Induced Seismicity Associated with Shale Energy Development

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What is Induced Seismicity

Induced seismicity is earthquake activity resulting from human activities that cause increased rates or instances of energy release (i.e. seismicity) beyond the historic or normal levels

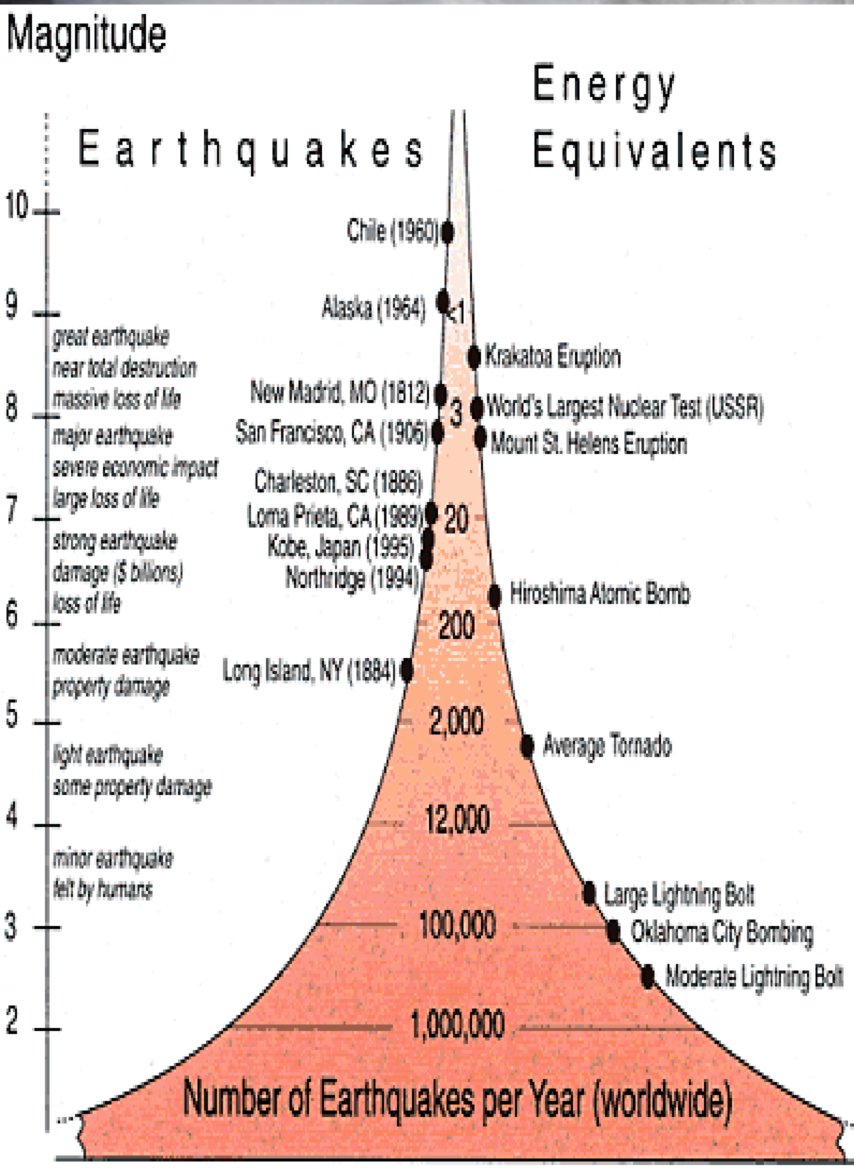
Known human actitivies

1) geothermal reservoirs
2) mining
3) dammed impoundments
4) oil and gas operations
5) underground injection of fluids for waste disposal

Two main types of induced seismicity:

1) Shear-cause of largest earthquakes
2) Tensile-associated with microseismic events, e.g. hydraulic fracturing

Earthquake Magnitude



The magnitude of an earthquake hinges on:

1) how much slip occurs on the fault,
2) how much stress there is on the fault before slipping,
3) how fast it fails, and
4) over how large an area the slip occurs

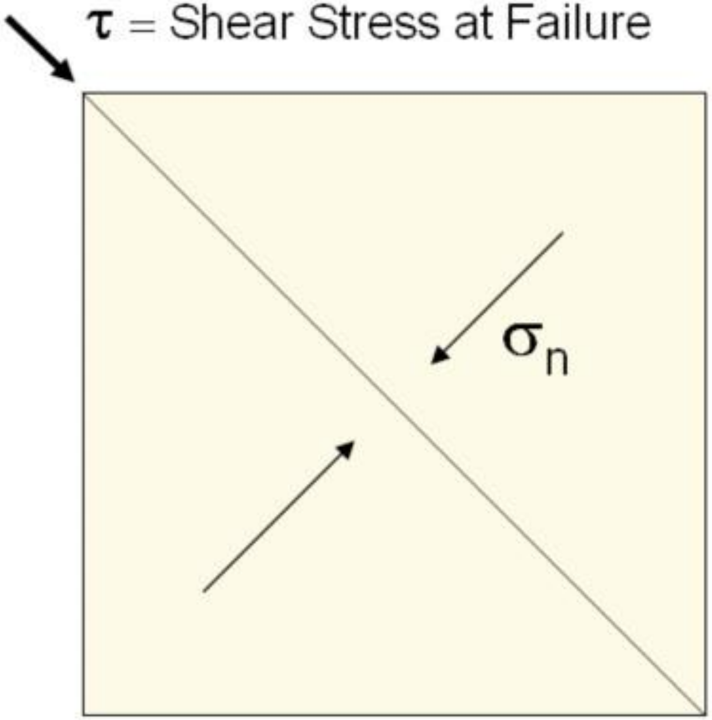
The seismic moment (M_0) of an earthquake which is the product of the average amount of slip (s), the area that slipped (A), and the rock rigidity (G). The equation is $M_0 = GsA$

- Large earthquakes (M>5) typically start at depths 5-10 Km where there can be enough stored energy
- Earthquakes with M<2 are generally not felt.
- Seismicity with hydraulic fracturing typically M<1, often M<-1

Shear Stress

Concept of Effective Stress

τ = Shear Stress at Failure



$\tau_D = S_o + \mu\sigma_n$

σ_n = Normal Stress

μ = Coefficient of Friction

S_o = Rock Strength

Effective Normal Stress = $(\sigma_n - P)$

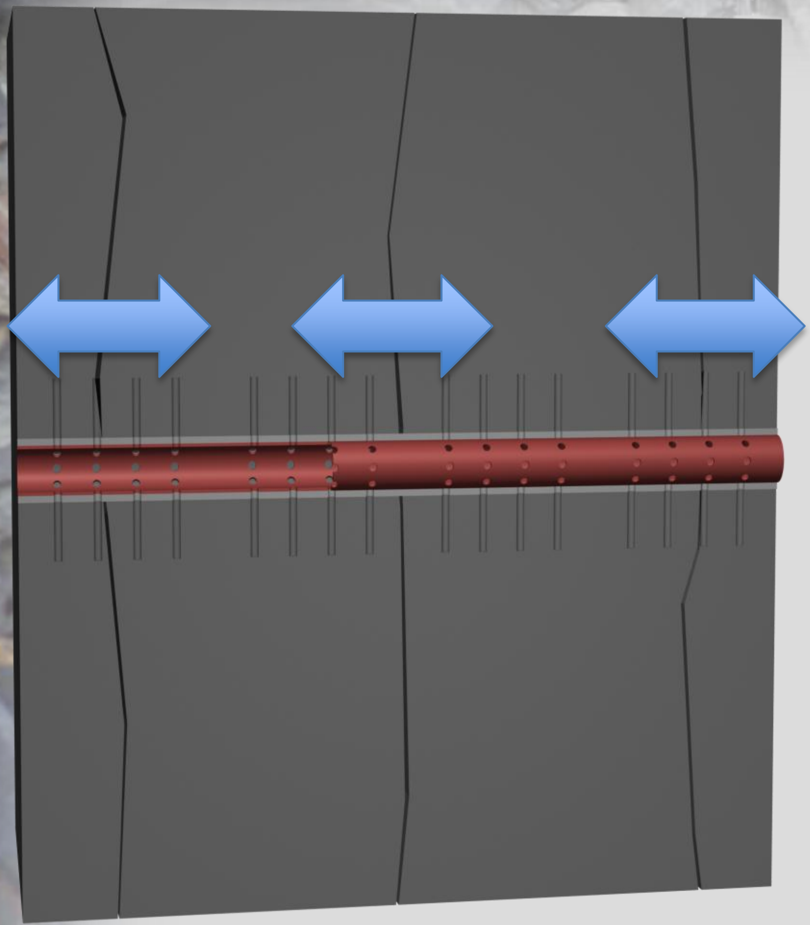
P = Pore Pressure

$\tau_f = S_o + (\sigma_n - P)$

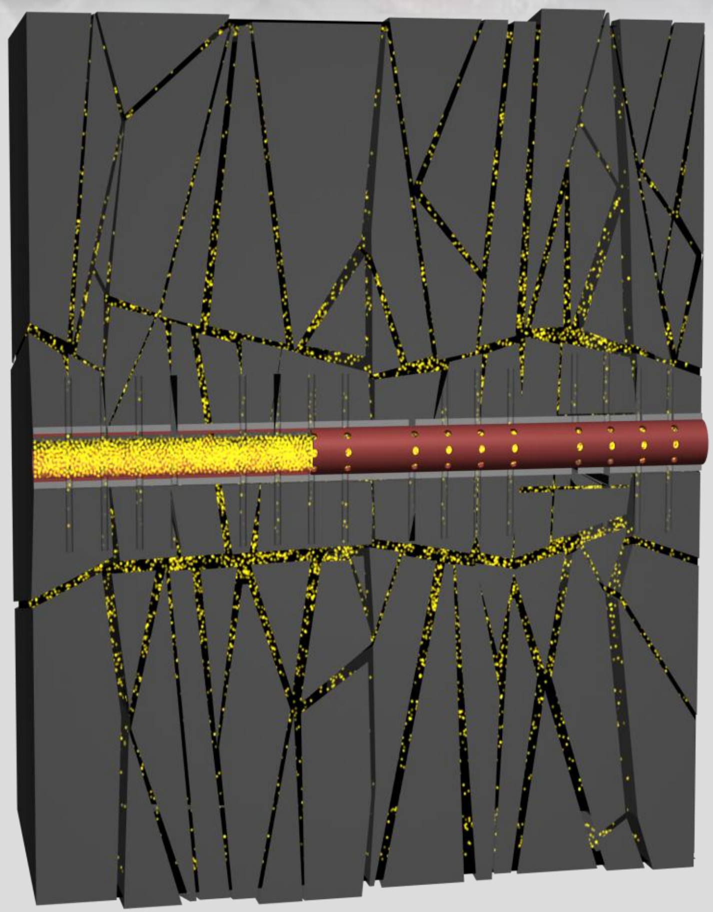
Source: US Dept. of Energy

Injecting fluids into the subsurface increases the pore pressure, reducing effective stress thus causing faults and fractures to fail or slip more easily, thereby inducing an earthquake.

Tensile Stress with Hydraulic Fracturing



Every 300-500 feet of casing is perforated to inject fluids into the shale for hydraulic fracturing.



Approximately 0.2-0.5 million gallons of fluids are injected into each stage.

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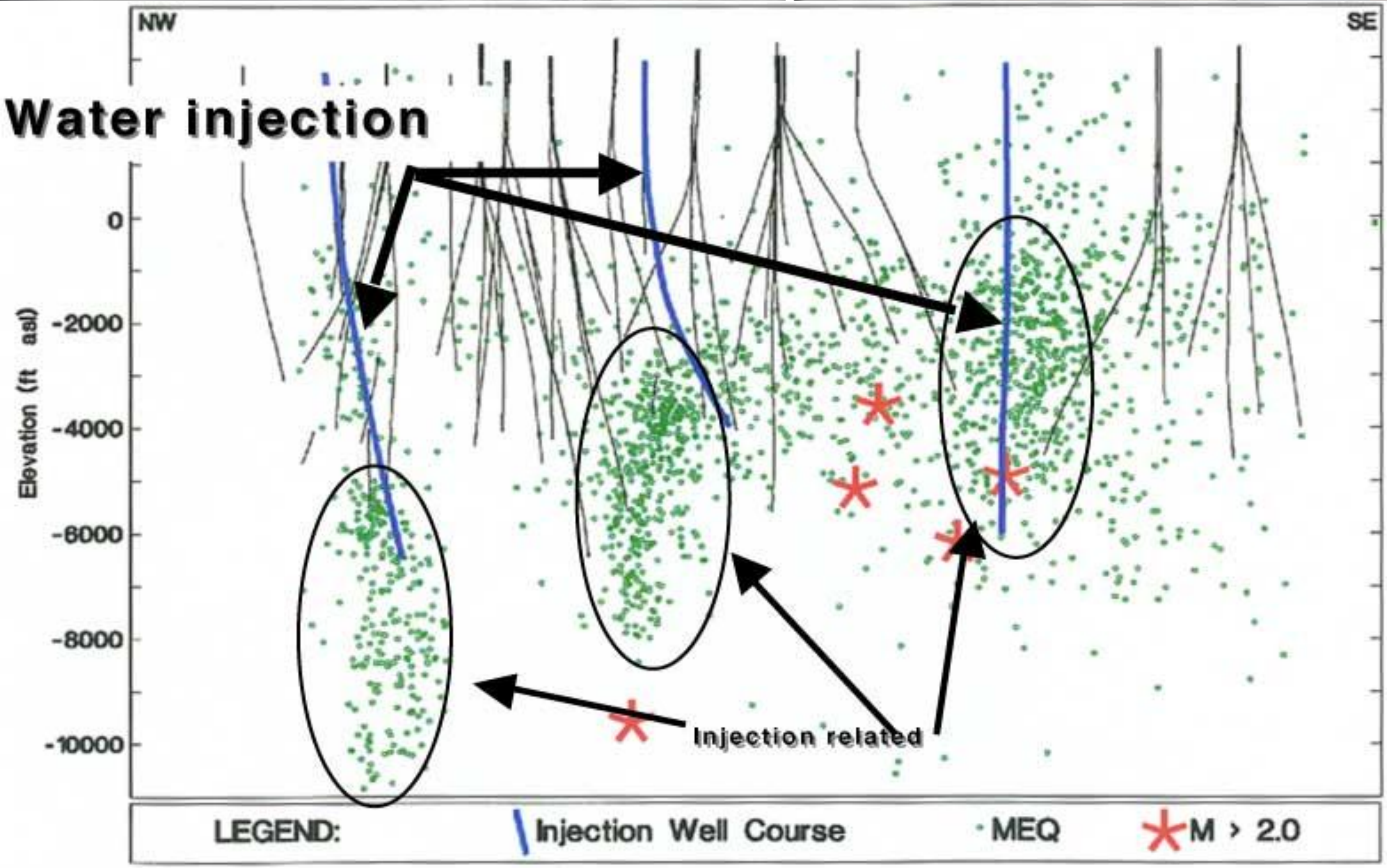
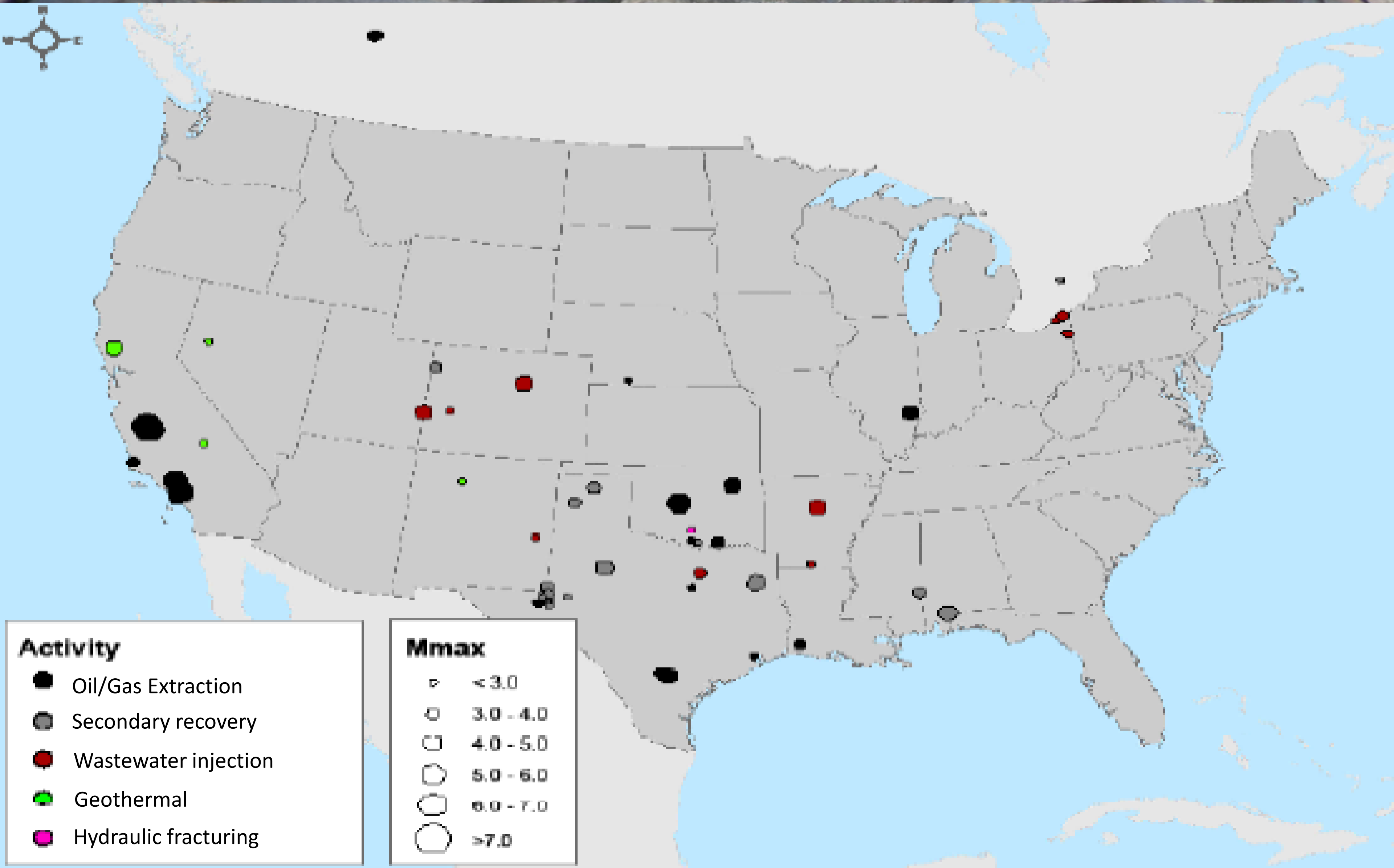
Fluid injection can increase seismic activity



Source: US Dept. of Energy

Cases of Induced Seismicity in US



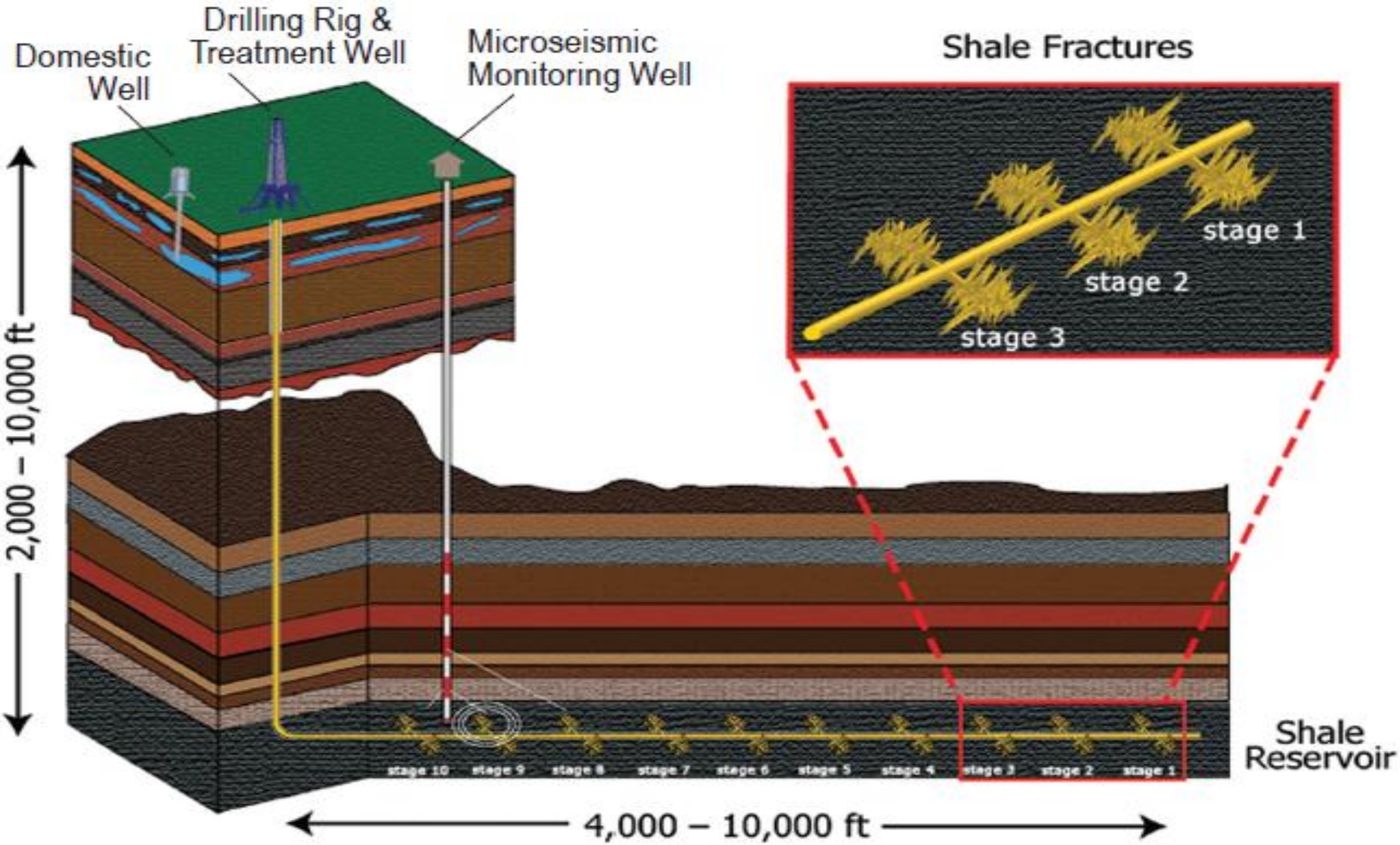
Source: Induced Seismicity Potential in Energy Technologies, National Academy of Sciences, 2012

Table 1. Felt Induced Seismic Events Related to Energy Technology in the United States

Energy Technology	Number of Current Projects	Number of Historical Felt Events	Number of Events M>4.0	Locations of Events M>2.0
Geothermal				
Vapor-dominated (The Geysers)	1	300-400 per year since 2005	1 to 3 per year	CA
Liquid-dominated	23	10-40 per year	Possibly one	CA
Enhanced Geothermal System	~8 pilot	2-10 per year	0	CA
Oil and gas				
Withdrawal	~6,000 fields	20 sites	5	CA, IL, NB, OK, TX
Secondary recovery (waterflooding)	~108,000 wells today	18 sites	3	AL, CA, CO, MS, OK, TX
Enhanced Oil Recovery	~13,000 wells today	None known	None known	None known
Hydraulic fracturing for shale gas recovery	~35,000 wells today	1	0	OK
Waste water disposal wells (Class II)	~30,000 wells today	8	7	AR, CO, OH
Carbon capture and storage (small scale)	1	None known	None known	None known

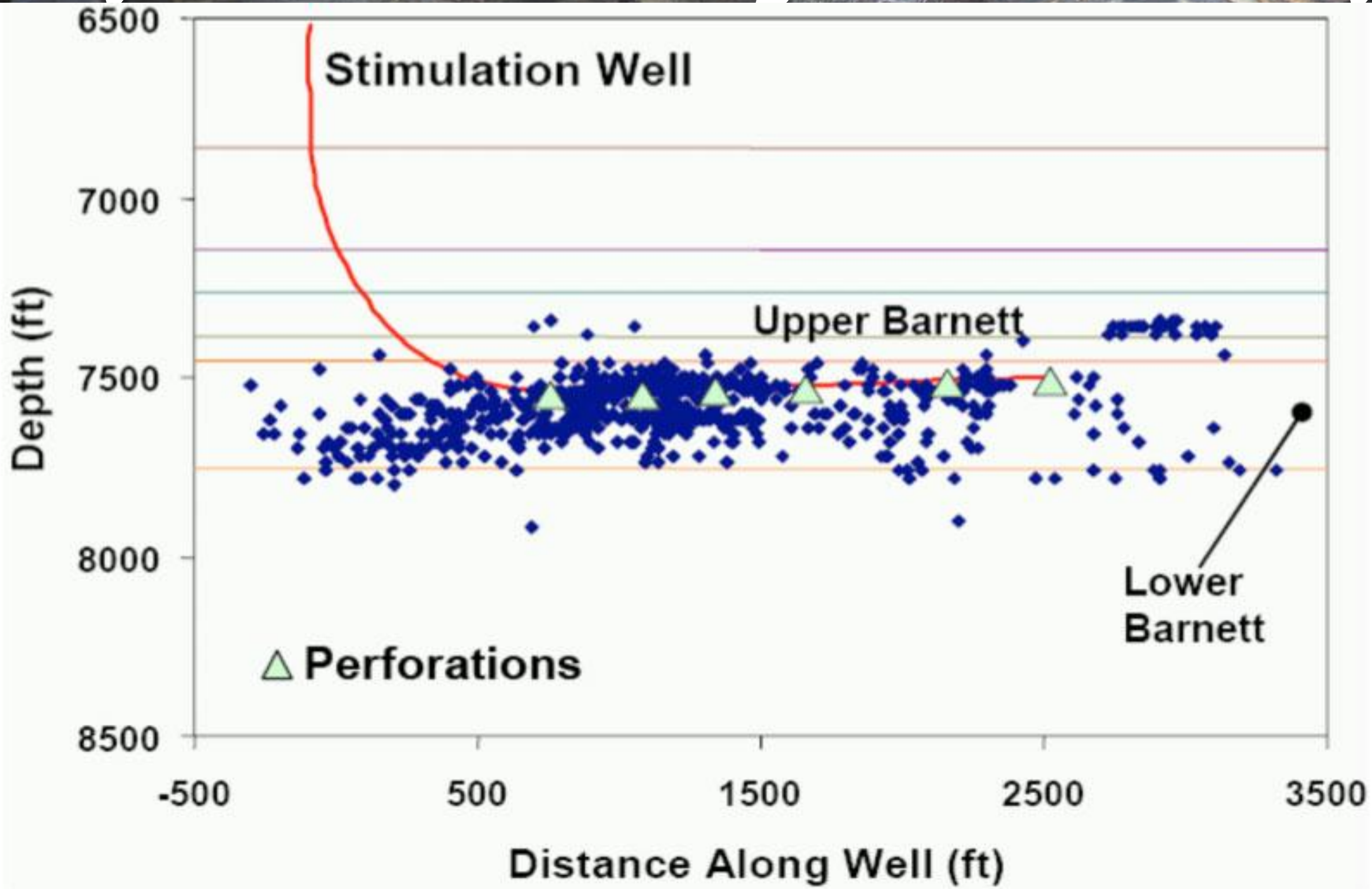
Source: Induced Seismicity Potential in Energy Technologies, National Academy of Sciences, 2012

Microseismic Monitoring During Fracturing



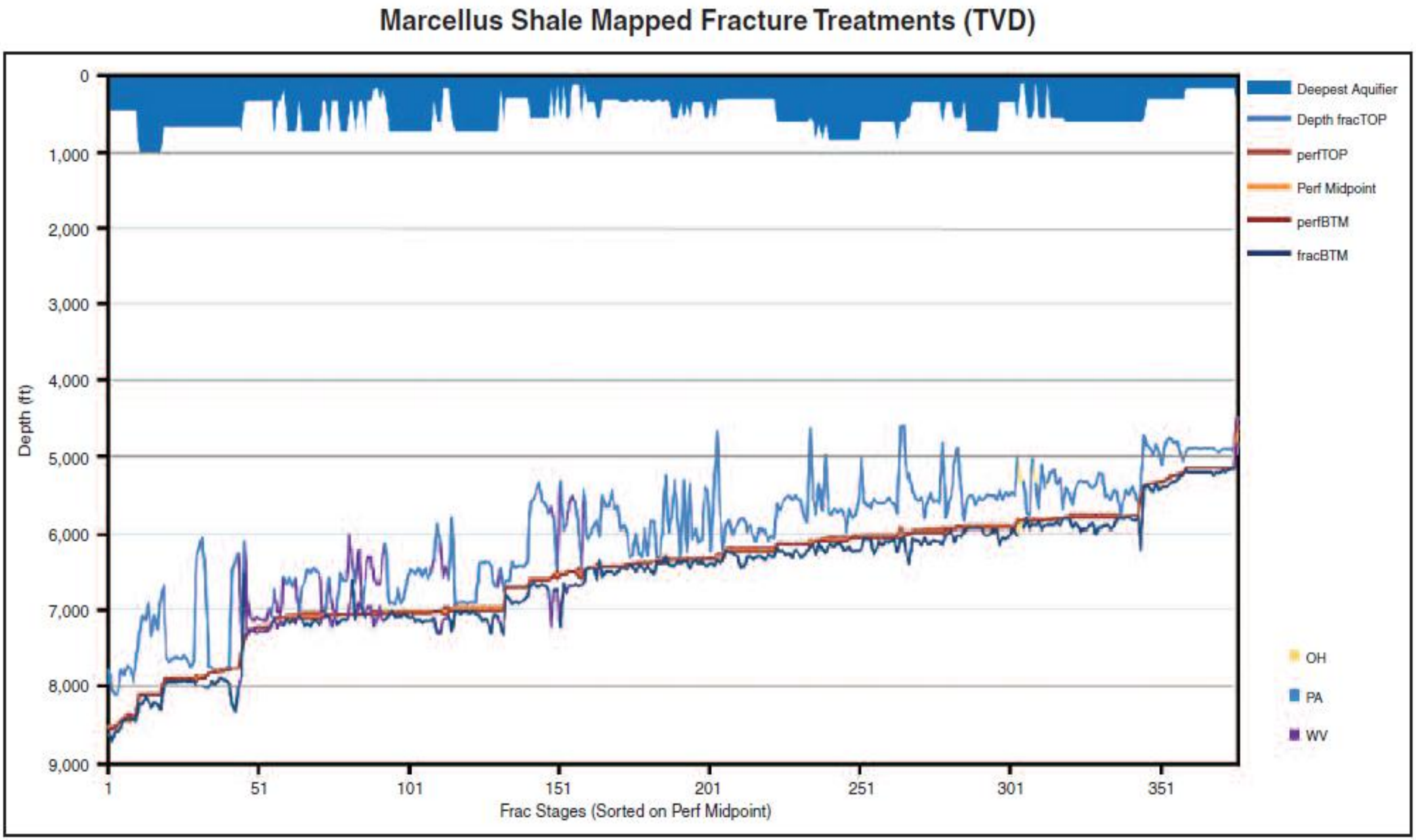
Source: Induced Seismicity Potential in Energy Technologies, National Academy of Sciences, 2012

Hydraulic Fracturing Microseismicity



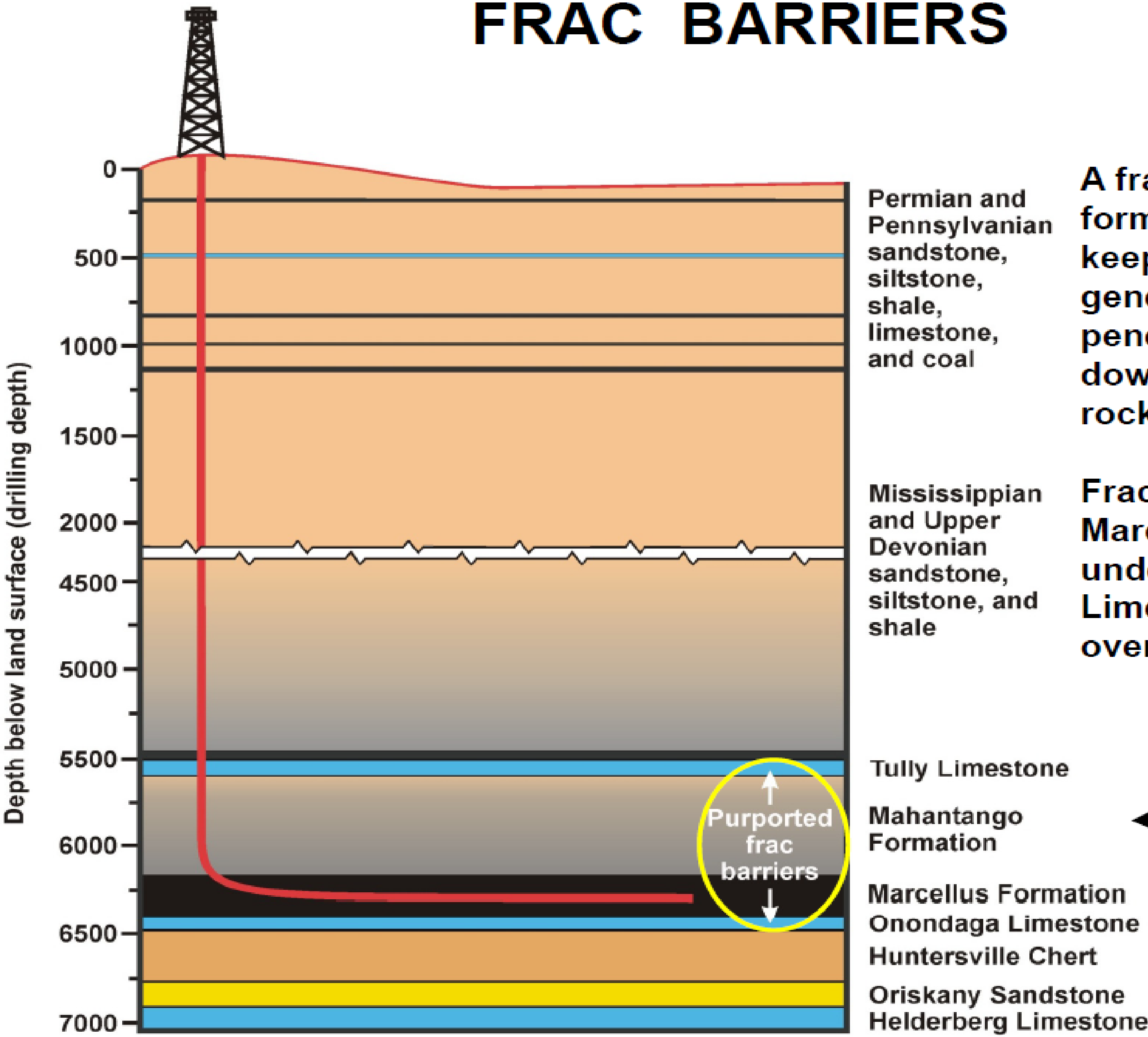
Cross section showing six different stages of hydrofracture stimulation and the associated seismicity (magnitude -1.0 to -2.5) Warpinski et al 2005.

Hydraulic Fracture Vertical Growth



Graphic from Fisher, 2010, Data Confirm Safety Of Well Fracturing, American Oil and Gas Reporter.

FRAC BARRIERS

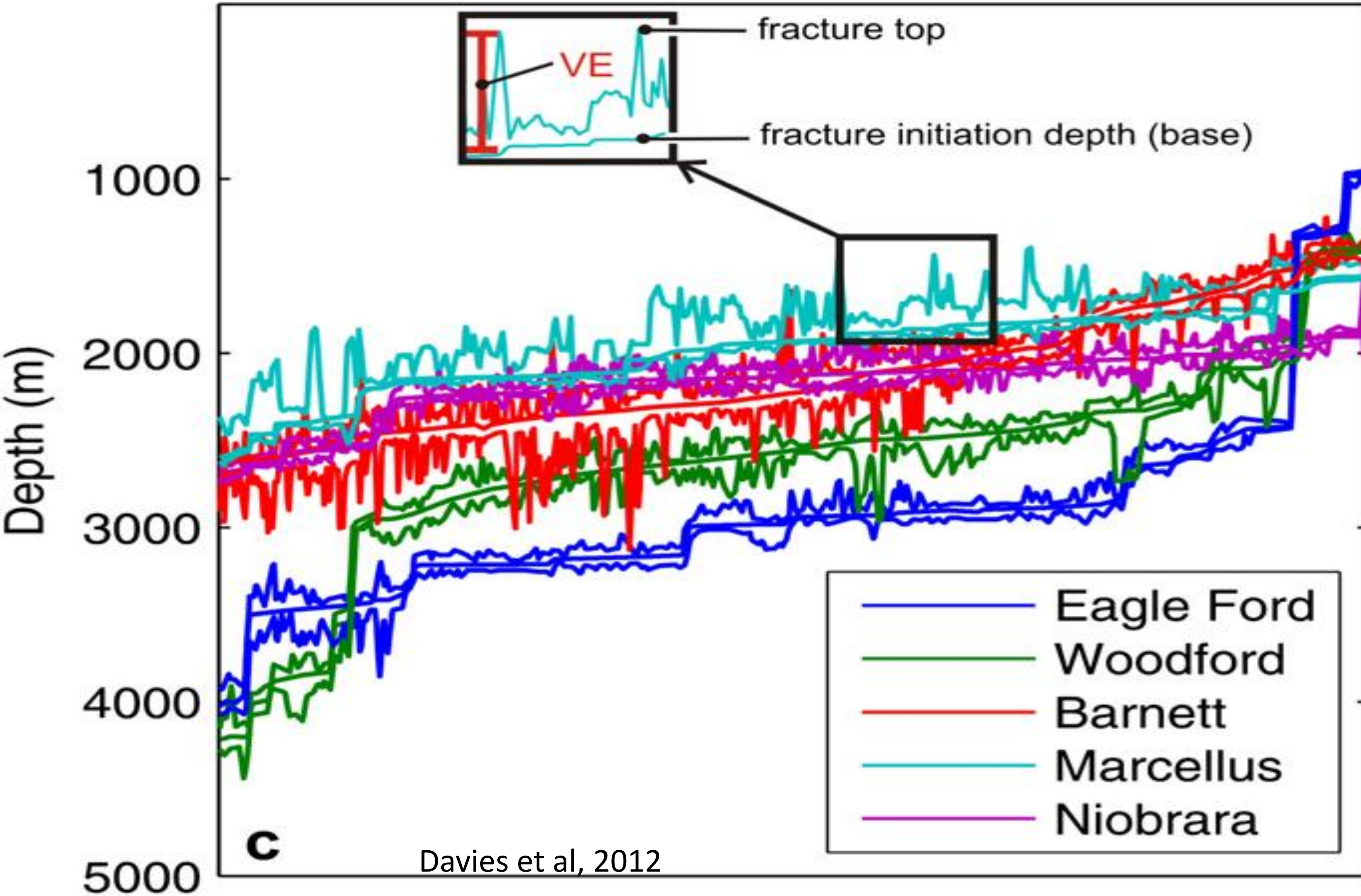


A frac barrier is a rock formation that supposedly keeps hydraulically generated fractures from penetrating upward and downward into adjacent rock formations.

Frac barriers for the Marcellus include the underlying Onondaga Limestone and the overlying Tully Limestone.

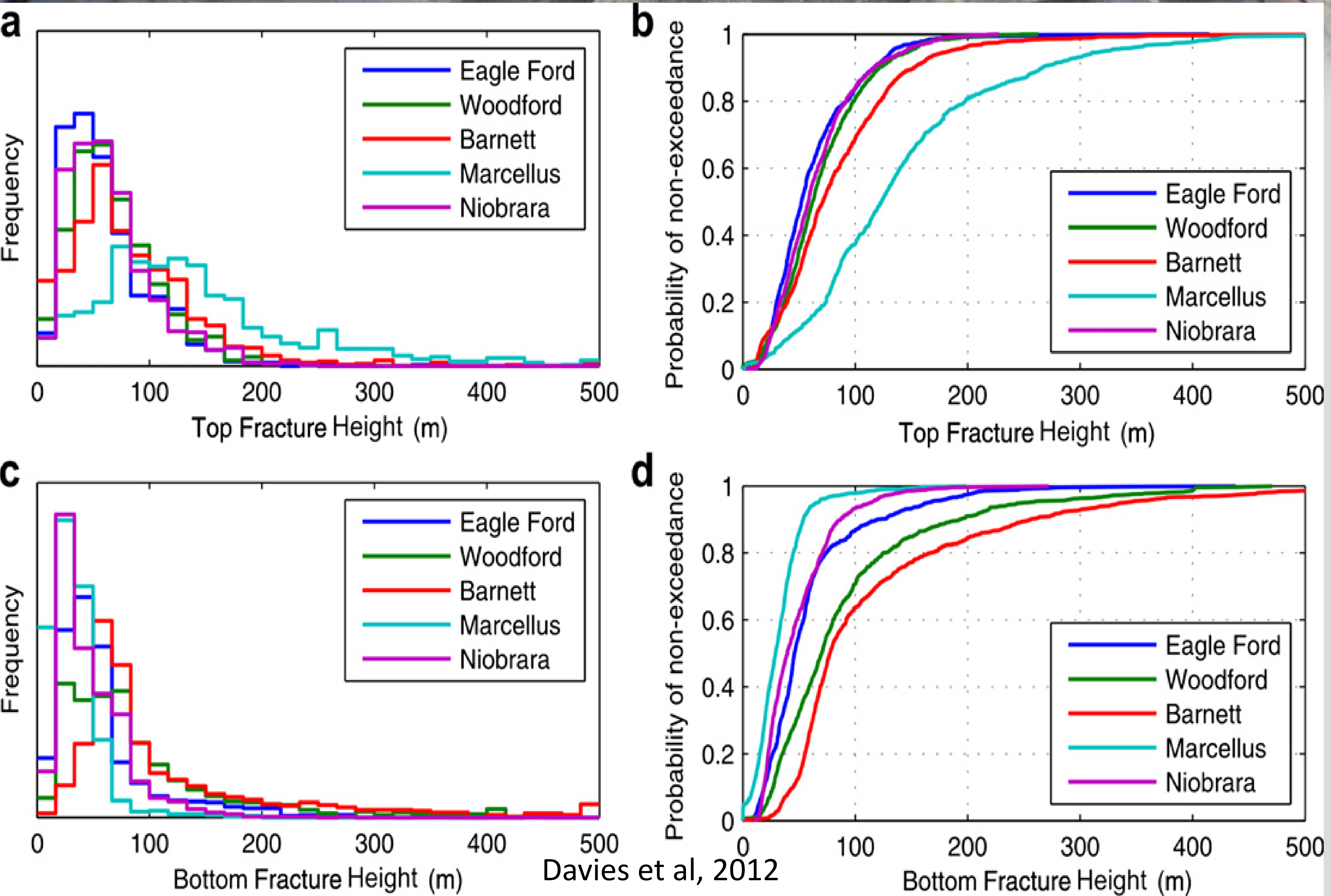
Source: PaDCNR

Fracture Growth in US Shale Plays



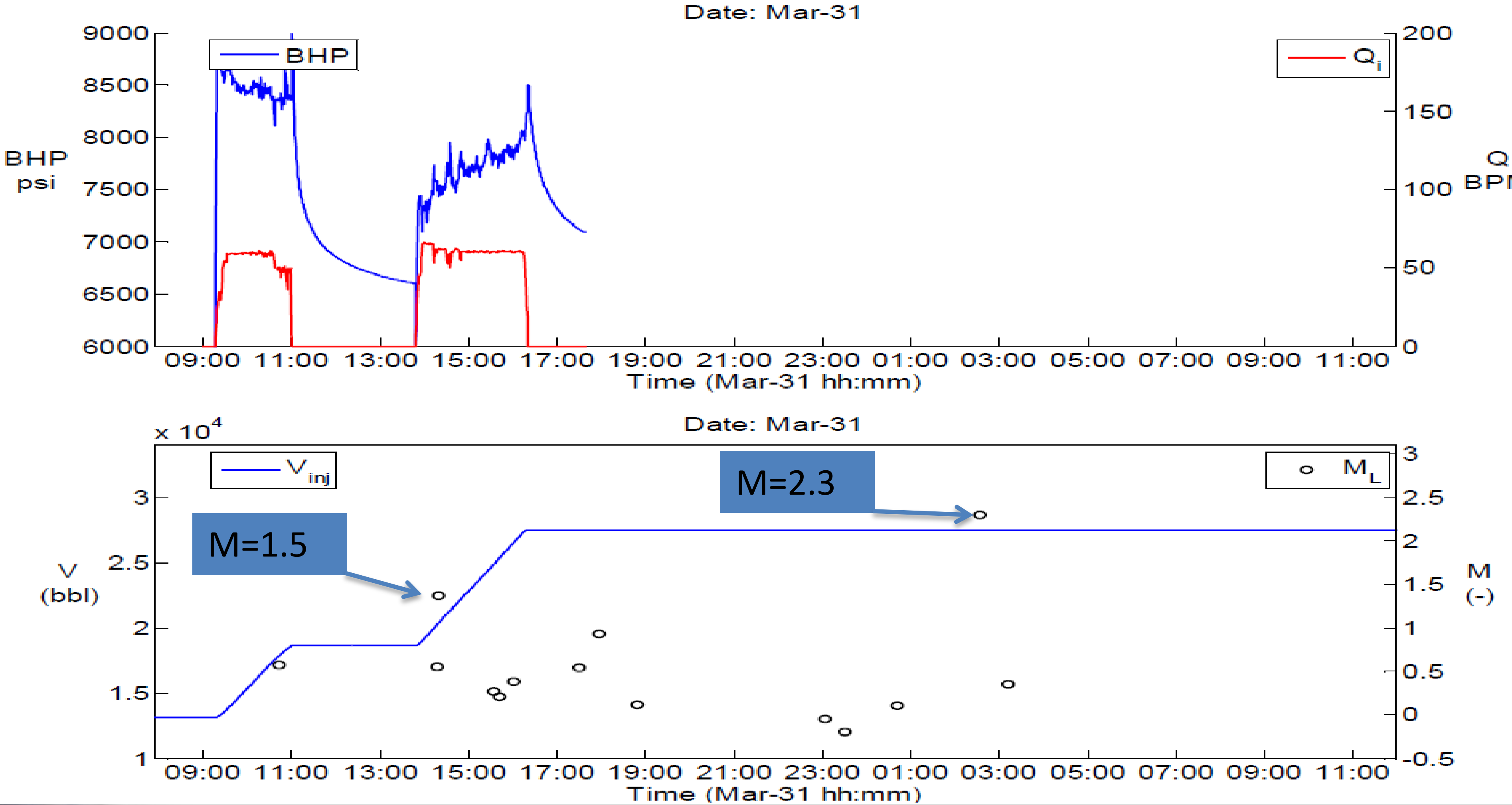
Davies et al, 2012

Probability of Fracture Growths



Davies et al, 2012

Bowland Basin, UK-Example of Hydraulic Fracturing Induced Seismicity



Source: Geomechanical Study of Bowland Shale Seismicity, De Pater and Baisch (2011)

Cuadrilla Resources fractured the Reese Hall well in the Bowland Shale of the UK and caused induced seismicity events (N=50) with highest magnitudes of 1.5 and 2.3

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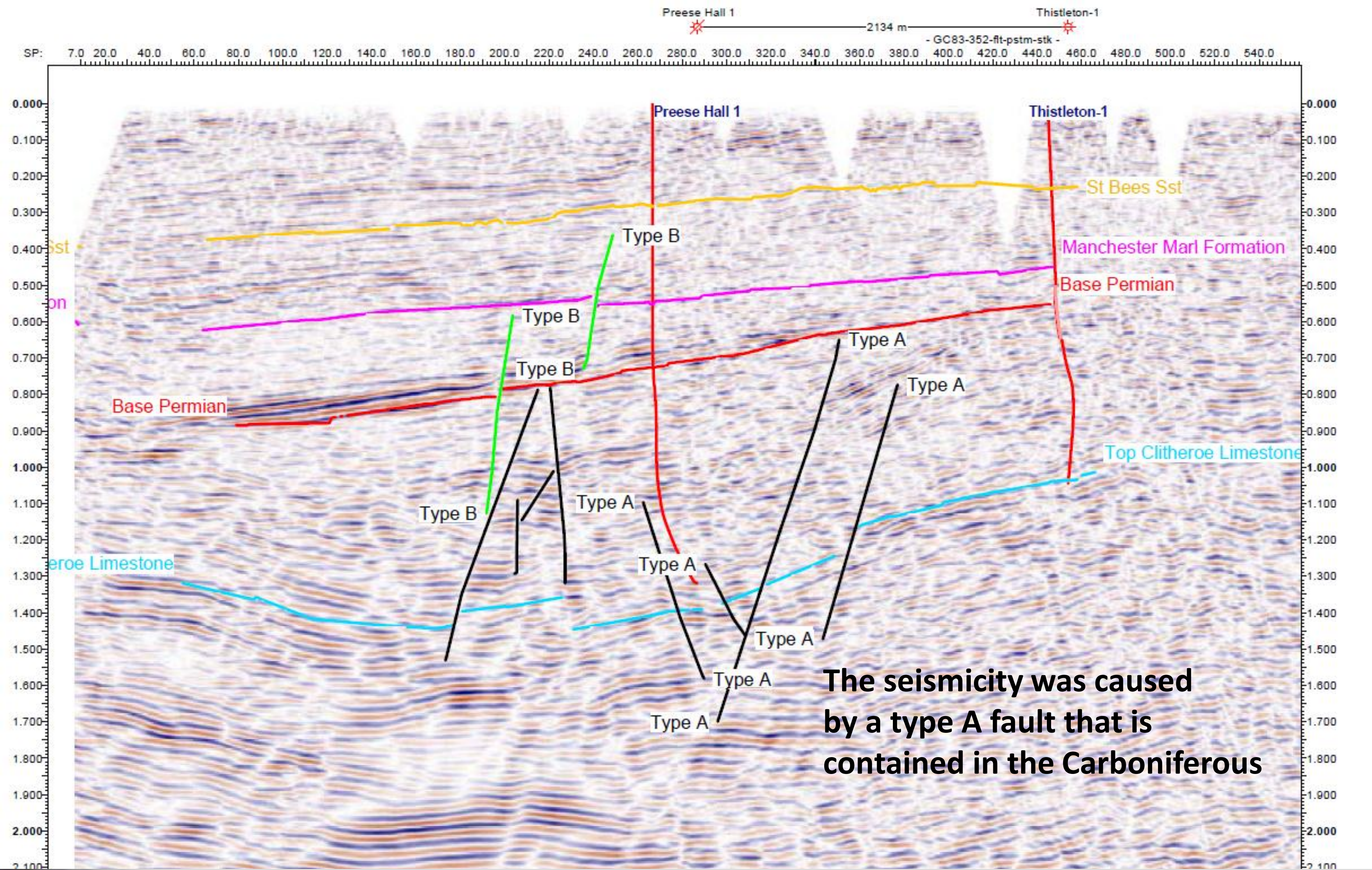
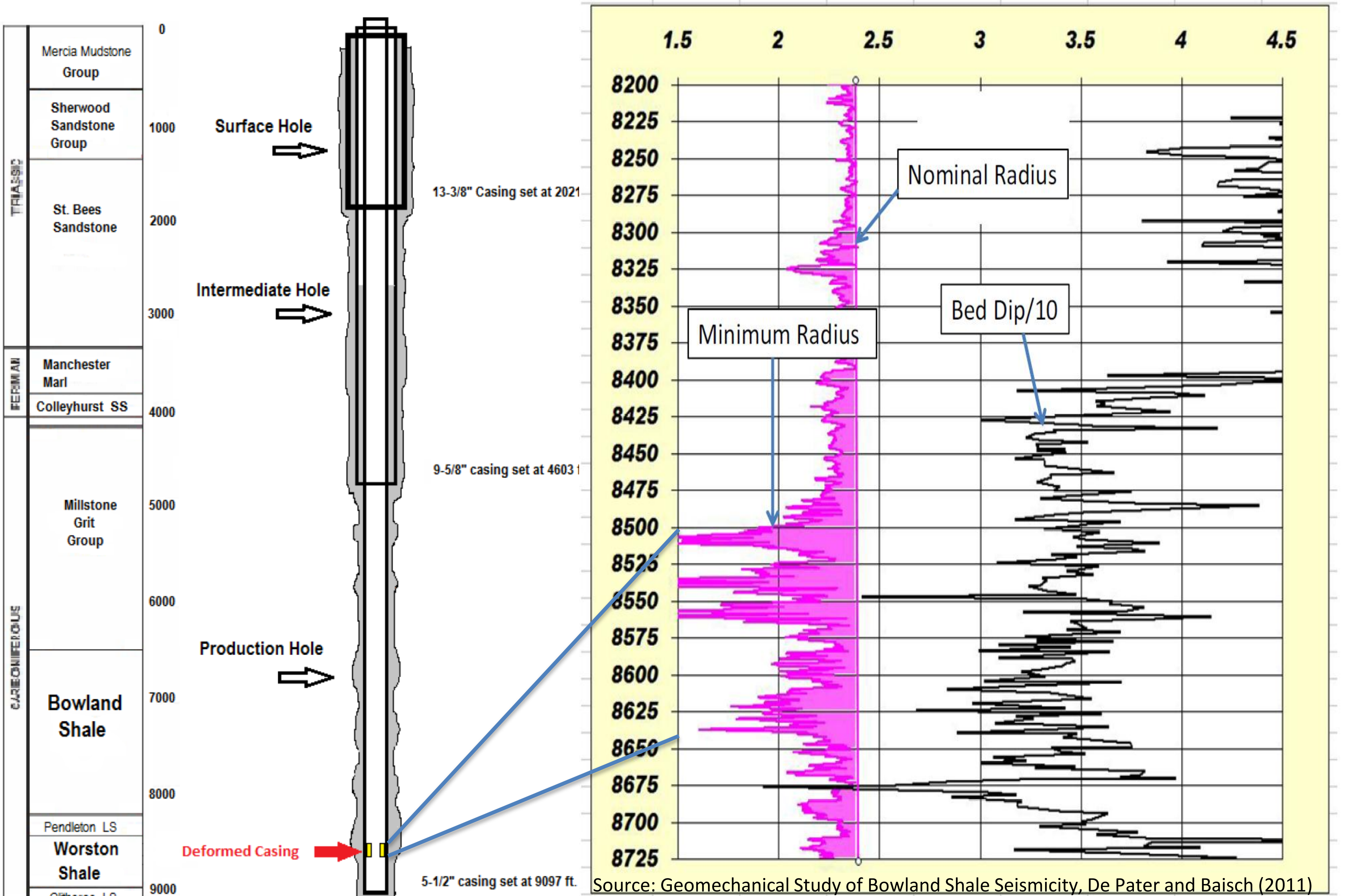
Seismic Section Near Preese Hall Well 1



The seismicity was caused by a type A fault that is contained in the Carboniferous

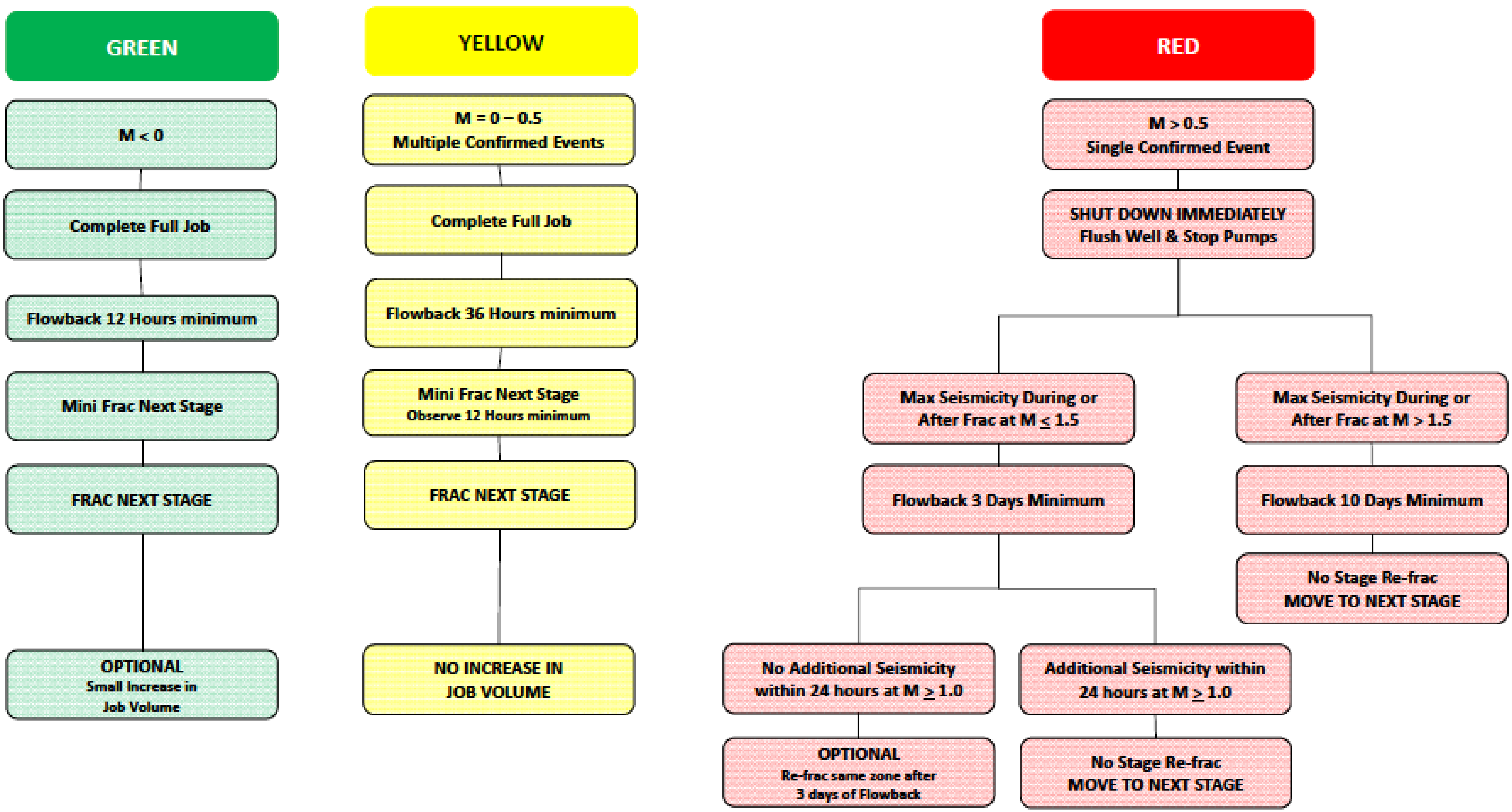
Source: Geomechanical Study of Bowland Shale Seismicity, De Pater and Baisch (2011)

Casing Deformation from Seismicity

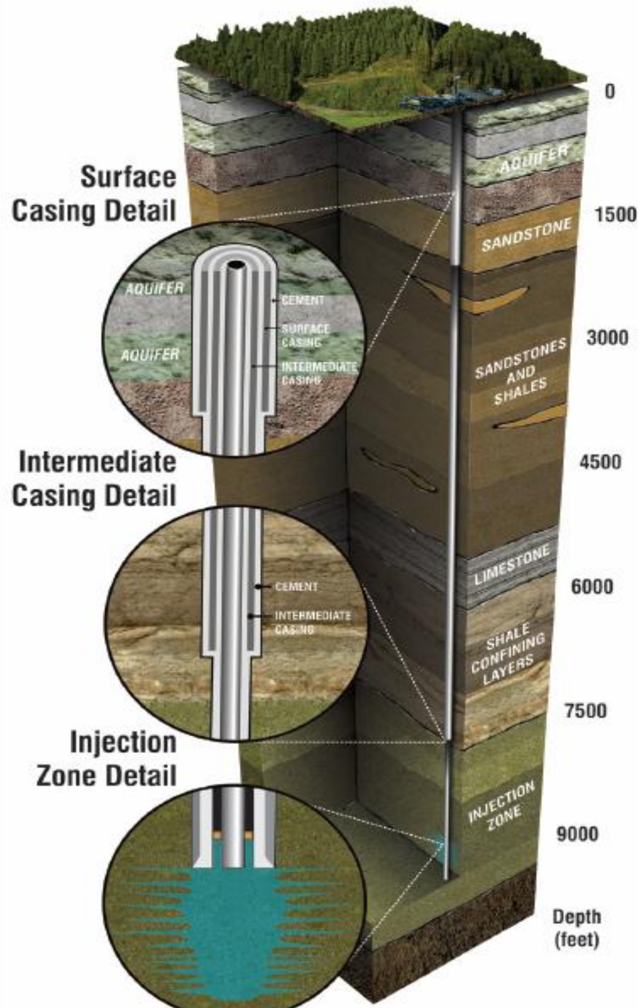


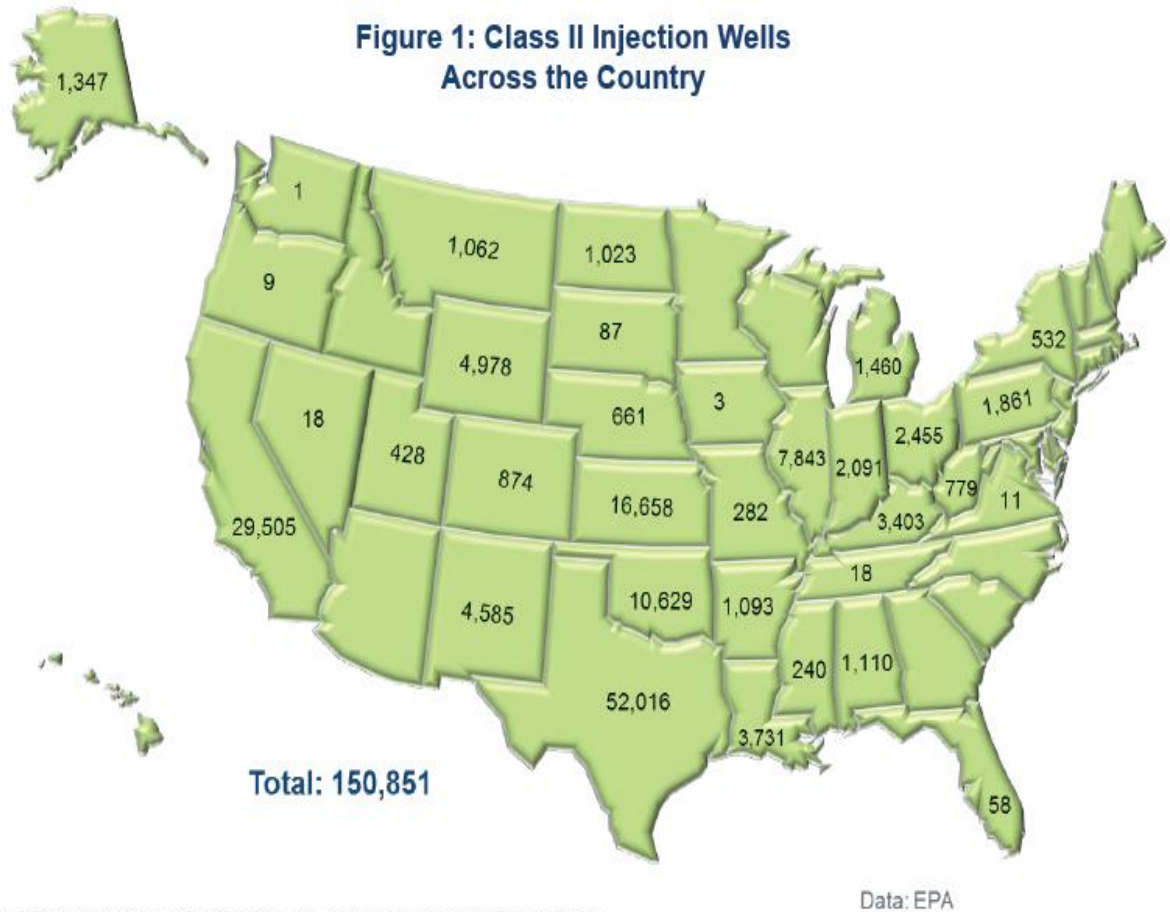
Source: Geomechanical Study of Bowland Shale Seismicity, De Pater and Baisch (2011)

CUADRILLA TRIAL TRAFFIC LIGHT PROCESS



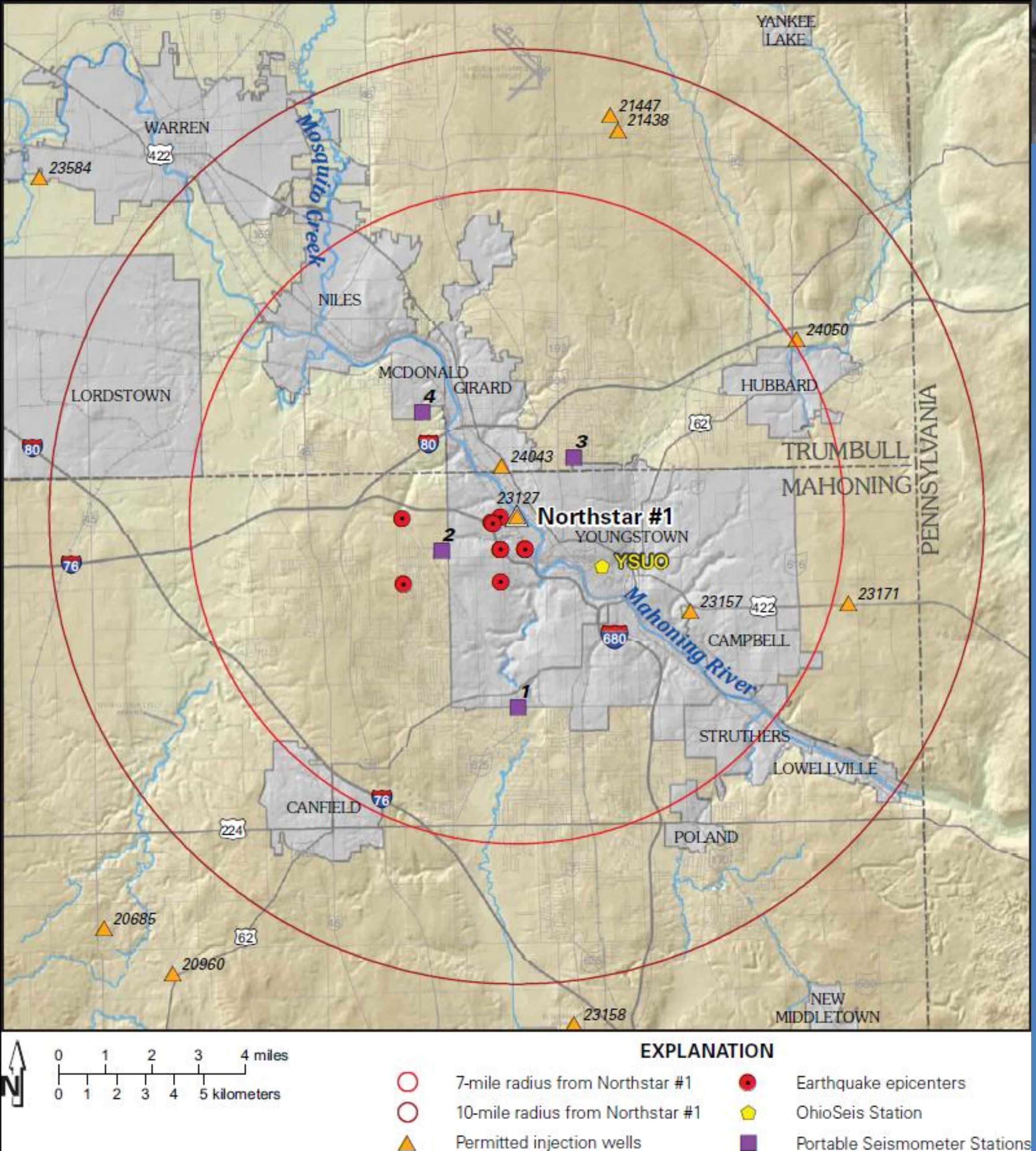
US Underground Injection Wells





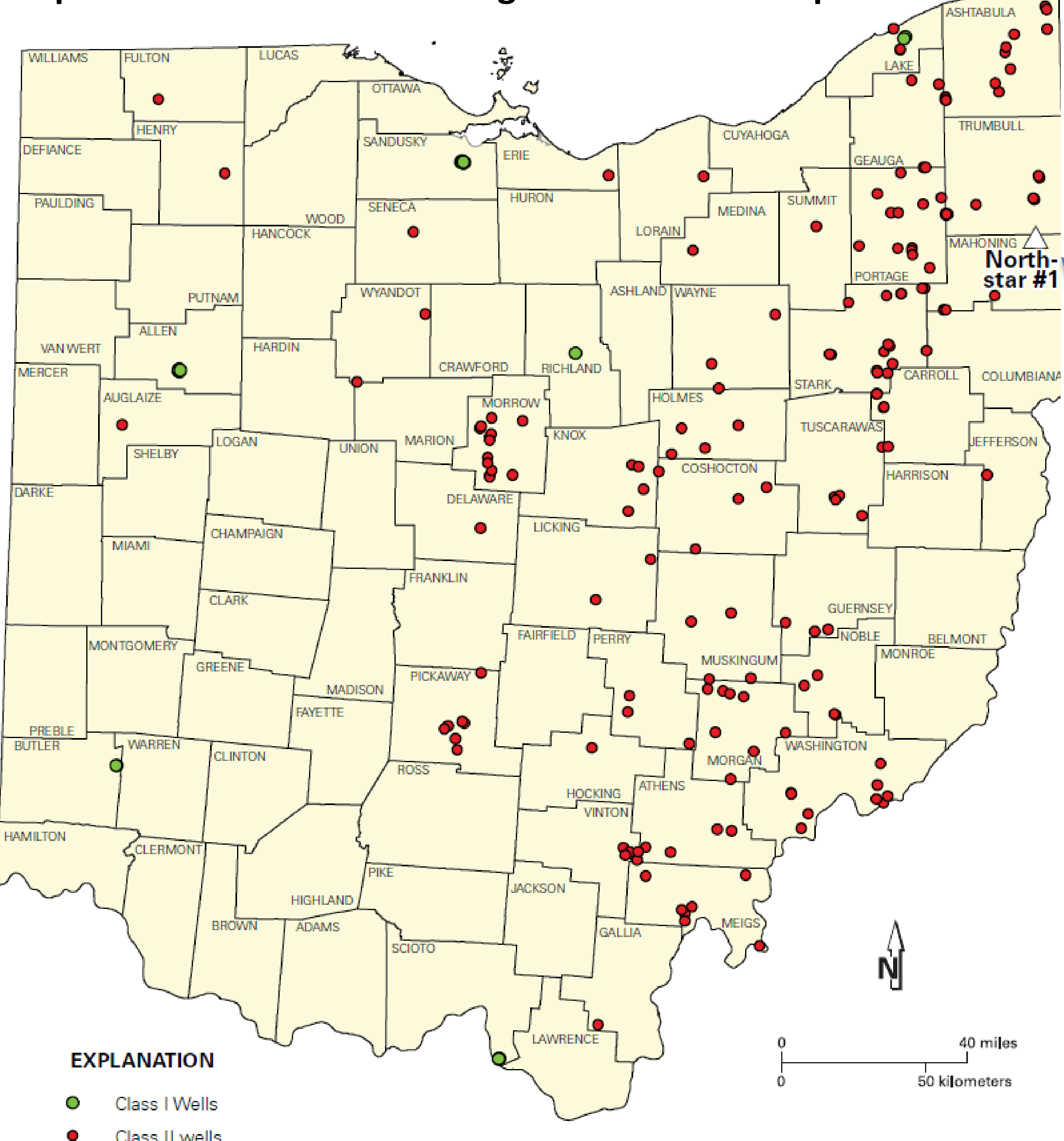
Review of the literature published in the past 5 decades indicates that fewer than 40 incidents of seismic activity that were felt at the surface were potentially associated with Class II injection wells in the United States.

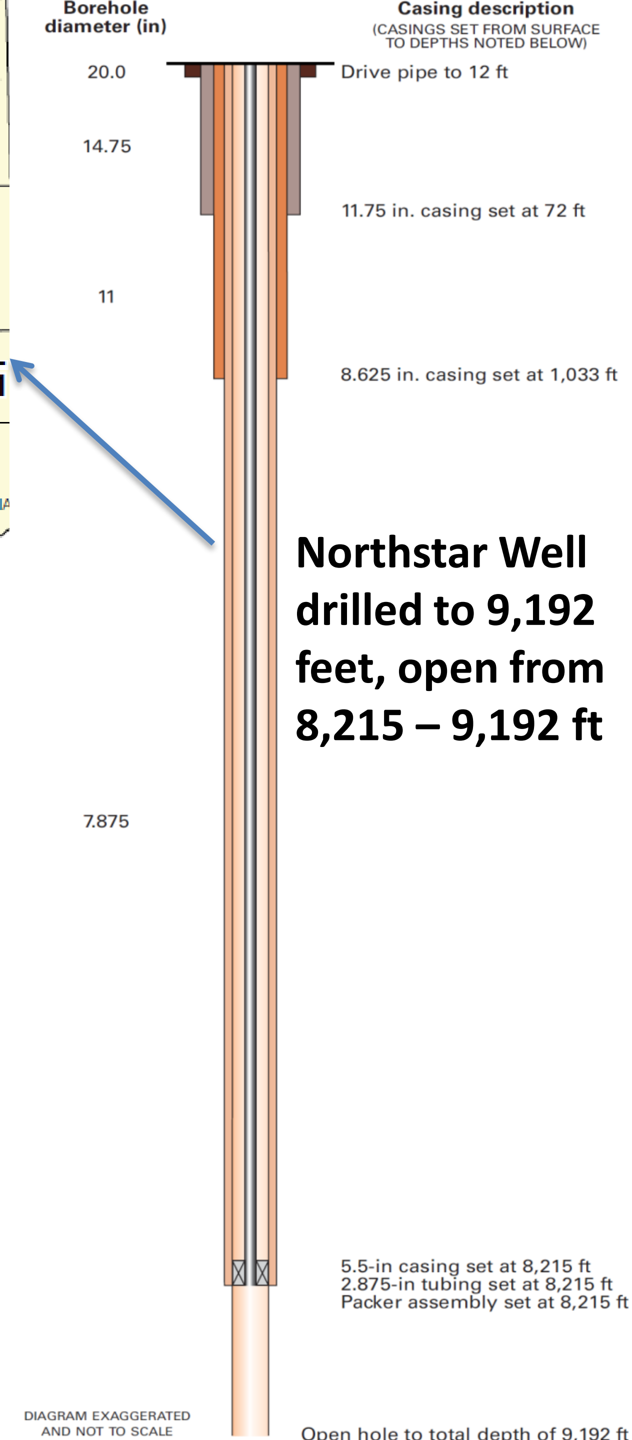
Northstar 1 Disposal Well



- The Youngstown, OH area has experienced 12 low-magnitude seismic events during 2011 ranging from 2.1- to 4.0-magnitude
- The Northstar 1 well began injection in December 2010, nearly three months later the first seismic events were noted.
- Subsequent seismic events were clustered around the vicinity of the wellbore.
- Evidence of open fractures and permeability zones within the Precambrian is noted in some of the geophysical logs
- Once seismic monitoring began, the focal depths of events were found to be about 4,000 ft (1,220 m) laterally and 2,500 ft (760 m) vertically from the wellbore terminus.

Map of Ohio UIC Wells Showing the Northstar Disposal Well





Northstar Well drilled to 9,192 feet, open from 8,215 – 9,192 ft

Ohio UIC Disposal Well Recommendations

- Review of existing geologic data for known faulted areas within the state
- Avoid the locating of new Class II disposal wells within Precambrian or faulted zones;
- Run complete suite of geophysical logs (including, at a minimum, gamma ray, compensated density-neutron, and resistivity logs) on newly drilled Class II disposal wells.
- Measurement or calculation of original downhole reservoir pressure prior to initial injection;
- Conducting a step-rate injection test to establish formation parting pressure and injection rates;
- Installation of a continuous pressure monitoring system;
- Installation of an automatic shut-off system set to operate if the fluid injection pressure exceeds a maximum pressure;
- Use of an electronic data recording system for purposes of tracking all fluids brought by a brine transporter for injection.

Conclusions

- Hydraulic fracturing creates permeability that rarely creates unwanted induced seismicity that is large enough to be detected on the surface

- UIC wells have caused detectable seismicity in isolated cases, with magnitude of 4 or less

- Assessment of subsurface stress, faulting, and other geologic structure conditions critical to avoid seismic induction

- Implementation of a robust regulatory and monitoring program can minimize the risk of induced seismicity with fracturing or disposal practices