



Cornell University
Department of Earth and Atmospheric Sciences

Challenges For Subsurface Energy, Opportunities For Earthquake Prediction*

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EARTH

Fracking Triggers More Ohio Earthquakes

OCT 14, 2014 06:45 PM ET // BY BECKY OSKIN, LIVESCIENCE

Earthquake Study Points to Possible Carbon Injection Risks

By Joe Eaton
For National Geographic

PUBLISHED NOVEMBER 4, 2013

Opinion | February 5, 2014

Shaken, Not Stirred: How Earthquakes Affected Natural Gas Production in the Netherlands

By: Tim Boersma and Geert Greving

Spain faces £1bn bill over gas plant linked to earthquakes

Spanish authorities accused of ignoring warnings to give go-ahead to gas storage facility thought to have caused earthquakes along Catalanian coast

The Telegraph

By Fiona Govan, Madrid
8:37PM BST 08 Oct 2013



The 2011 Magnitude 9.0 Tohoku-Okii Earthquake: Mosaicking the Megathrust from Seconds to Centuries

Mark Simons,^{1*} Sa
Susan E. Owen,³ Li
Donald V. Helmbert

“What is most tragic is that the collective genius of all of these experts, combined with the sensors and satellite observations and seismographic data and all the other tools of science and technology, could not send the important message at the key moment: Run. Run for your lives.”

—Joel Achenbach, Washington Post, January 30, 2005 (Sumatra earthquakes and tsunami, >200,000 deaths)

Complex rupture during the 12 January 2010 Haiti earthquake

G. P. Hayes^{1,2*}, R. W. Briggs¹, A. Sladen³, E. J. Fielding⁴, C. Prentice⁵, K. Hudnut⁶, P. Mann⁷, F. W. Taylor⁷, A. J. Crone¹, R. Gold¹, T. Ito^{3,8} and M. Simons³



A single, unexpected natural disaster can impact global energy policy

THE FUTURE OF NUCLEAR

The knock-on effects of Japan's nuclear emergency on global energy policy.

NATURE NEWS BLOG

China suspends nuclear plant construction

17 Mar 2011 | 14:11 BST | Posted by [alison abbott](#) | Category: [Energy](#)

China has temporarily suspended work on 26 or so nuclear reactors currently under construction, pending revision of its safety standards.

The decision was made at a meeting of China's State Council today, and reflects the country's increasing concern about safety following the nuclear accident at Fukushima, Japan.

A statement from the State Council said that existing nuclear plants would also be checked for safety. Medium- and long-term plans for expansion of its nuclear programme would be re-considered, it said.

China has 13 reactors in operation and plans to increase that number to 110 in the next decade or so, to reduce its current dependence on coal. There are currently 440 nuclear power stations operating in the world in 30 countries.

Virginia nuclear plant shut down by quake

By **the CNN Wire Staff**

August 23, 2011 9:01 p.m. EDT

It's not just Fukushima: mass disaster evacuations challenge planners

The Fukushima evacuation zone raises the issue of what would happen during an evacuation in heavily populated US metropolises during a nuclear meltdown.

[David Biello](#)

05 March 2012

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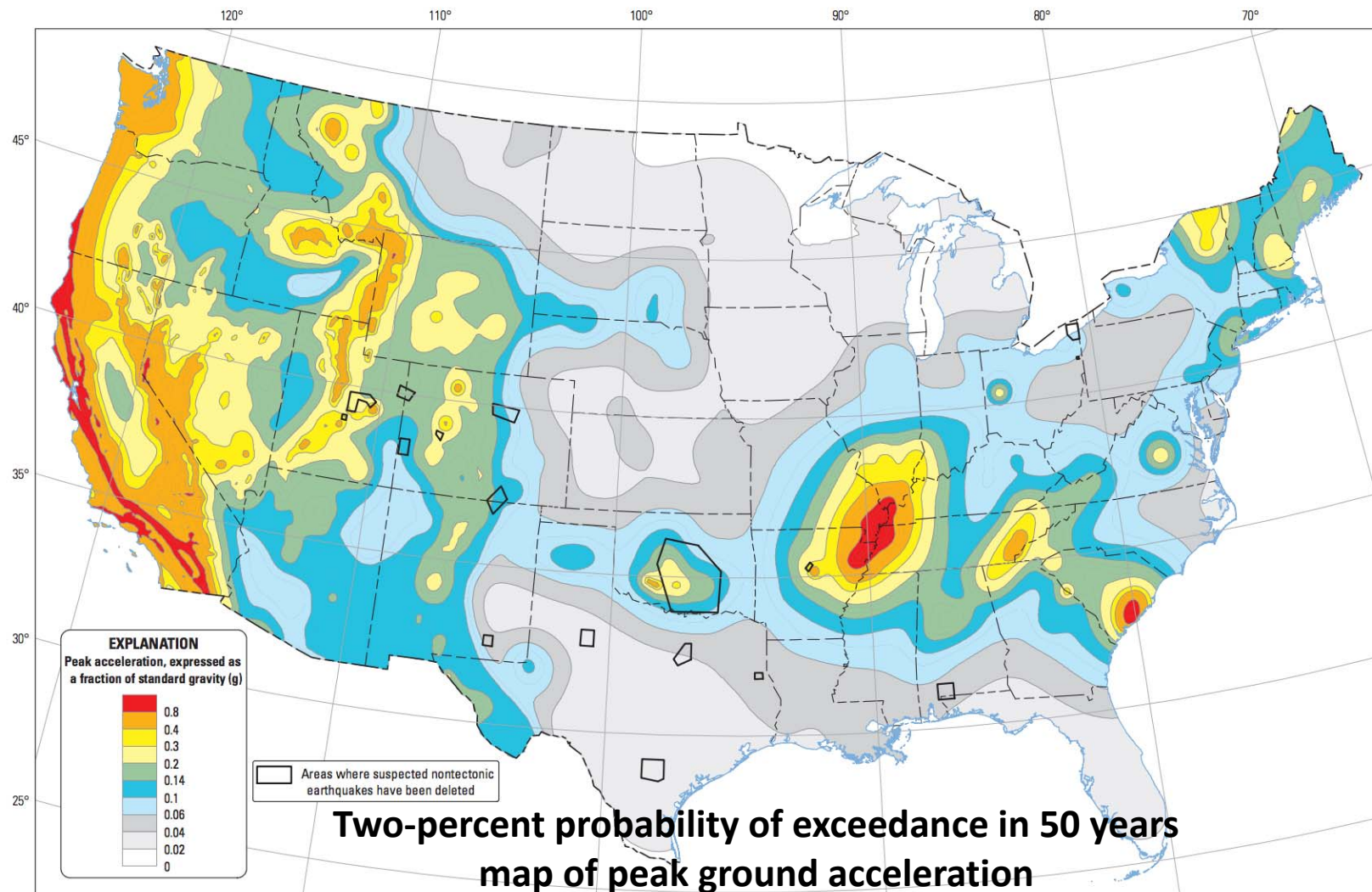


Jeff Fusco/Getty Images

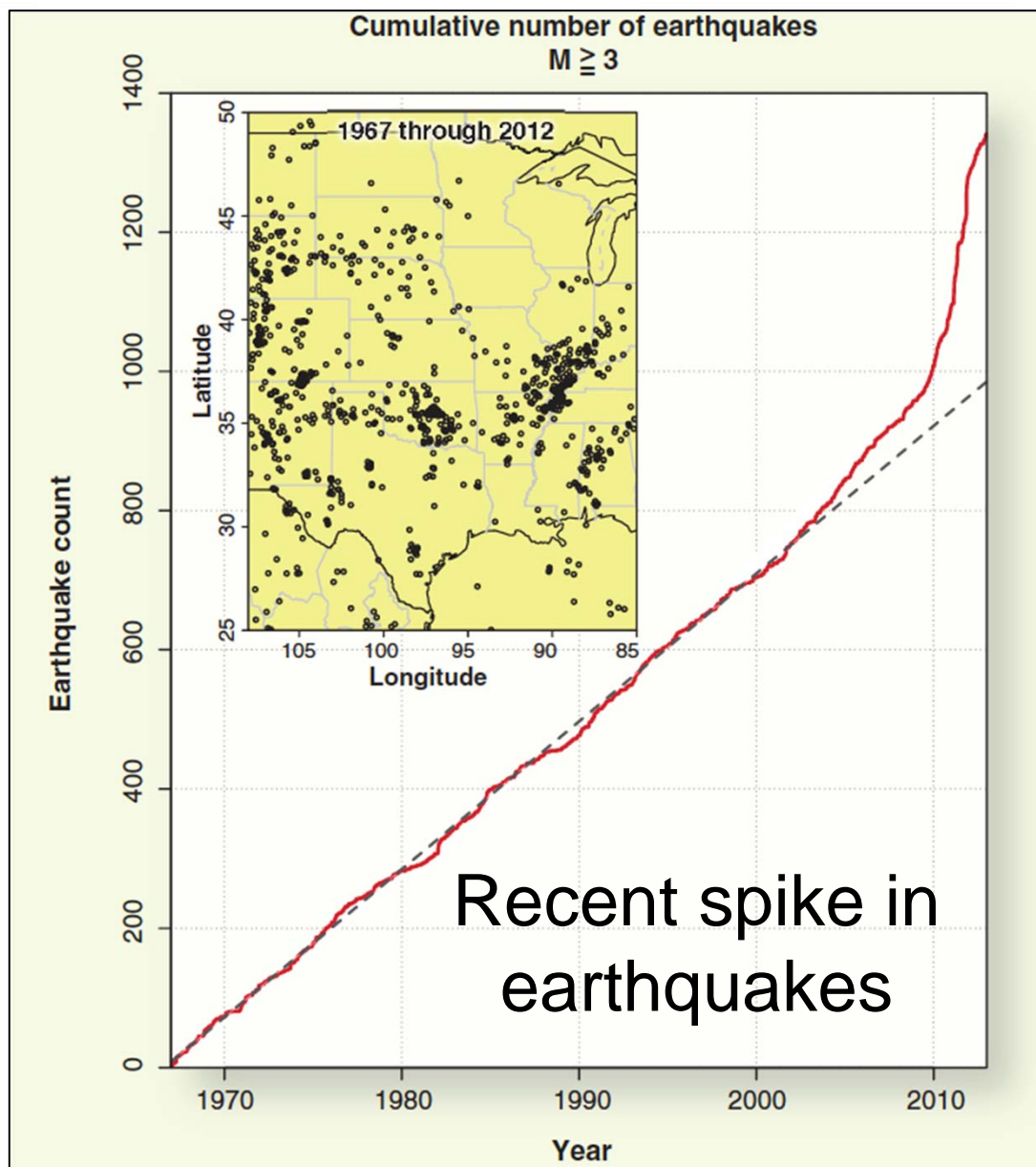
More than 180 million people live within 50 miles of a nuclear power plant in the US — the radius the US suggested be evacuated during the nuclear crisis at Fukushima Daiichi.



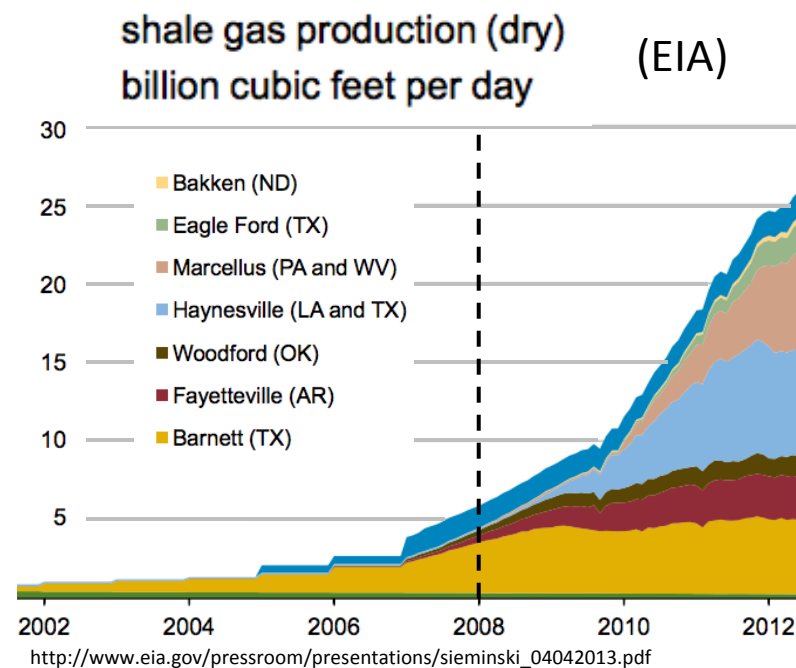
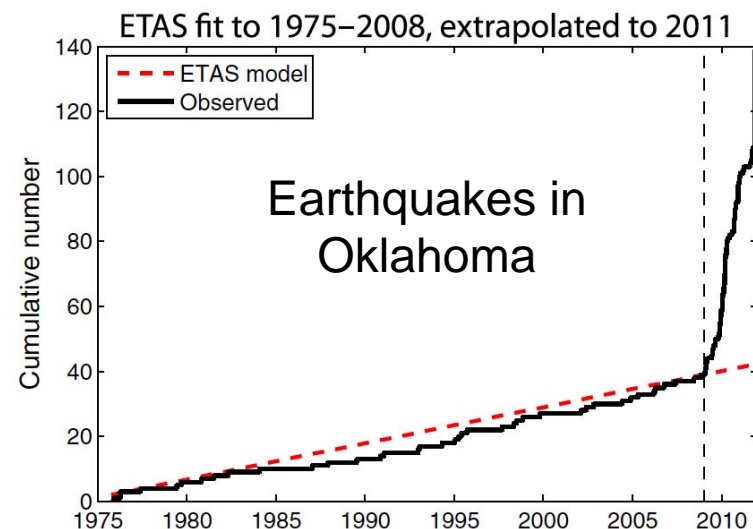
Earthquake prediction? “Earthquake prediction research in the U.S. has been **stagnant** since the early optimism regarding precursory phenomena was dissipated by negative observations.” – Keiiti Aki, 1995



USGS Earthquake Hazard Map 2014

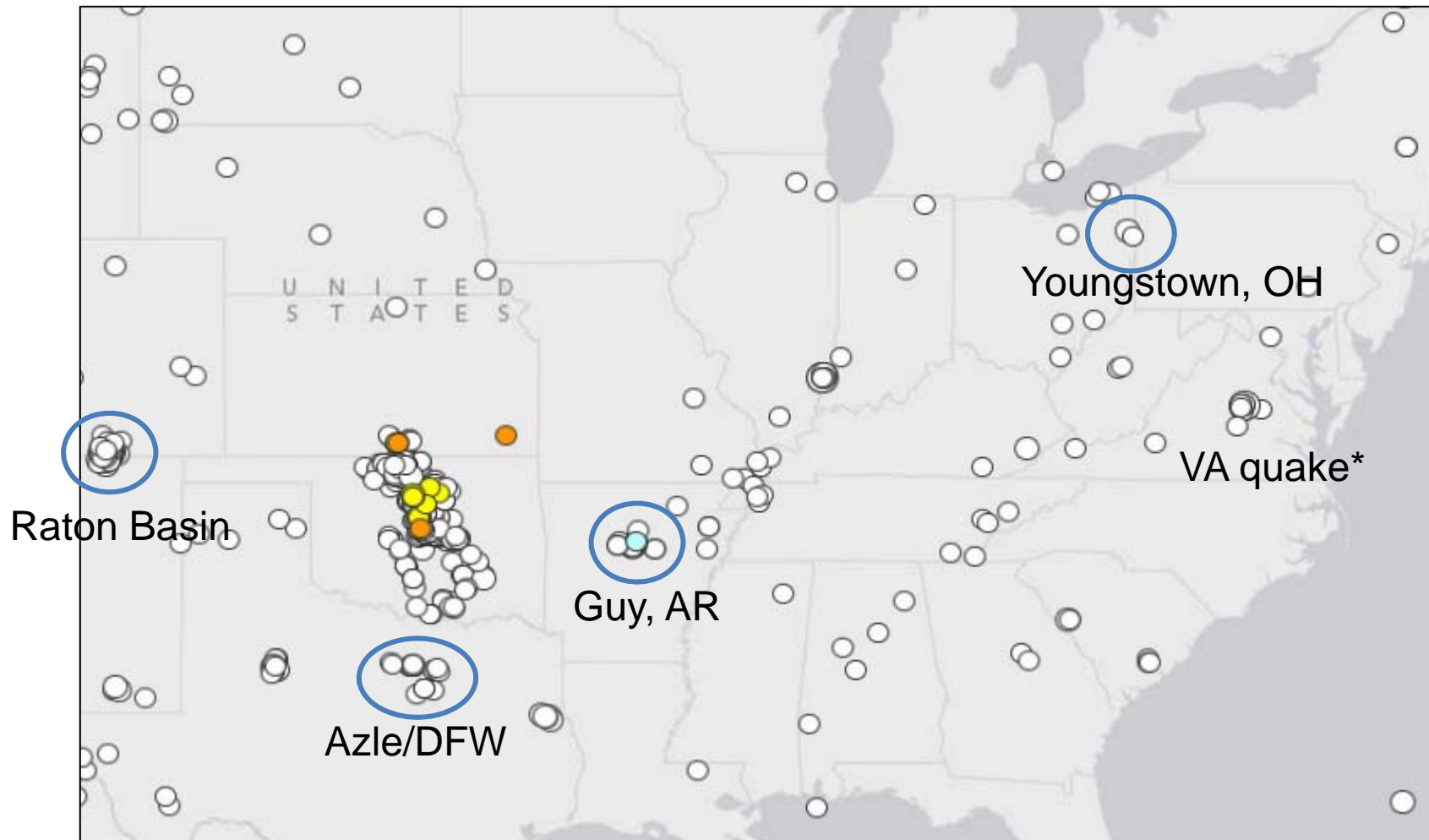


Ellsworth, 2013



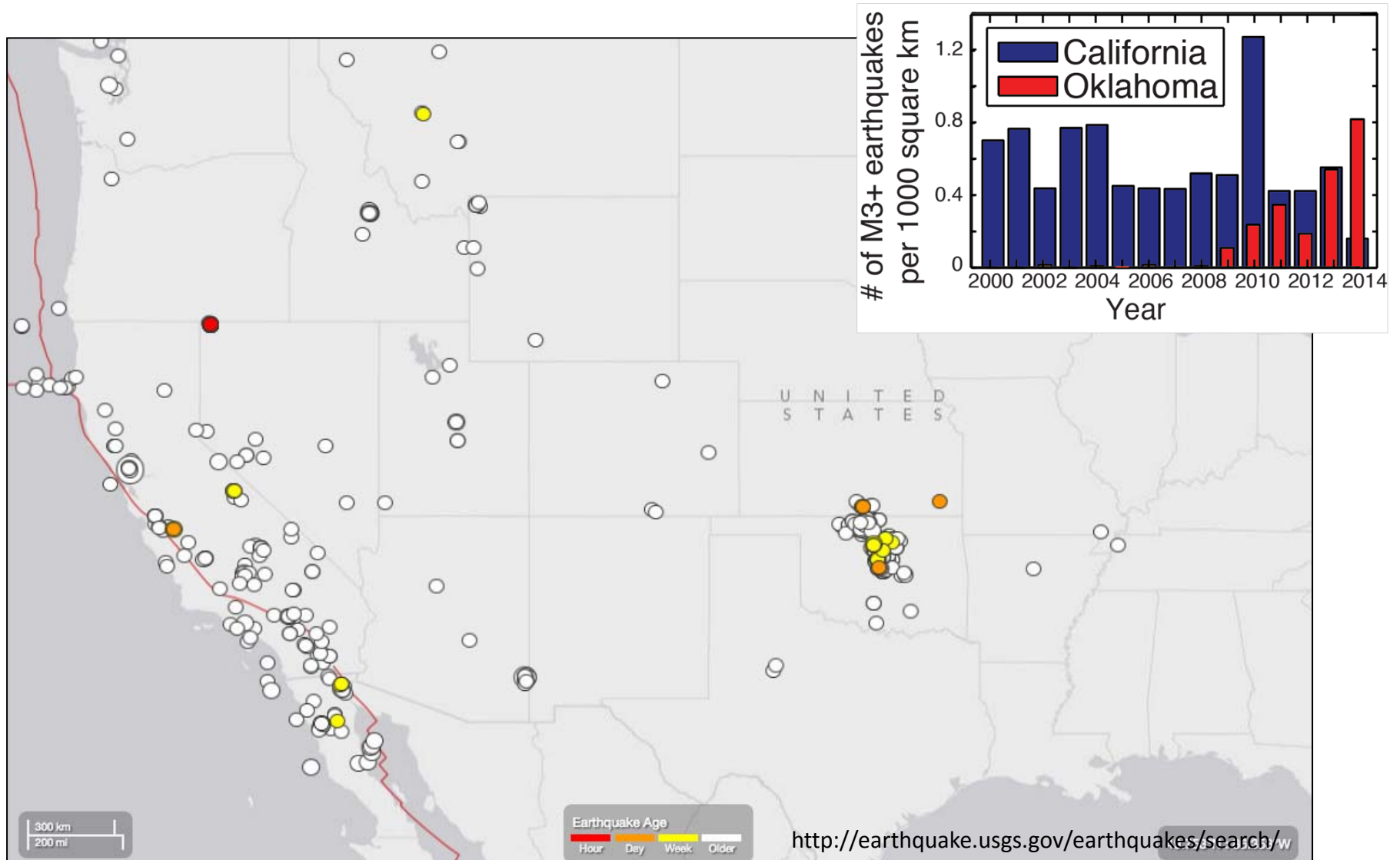


M3+ earthquakes, 2008-present





US Earthquakes, M3+ past 6 months



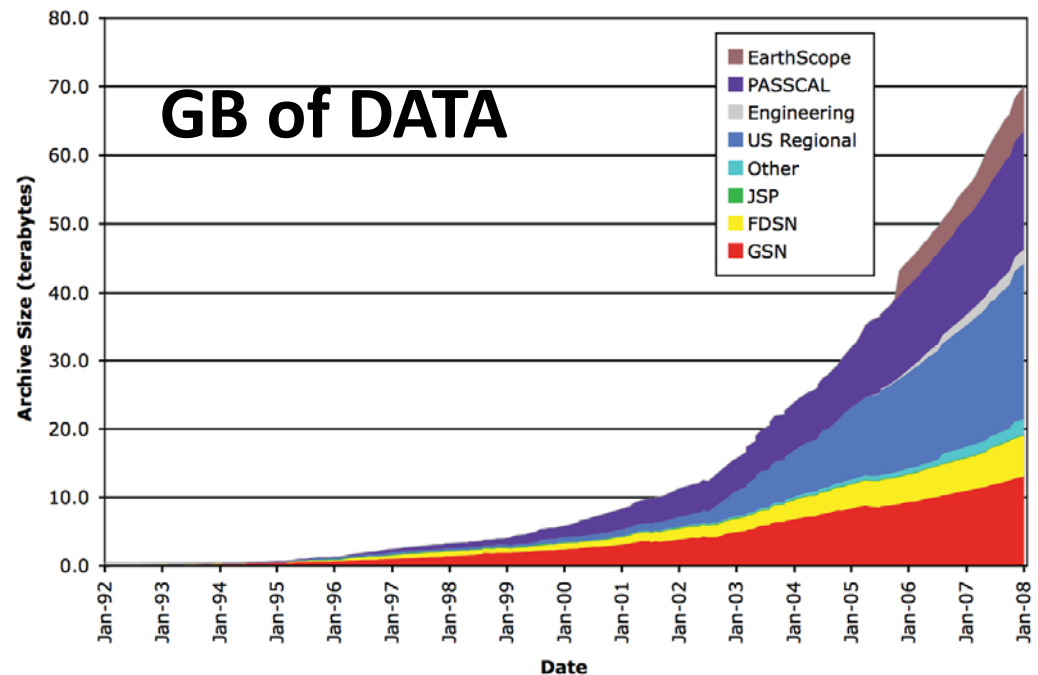
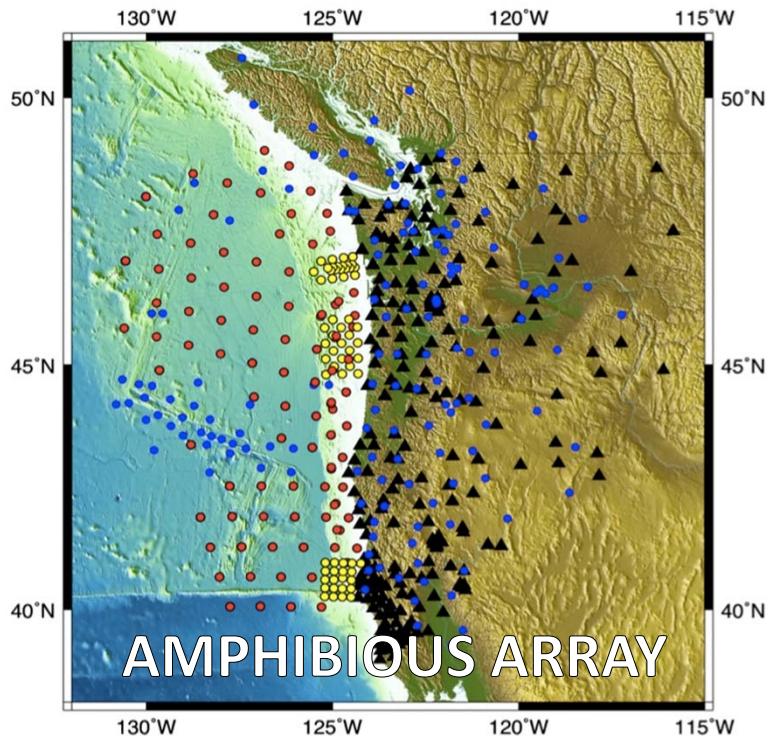
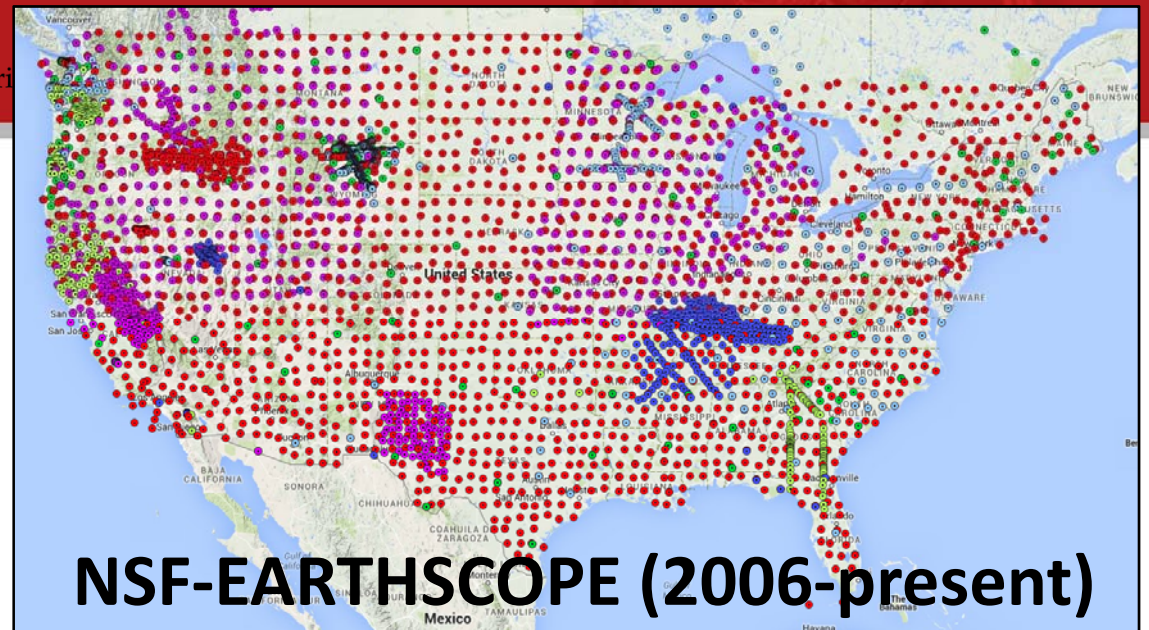


M3+ earthquakes, 1993-2000





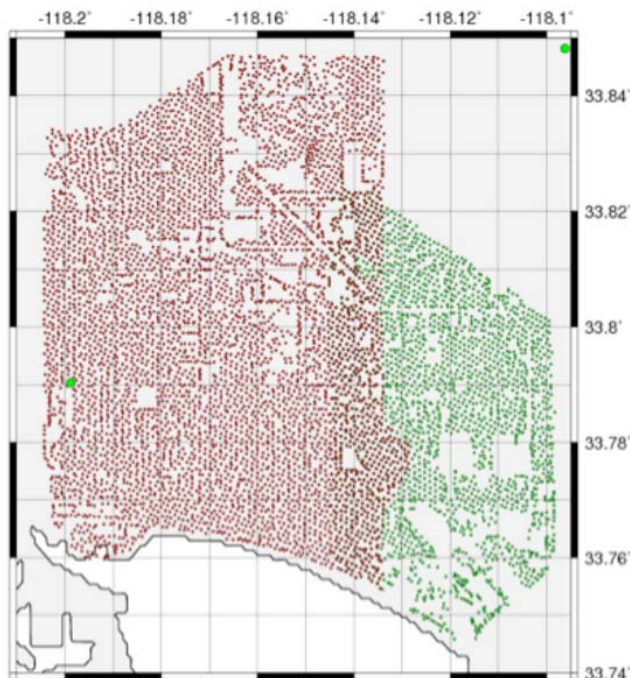
Rapid growth in seismological data



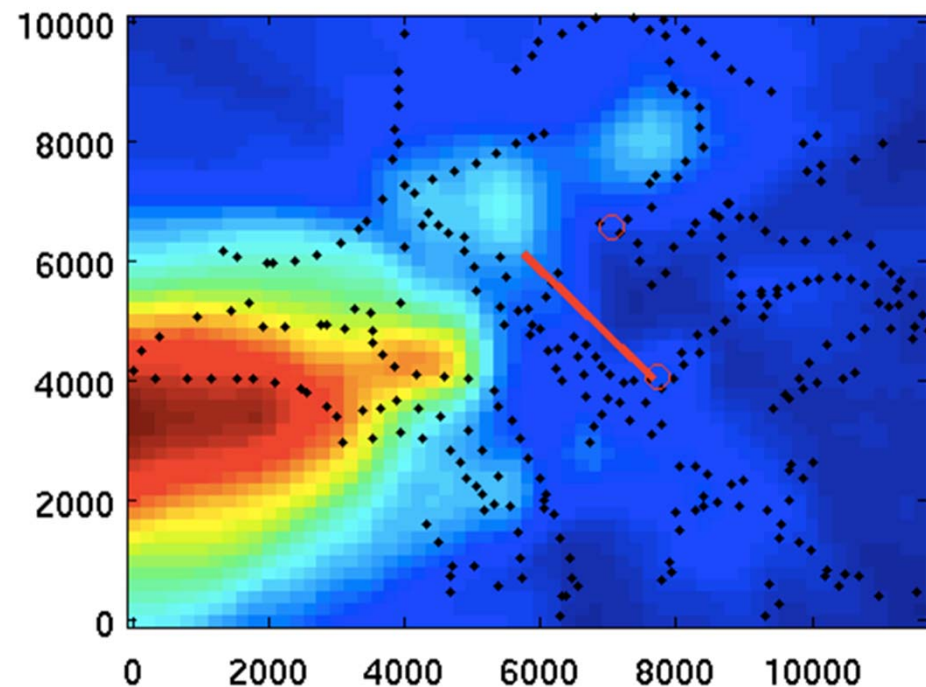


Shift in industry data acquisition → continuous recording = a burst in data + new technology

- Long Beach: 2500 receivers, ~100 meters apart
- Microseismic: Hundreds of sensors, clustered around wells

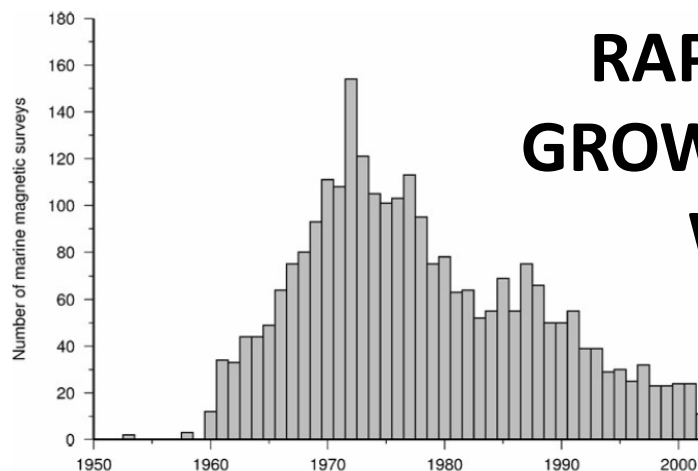
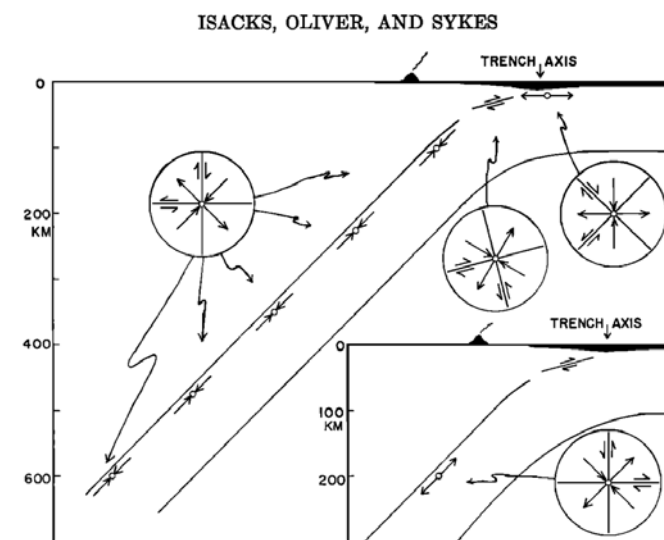
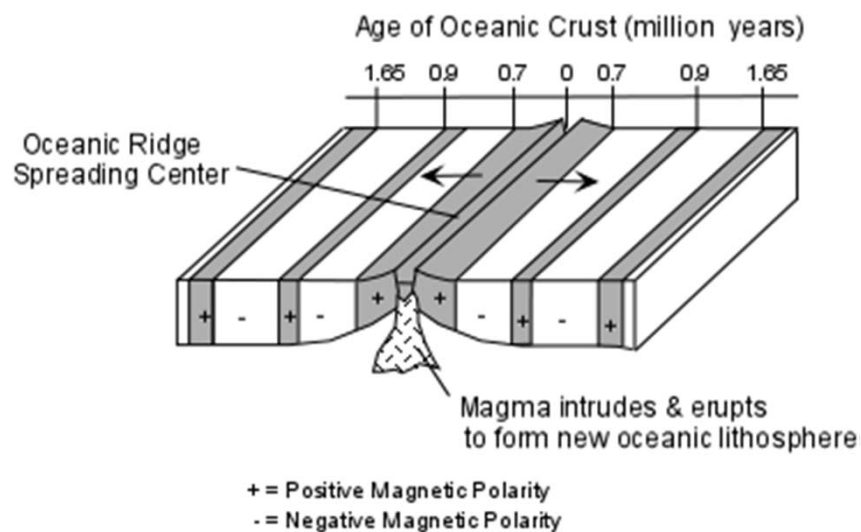


Long Beach 3D seismic survey covered 38 sq. miles. Red dots are phase one, green dots phase two. Large green dots are Southern California Seismic Network (SCSN) stations.
Source: NodalSeismic

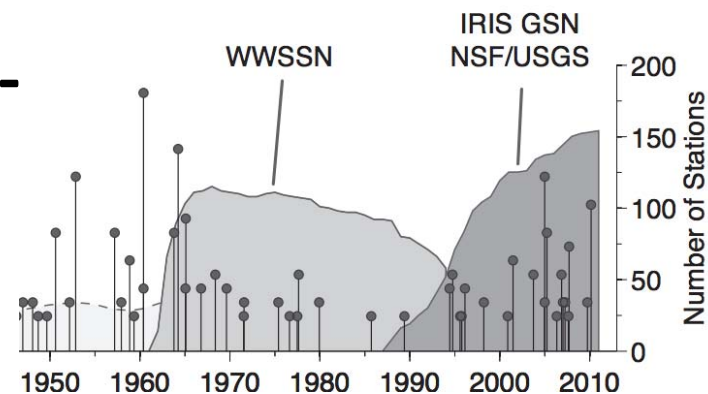




What came out of the last burst in data? The plate tectonic revolution (why is earth deforming?)

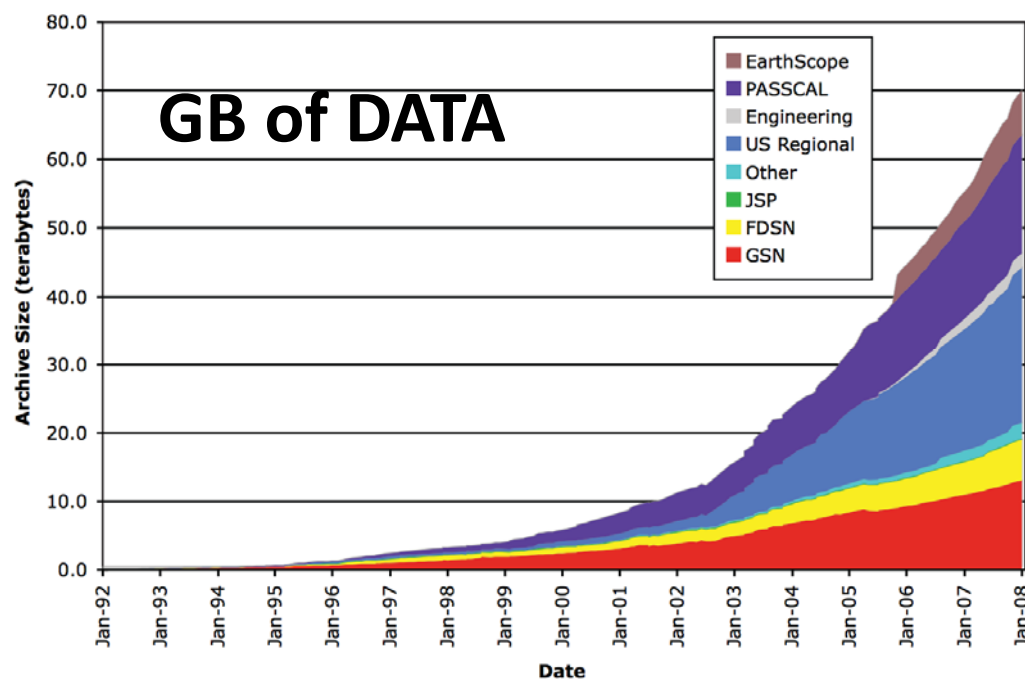
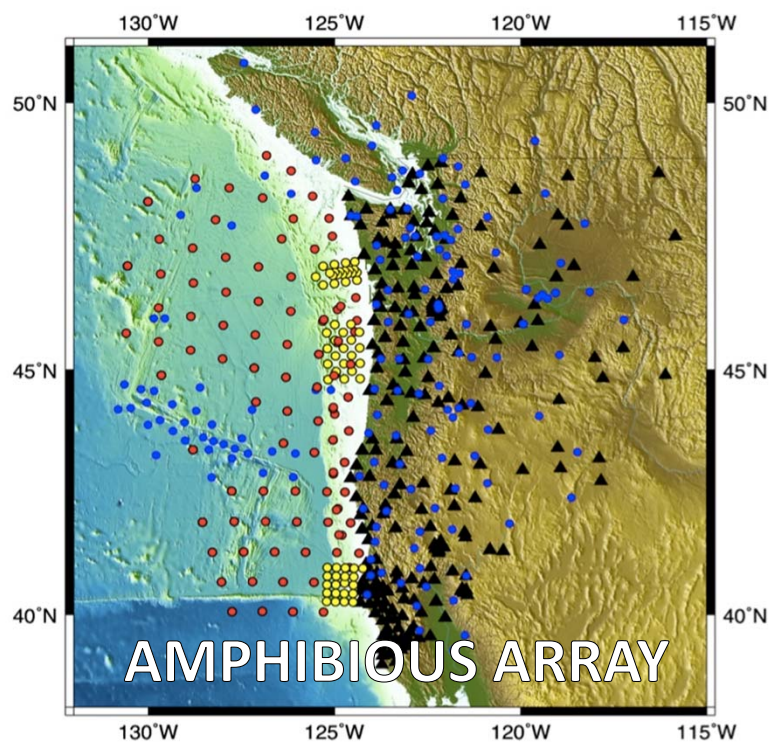
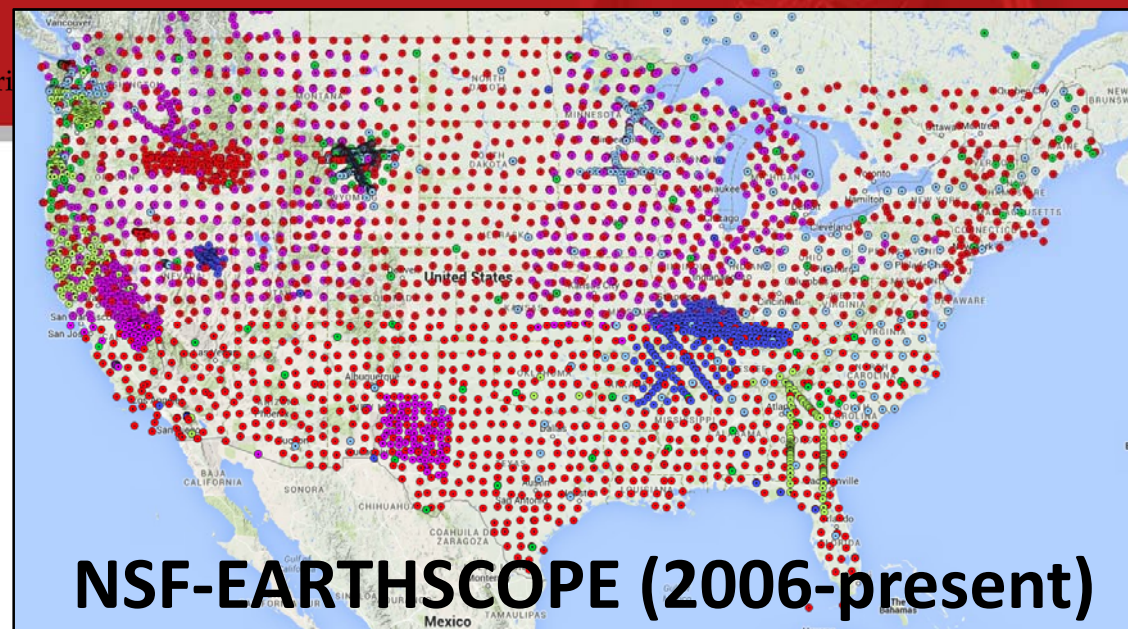


RAPID DATA GROWTH POST- WWII





Massive data +
instrumentation
+ computing



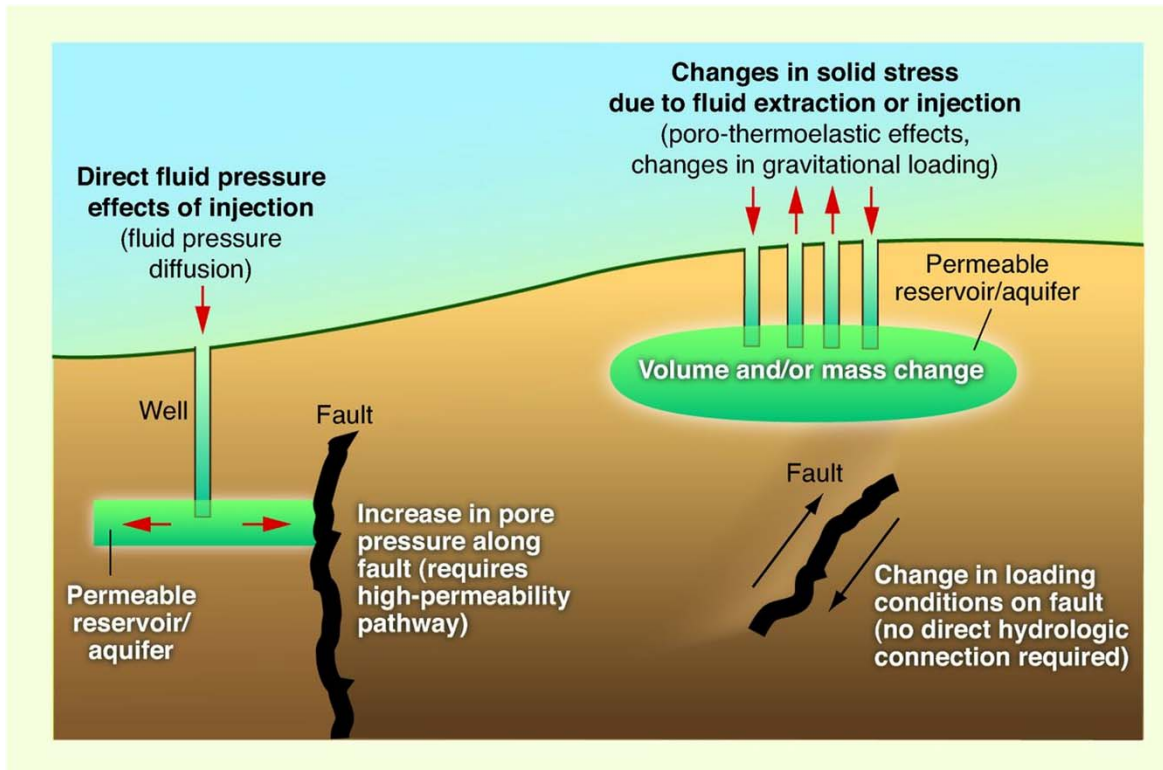


Critical challenges: 5-10 years

1. Can we determine how far (in MPa) a fault is from failure? Is it possible to deterministically characterize the “triggerability”?
 2. Are seismic signals capable of routinely detecting and monitoring (over)pressure near or along faults?
 3. Can we forecast the probability of damaging earthquakes related to fluid injection?
 - Can we revise the forecast as operations proceed?
- *Are there reliable precursory signals produced during earthquake nucleation?***



Earthquake triggering

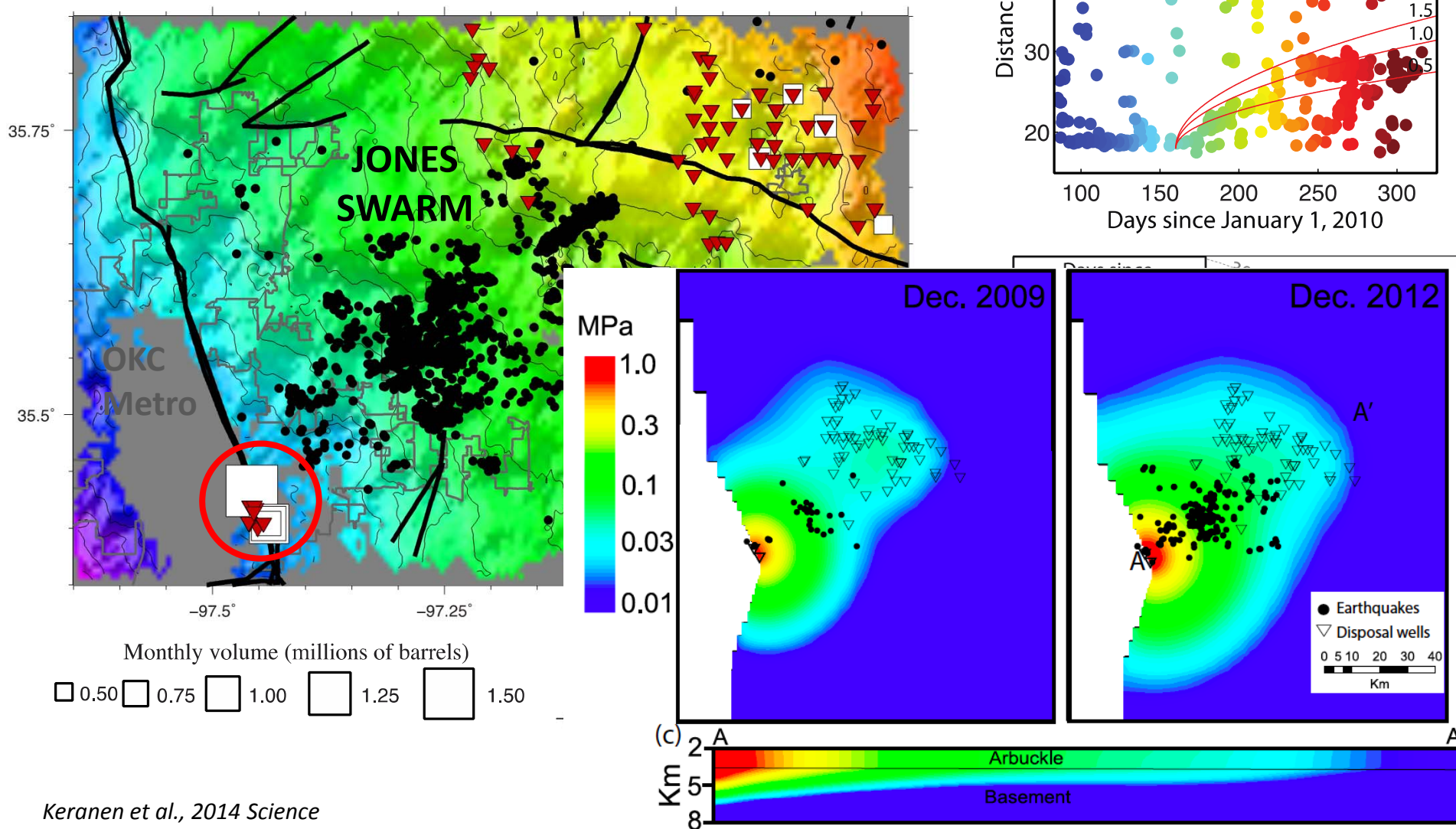


Studies in natural systems show triggering at stress perturbations as low as ~ 3 kPa
(0.003 MPa, 0.03 bars, 0.4 psi, 0.3 meters of head)

- Natural causes:
 - Local or remote earthquakes
 - Deglaciation
 - Magmatic fluid migration
 - Ocean and solid earth tides
- Anthropogenic, non-fluid:
 - Nuclear bombs
 - Reservoir impoundment (dams)
 - Mining - removal of rock
- Fluid-related:
 - Water injection/disposal
 - Geothermal fluid
 - Production of hydrocarbons
 - Secondary recovery
 - Hydraulic fracturing
 - Carbon sequestration**



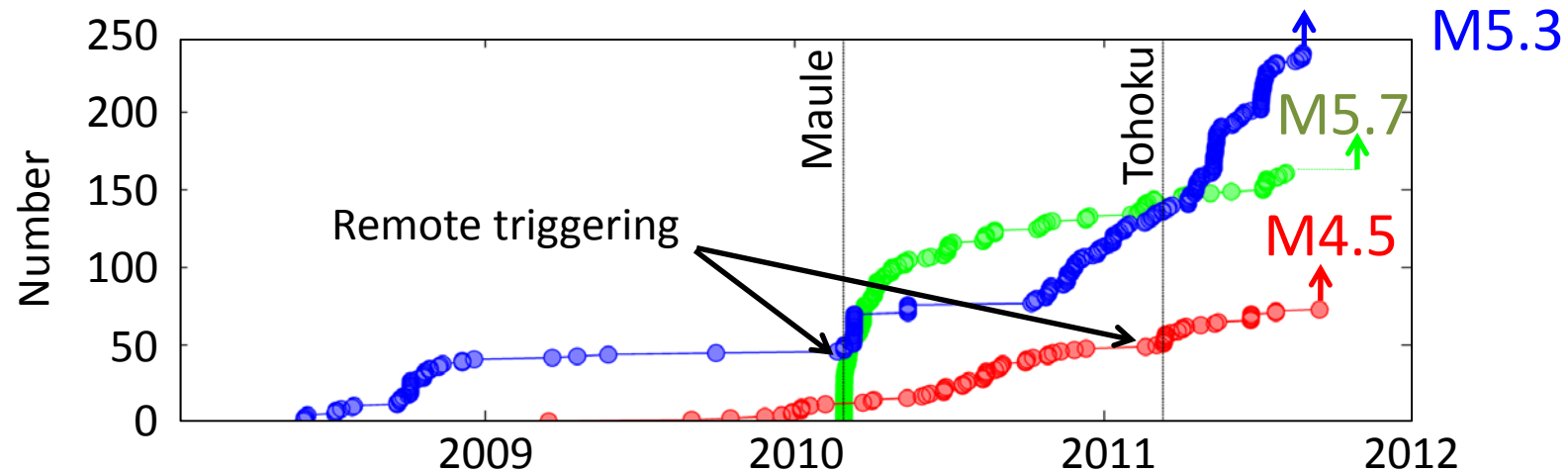
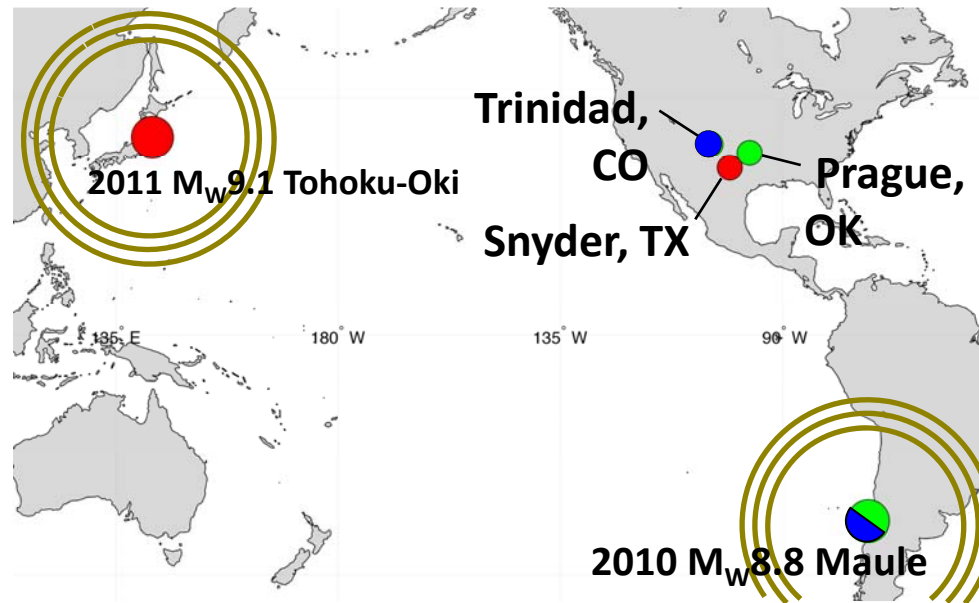
Fluid triggering in Oklahoma

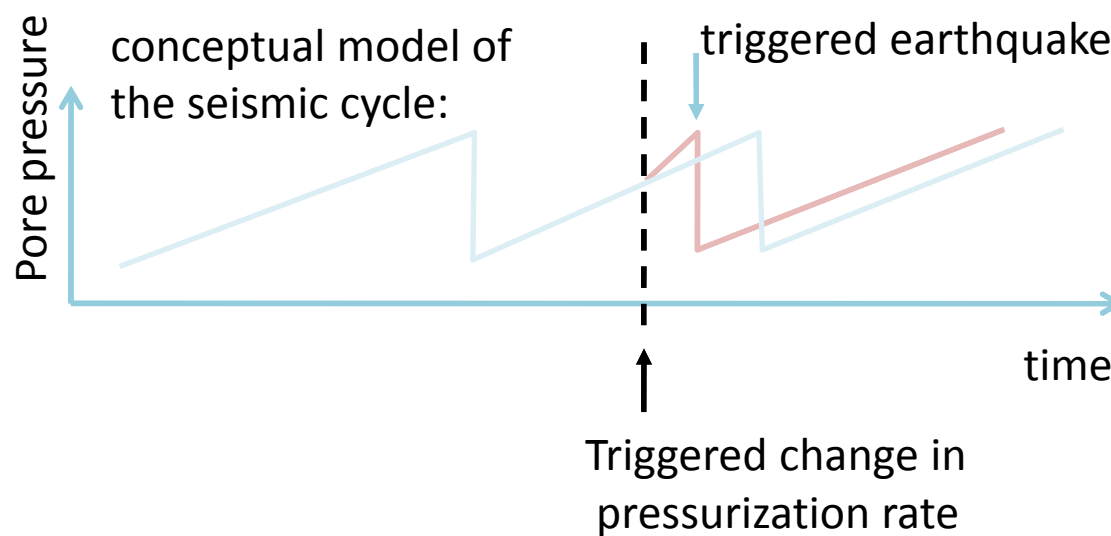
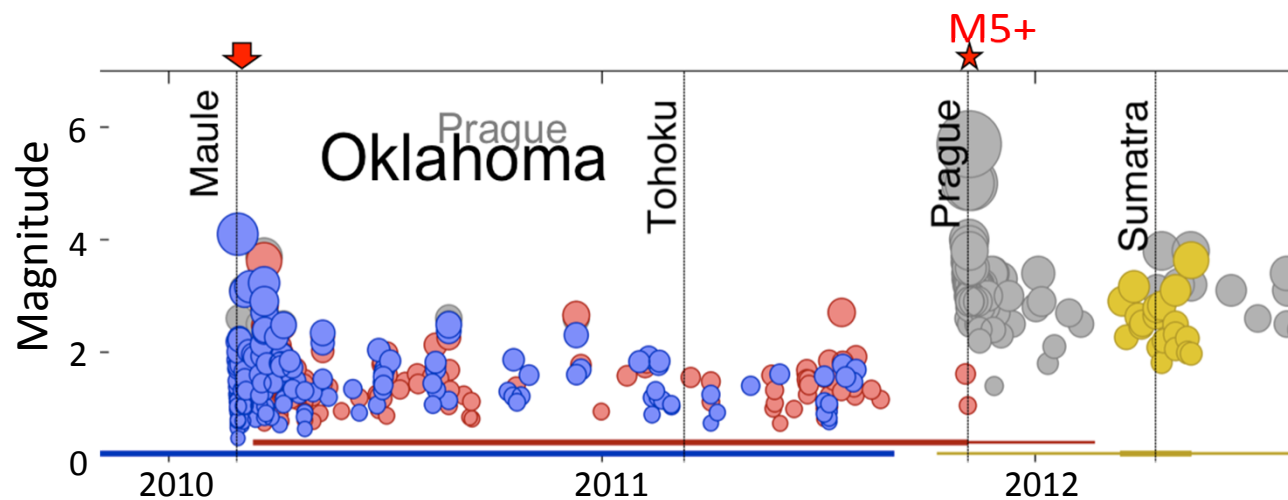




Remote triggering at fluid injection sites

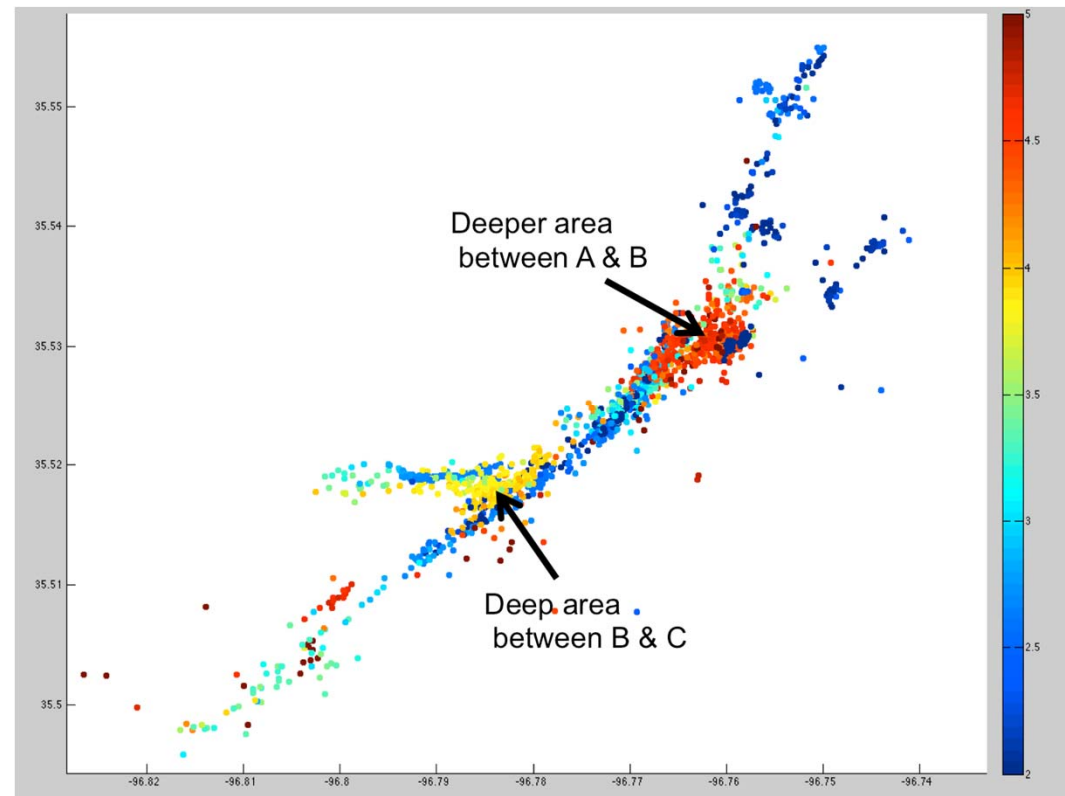
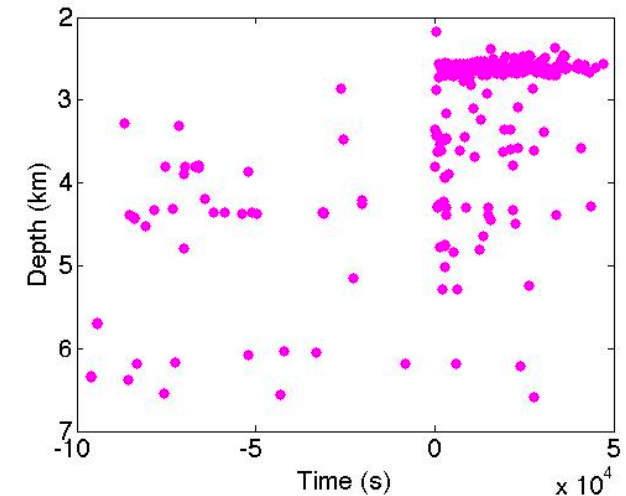
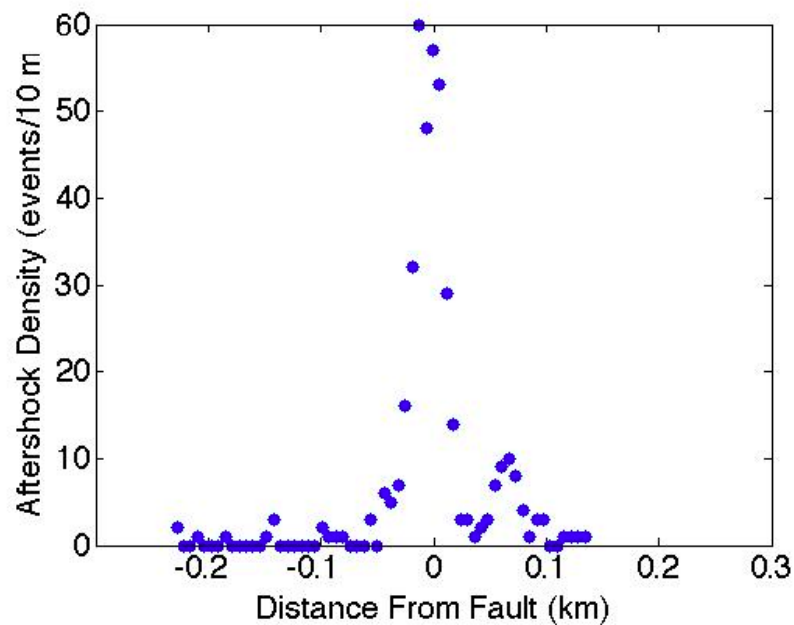
van der Elst et al., 2013 Science







Cascading ruptures and deformation prior to earthquake nucleation





Perturbing stress and recording signals

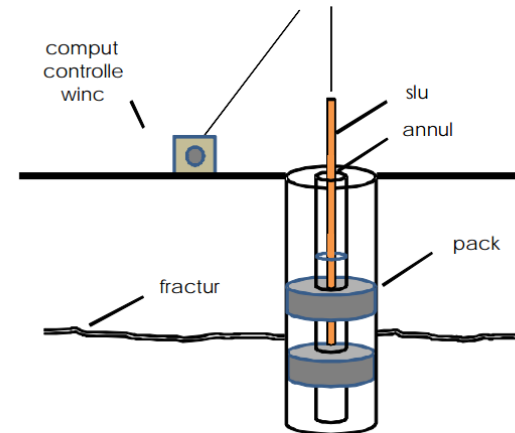
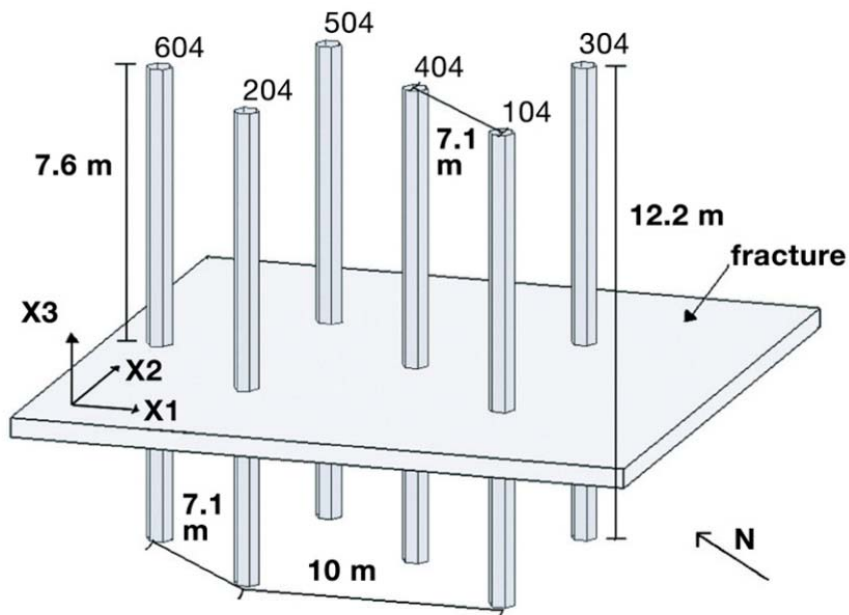
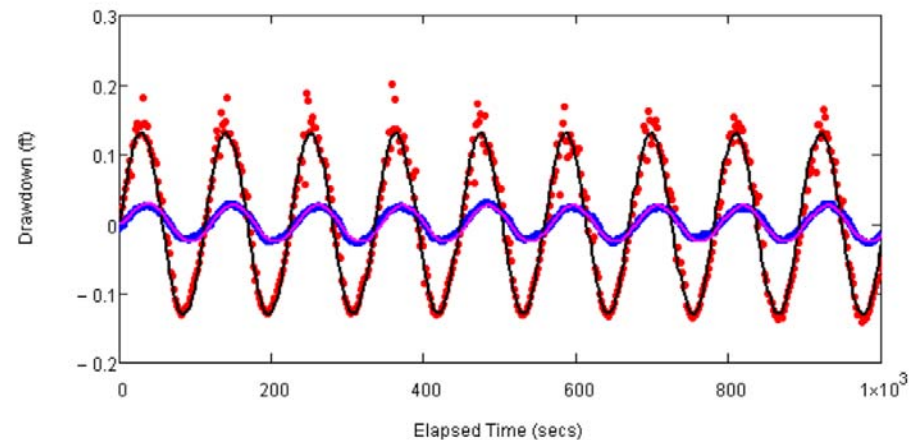


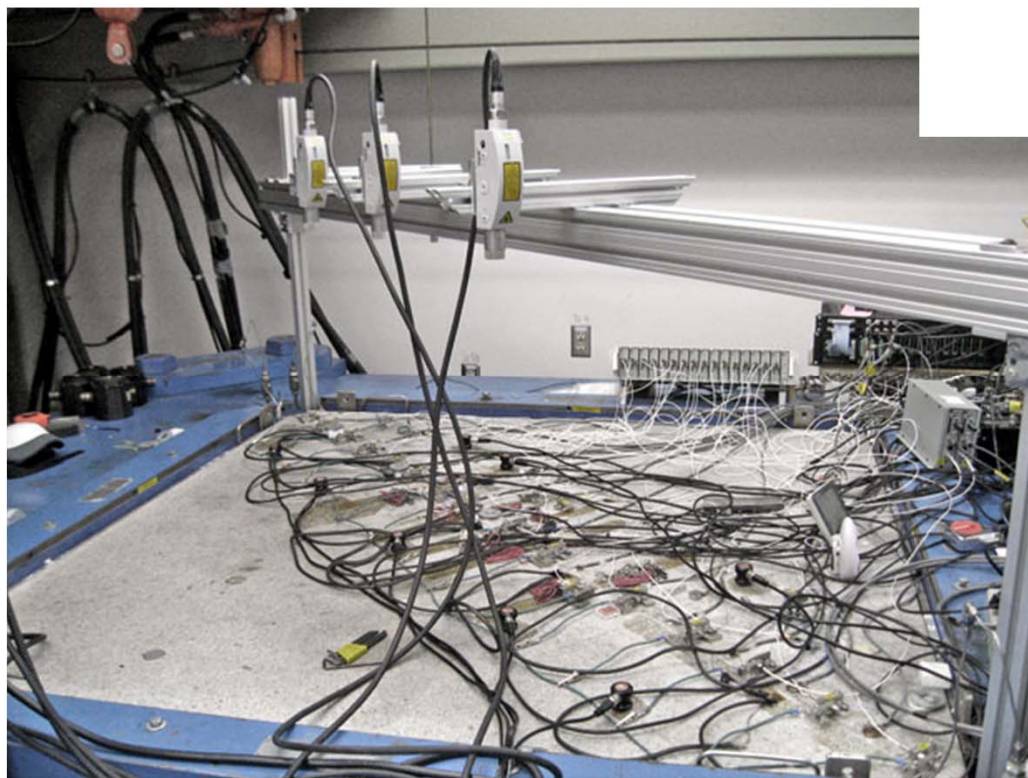
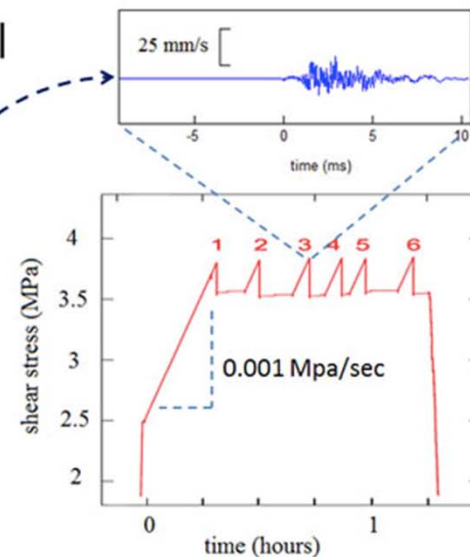
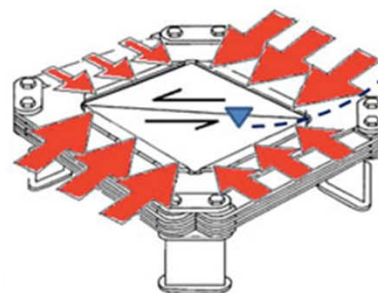
Figure 2: Well field configuration at the Altona Flat Rock Site.





Perturbing stress and recording signals

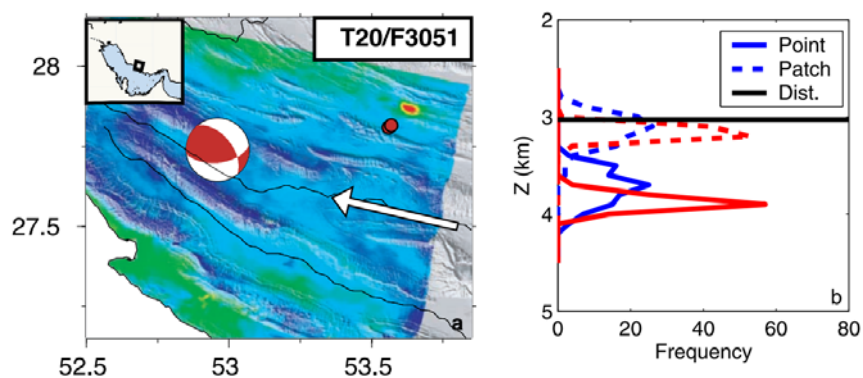
Typical experimental procedure



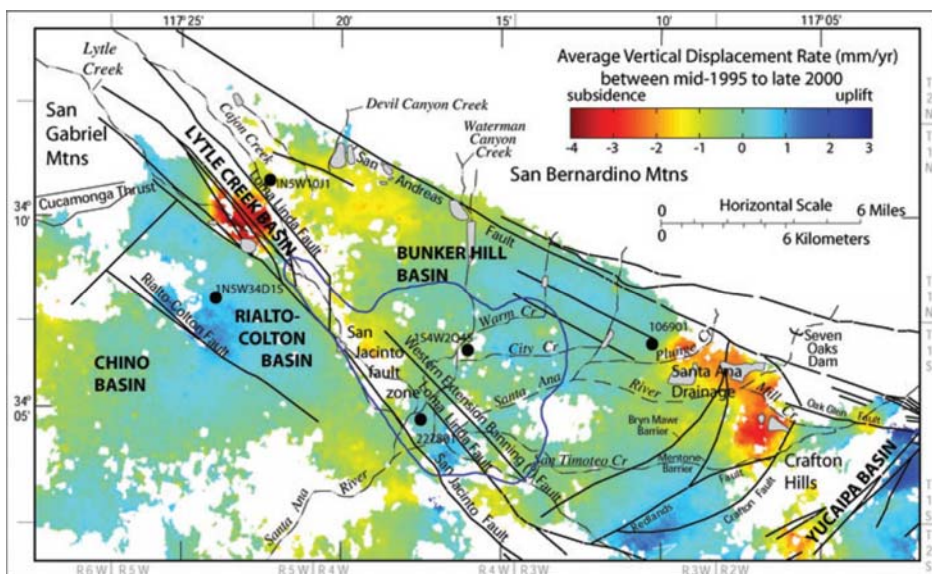
Greg McLaskey, Cornell CEE



InSAR hydrology + earthquakes (+ volcanoes)

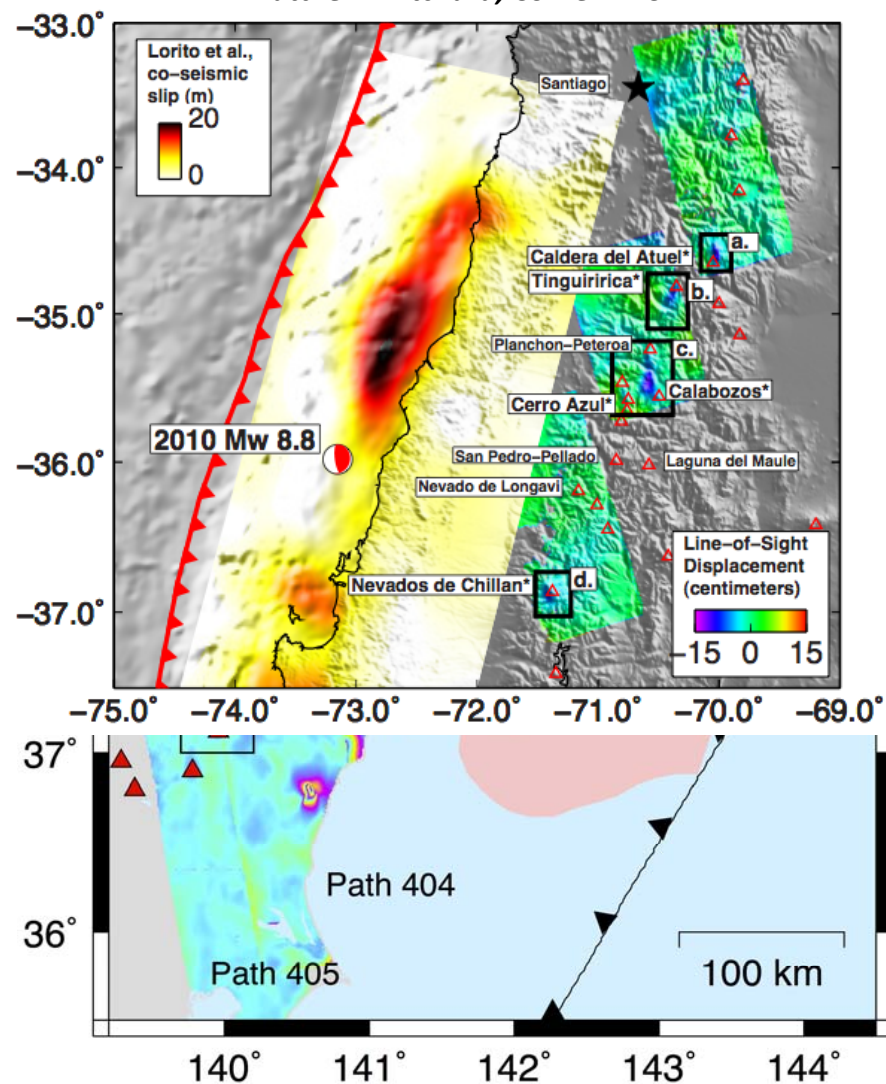


Rowena Lohman, Cornell EAS



Wisely and Schmidt, 2009

Matthew Pritchard, Cornell EAS





Global injection and cycling of fluid projected to grow steadily: an opportunity and a challenge

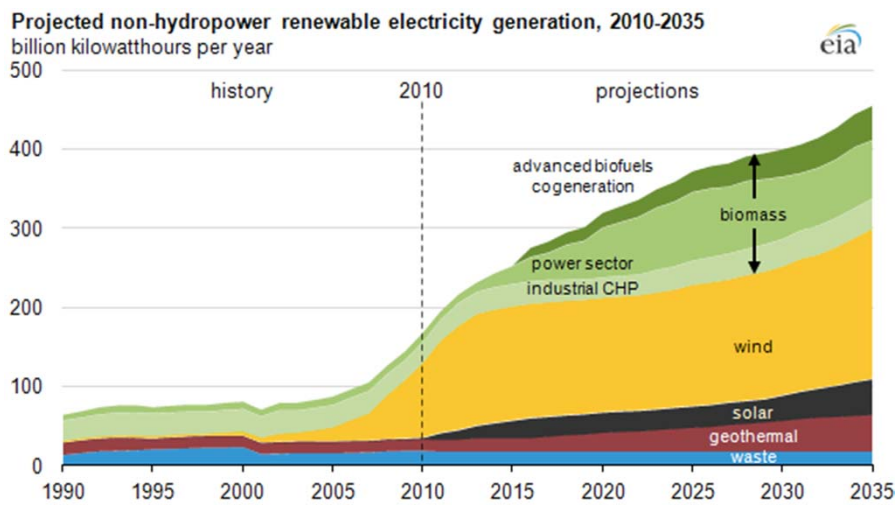
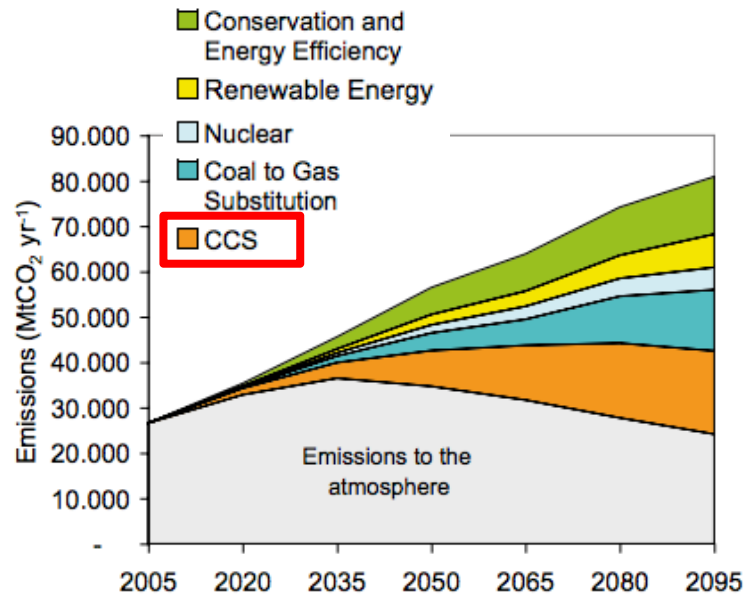
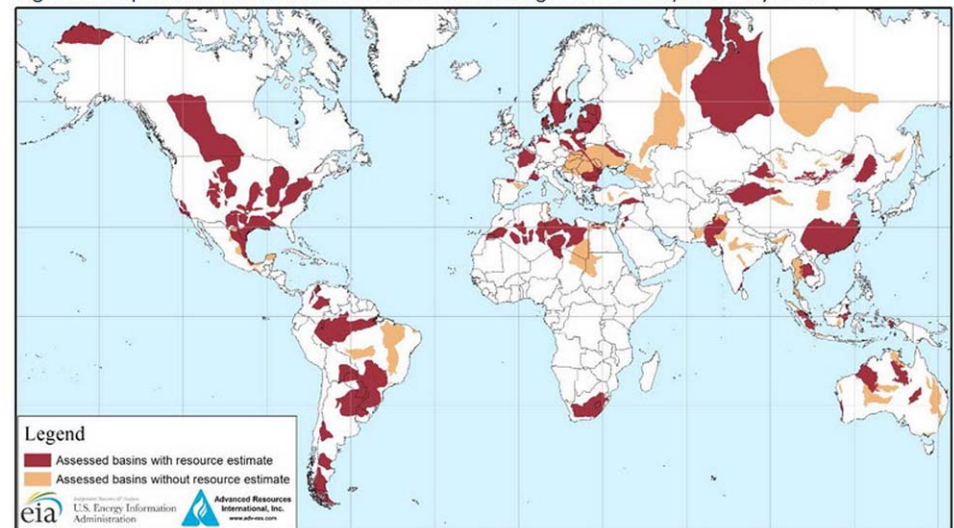


Figure 1. Map of basins with assessed shale oil and shale gas formations, as of May 2013



Source: EIA, Annual Energy Outlook 2013 Early Release



This research has benefitted from numerous discussions with:

- Geoff Abers (Cornell EAS)
- Matthew Weingarten, Shemin Ge (UC-Boulder)
- Barbara Bekins (USGS)
- Elizabeth Cochran (USGS-Pasadena)
- Heather Savage and Nicholas van der Elst (LDEO)
- Bill Ellsworth (USGS)
- Powell Center hydrogeology working group