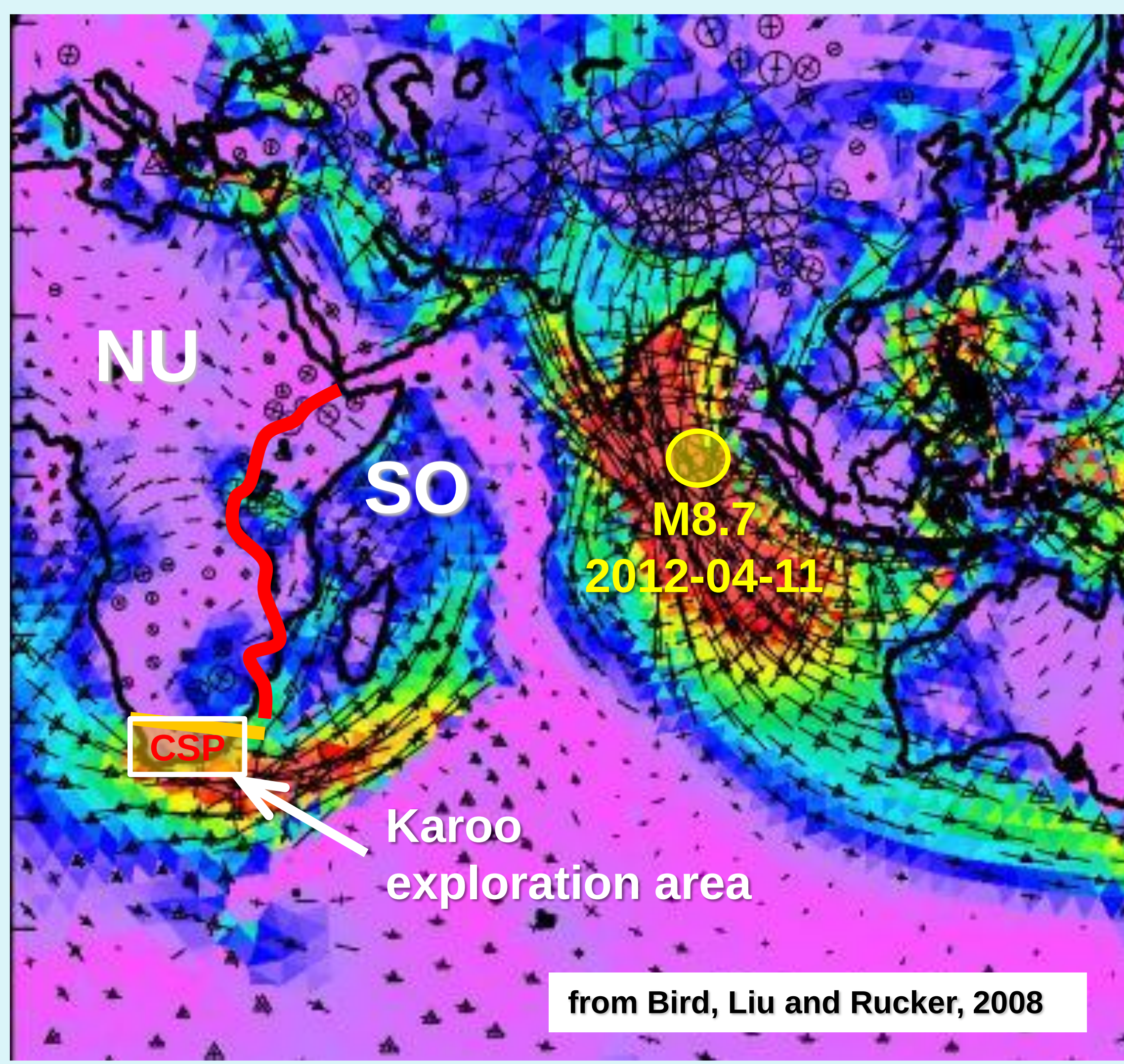


Figure X-3. Schematic Cross-Section of Southern Karoo Basin and Ecca Group Shales[7]



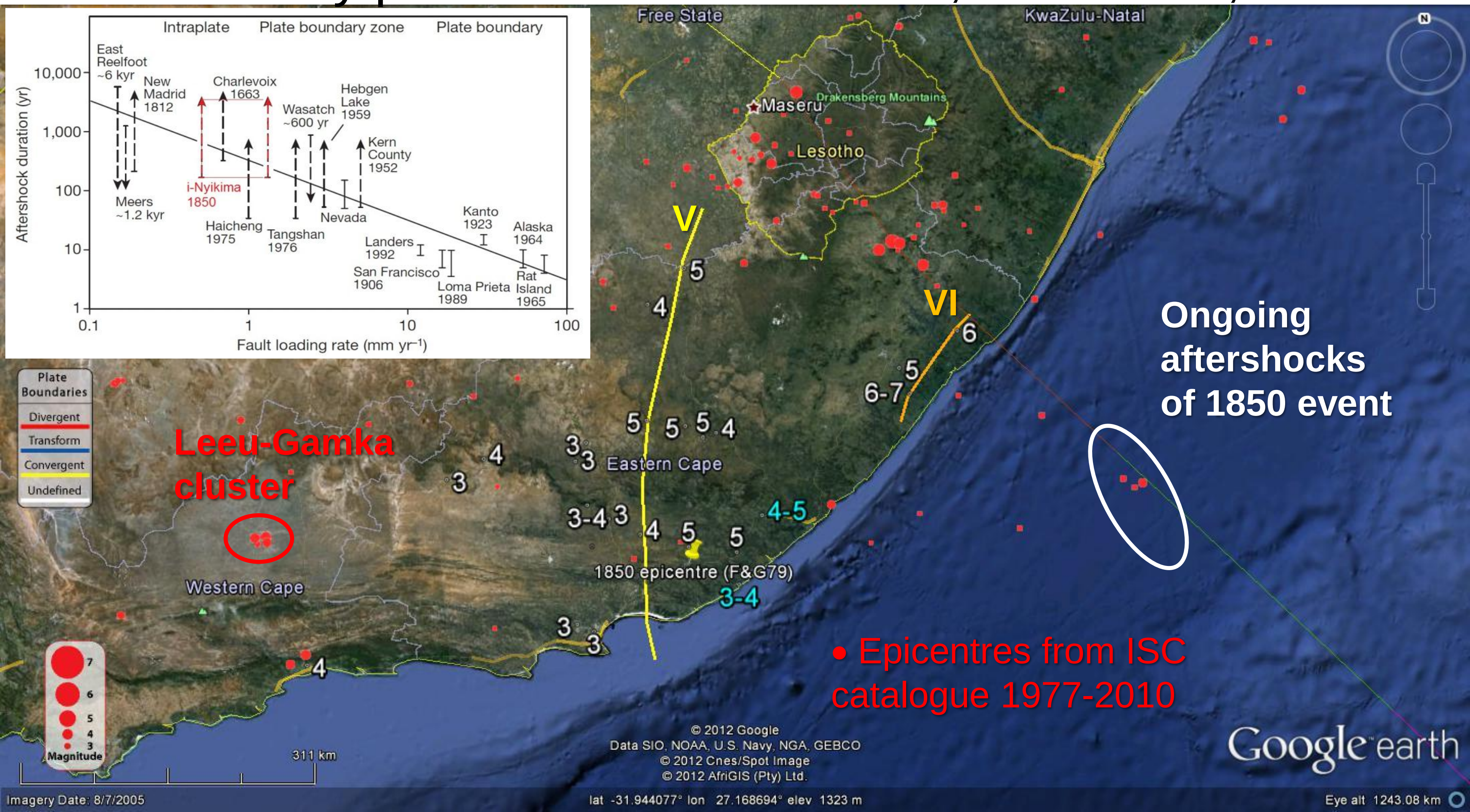
Lithospheric stress patterns

- Dynamic model of vertical integrated stress anomaly (VISA)
- Karoo within N part of ***‘Cape Stress Province’*** (Hartnady, 1998)
- Reflects high crustal stresses generated by break-up of Africa between Nubia (NU) and Somalia (SO) plates



i-Nyikima – ‘great earthquake’ of 1850

- MM Intensity pattern from 1850-05-21; after Albini, 2012



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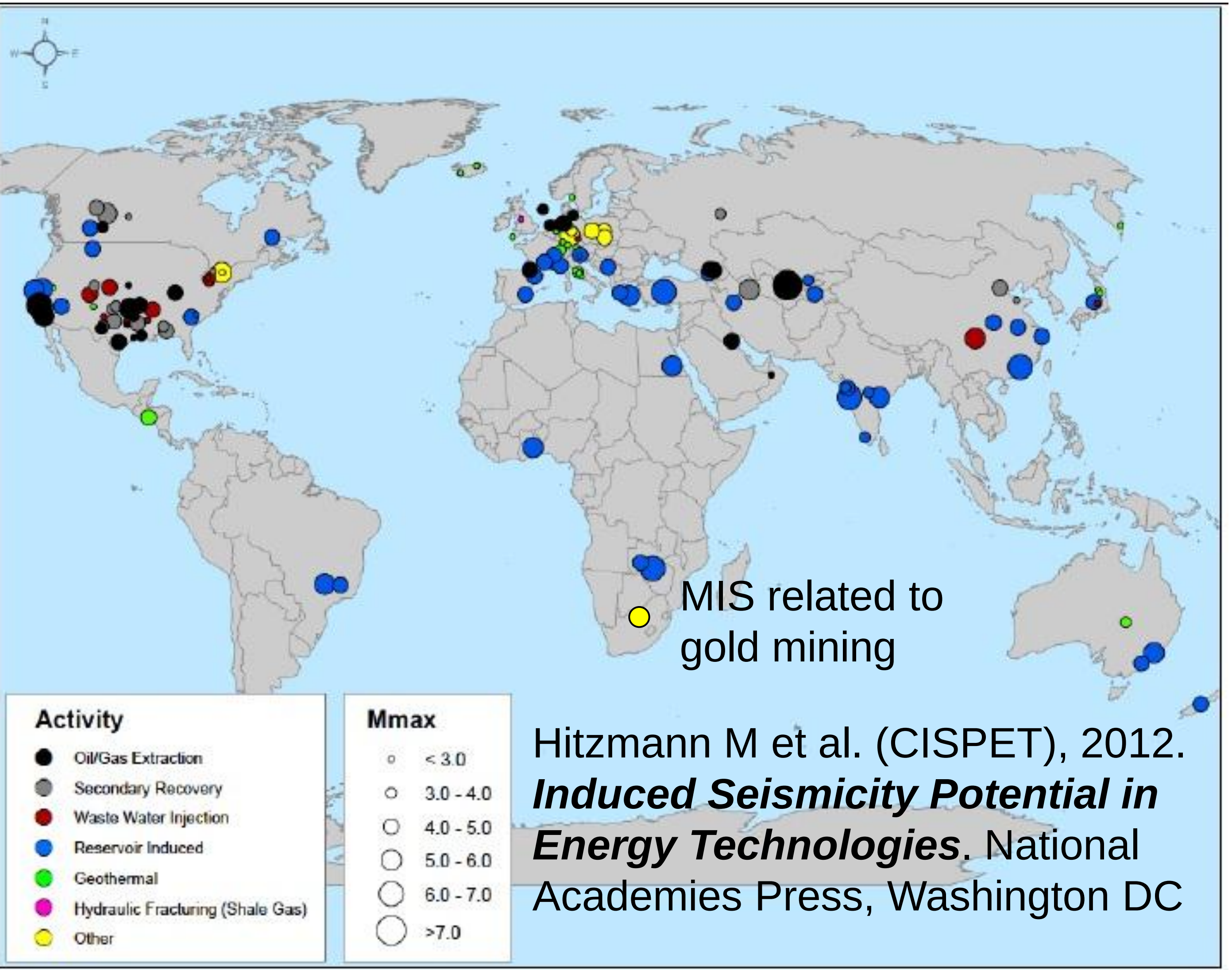
Global anthropogenic ('induced') quakes



Hitzmann M et al. (CISPET), 2012. ***Induced Seismicity Potential in Energy Technologies***. National Academies Press, Washington DC

Triggered by:

- Oil & gas extraction
- Secondary recovery
- Wastewater injection
- Reservoir impoundment
- Geothermal development
- Hydraulic fracturing (shale gas)
- Other (e.g., mining)

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CISPET: Three major findings

" …

- (1) the process of hydraulic fracturing a well as presently implemented for shale gas recovery does not pose a high risk for inducing felt seismic events;
- (2) injection for disposal of waste water derived from energy technologies into the subsurface does pose some risk for induced seismicity, but very few events have been documented over the past several decades relative to the large number of disposal wells in operation; and
- (3) CCS, due to the large net volumes of injected fluids, may have potential for inducing larger seismic events. …"

Hitzmann M et al. (CISPET), 2012, p. 2

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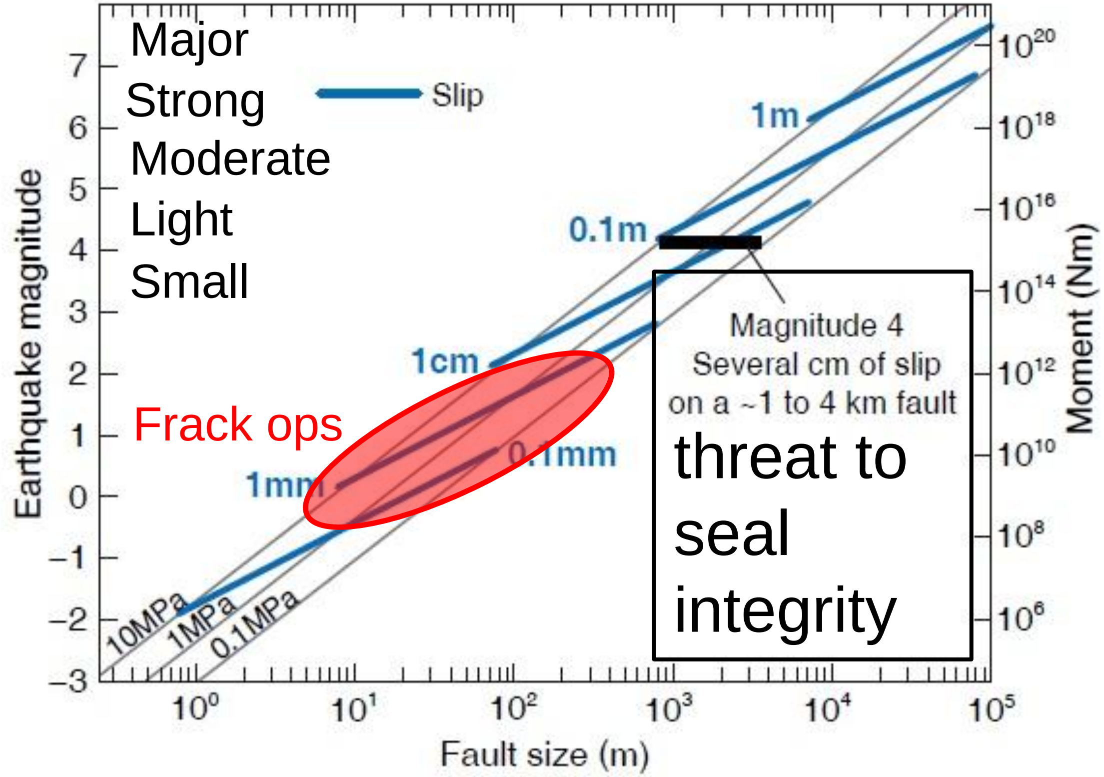
Triggered earthquakes as CCS show-stopper?



We argue here that there is a high probability that earthquakes will be triggered by injection of large volumes of CO_2 into the brittle rocks commonly found in continental interiors. Because even small- to moderate-sized earthquakes threaten the seal integrity of CO_2 repositories, in this context, large-scale CCS is a risky, and likely unsuccessful, strategy for significantly reducing greenhouse gas emissions.

PNAS

Earthquake triggering and large-scale geologic storage of carbon dioxide

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Departments of [a]Geophysics and [b]Environmental Earth System Science, Stanford University, Stanford, CA 94305

Edited by Pamela A. Matson, Stanford University, Stanford, CA, and approved May 4, 2012 (received for review March 27, 2012)

Despite its enormous cost, large-scale carbon capture and storage (CCS) is considered a viable strategy for significantly reducing CO_2 emissions associated with coal-based electrical power generation and other industrial sources of CO_2 [Intergovernmental Panel on Climate Change (2005) IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change, eds Metz B, et al. (Cambridge Univ Press, Cambridge, UK); Szulczewski ML, et al. (2012) *Proc Natl Acad Sci USA* 109:5185–5189]. We argue here that there is a high probability that earthquakes will be triggered by injection of large volumes of CO_2 into the brittle rocks commonly found in continental interiors. Because even small- to moderate-sized earthquakes threaten the seal integrity of CO_2 repositories, in this context, large-scale CCS is a risky, and likely unsuccessful, strategy for significantly reducing greenhouse gas emissions.

carbon sequestration | climate change | triggered earthquakes

SPECTIVE

"… large-scale CCS is a risky, and likely unsuccessful, strategy …"

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Multi-stage fracking

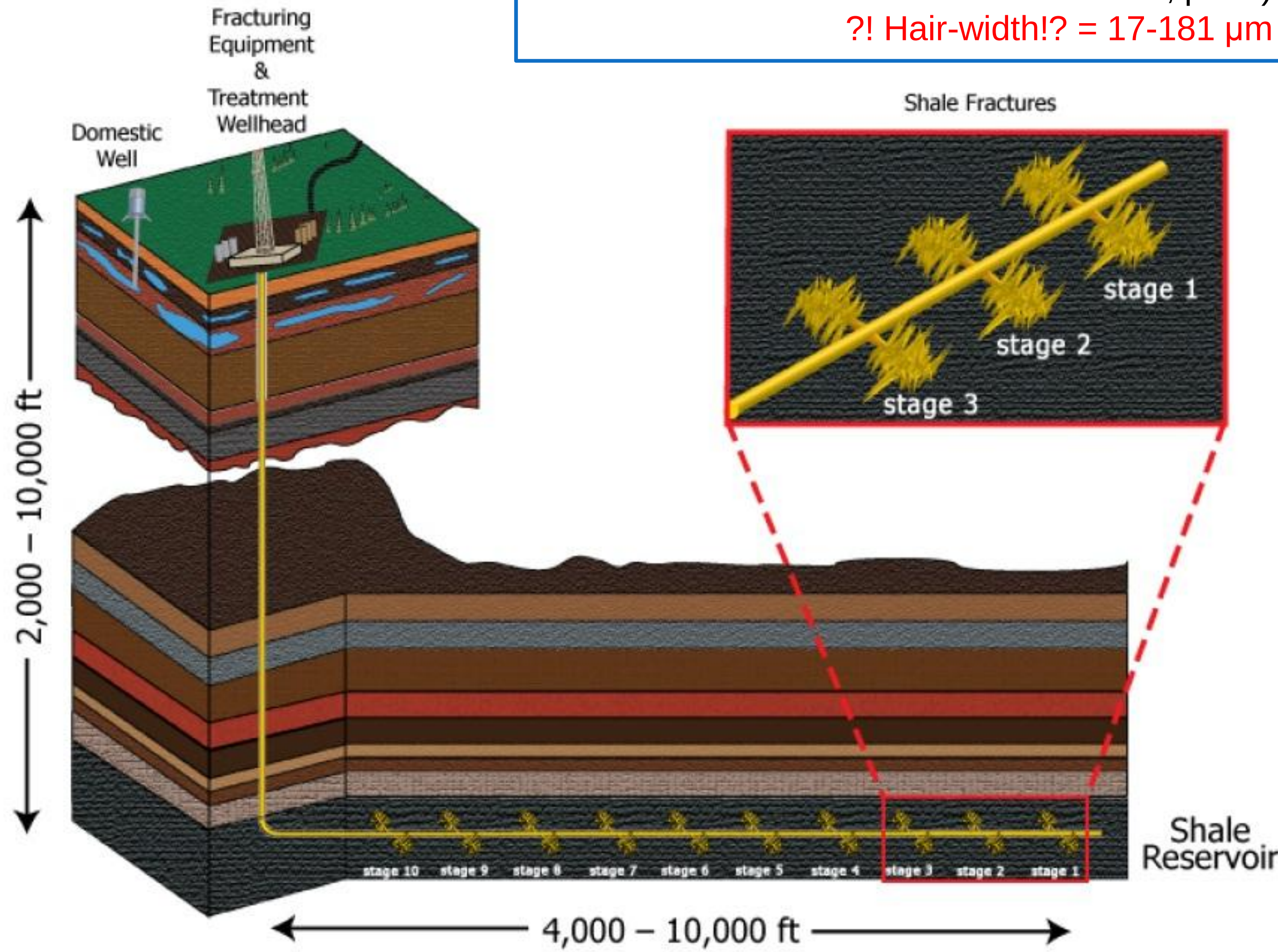
- CISPET, 2012, Box 3.5, p.75

‘… after discussions with Shell, I am led to believe that the size of cracks is the length of toothpicks, a hair-width in size, a couple of kilometres underground. Based on this, I would consider potential seismic disturbances quite a low risk.’

A Tiplady, SKA project, quoted by I Vegter, 2012, p. 75)

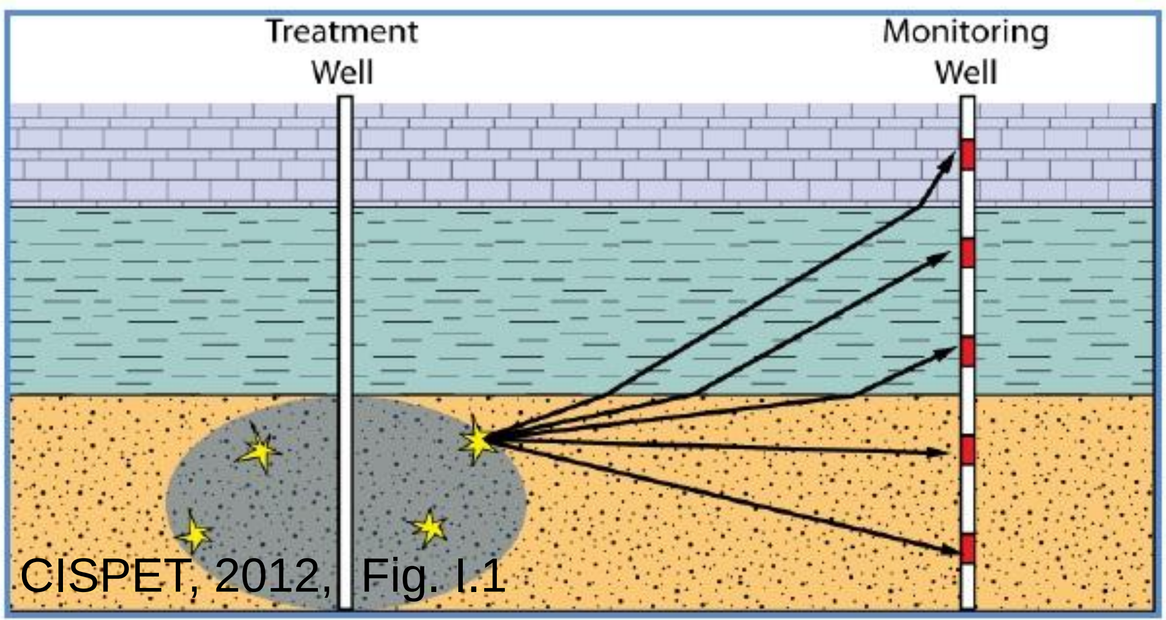
?! Hair-width!? = 17-181 μm

Threat to integrity of seal between shallow groundwater resources and deep shale gas reservoir (‘fraquifer’)?

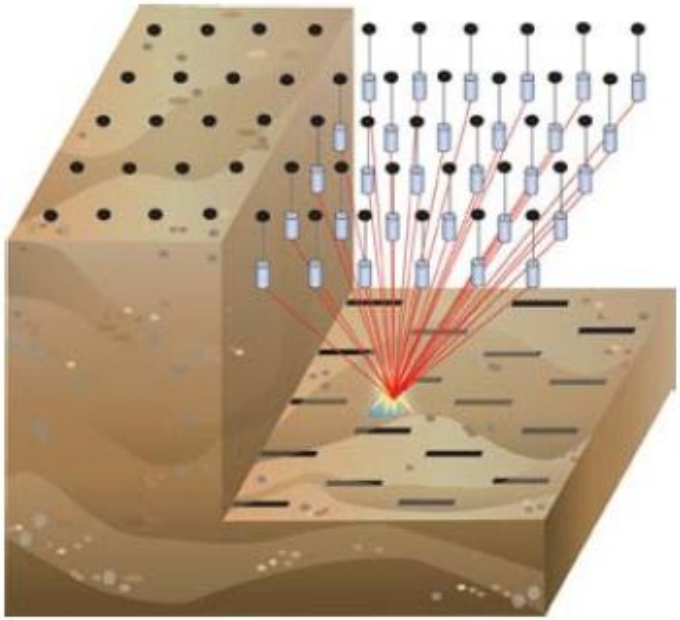


Fracking tremors

- Induced micro-earthquakes usually closely monitored to ensure efficient stimulation by
  - array of suspended seismometers in monitoring well(s)
  - large array (grid) of seismometers at or near surface

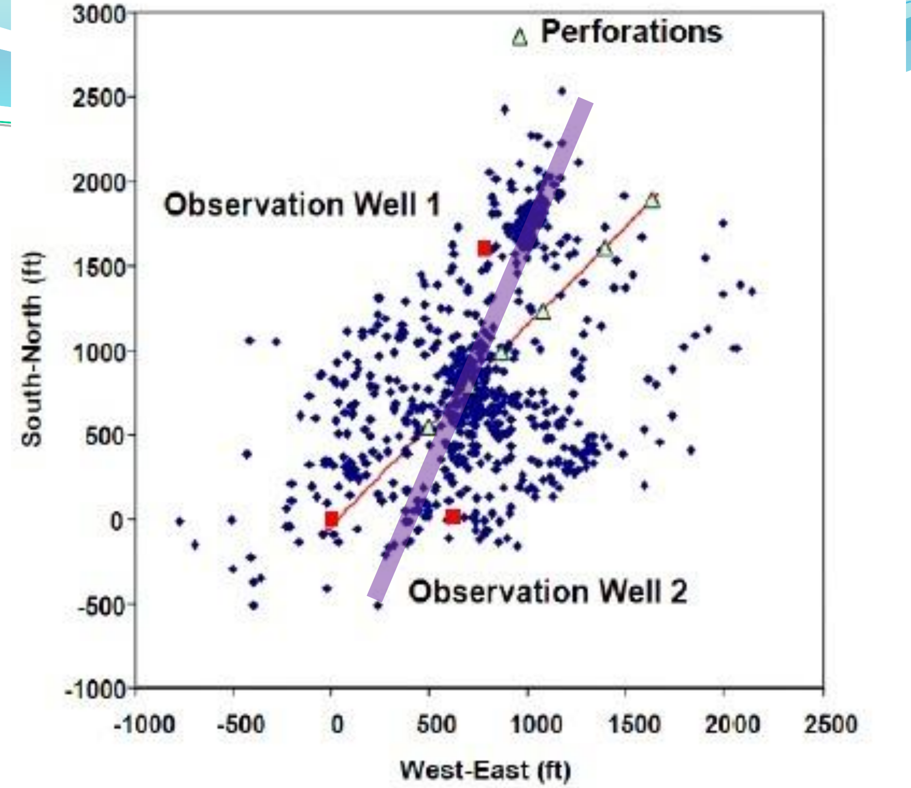


CISPET, 2012, Fig. I.1

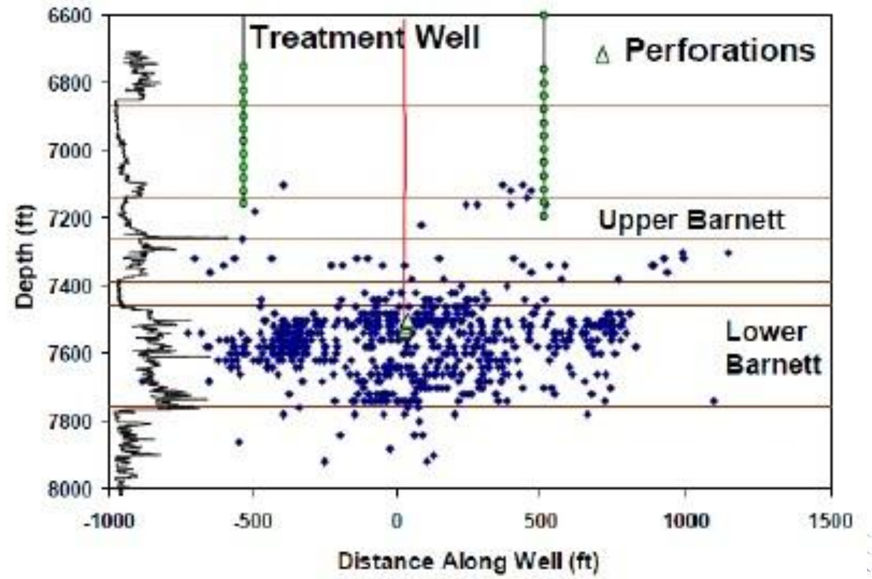


Fracking micro-earthquake location

- Barnett Shale (TX) example
  - Two 12-seismometer arrays in observation wells 1 & 2
  - Long lateral in Lower Barnett FM with six perforations along SW-NE trend
  - Tremors extend ~1000 ft (300 m) horizontally, ~500 ft vertically from long lateral, cluster along principal crustal-stress direction

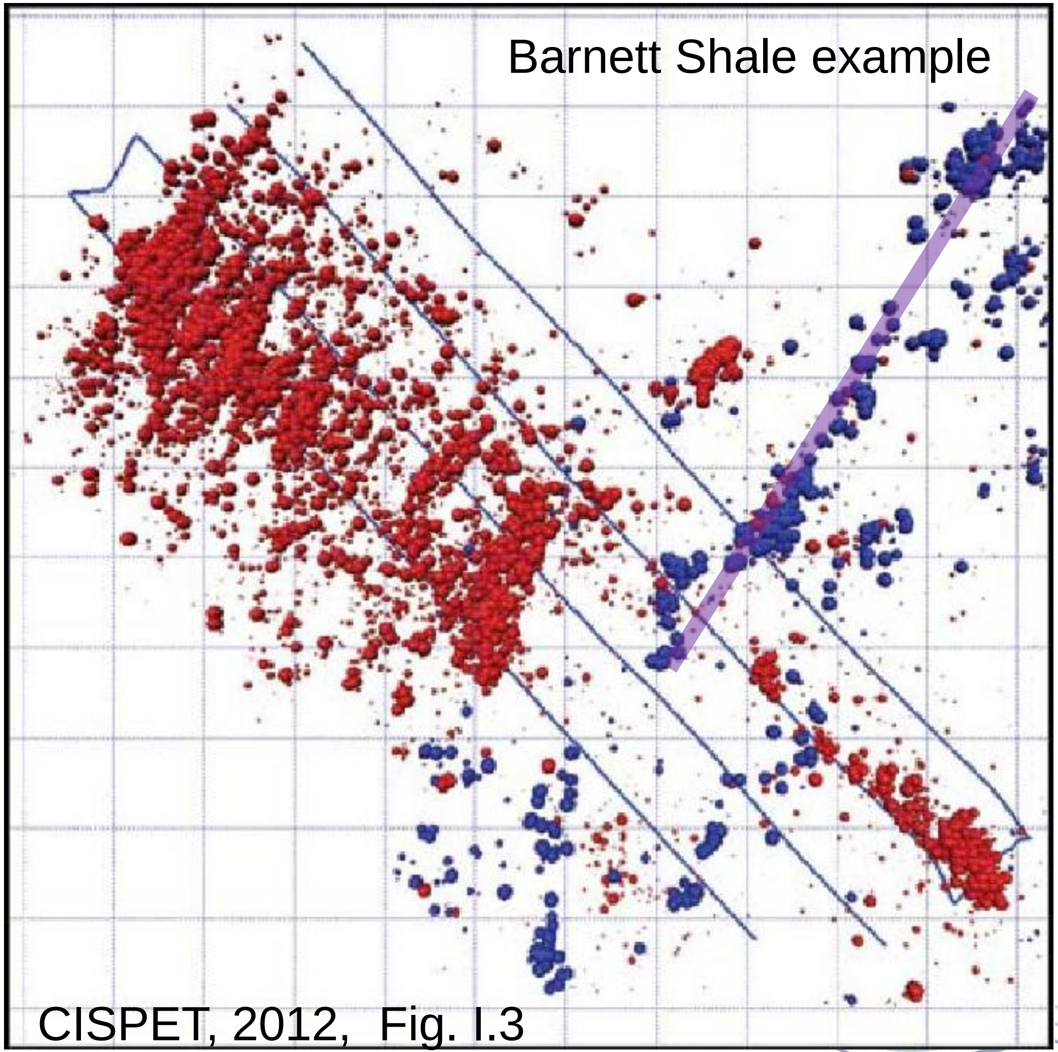


CISPET, 2012, Fig. I.2(a)



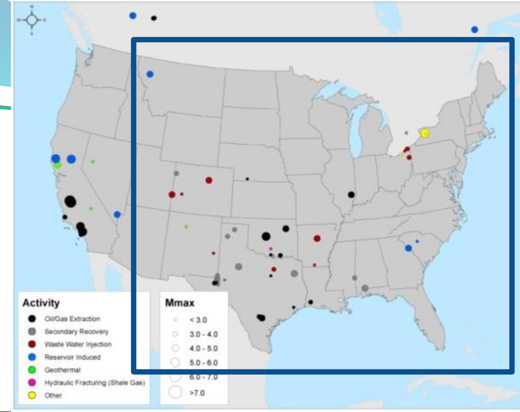
Pre-existing fault re-activation

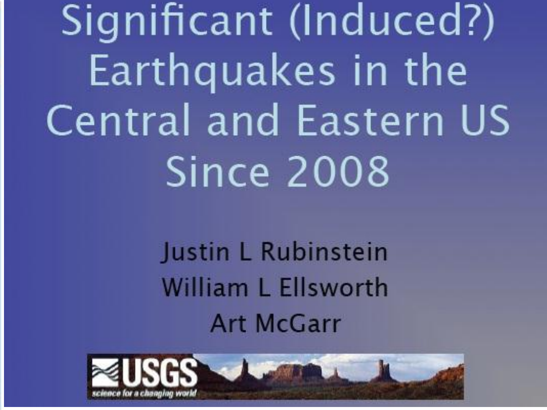
- '… Hydraulic fracture wells are often drilled to avoid large natural faults distinguished from 3D surface seismic images, as faults can "steal" fracturing fluid and divert fluids away from the formation targeted for hydraulic fracturing. …' (CISPET, 2012, p.210)

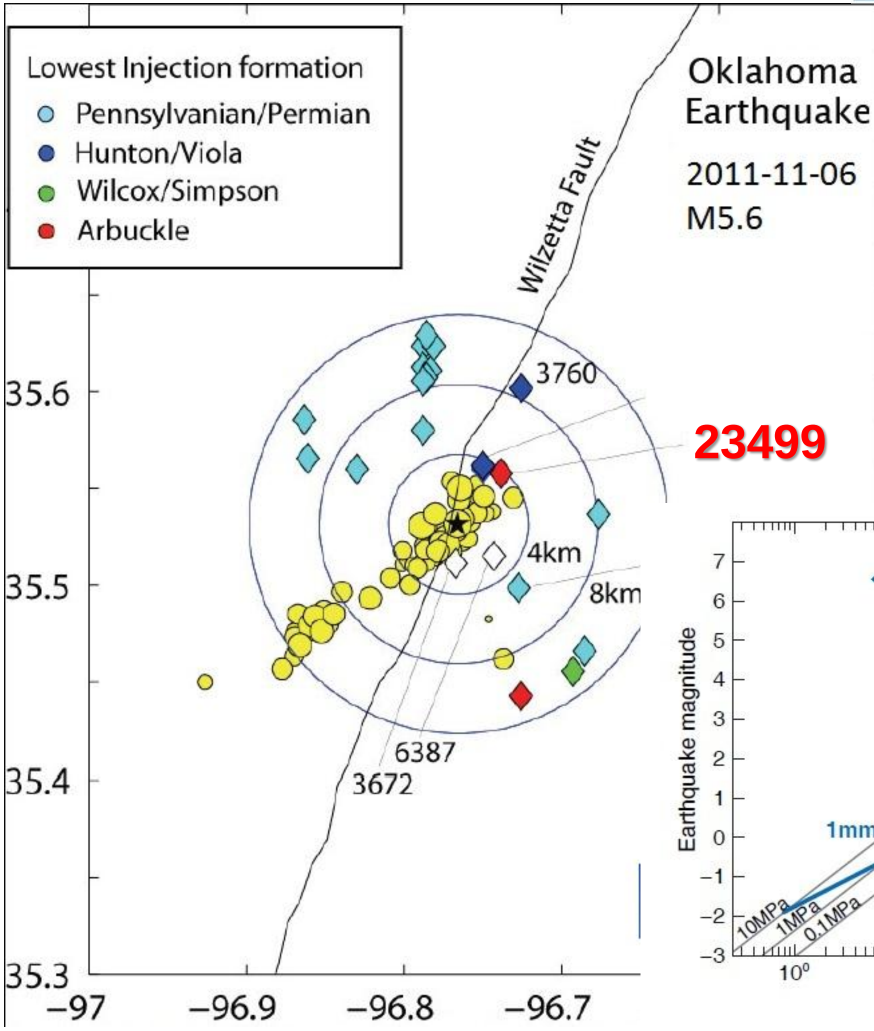


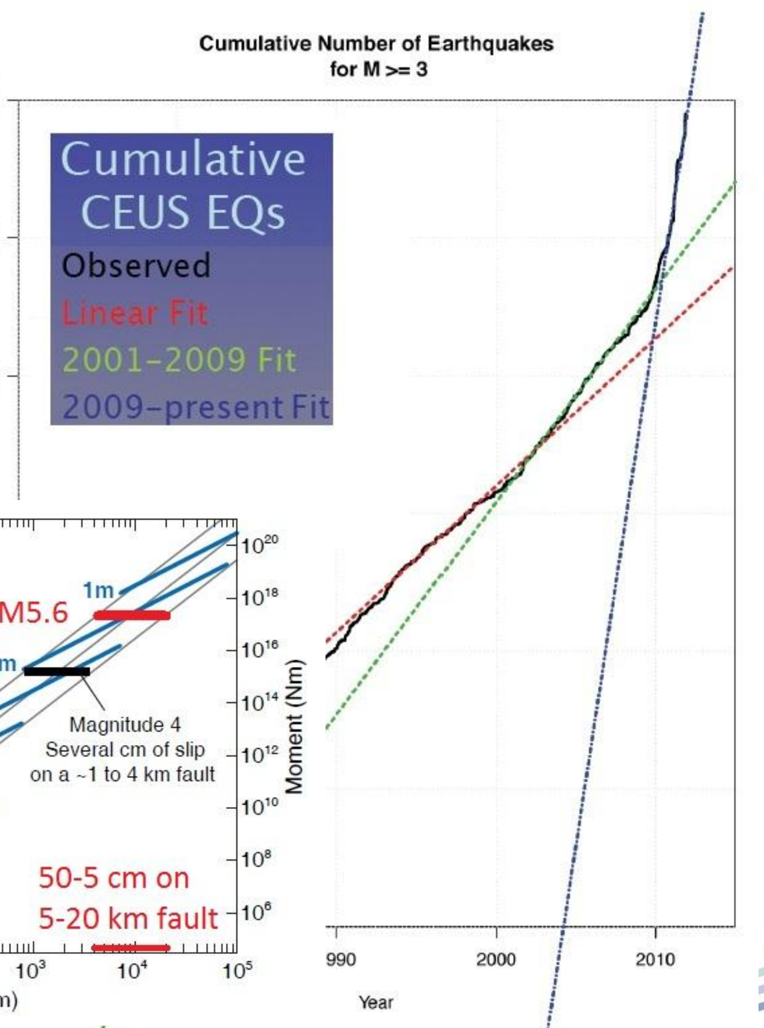
CISPET, 2012, Fig. I.3

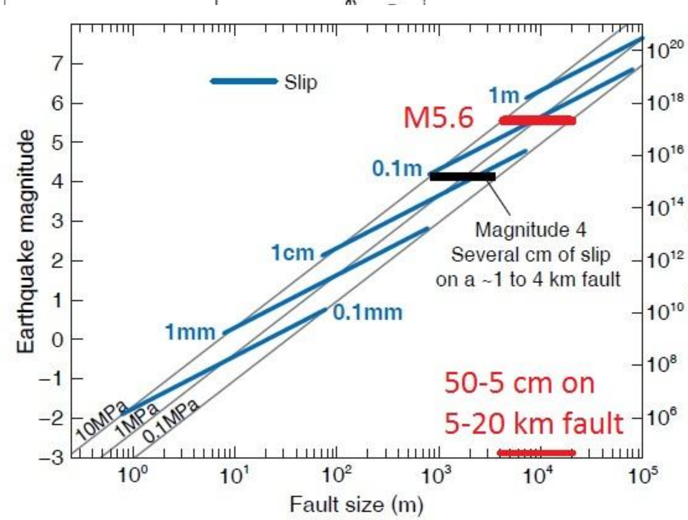
CEUS seismicity:
new hockey-stick ?











Recent injection-well development

- Google Earth imagery change analysis
- Well near M5.6 epicentre

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Hydrogeodesy for water-energy nexus

- Establish combined GNSS, InSAR and micro-gravity monitoring systems and protocols for
  - Deep groundwater exploration and abstraction
  - Shale-gas drilling, fracking and exploitation
  - Wastewater disposal by injection-well technology
  - Carbon-capture-and-storage (CCS) development in deep saline aquifers
  - Coal-bed methane & underground coal gasification (UCG) schemes
  - Large-scale water-supply and hydro-electric power schemes
- Take advantage of and locally enhance existing TrigNet infrastructure

Conclusion

- Earth's crust is permeable to fluid flow throughout brittle-fracture regime (<10 km) and therefore susceptible to natural and triggered hydroseismicity
- Within fringe of crustal-stress anomaly around developing NU-LW boundary , Karoo prospect areas for potential shale-gas may be especially vulnerable to large hydro-triggered earthquakes; require cautious approach
- Prior geoscientific research and experimentation is needed for regulation of shale-gas and other energy developments and concurrent protection of water resources
- Research focus on hydrogeological, geothermal, seismological, geodynamic (crustal stress & strain) objectives over a range of energy technologies should incorporate modern GGOS approaches

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Thank You