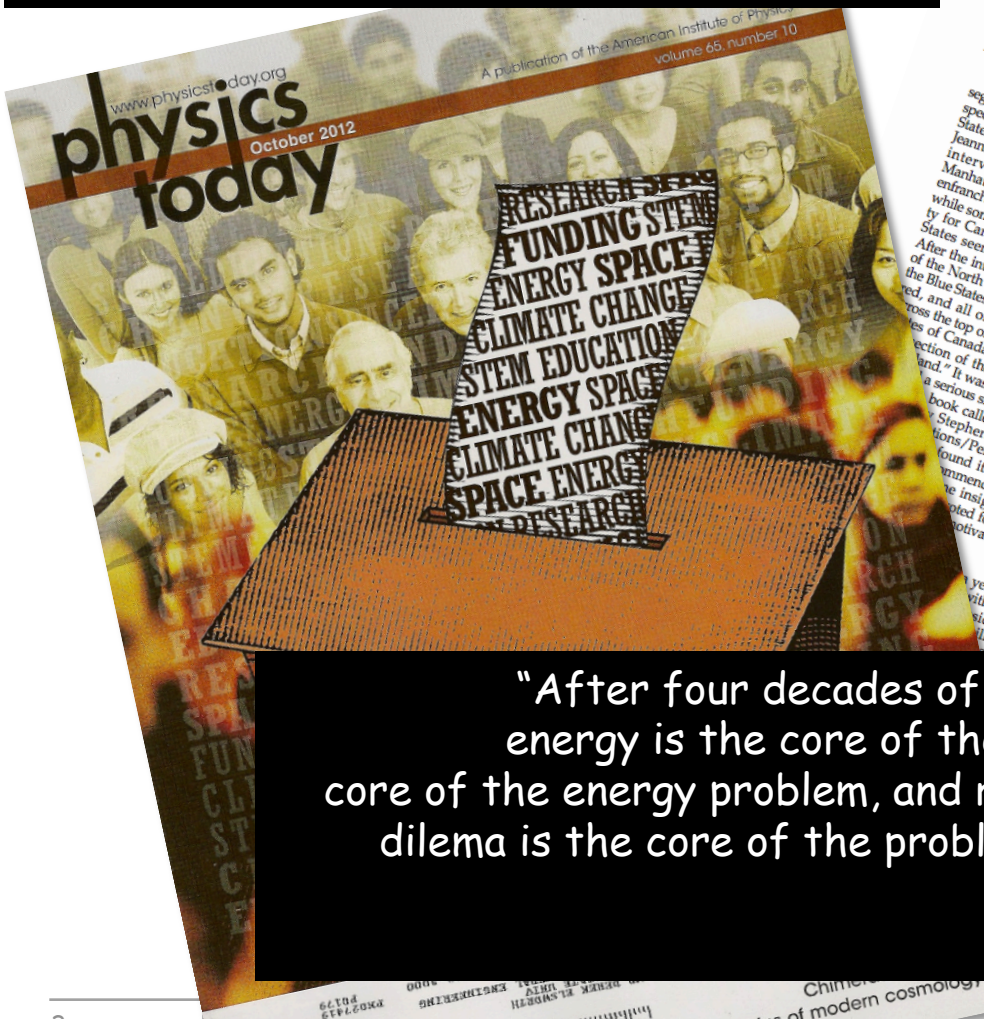
What are the Big Questions (for us)?

"…. we can see how energy is the key to solving all of the rest of the problems – from water to population"
--Richard E. Smalley




www.mrs.org/publications/bulletin
MATERIAL MATTERS

Future Global Energy Prosperity: The Terawatt Challenge

Richard E. Smalley

The following article is an edited transcript based on the Symposium X—Frontiers of Materials Research presentation given by Richard E. Smalley of Rice University on December 2, 2004, at the Materials Research Society Fall Meeting in Boston.

Recently, I watched a humorous news segment on CNN about the U.S. election, specifically about the Blue States and Red States. In this piece, CNN correspondent Jeanne Moos was touring New York City, interviewing people in downtown Manhattan. Many of them felt rather disenfranchised from the rest of the country, while some actually felt much more affinity for Canada than for what the United States seems to have become for them. After the interviews, up popped this map of the North American continent, with all the Blue States in blue, all the Red States in red, and all of Canada in blue. Written across the top of Canada was "The United States of Canada" and written across the bottom of the United States, it said, "and." It was funny, of course, but it had a serious side. I have just finished book called *The Faith of George* by Stephen Mansfield (Strang tions/Penguin Group. New found it to be an excellent mmend it for those who e insight into why the ted for this man, and otivates him.

and remarked that he had a personal connection to this painting. The subject of the work is a lone horseman riding western saddle up over a difficult hill, probably someplace out in Texas. The horseman is actually a Methodist circuit rider, and the whole notion is that this rider is on a mission to go out and do good work, specifically, to spread religion and belief in God across the early Western frontier.

The more I think about that experience and the significance of that painting, the more I believe that the concept of "mission" is at the core of what really does motivate our president. Now that we are embarking on four more years of the Bush administration, I have also been pondering just what implications that mission might have for us. With a Republican majority in both the House and the Senate, and four years to move his agenda forward, President Bush has an excellent opportunity to make his mark on history.

"At some point, almost certainly within this decade, we will peak in the amount of oil that

Problem 1: Creating a "Sputnik" Effect

The top charge to keep on my list for President Bush should be to inspire the next generation of U.S. scientists and engineers. Currently, despite all we have done in the past decade, we are not spurring young Americans to go into the physical sciences and engineering. This problem is getting worse as the years go by. Today, the number of U.S. citizens getting degrees in physical science and engineering alone is low—it is at best static, and dropping off. My latest data is for the year 2002 (see Figure 1); the 2003 and 2004 numbers will be a bit lower. The number of Americans getting degrees in all fields of sciences and engineering, excluding psychology and social sciences (the increase coming mostly from the life sciences), is about a factor of two higher but is still static and tapering off.

Another bleak indicator is the waning influence of the United States on the scientific education of students from other countries. For a number of decades, the United States, particularly after World War II, was the premier place for the advancement of physical science and engineering. Now, that is no longer true. In fact, in today's world, Europe and Asia, having recovered from their wars, have dramatically enhanced their education experience and are strongly pushing the physical sciences and engineering, along with the life sciences. This trend has been remarkable. Back in the early 1980s, some of the first bright students I had in my group—very Asian students from China—were among the first who came over during the Carter administration. In the decades that followed, many young Asians their degrees here United States

"After four decades of studying these issues, I've concluded that energy is the core of the environment problem, environment is the core of the energy problem, and resolving the energy-economy-environment dilemma is the core of the problem of sustainable well-being for industrial and developing countries alike."
--John Holdren

k.elsworth@psu.edu

Zero-Carbon Solution? - Enhanced Geothermal Systems

Challenges

- Prospecting (characterization)
- Accessing (drilling)
- Creating reservoir
- Sustaining reservoir
- Environmental issues

Observation

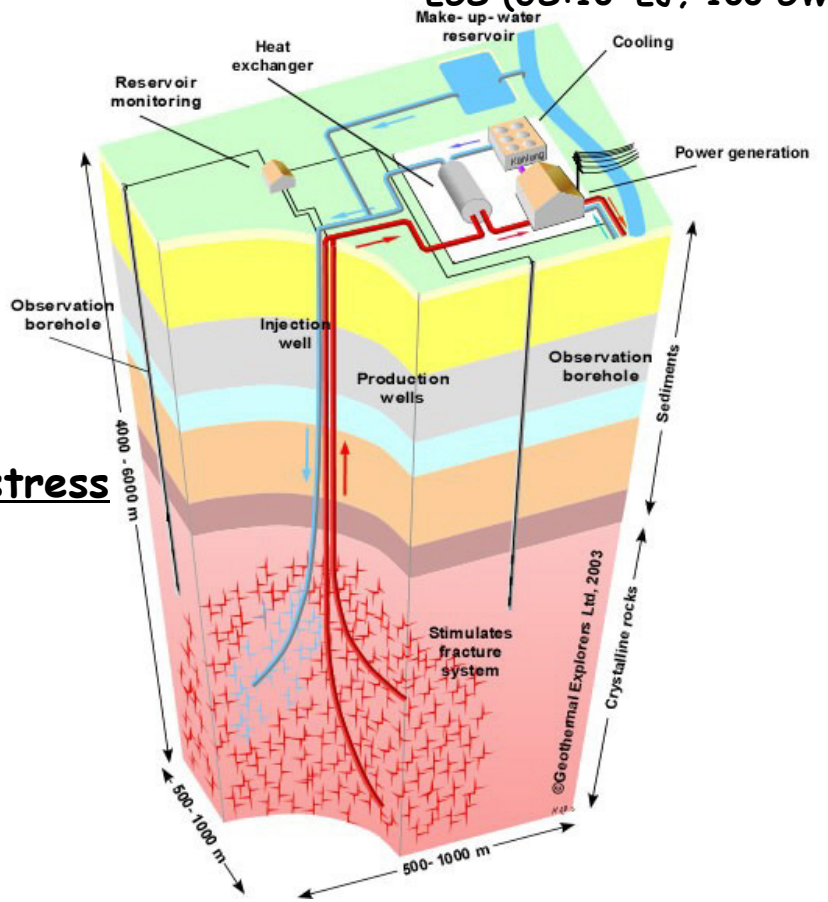
- Stress-sensitive reservoirs
- T H M C all influence via <u>effective stress</u>
- <u>Effective stresses</u> influence
  - Permeability
  - Reactive surface area
  - Induced seismicity

Understanding T H M C is key:

- Size of relative effects of THMC
- Timing of effects
- Migration within reservoir
- Using them to engineer the reservoir

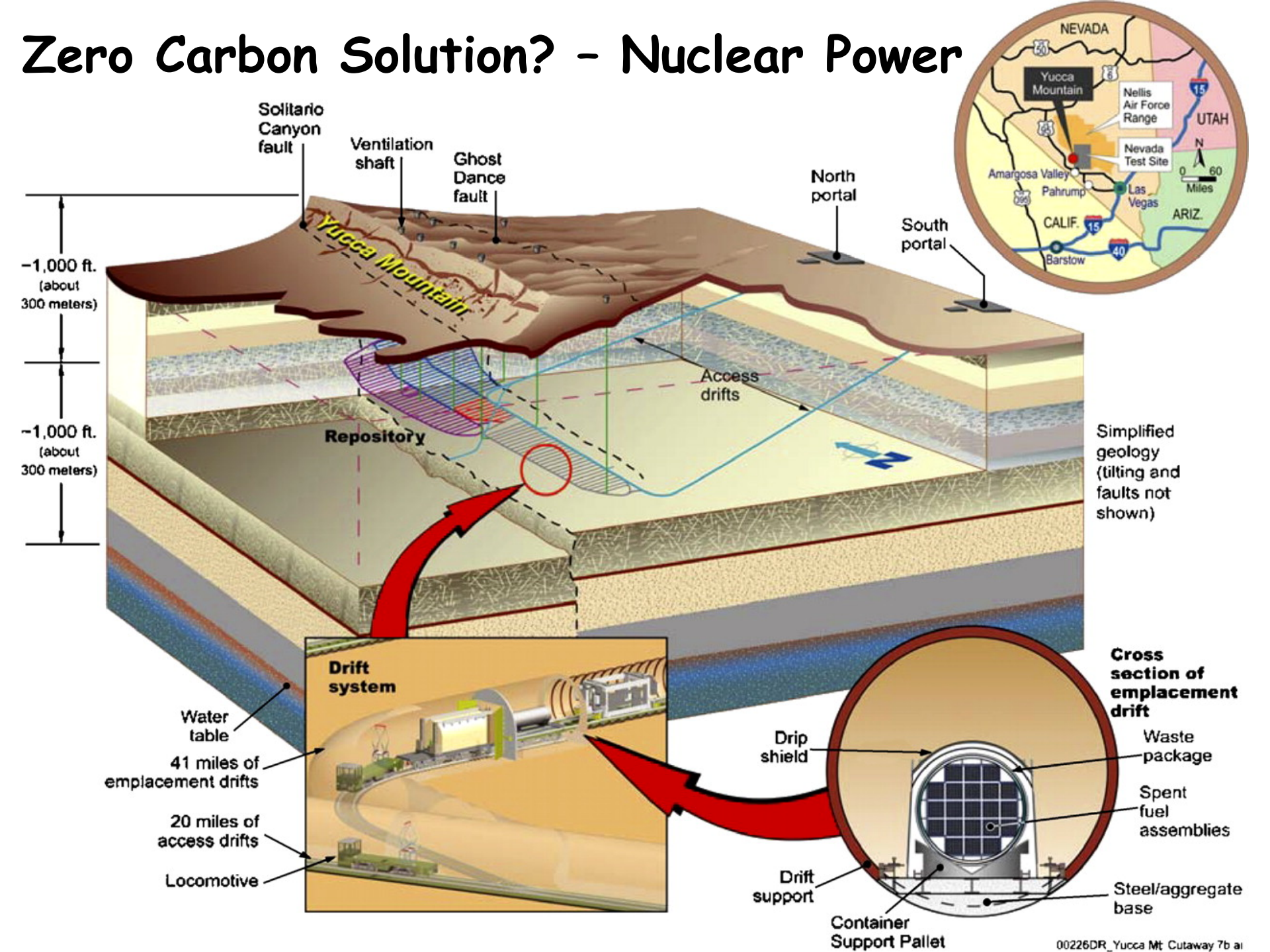
Resource

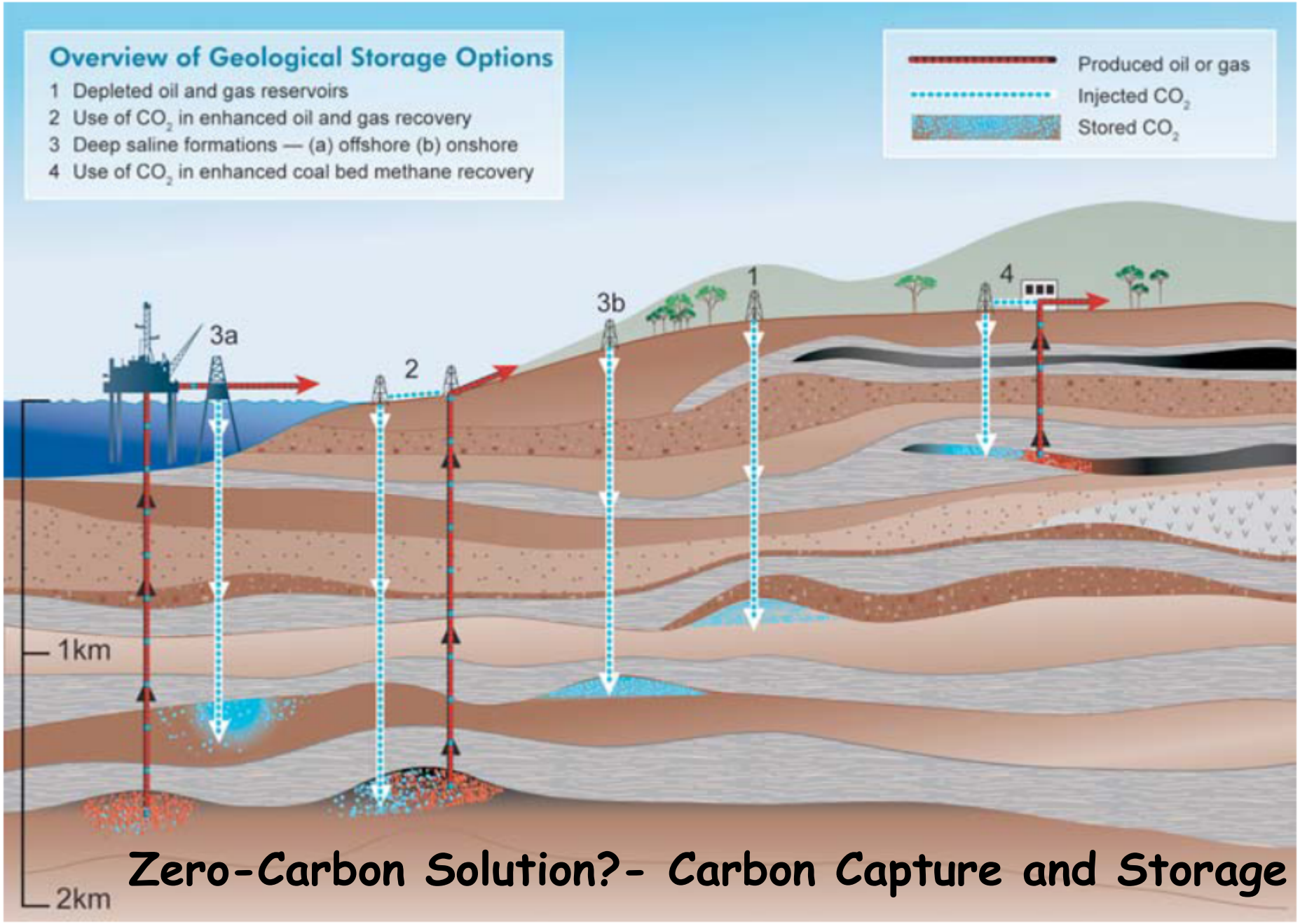
- Hydrothermal (US:10^4 EJ)
- EGS (US:10^7 EJ; 100 GW in 50y)



Permeability
Reactive surface area
Induced seismicity

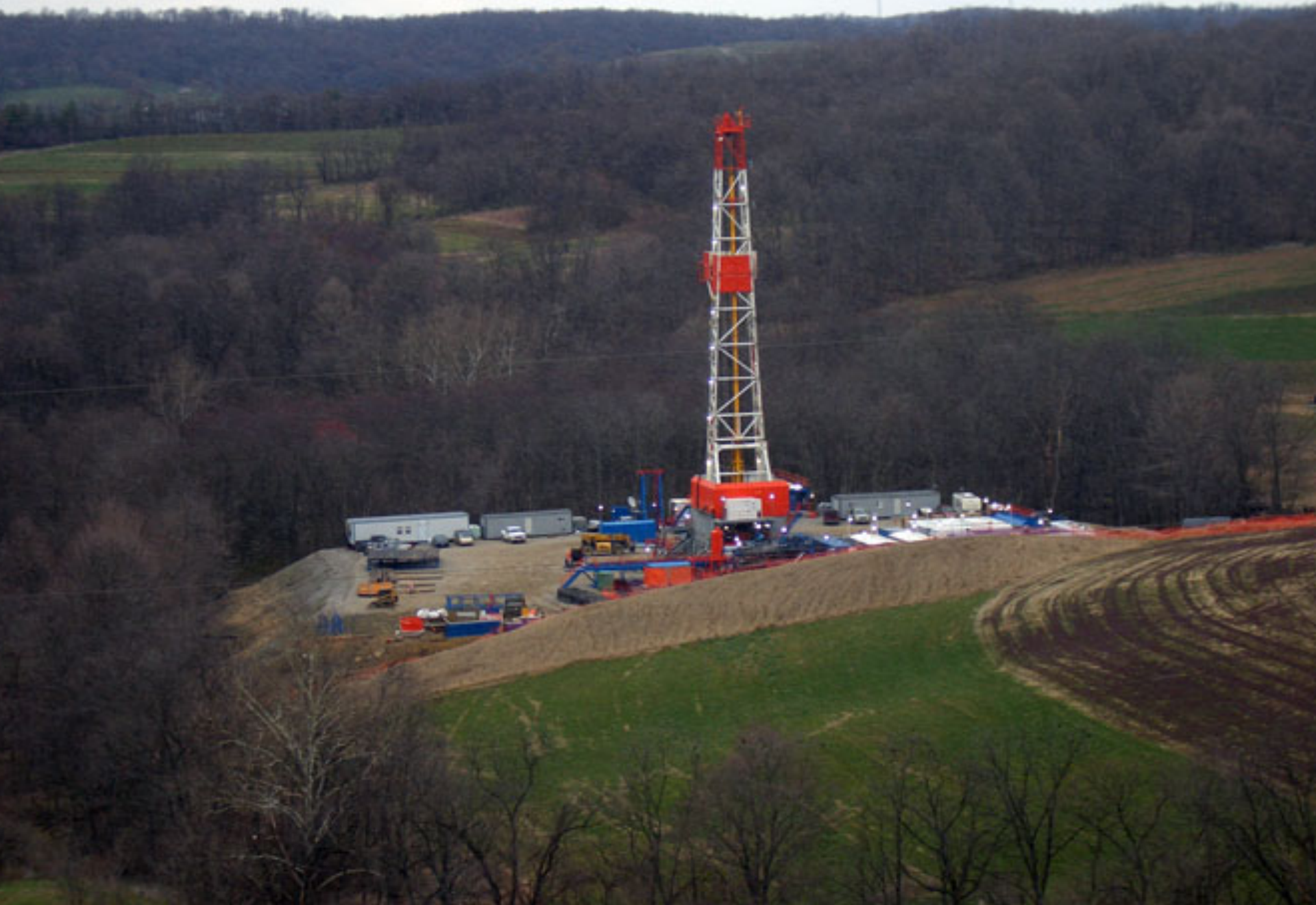
Zero Carbon Solution? – Nuclear Power





Courtesy of CO2CRC, http://www.co2crc.com.au/

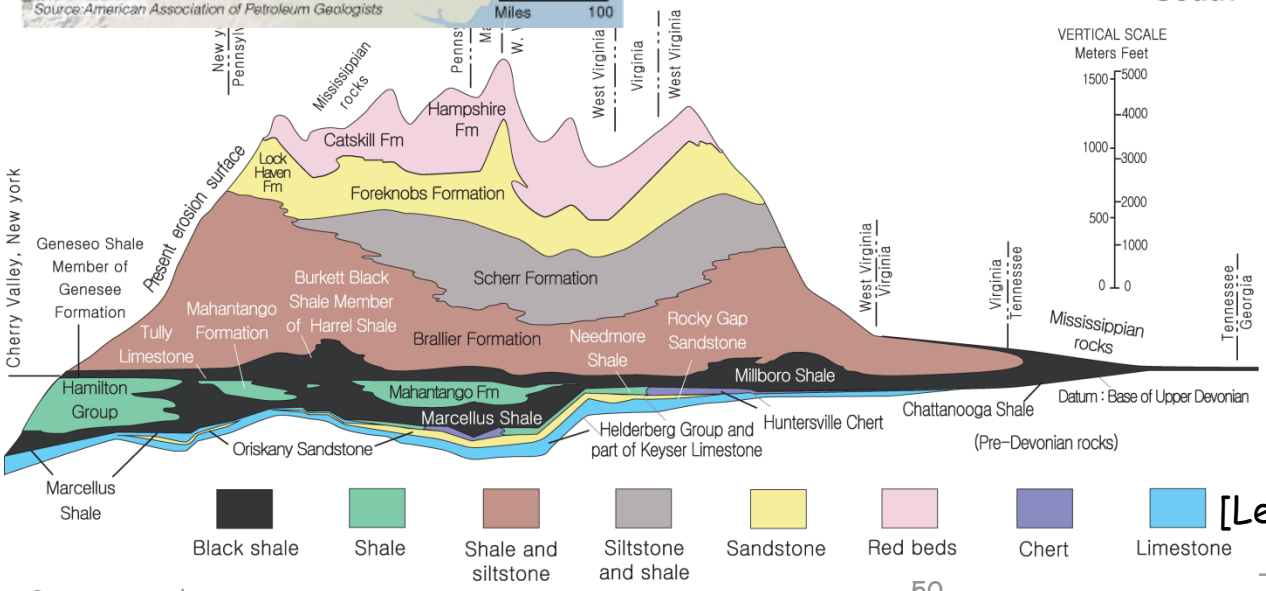
Low-Carbon Fuel Solution? – Gas Shales



Low-Carbon Fuel Solution? – Gas Shales

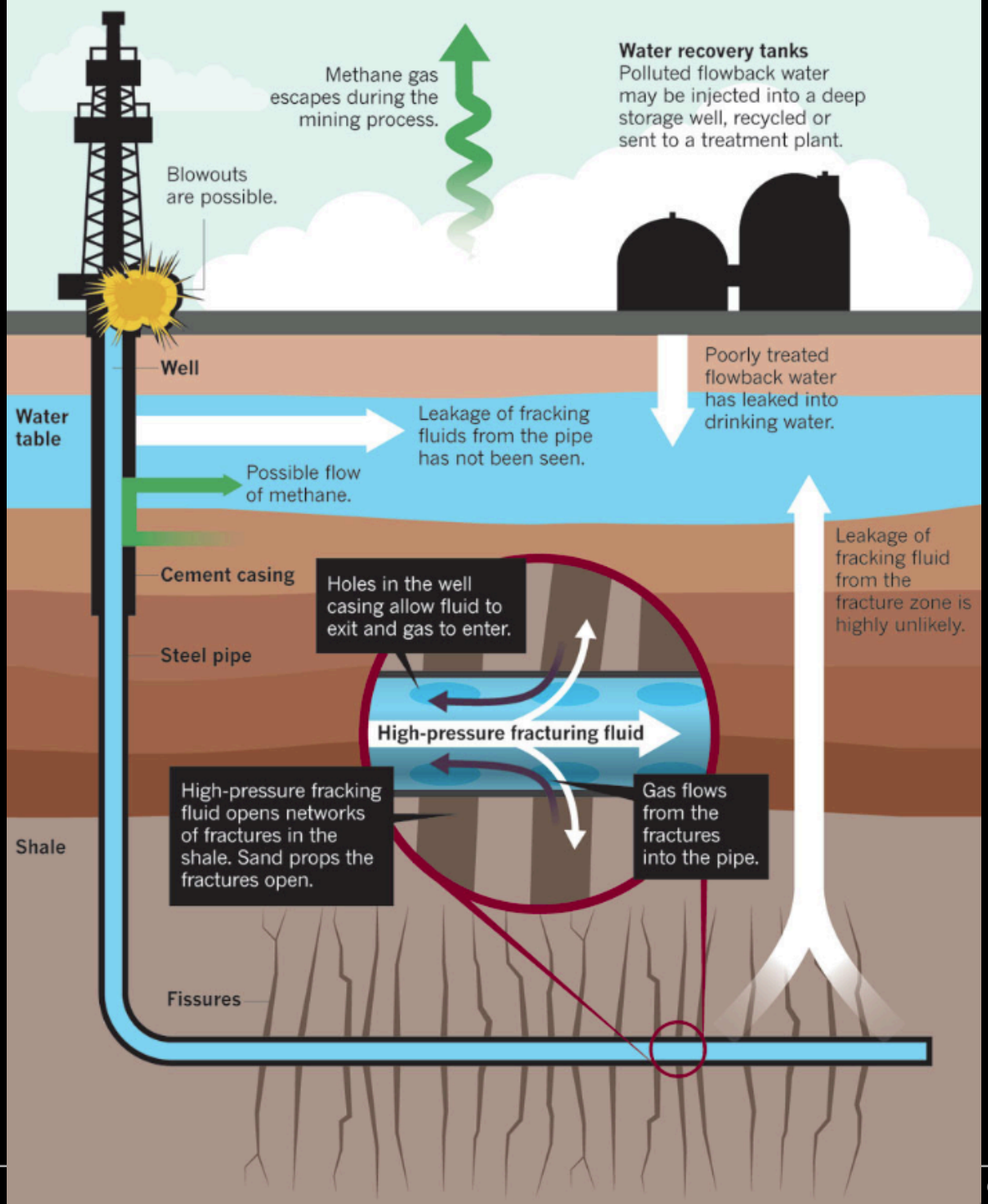
The Marcellus Shale Gas

- underlies 140,000 km^2 of the Appalachian Basin
- average depth of 2 km
- thickness: average 30m, high ~ 75 m
- 295 ~ 2,700 TCF (gas in place)
- annual US consumption (21 TCF/yr)
- porosity: 0.5 ~ 5%
- permeability: micro to nano Darcy range
  - fracture porosity: 2 ~7 %



Technological challenges & Potential solutions

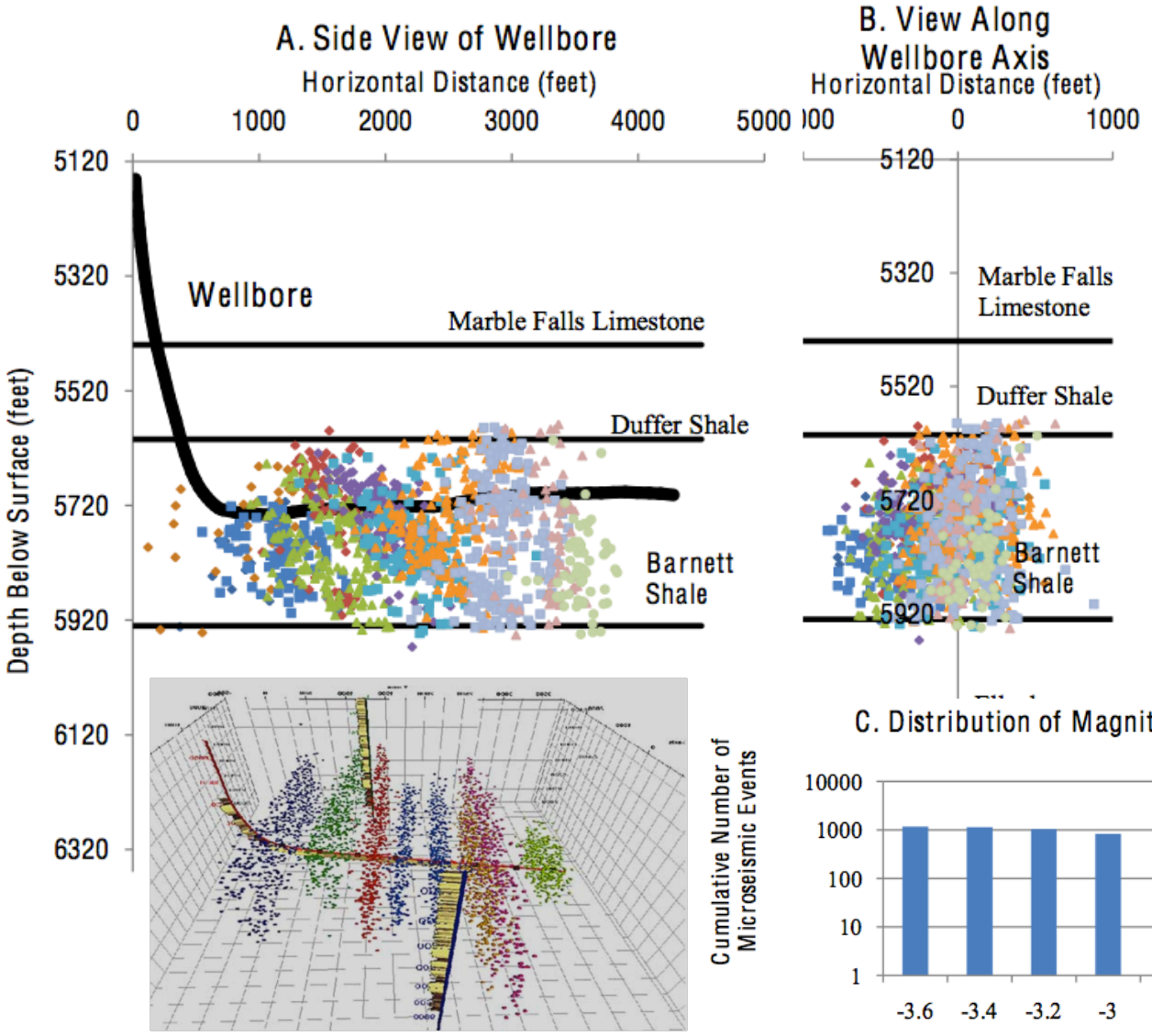
[Lee, Herman, Elsworth et al., 2011]

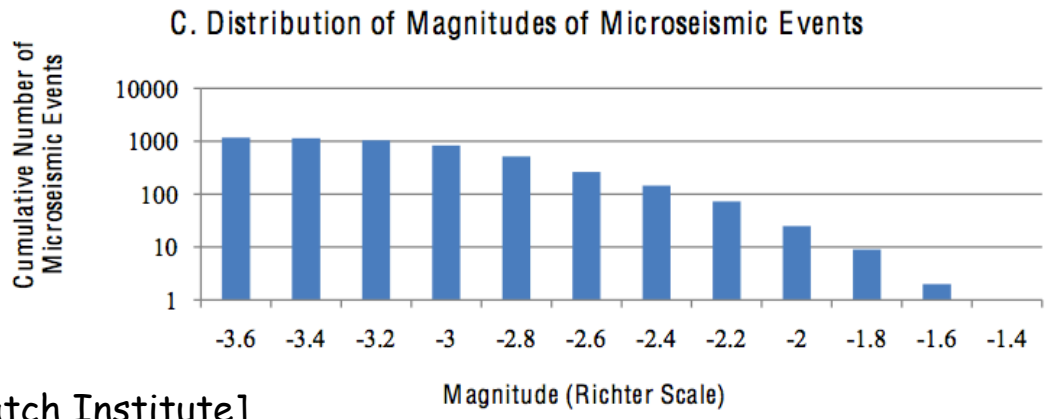


derek.elsworth@psu.edu

Issues - Rural Industrialization

Induced Seismicity





Observations of Events in Barnett Shale (TX)

- Small <-1.4
- Clustered close to fracs
- No obvious events distant from fracs
- Cease after the stimulation

[Zoback, Kitasei, Copithorne, 2010, Worldwatch Institute]

Induced Seismicity

NEWSFOCUS

SEISMOLOGY

Learning How to NOT Make Your Own Earthquakes

As fluid injections into Earth's crust trigger quakes across the United States, researchers are scrambling to learn how to avoid making more

First off, fracking for shale gas is not touching off the earthquakes that have been shaking previously calm regions from New Mexico to Texas, Ohio, and Arkansas. But all manner of other energy-related fluid injection—including deep disposal of fracking's wastewater, extraction of methane from coal beds, and creation of geothermal energy reservoirs—is in fact setting off disturbingly strong earthquakes. These quakes of magnitude 4 and 5 are rattling the local populace, shutting down clean energy projects, and prompting a flurry of new regulations.

Researchers have known for decades that deep, high-pressure fluid injection can trigger sizable earthquakes. But after a decades-long lull in triggered quake studies, researchers are playing catch-up with the latest round of temblors. When triggered quakes surprise drillers, "we're often in the position of ambulance chasers without the necessary science done ahead of time," says seismologist William Ellsworth of the U.S. Geological Survey (USGS) in Menlo Park, California.

As researchers link cause and effect in recent cases of triggered seismicity, they are beginning to see a way ahead: learn as you go. Thorough preinjection studies followed by close monitoring of cautiously increasing injection offer to lower, although never eliminate, the risk of triggering intolerable earthquakes.

An injection too deep

"I'm told it feels like a car running into the house," says Stephen Horton, speaking of the magnitude-4 triggered quakes he saw coming a couple of years ago in north-central

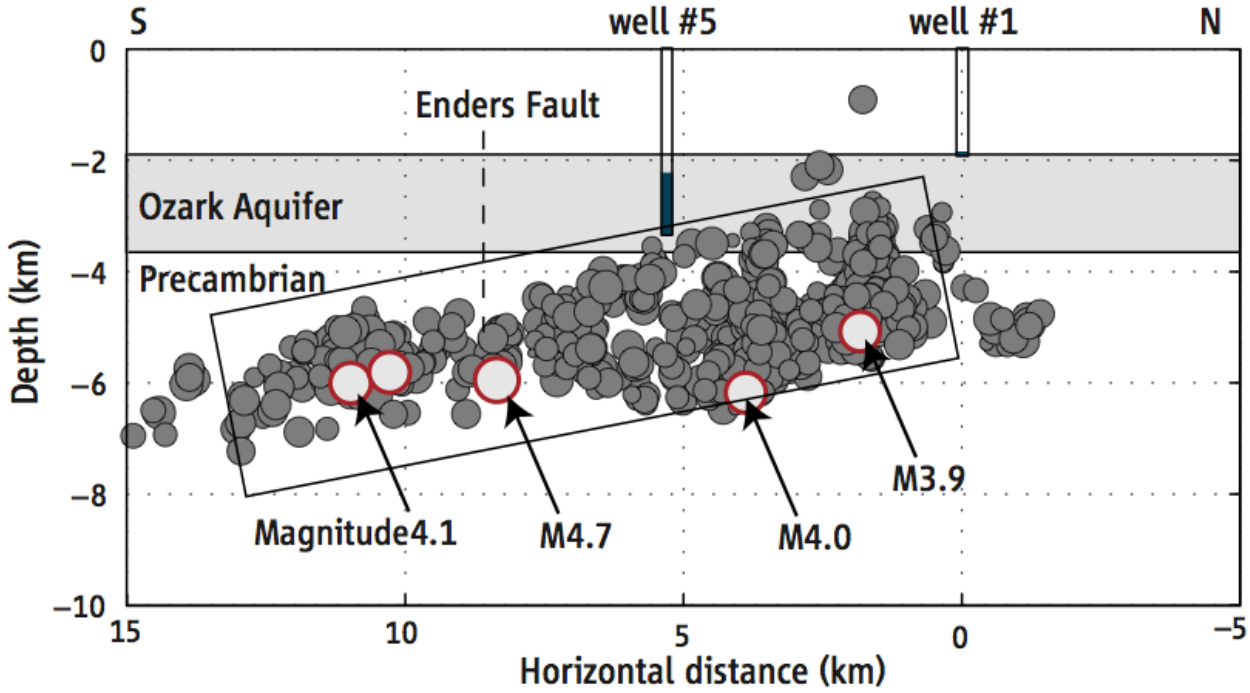
Quake masters. USGS geophysicists Barry Raleigh (*left*) and Jack Healy are poised to open a valve and pressurize deep rock to turn on earthquakes. They could also turn them off in this 1970s study.

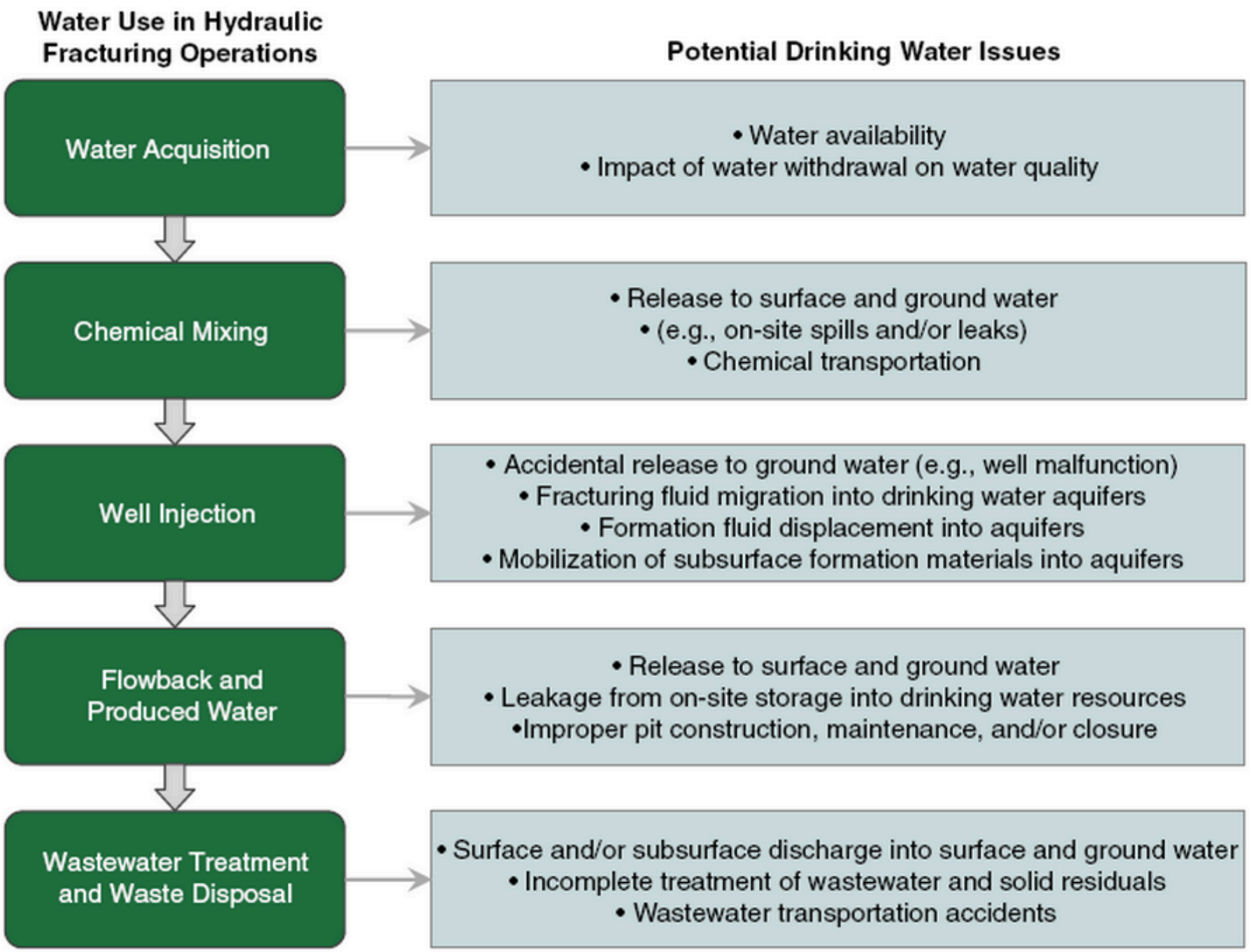
CREDIT: TOP TO BOTTOM: AMY KANCZUZEWSKI/USGS PHOTO; C. BARRY RALEIGH

Horton and Ausbrooks cast a network of seismometers around two new wells that would start injecting in July and in August 2010. On 1 October of that year, Horton warned the director of the Arkansas Oil and Gas Commission, the state agency that regulates deep injection, to "watch out" for more earthquakes. Ten days later, a magnitude 4.0 struck about a kilometer northeast of the deeper of the two new wells. On 20 November, a magnitude 3.9 struck 2 kilometers farther to the northeast toward Guy. Then, in February 2011, magnitude-4.1 and -4.7 quakes struck to the southwest of the deeper well, toward Greenbrier.

By spring, nearly 1000 recorded quakes had struck the area since the wells had started up. "People were feeling a lot of earthquakes,"

Published by AAAS





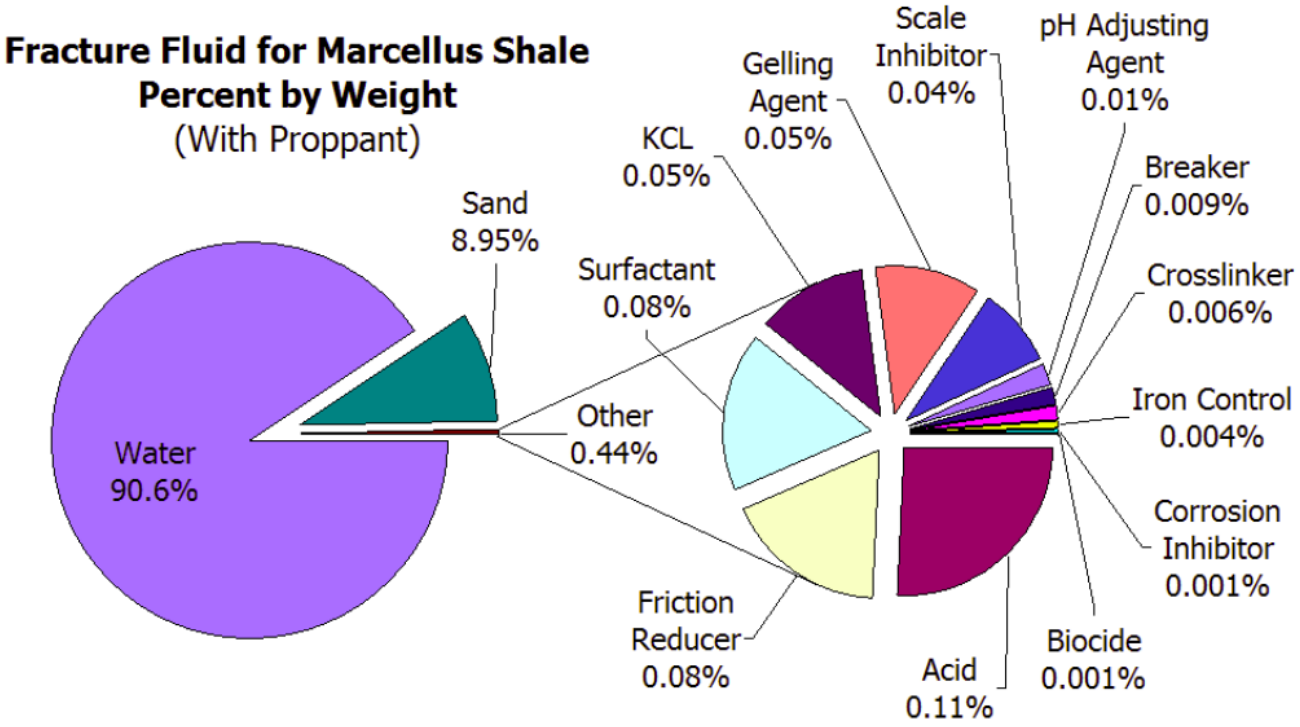
US EPA, Draft to Study the Potential Impacts of Hydraulic Fracturing on Drinking Water, February 2011, p 14

Water Usage – Quantity & Quality

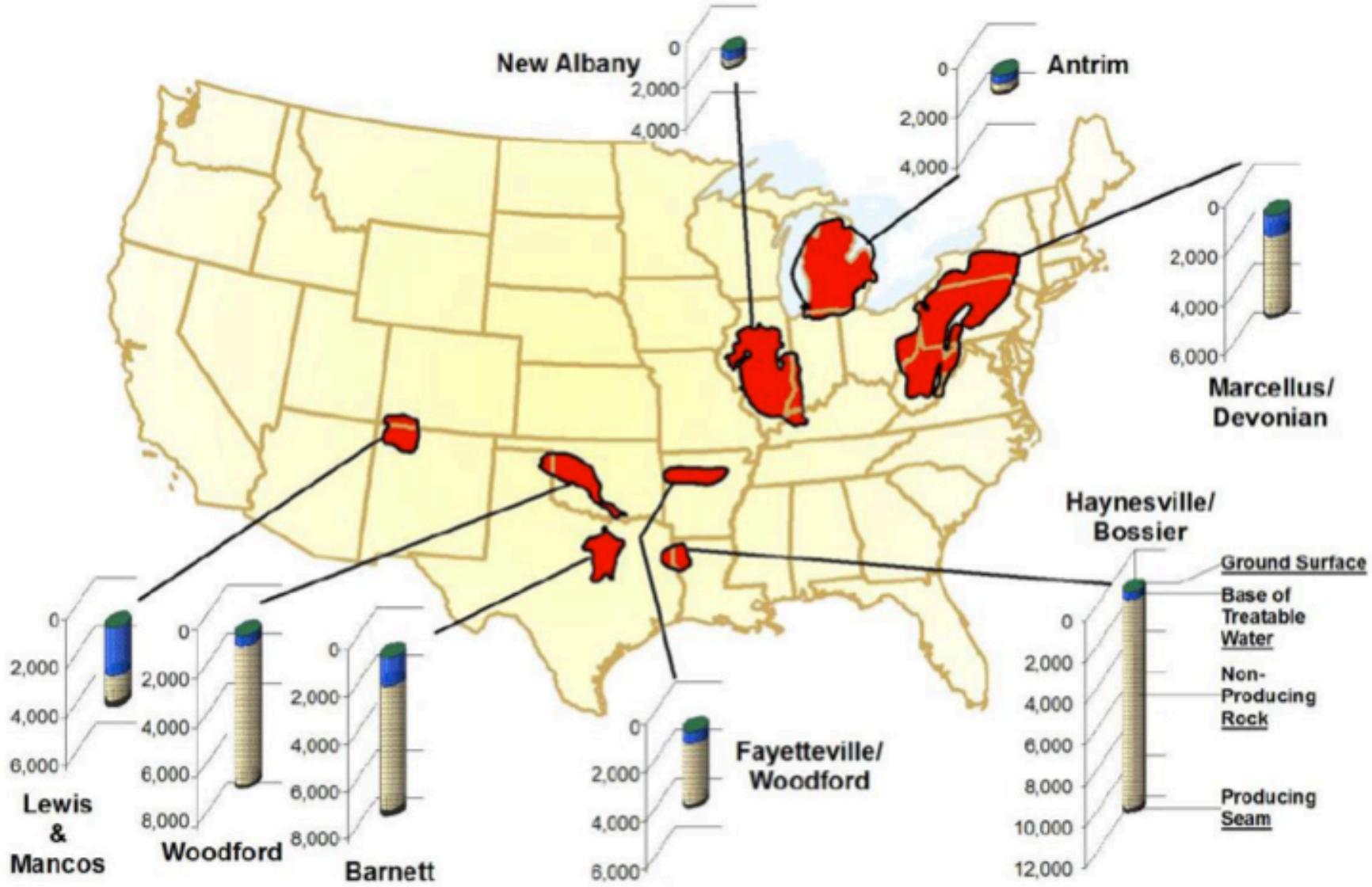
Typical water usage:

~3,500,000 gals/frac for single horizontal well

~86% of fluid recovered as flow-back

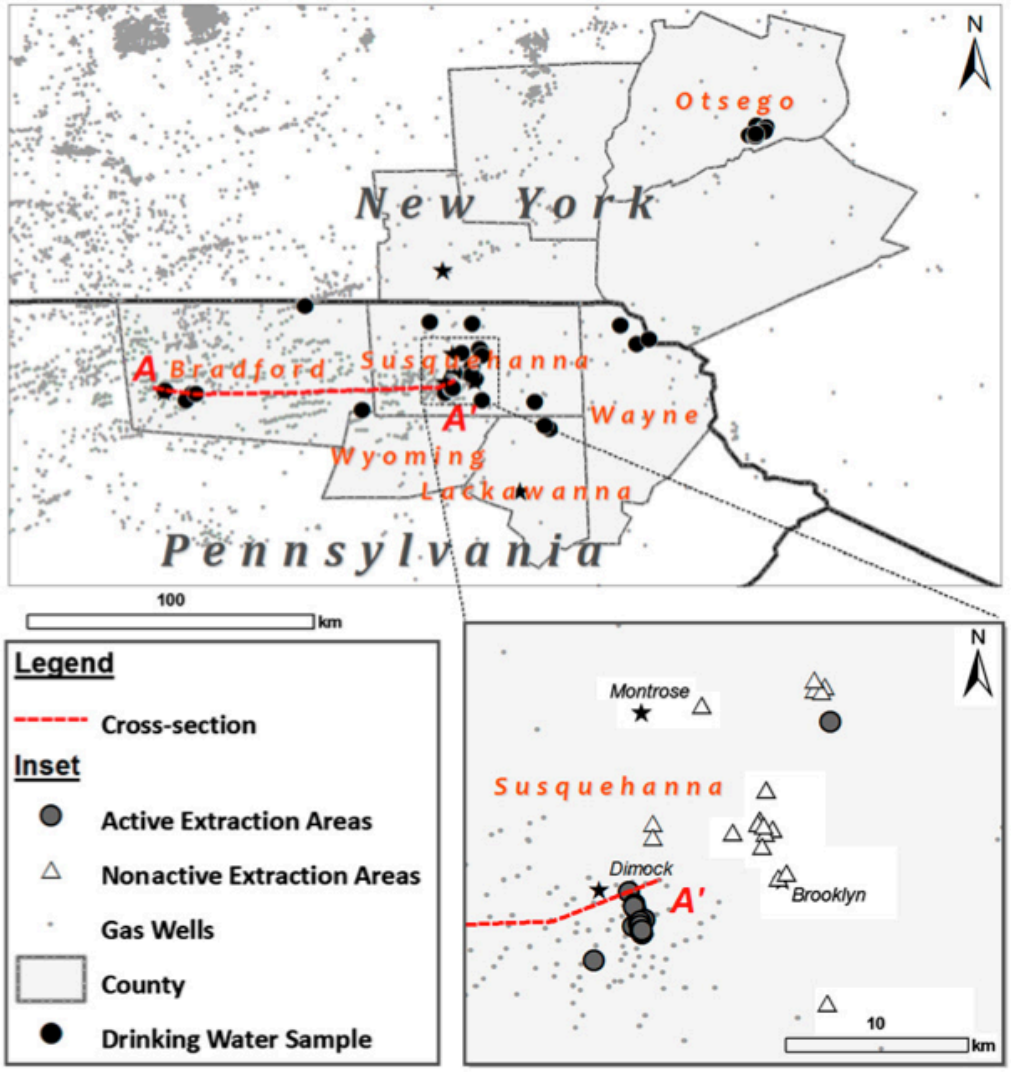


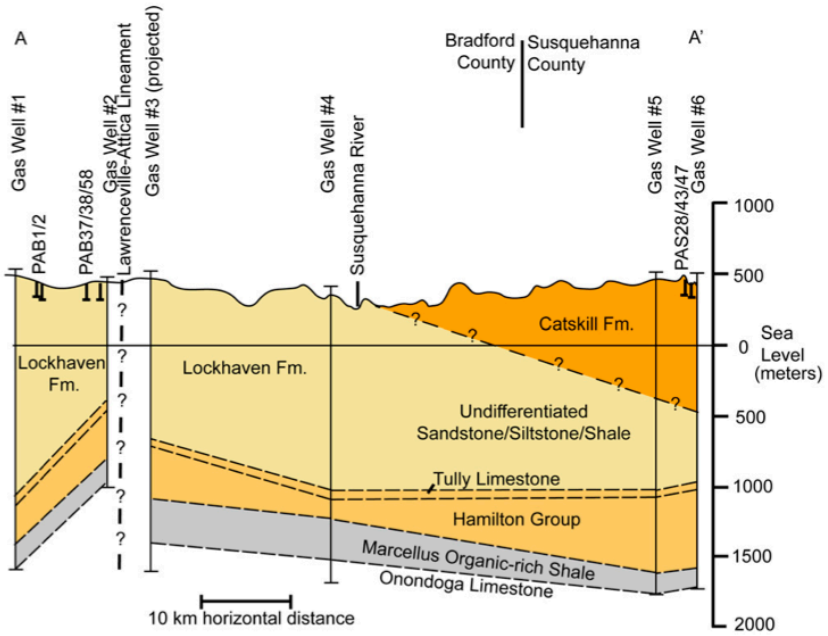
Groundwater



[Zoback, Kitasei, Copithorne, 2010, Worldwatch Institute]

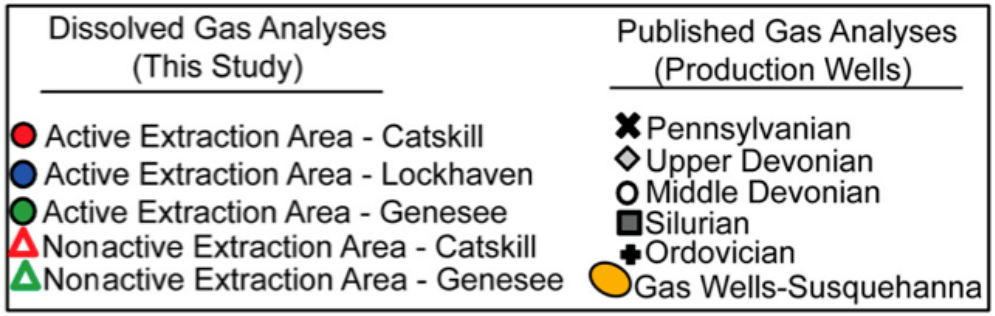
Groundwater Near-Wellbore

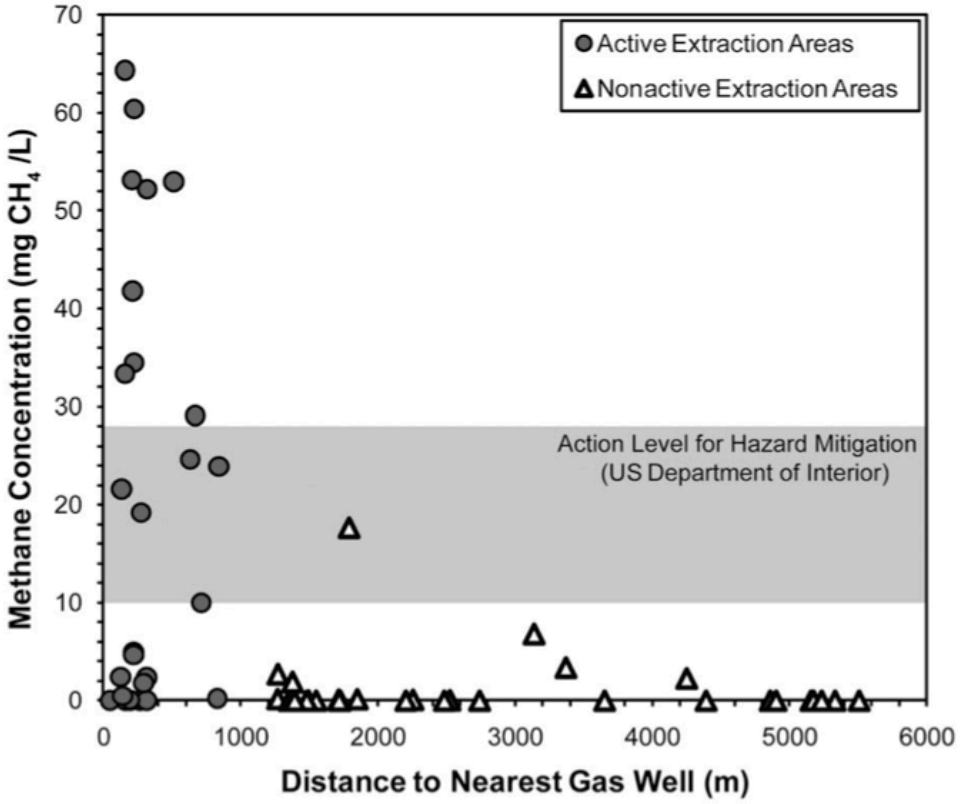


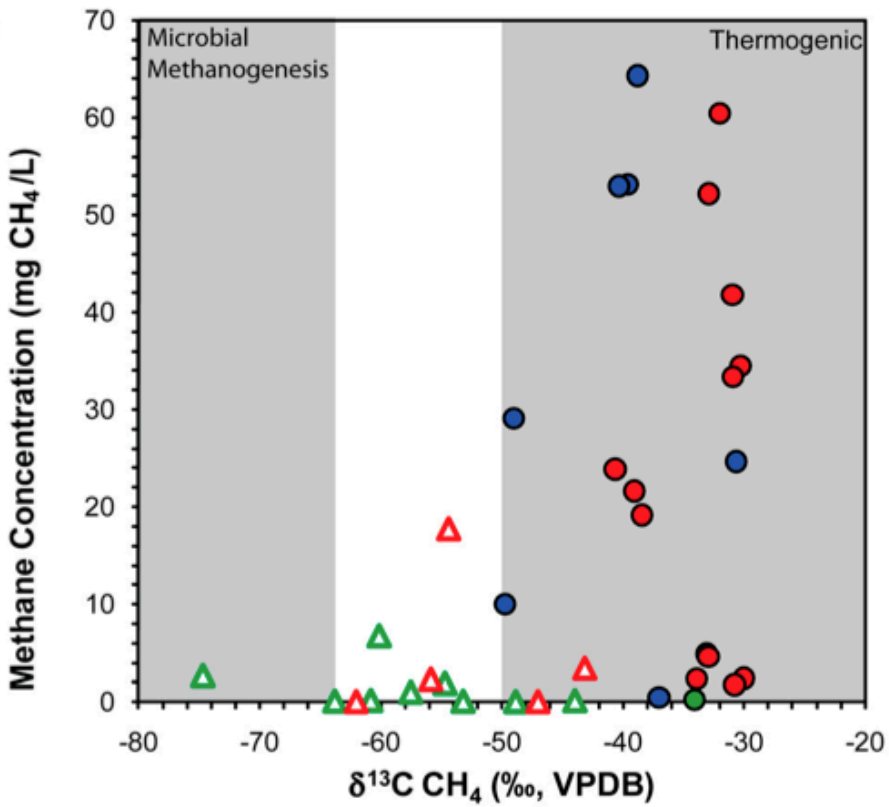


[Osborne, Vengosh, Warner, Jackson, 2011, PNAS]

Groundwater Near-Wellbore

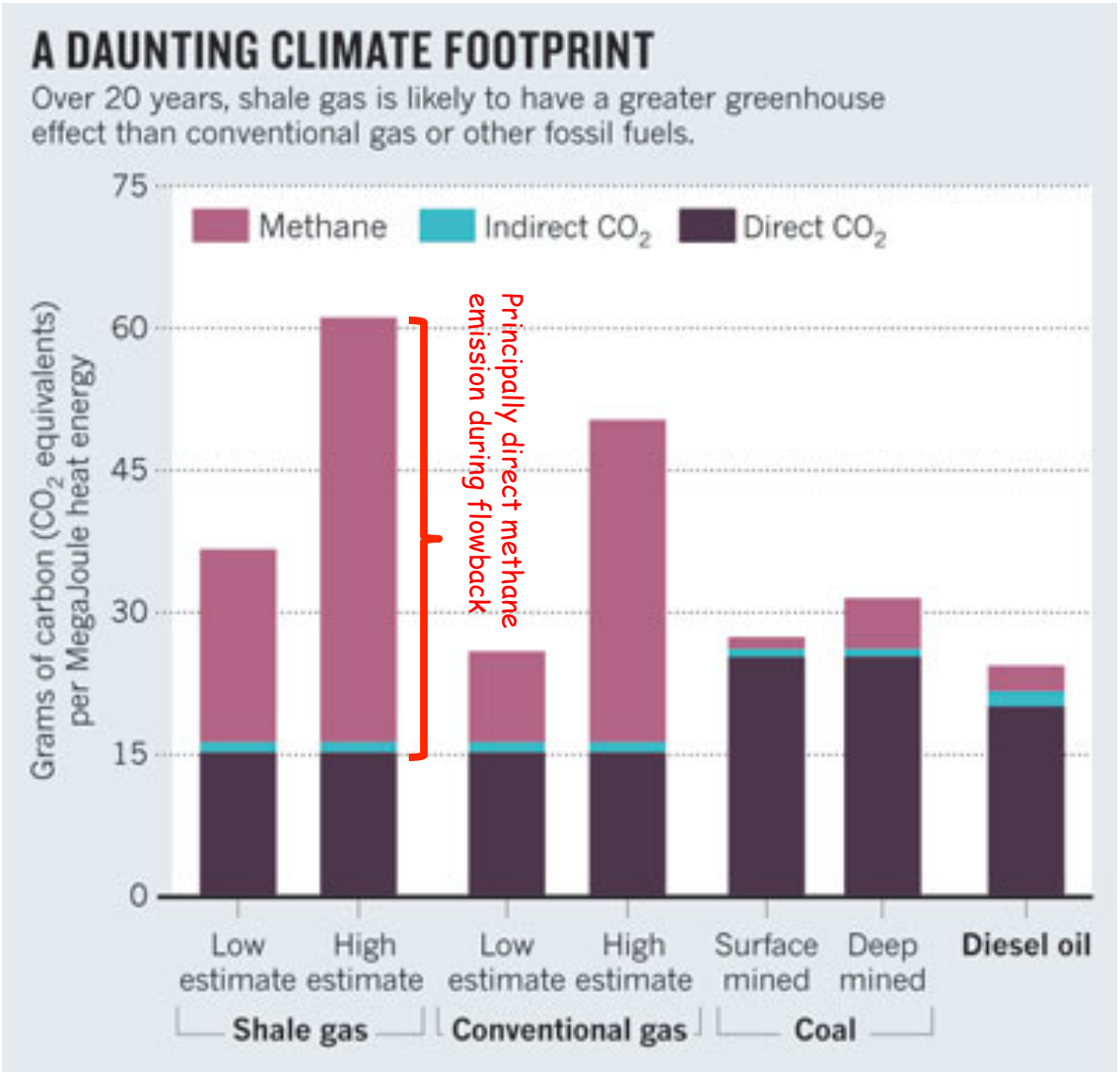






[Osborne, Vengosh, Warner, Jackson, 2011, PNAS]

Life-Cycle Loadings



[Howarth, Santoro, Ingraffea, 2011, Climatic Change]