Recent triggered (hydro)seismicity in Oklahoma: A cautionary tale?

C.J.H Hartnady [1]

M.S. Fynn [2]

[1] Umvoto Africa (Pty) Ltd, PO Box 61, Muizenberg, 7950 South Africa
chris@umvoto.com

[2] Geological Sciences, Univ. of Cape Town, Rondebosch, 7750 South Africa

GSA South-Central Section - 49th Ann. Meeting

Stillwater, Oklahoma, USA

19–20 March 2015

Outline

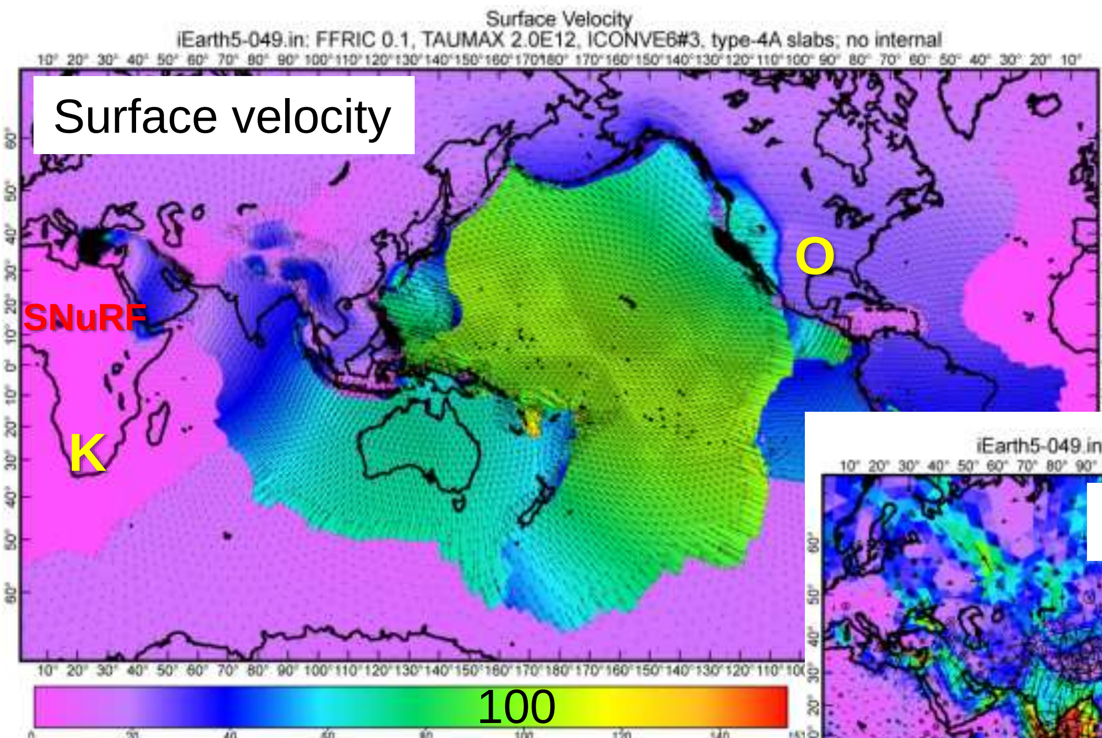
1. Karoo-Oklahoma and lithospheric stress context
2. Oklahoma hydrocarbon development
3. Recent seismicity record & ASR pattern
4. Causes: natural or anthropogenic?
5. Role of failure-critical faults, epicentre trends
6. Earthquake-fault scaling issues
7. Conclusions

Global context

Lithospheric plate motions and stress anomalies

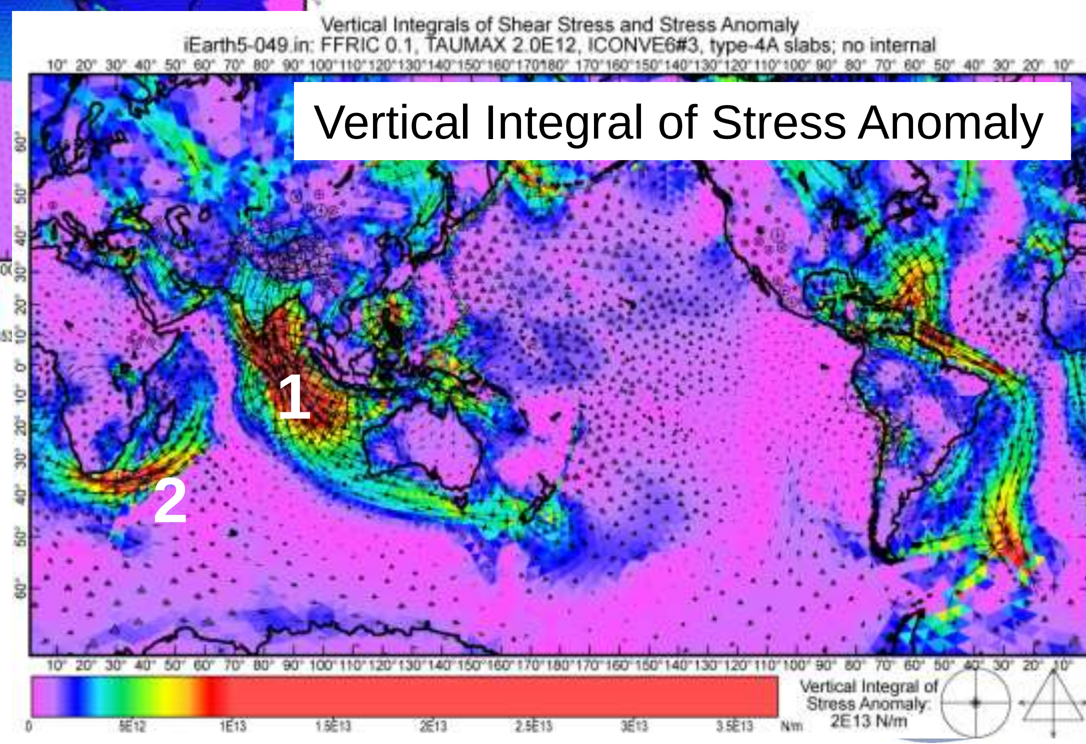
from Bird, Liu & Rucker, 2008

SNuRF = Stable Nubia Reference Frame



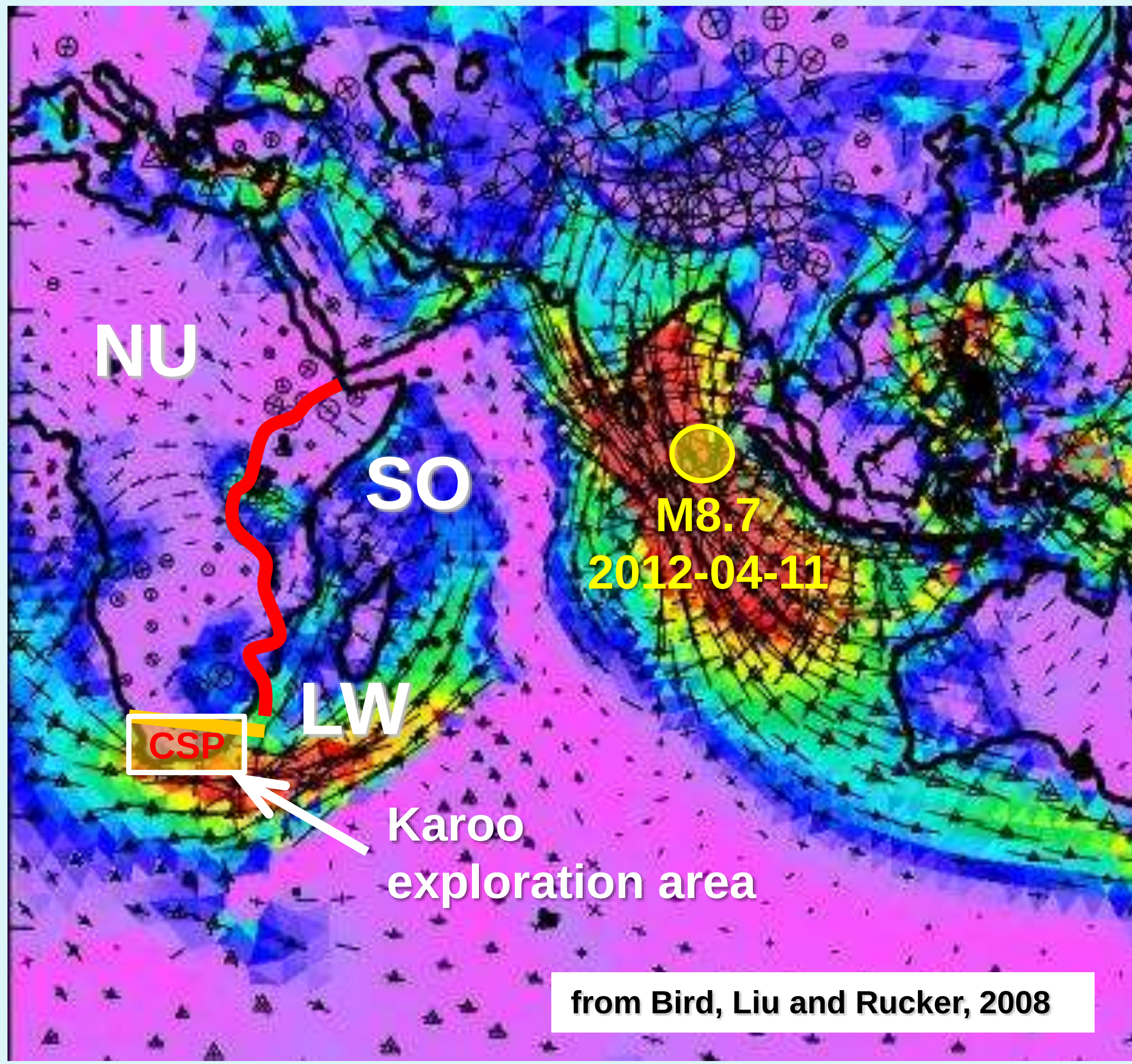
Velocity range = 0 – 153.9 mm/a

VISA anomalies 1 & 2 in Indian Ocean are largest on planet, related to new plate boundaries (IN-AU, NU-LW) breaking old, strong, oceanic lithosphere



Lithospheric stress patterns

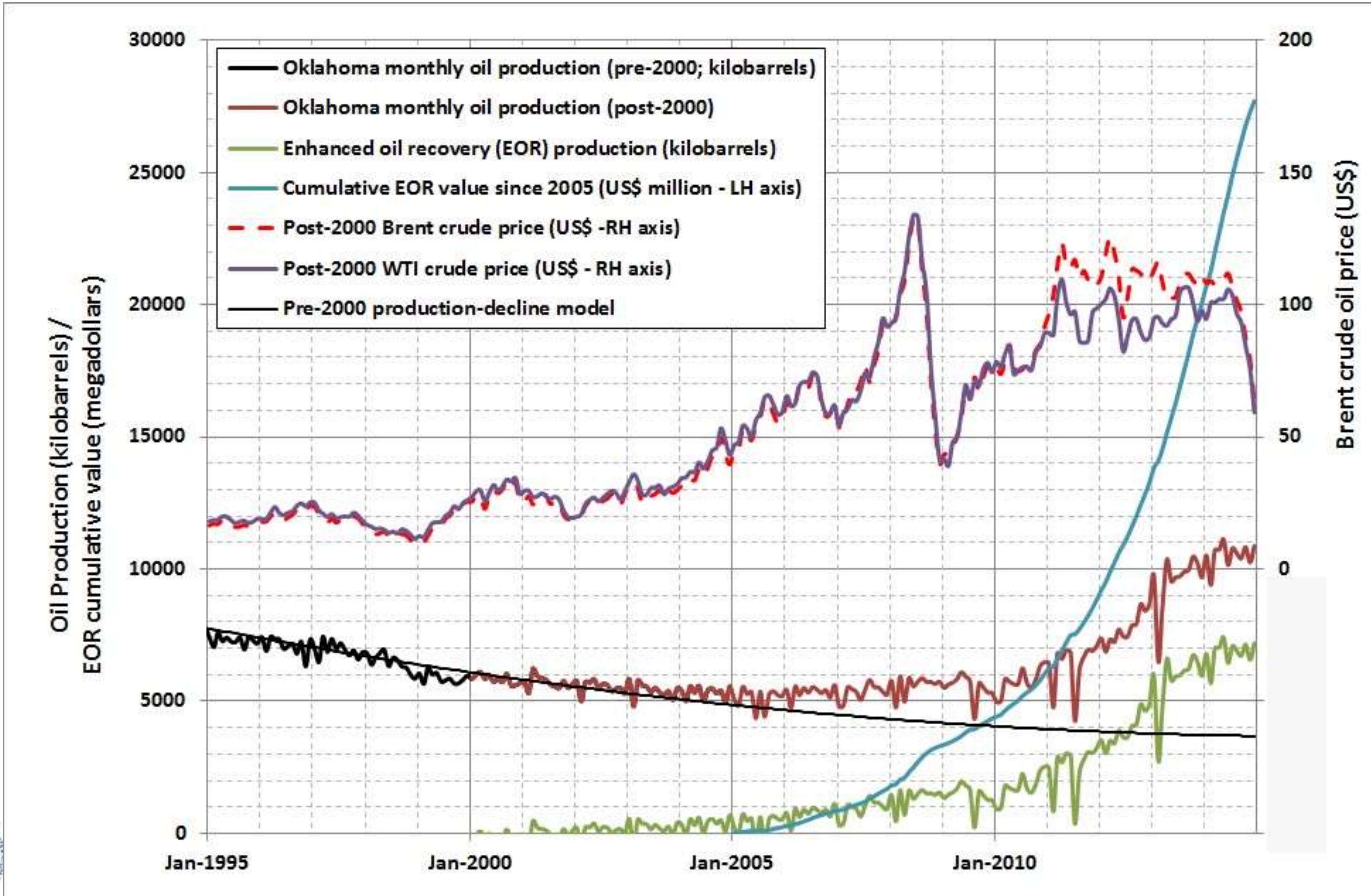
- Dynamic model of vertical integrated stress anomaly (VISA)
- Karoo Basin in N part of ***'Cape Stress Province'*** (Hartnady, 1998)
- Reflects high crustal stresses generated by break-up of Africa between Nubia (NU), Somalia (SO) & Lwandle (LW) plates



Outline

1. Karoo-Oklahoma and lithospheric stress context
2. Oklahoma hydrocarbon development
3. Recent seismicity record & ASR pattern
4. Causes: natural or anthropogenic?
5. Role of failure-critical faults, epicentre trends
6. Earthquake-fault scaling issues
7. Conclusions

Oklahoma petro-economics (1995-2014)



Outline

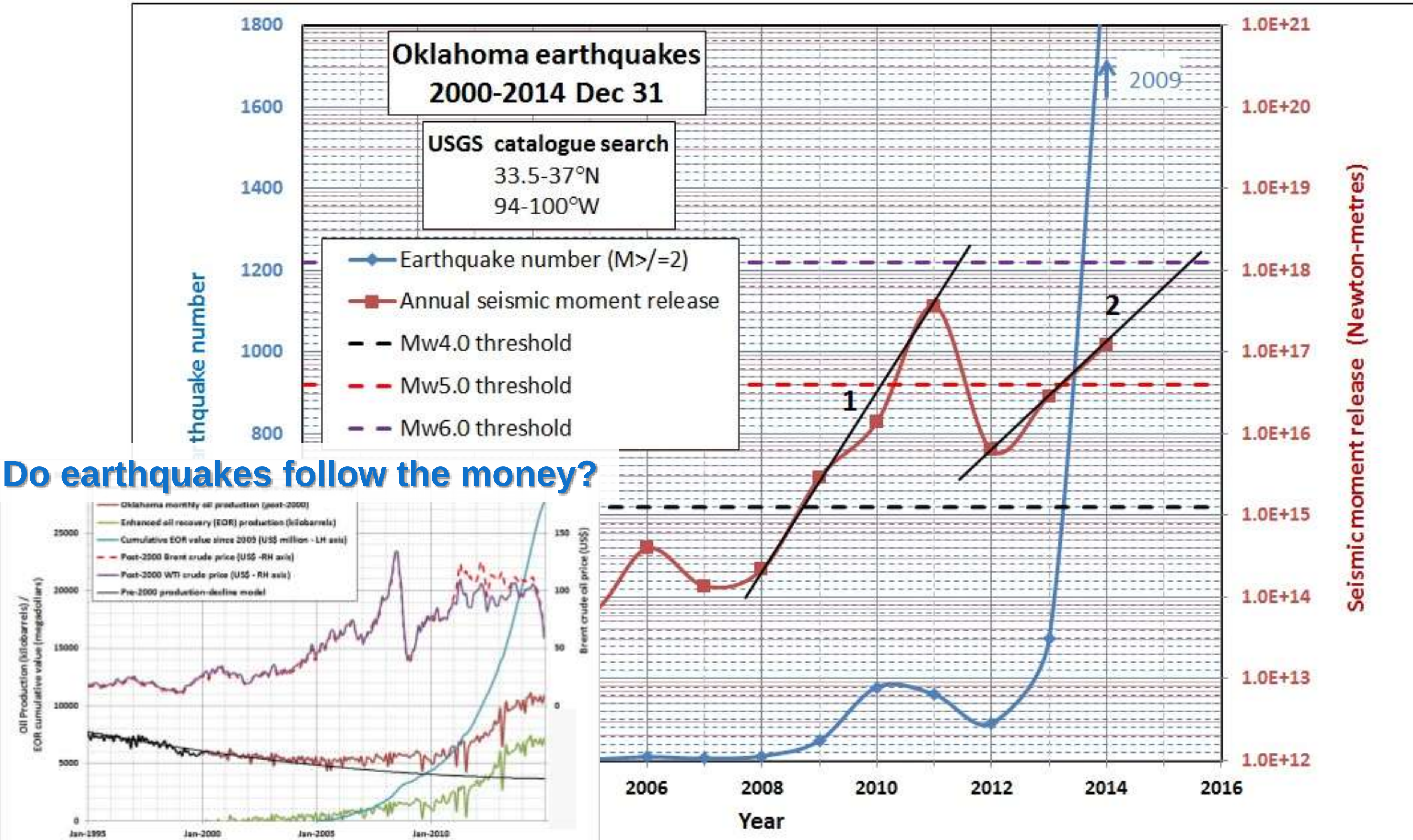
1. Karoo-Oklahoma and lithospheric stress context
2. Oklahoma hydrocarbon development
3. Recent seismicity record & ASR pattern
4. Causes: natural or anthropogenic?
5. Role of failure-critical faults, epicentre trends
6. Earthquake-fault scaling issues
7. Conclusions

Accelerating Seismic(-moment) Release

- Hypothesis that large earthquakes may be preceded by period of ASR proposed about twenty years ago
- Rate of ASR studies increased until 2004, decreased afterwards due to negative results & criticisms of formulation as power-law fit to cumulative seismicity series (intrinsically linked to holistic ‘consensus for criticality’ re emergence of power-laws in earthquake populations)
- New approach in 2007 explains ASR power-law from combined concepts of elastic rebound and geometry

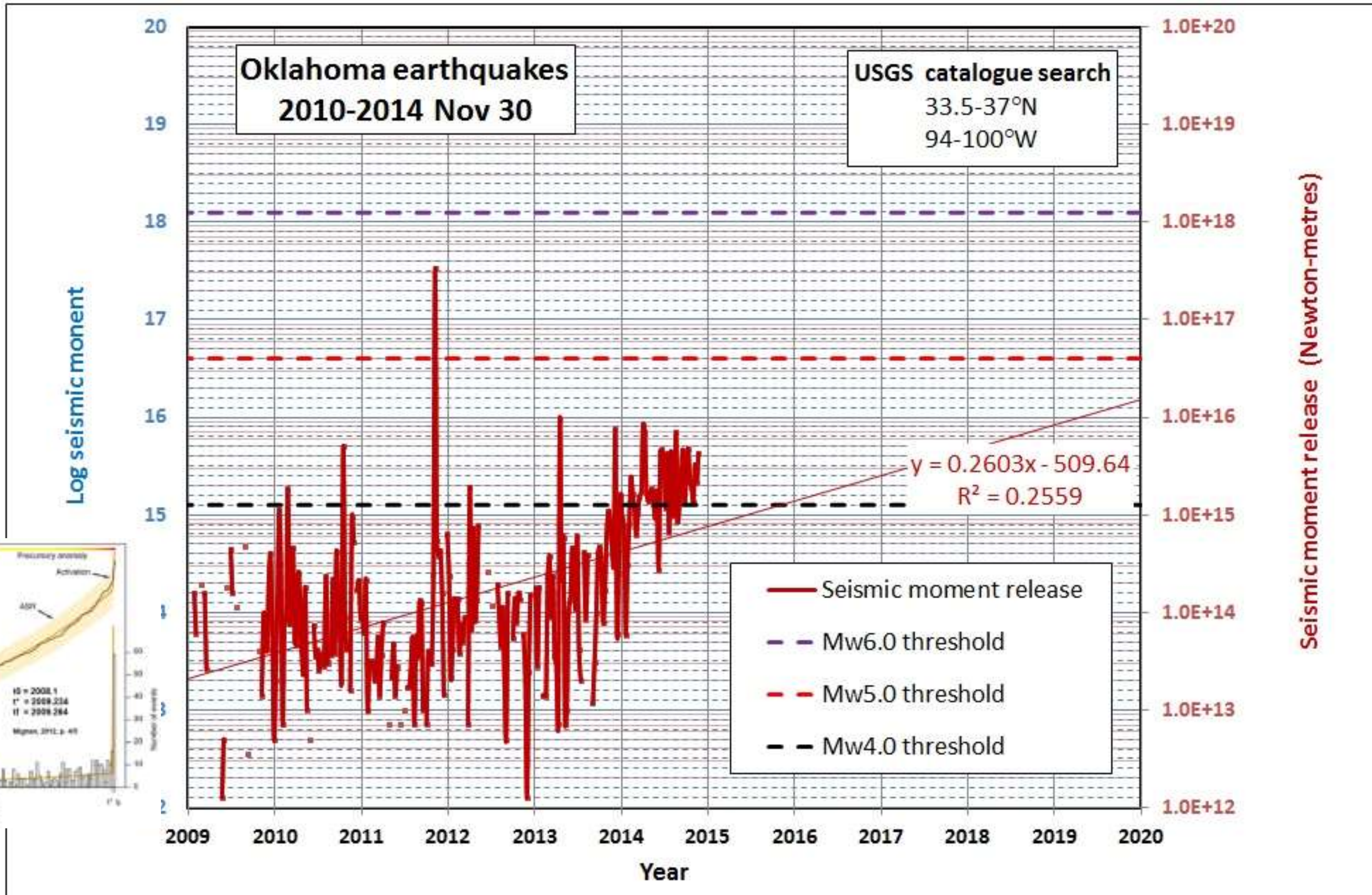
from:
Mignan, A. Retrospective on the Accelerating Seismic Release (ASR) hypothesis: Controversy and new horizons. Tectonophysics 505, 1-16 doi:10.1016/j.tecto.2011.03.010 (2011).

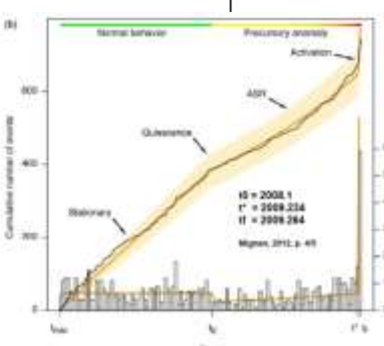
Oklahoma seismic history (post-2000)



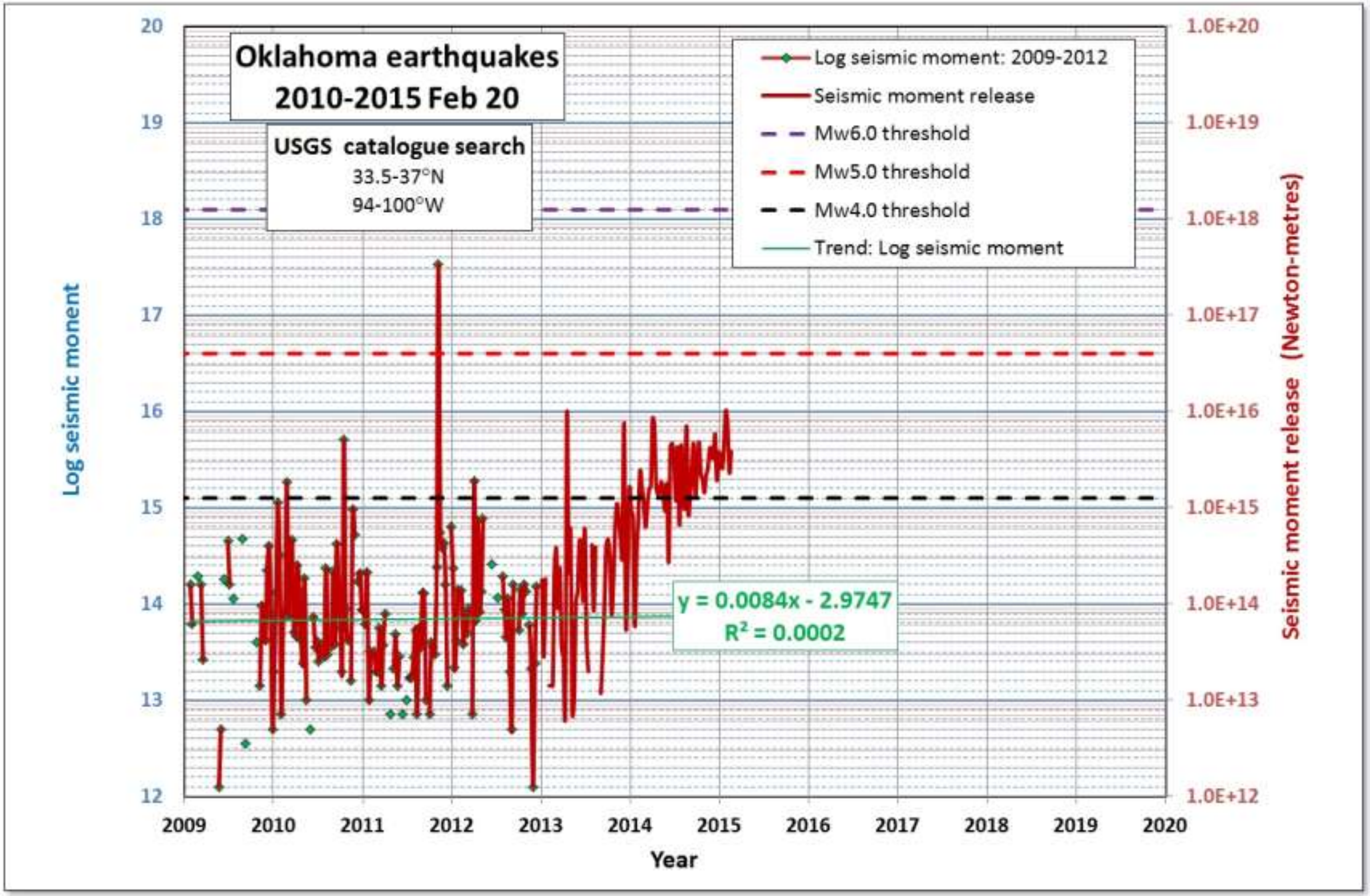
ASR in 0.02-year bins

- Follows precedent of L'Aquila study (Mignan, 2012)

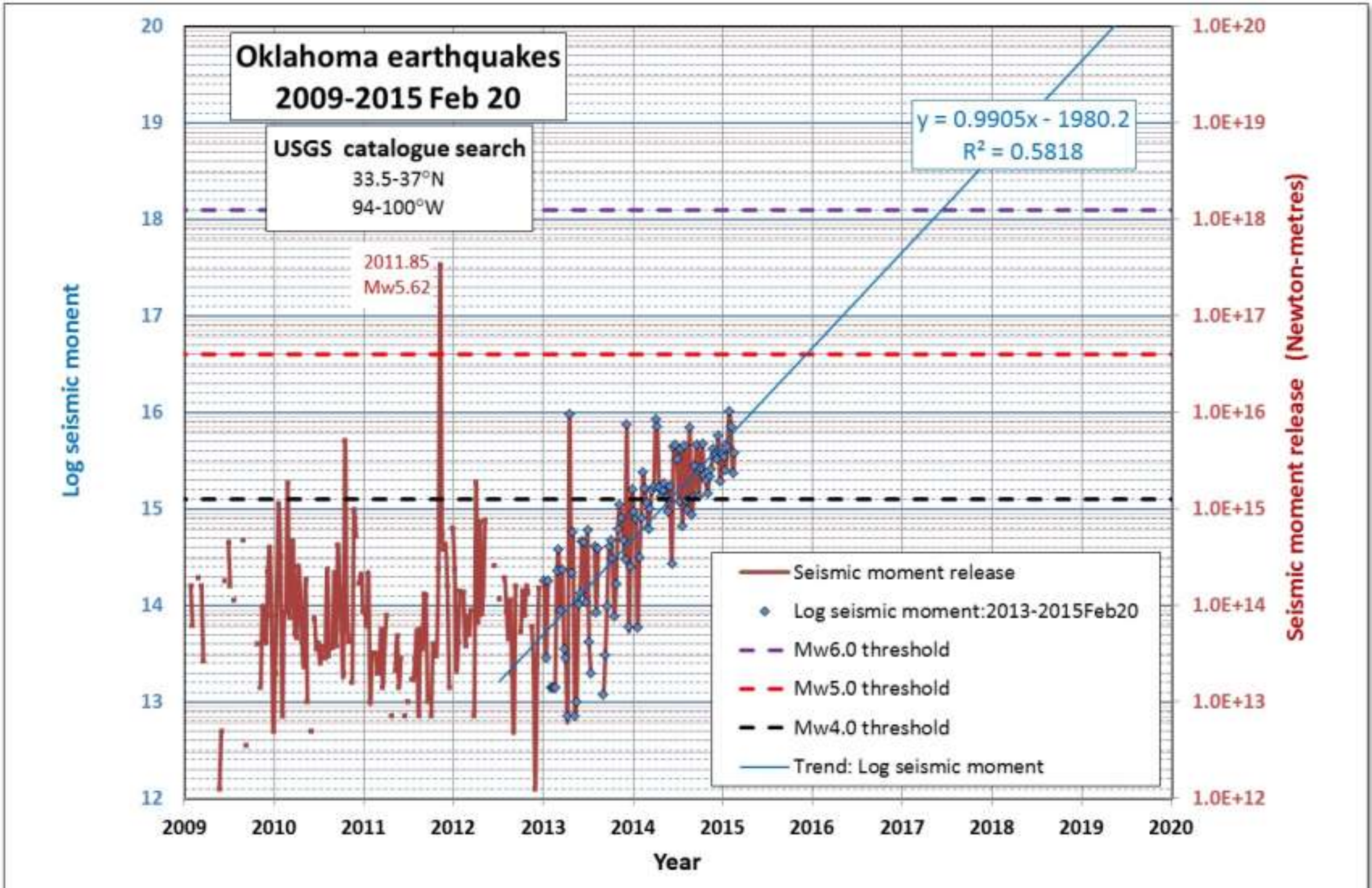




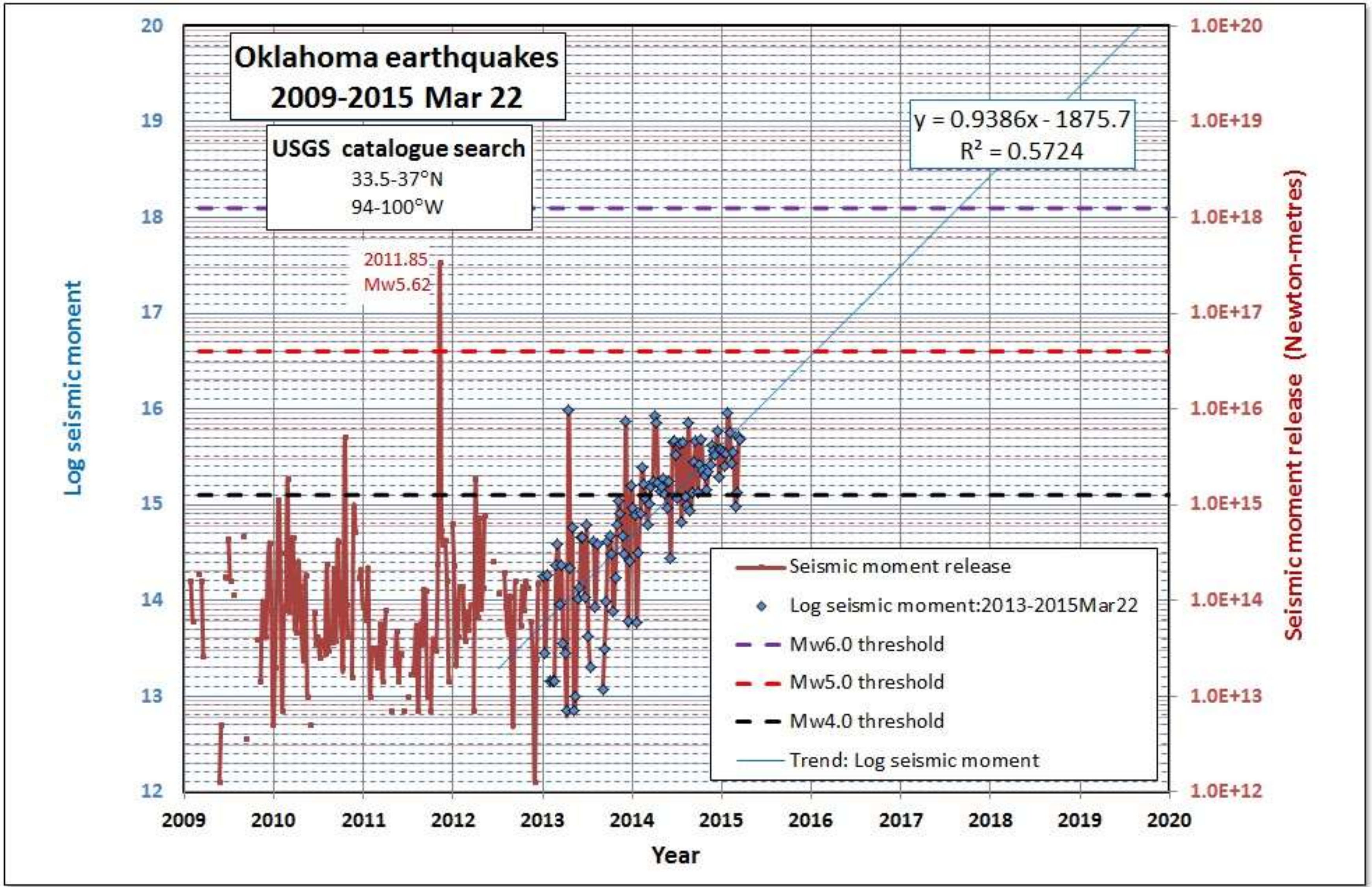
2009-2012 ASR pattern



Post-2012 ASR pattern



Post-2012 ASR pattern (updated)

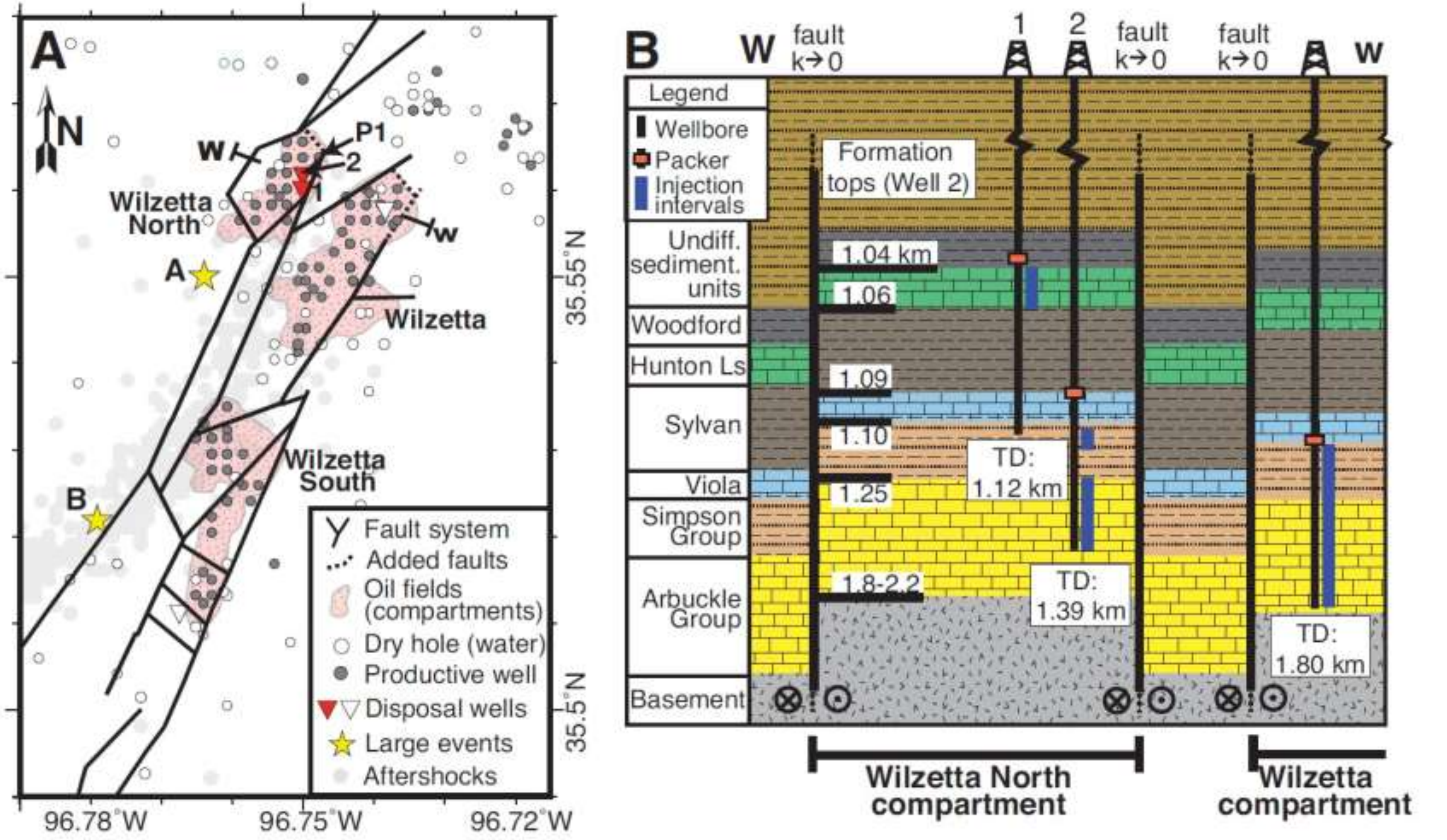


Outline

1. Karoo-Oklahoma and lithospheric stress context
2. Oklahoma hydrocarbon development
3. Recent seismicity record & ASR pattern
4. Causes: natural or anthropogenic?
5. Role of failure-critical faults, epicentre trends
6. Earthquake-fault scaling issues
7. Conclusions

Injection-well triggering

Keranen et al., 2012, Figure 2



Anthropogenic triggering factors (1)

1. **Time-invariance of geological process**
   - 100- to 1000-yr time scale of earthquake recurrence on same fault; driving mechanism is geological process 3–4 orders of magnitude slower; earthquakes repeat on existing weakness zones — faults
2. **Faults close to failure by unknown extent**
   - Stress history depends on interaction with neighbouring faults and on variety of factors practically unquantifiable
3. **Low static-friction coefficients**
   - μ-value < 0.3, much lower on fault zones than in bulk (undamaged) rocks and in laboratory,

UMVOTO

Anthropogenic triggering factors (2)

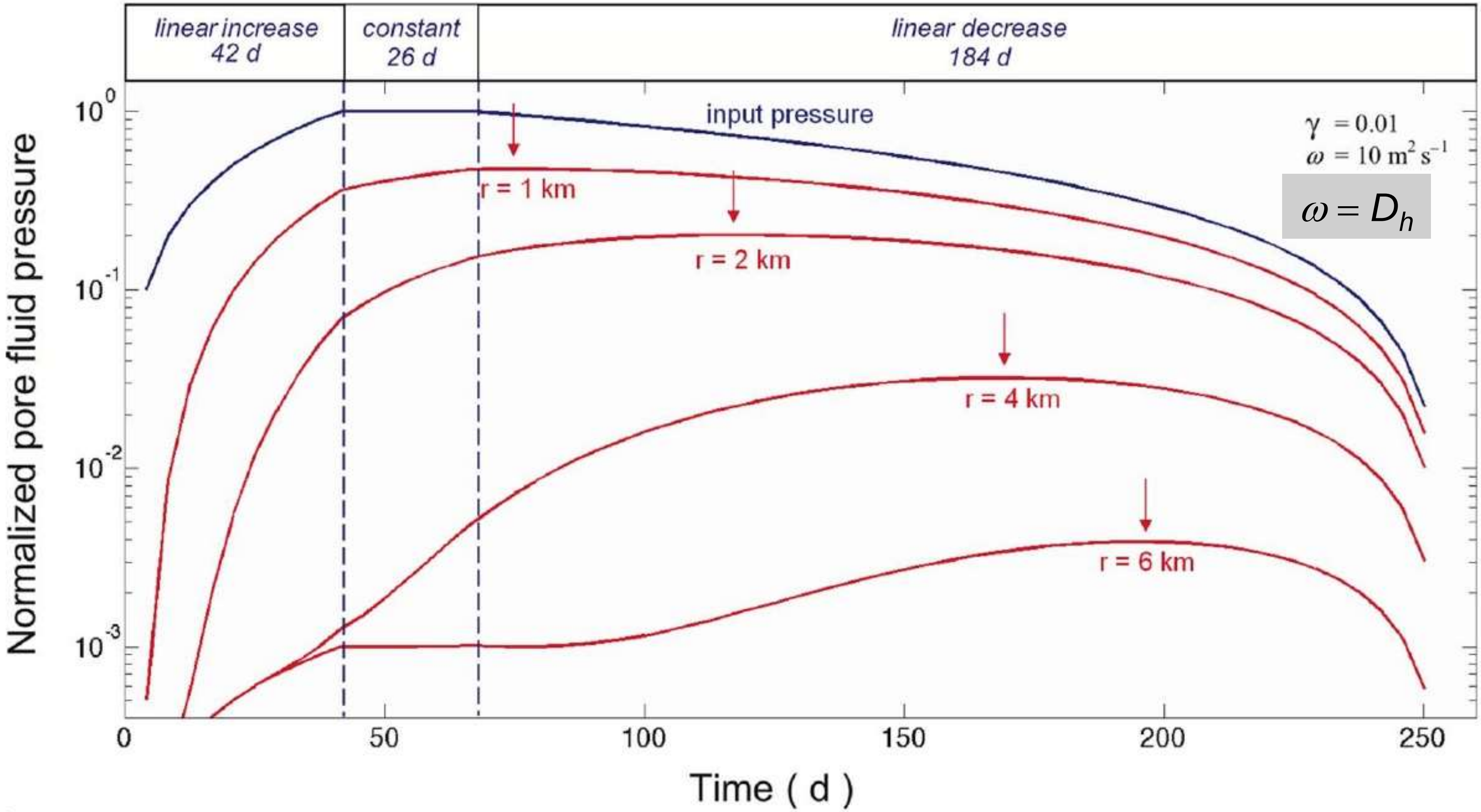
4. **Very low stress thresholds**
   - Additional fluid pressures of 0.05 MPa due to artificial reservoirs have triggered destructive earthquakes; similar low values in dynamic triggering by nearby earthquakes
5. **Considerable time delay**
   - Earthquakes triggered with time delays $>$ 10 years, subject to crustal hydraulic diffusivity D_h (0.1 - 10 m^2/s)
6. **Considerable spatial distance**
   - Earthquakes triggered at up to 30 kilometres

from:

Mulargia, F. & Bizzarri, A. Anthropogenic Triggering of Large Earthquakes. Nature Sci. Rep. 4, 6100; DOI:10.1038/srep06100 (2014).

Fluid-pressure diffusion with r & t

'Biot slow wave' in poro-elastic medium (Biot, 1956; 1962 - EPRL, Shell, Houston)



from: Mulargia, F. & Bizzarri, A., 2014, Figure `3

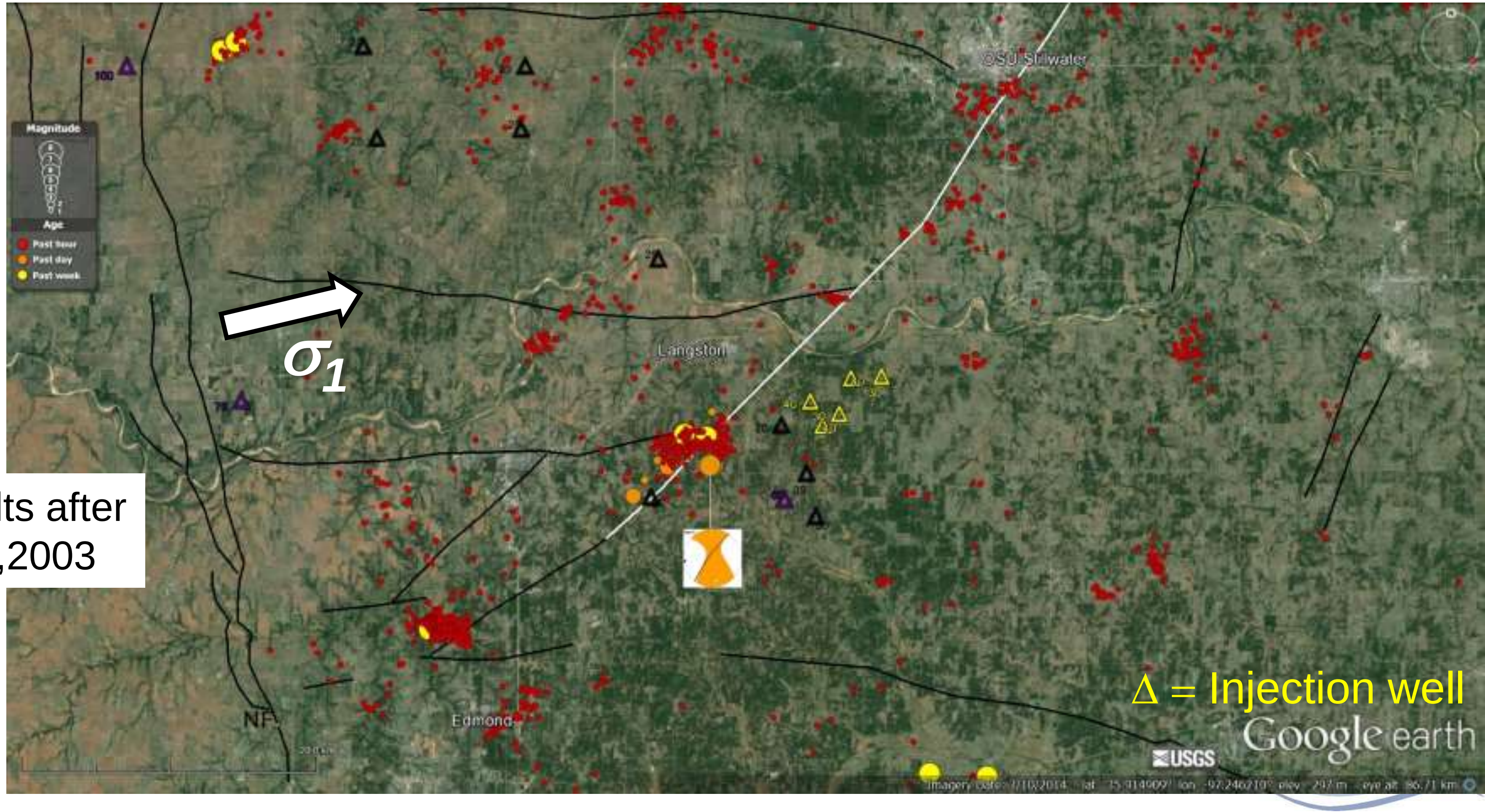
UMVOTO

Outline

1. Karoo-Oklahoma and lithospheric stress context
2. Oklahoma hydrocarbon development
3. Recent seismicity record & ASR pattern
4. Causes: natural or anthropogenic?
5. Role of failure-critical faults, epicentre trends
6. Earthquake-fault scaling issues
7. Conclusions

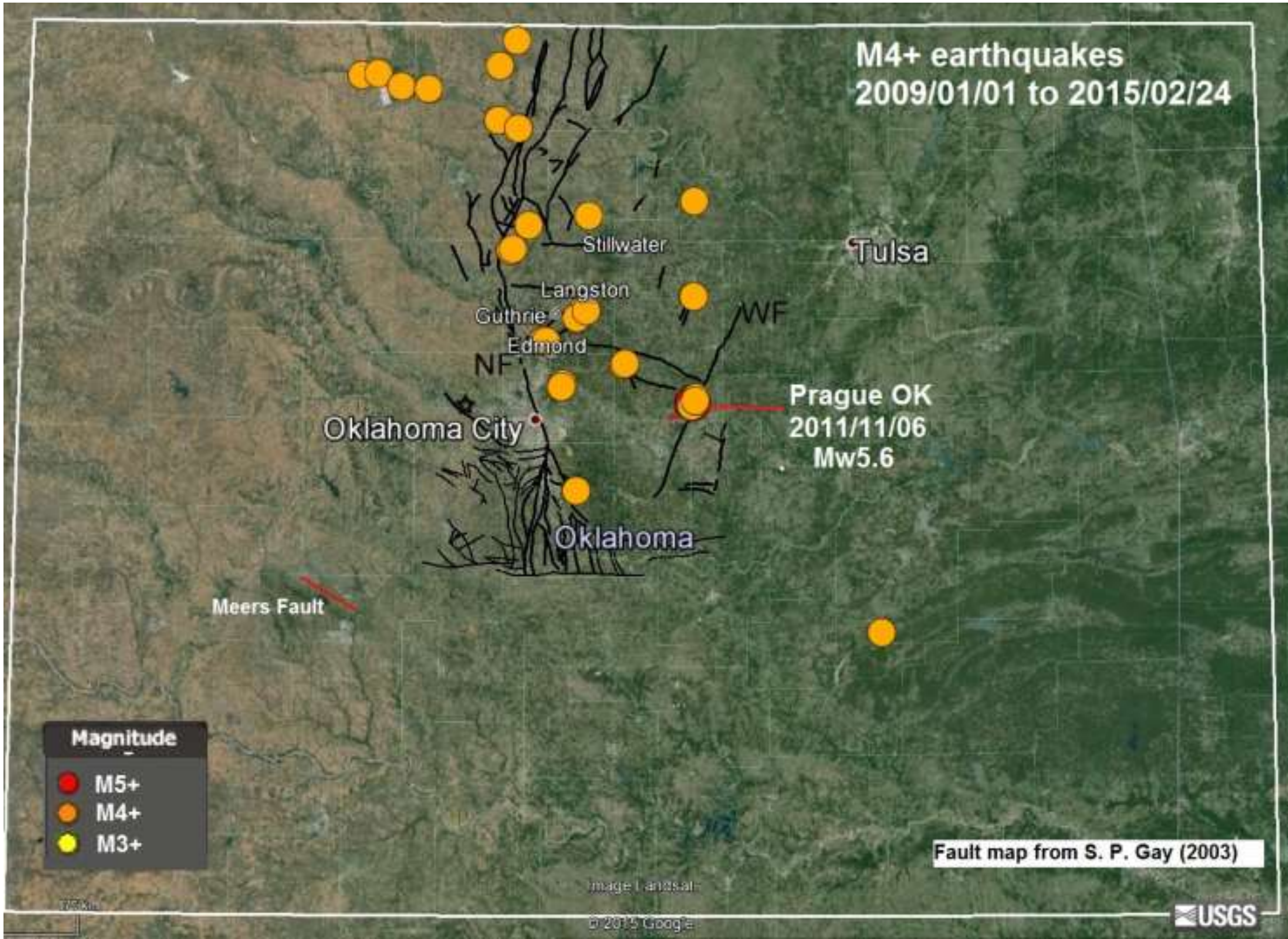
Early definition of GLS trend

- Guthrie-Langston-Stillwater (GLS) alignment – 2014/07/13

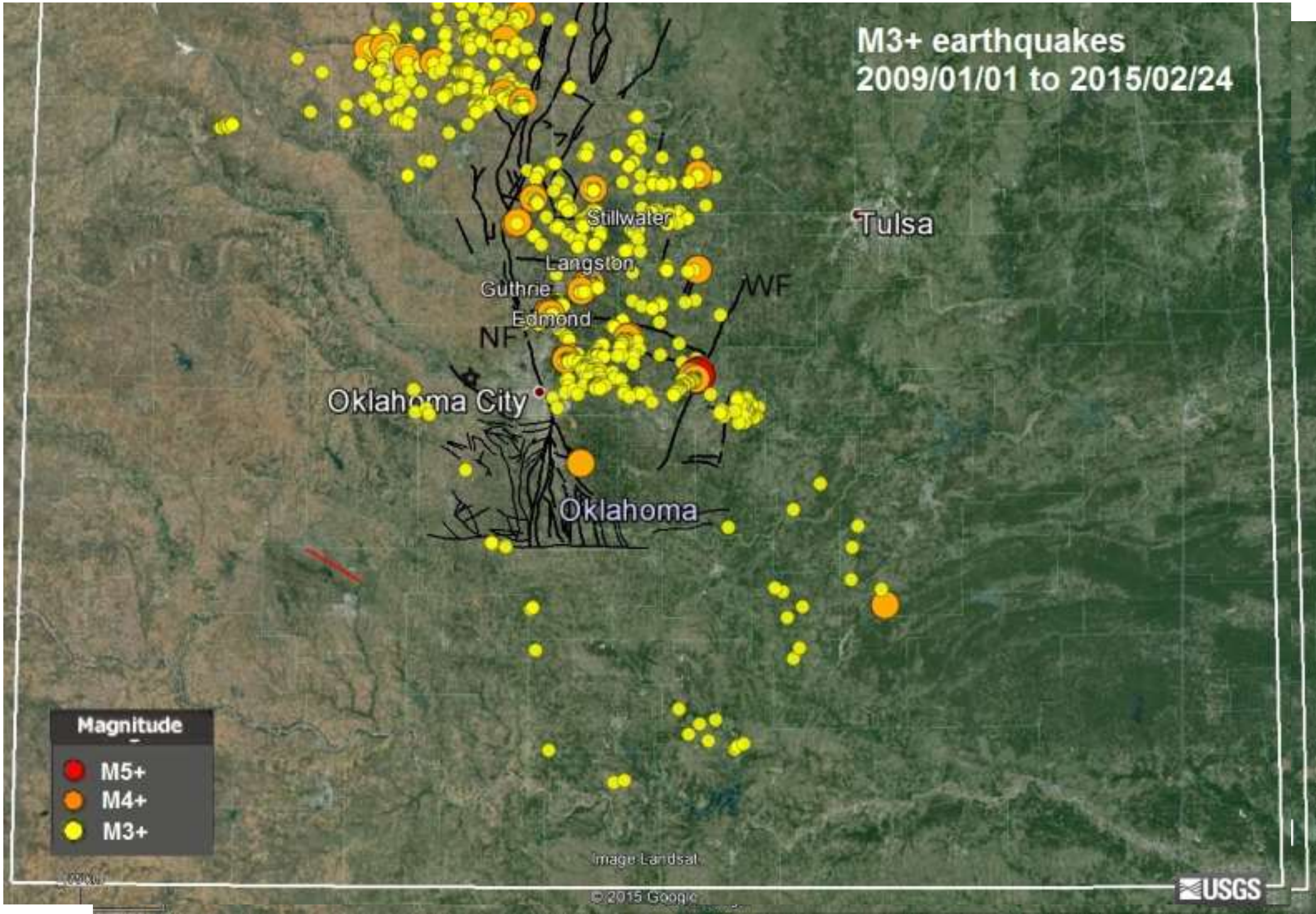


Faults after Gay,2003

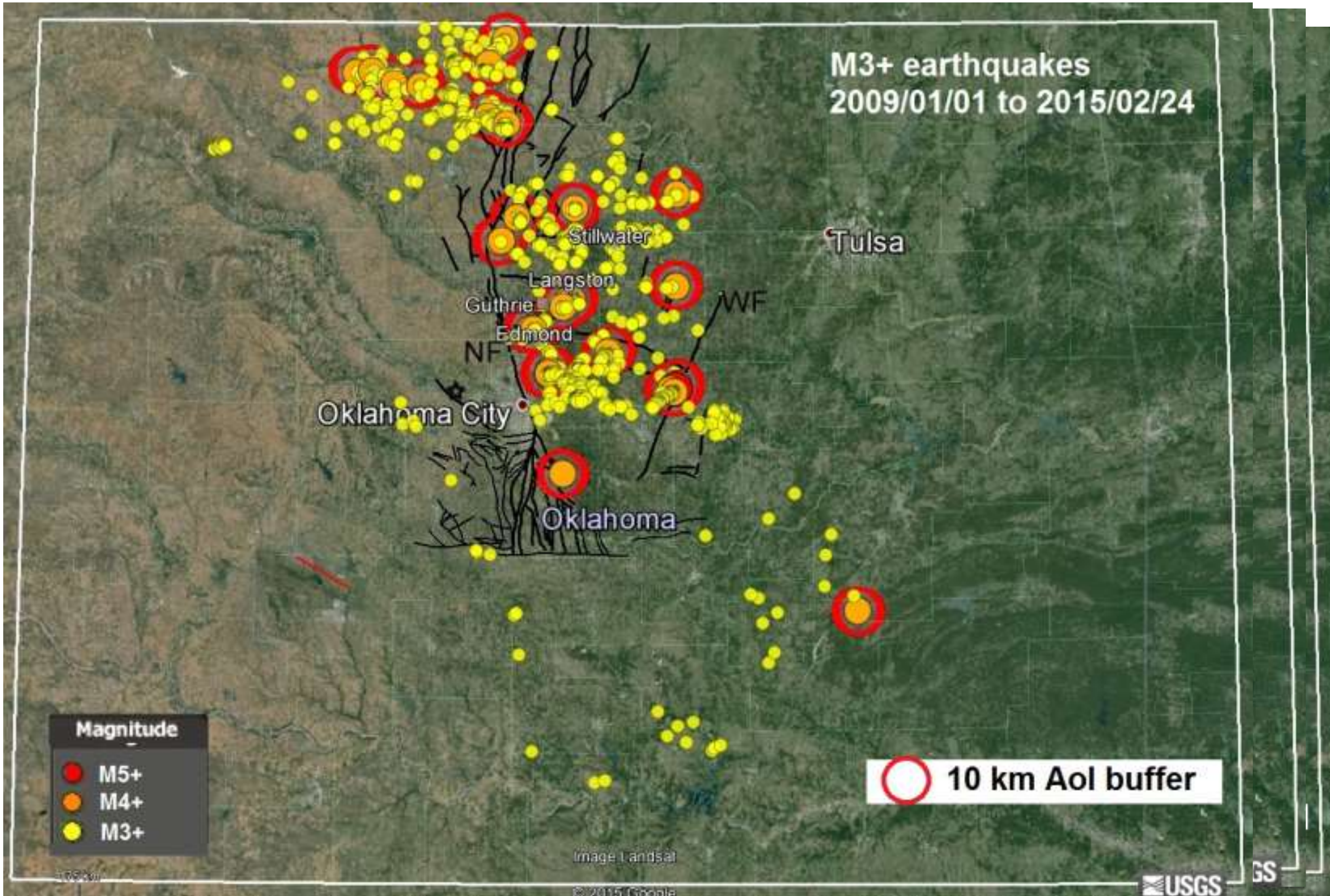
Areas of 'Seismotectonic Interest' (1)



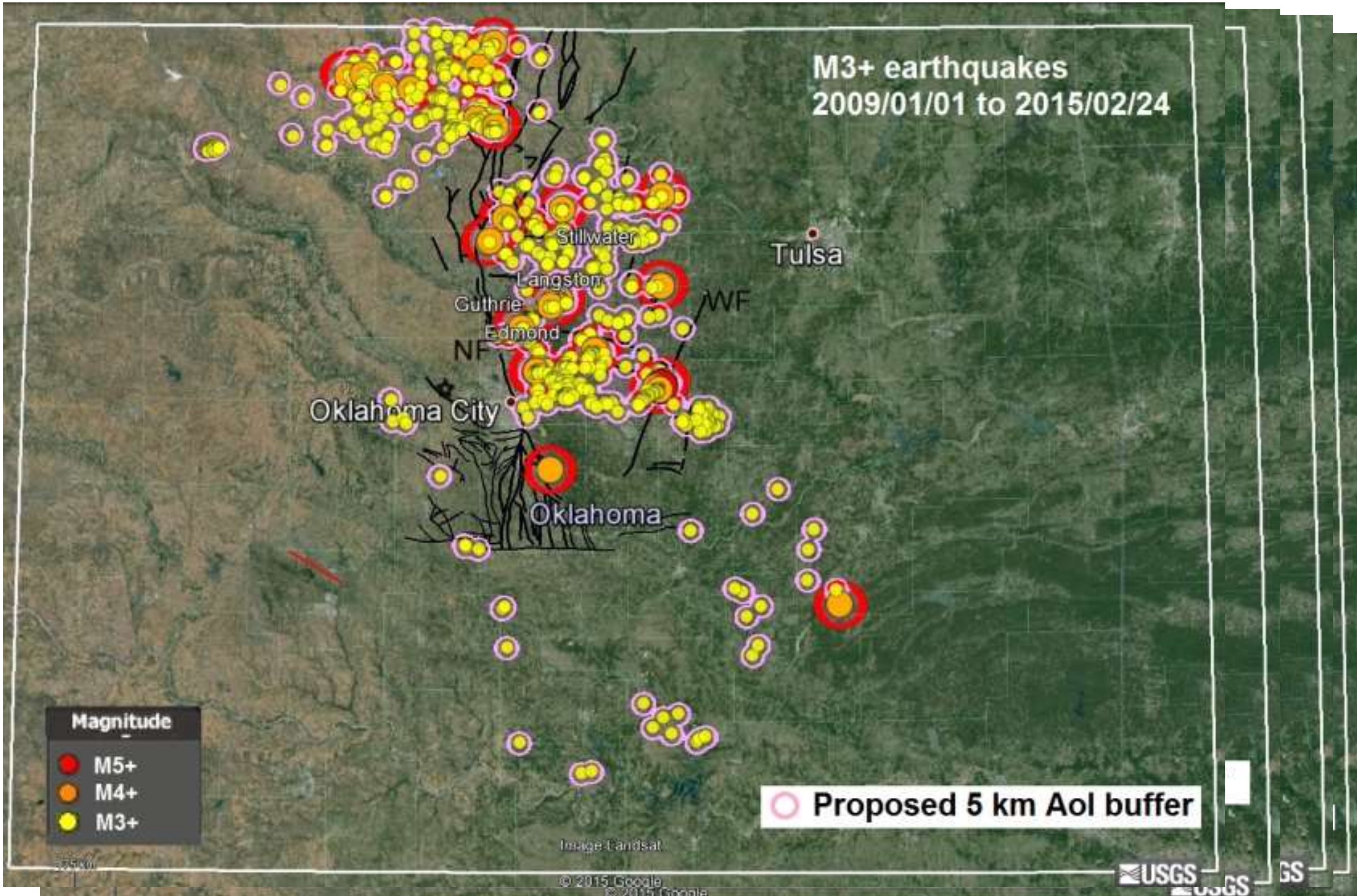
Areas of 'Seismotectonic Interest' (2)



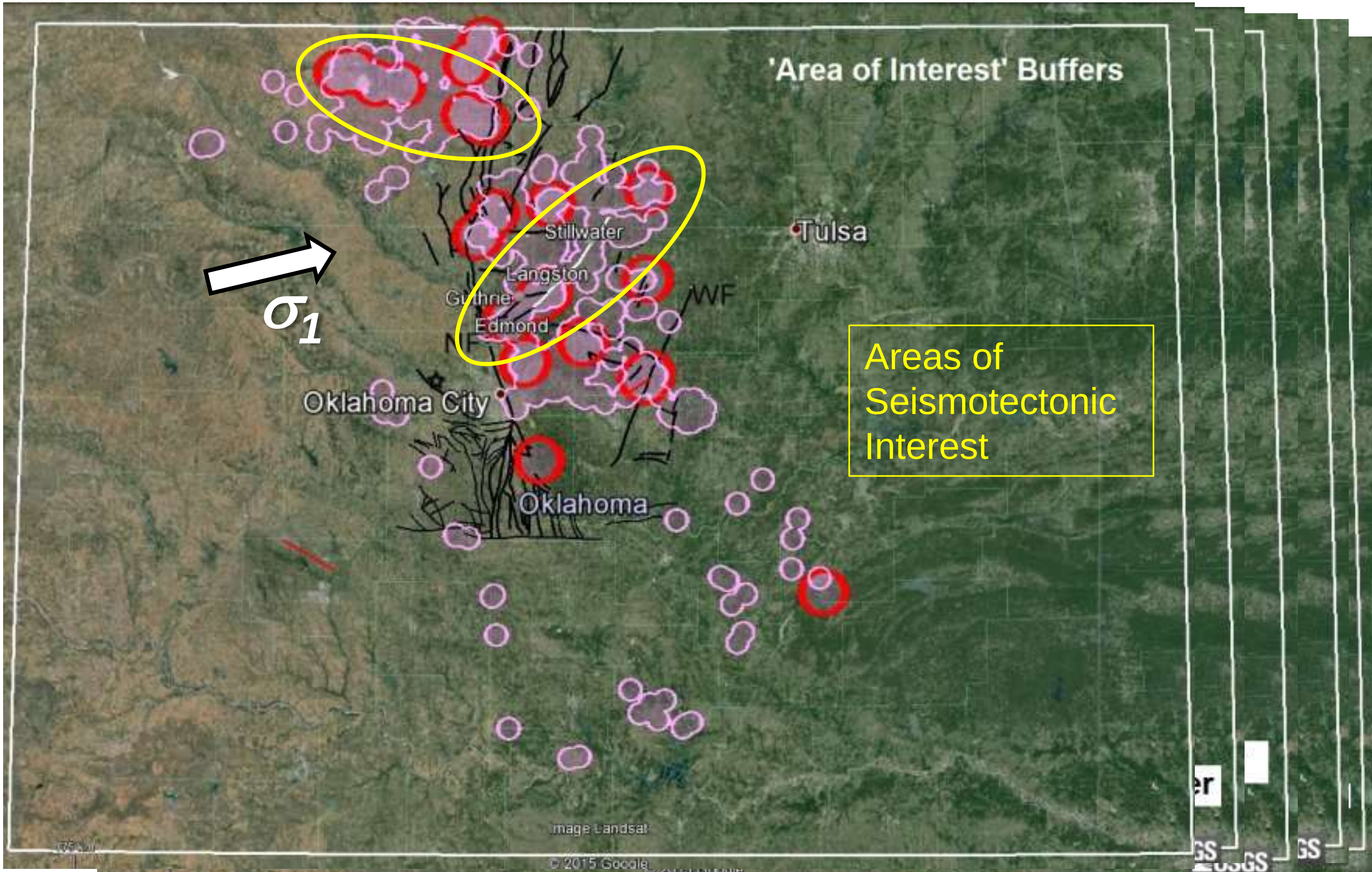
Areas of 'Seismotectonic Interest' (3)



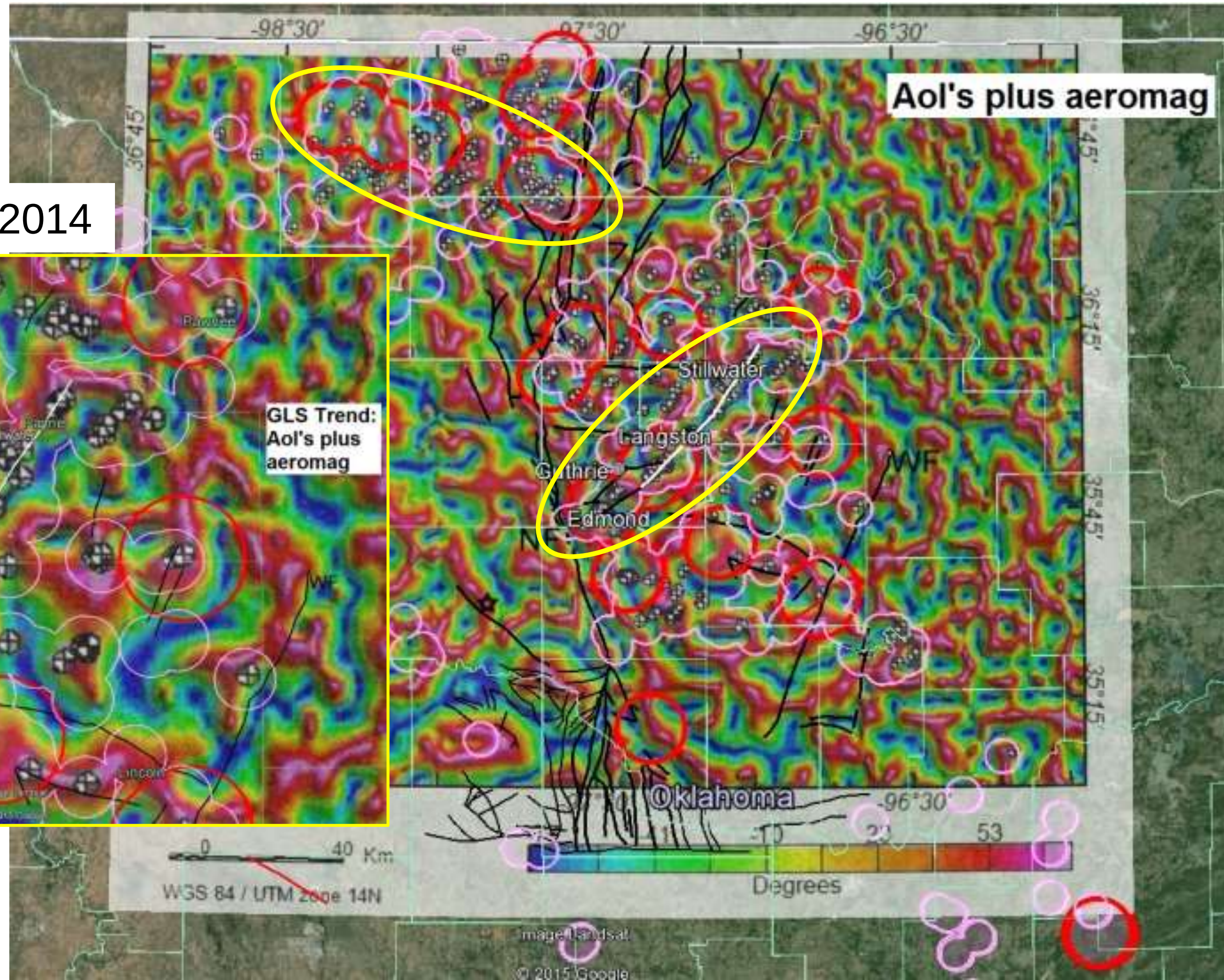
Areas of 'Seismotectonic Interest' (4)



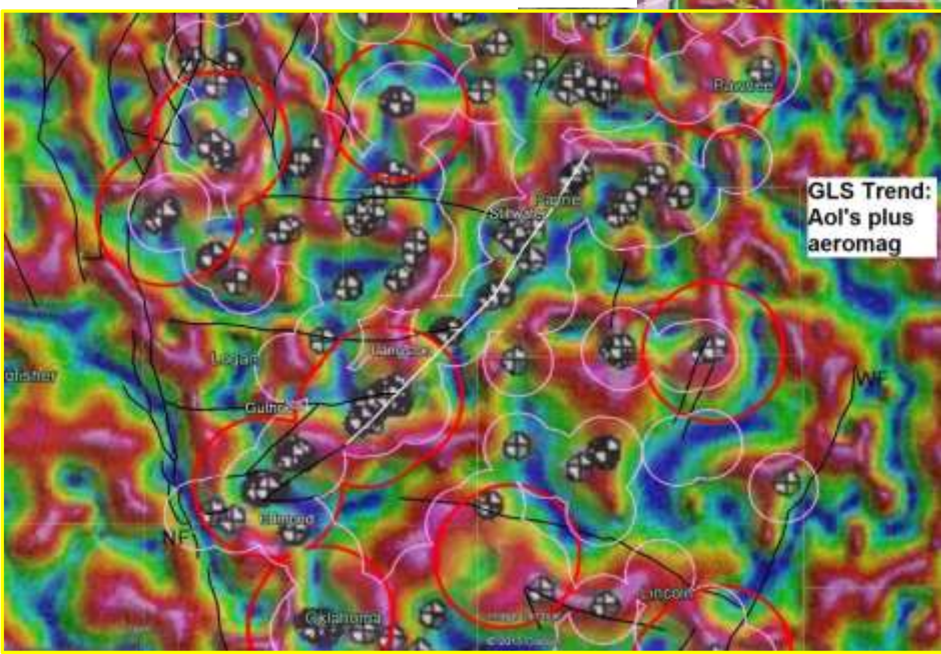
Areas of ‘Seismotectonic Interest’ (5)



Focus on GLS trend



Sickbert & Atekwana, 2014



Outline

1. Karoo-Oklahoma and lithospheric stress context
2. Oklahoma hydrocarbon development
3. Recent seismicity record & ASR pattern
4. Causes: natural or anthropogenic?
5. Role of failure-critical faults, epicentre trends
6. Earthquake-fault scaling issues
7. Conclusions

Earthquake scaling relations

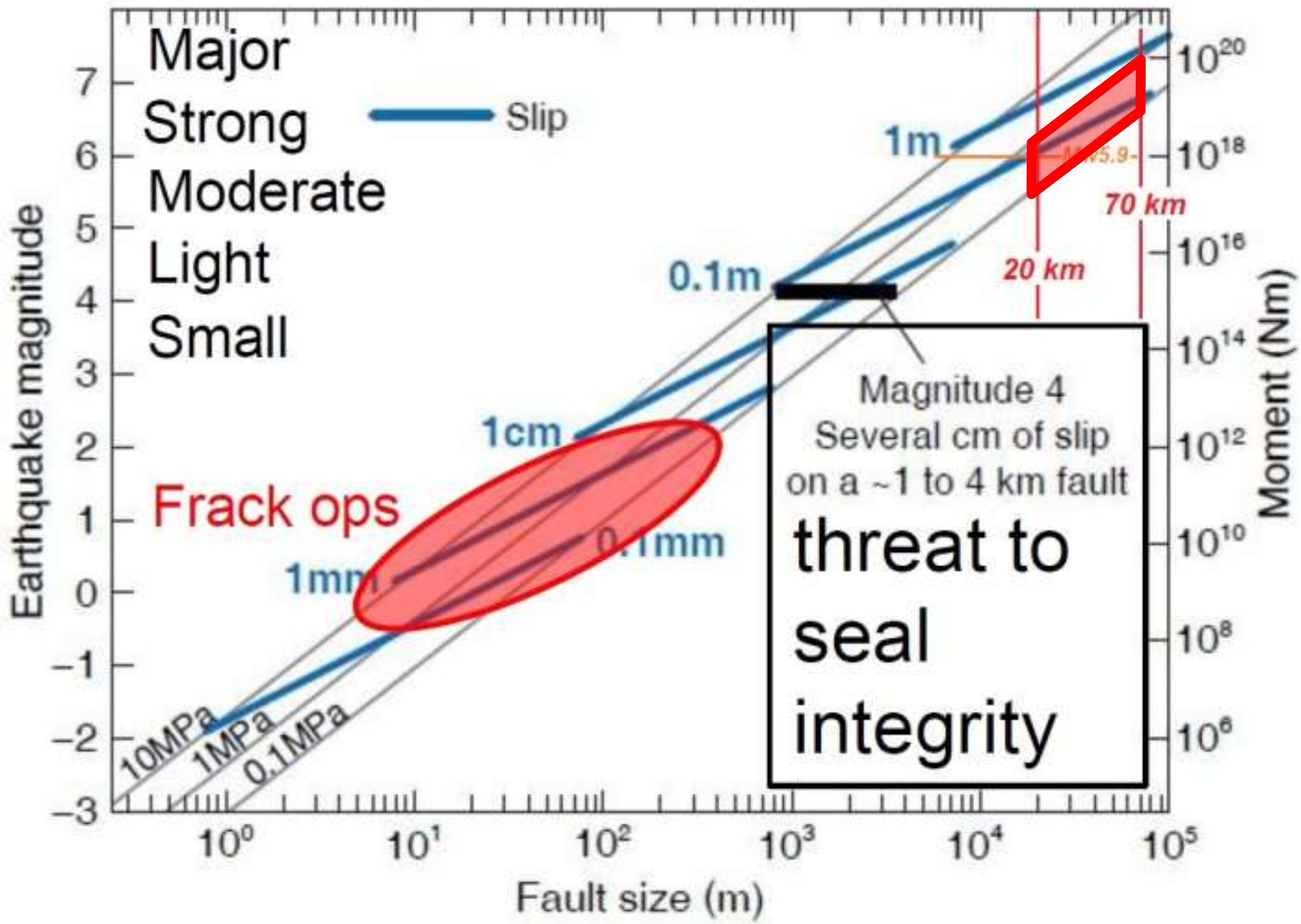
Earthquake scaling relations for Guthrie-Langston-Stillwater trend

$M_0 = \mu A \bar{d}$

Fault length L	**Fault width W**	**Fault area (A = L x W)**	**Average slip $\bar{d}$**	**Seismic Moment M0**	**Moment Magnitude Mw**	**Stress Drop $\Delta\sigma$**
km	km	km2	m	N m		MPa
20	20	400	0.063	8.06E+17	5.9	0.1
	15	300	0.054	5.18E+17	5.7	
	20	400	0.625	8.00E+18	6.5	1.0
	15	300	0.54	5.18E+18	6.4	
70	20	1400	0.117	5.24E+18	6.4	0.1
	15	1050	0.101	3.39E+18	6.3	
	20	1400	1.170	5.24E+19	7.1	1.0
	15	1050	1.010	3.39E+19	7.0	

Crustal shear modulus μ = 32 GPa

Large, low-stress-drop quake on GLS?



Zoback MD, Gorelick SM (2012) Earthquake triggering and large-scale geologic storage of carbon dioxide. Proc Natl Acad Sci USA 109(26):10164–10168.

UMVOTO

Outline

1. Karoo-Oklahoma and lithospheric stress context
2. Oklahoma hydrocarbon development
3. Recent seismicity record & ASR pattern
4. Causes: natural or anthropogenic?
5. Role of failure-critical faults, epicentre trends
6. Earthquake-fault scaling issues
7. Conclusions

Conclusions (1)

- Earth's crust permeable to fluid flow throughout brittle-fracture regime (<10 km depth) and therefore susceptible to natural and triggered hydroseismicity
- Driven mainly by high-volume injection of oil-industry wastewater, Oklahoma now experiences the second of two cycles of accelerating seismic-moment release (ASR), at rates **projected** to exceed magnitude M5 threshold on weekly basis before end of 2015
- Fluid-pressure diffusion can peak at seismogenic depths long after pressurization near surface has already terminated, hence early-warning procedures to halt injection based on seismographic monitoring can hardly be effective

Conclusions (2)

- Small-moderate (~M4-*M*5) locally triggered events can potentially result in cascading failure along favourably oriented (~NE/SW- or WNW/ESE-striking) elements of complex Nemaha-Wilzetta fault system, thus nucleating large (>M6) quakes
- Large-scale fluid-injection projects should primarily include:
  - detailed mapping of nearby potentially active faults;
  - quantitative loss-modelling of worst-case rupture scenarios;
  - earthquake-engineering review of vulnerable infrastructure;
  - preparedness exercises for identified vulnerable communities

UMVOTO

Lessons from L'Aquila, Italy

" … The first lesson to be learned is that communications to the public about earthquake hazard and risk must … be carefully prepared by experts. The more significant lesson is that the approach to calm the population and the standard probabilistic hazard and risk assessment, …are misleading. The latter has been criticized as being incorrect for scientific reasons and here I argue that it is also ineffective for psychological reasons. Instead of calming the people (or) by underestimating the hazard in strongly active areas …, they should be told quantitatively the consequences of the reasonably worst case and be motivated to prepare for it, whether or not it may hit the present or the next generation. … "

Max Wyss, 2013. Lessons from the conviction of the L'Aquila seven: The standard probabilistic earthquake hazard and risk assessment is ineffective. Geophysical Research Abstracts Vol. 15, EGU2013-3402, 2013

Acknowledgements

- US Geological Survey (USGS) for provision of online Preliminary Determination of Epicentres database
- Oklahoma Geological Survey (OGS; Leonard Geophysical Observatory) for impressive accessibility of its online earthquake catalogues
- Rowena Hay (Umvoto) for support and constructive critique

Thank You

UMVOTO