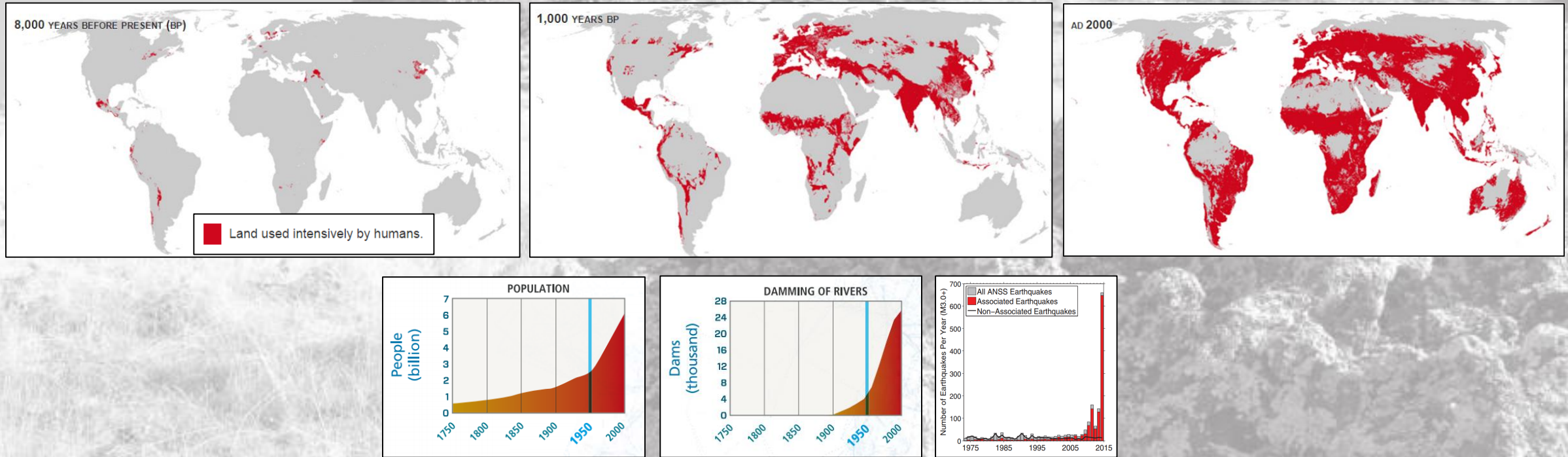
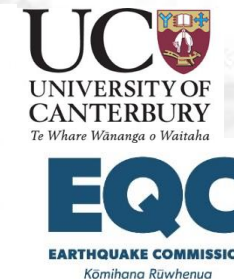


# Earthquakes in the Anthropocene

The human influence on earthquakes and their environmental effects



Mark Quigley  
University of Melbourne



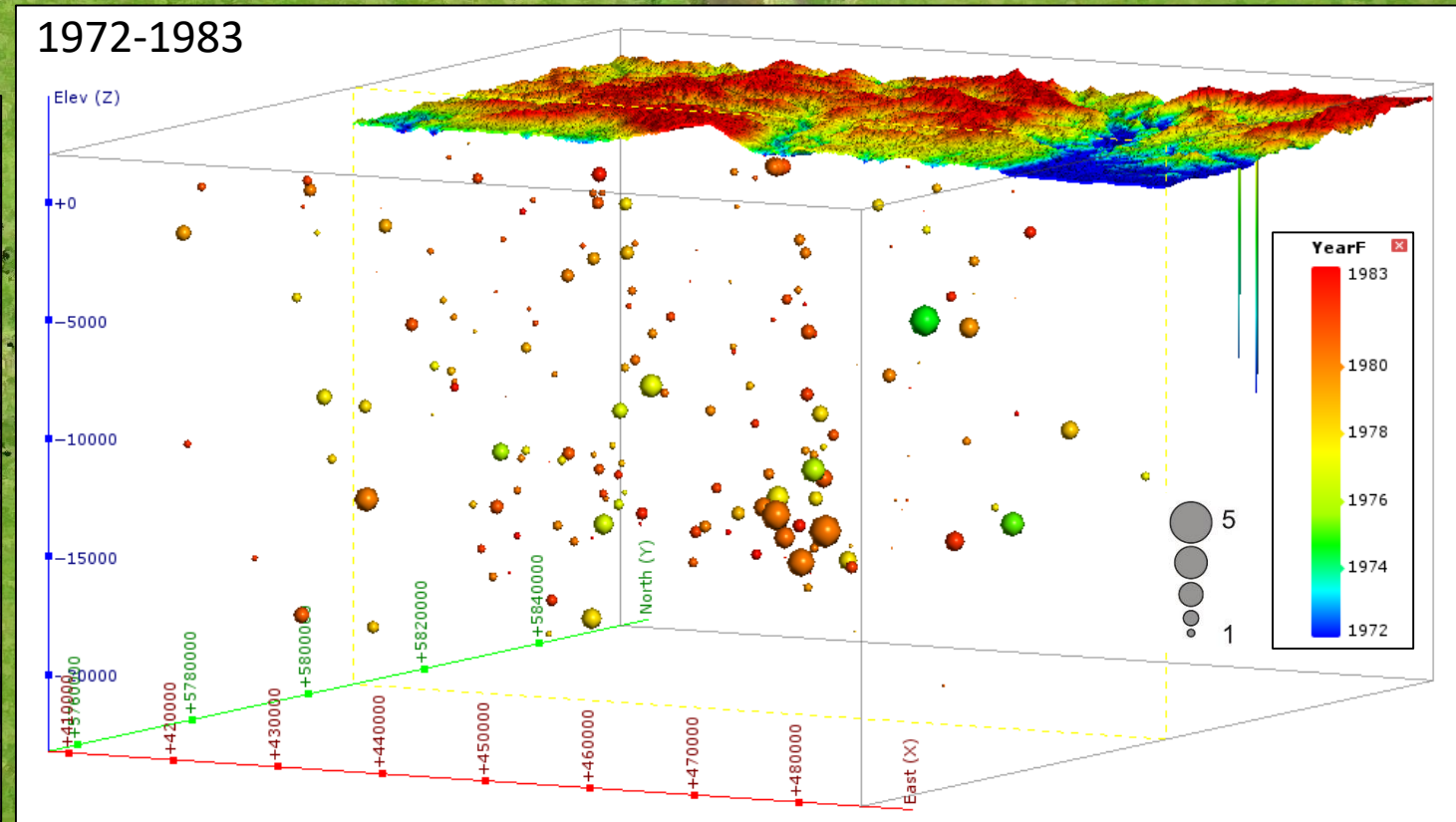
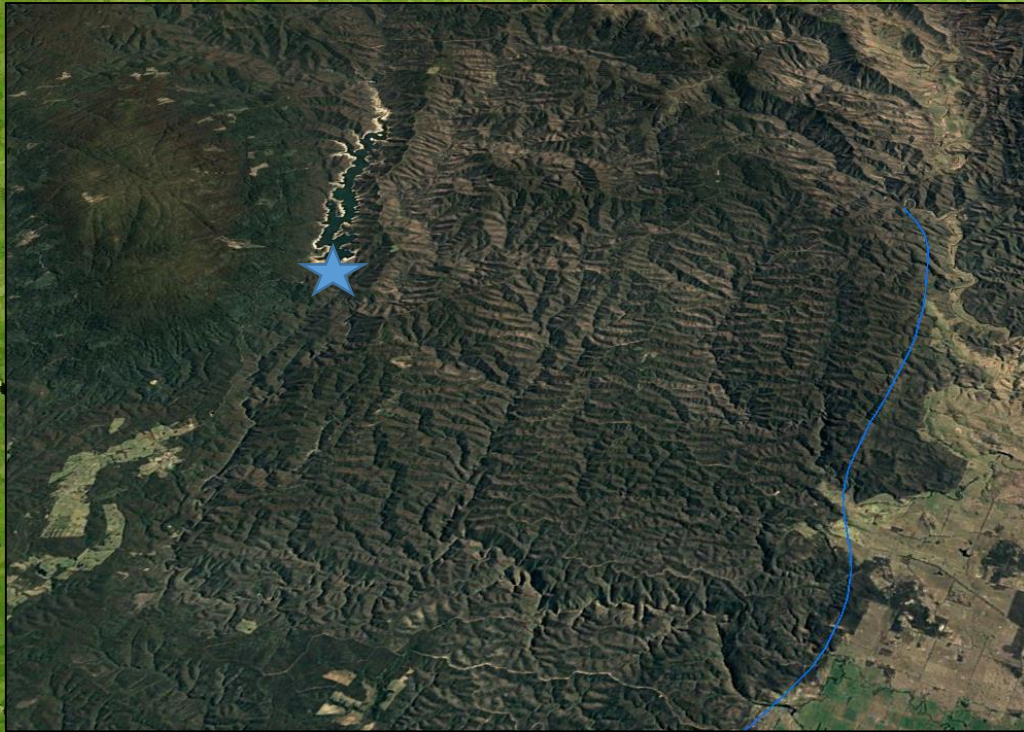
Sources: E. C. Ellis Phil. Trans. R. Soc. A 369, 1010–1035 (2011); <http://www.nature.com/news/anthropocene-the-human-age-1.17085>  
Waters et al. (2016) Science, DOI: 10.1126/science.aad2622; <http://www.igbp.net/download/18.1081640c135c7c04eb480001178/1376383107963/NL78-anthropocene.pdf>; Weingarten et al. “High-rate injection is associated with the increase in U.S. mid-continent seismicity” Science, 348, 6241 (2015)



# Thompson Dam, Victoria, Australia

Dam constructed 1976-1983

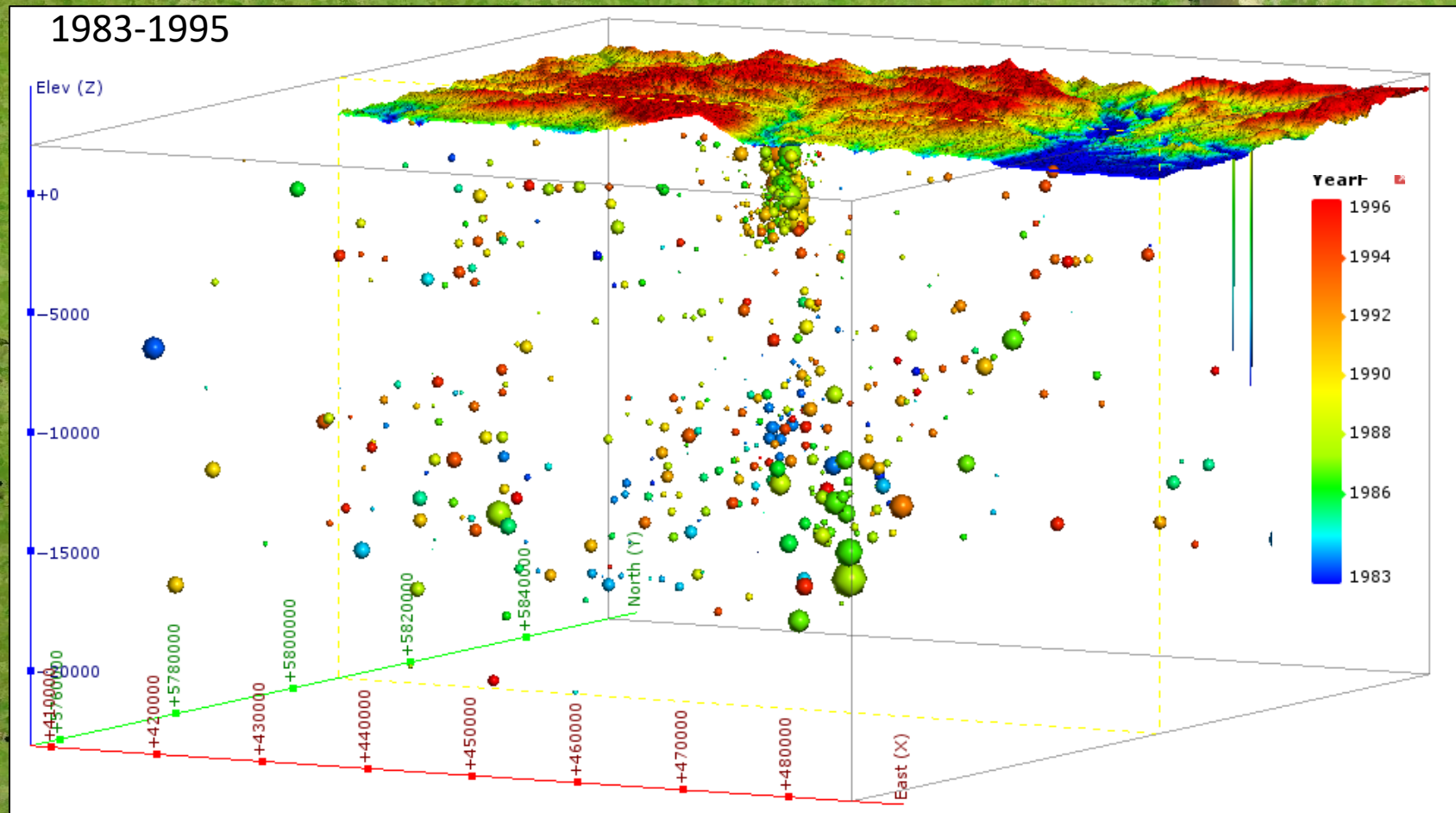
Pre-reservoir filling seismic monitoring





# Thompson Dam, Victoria, Australia

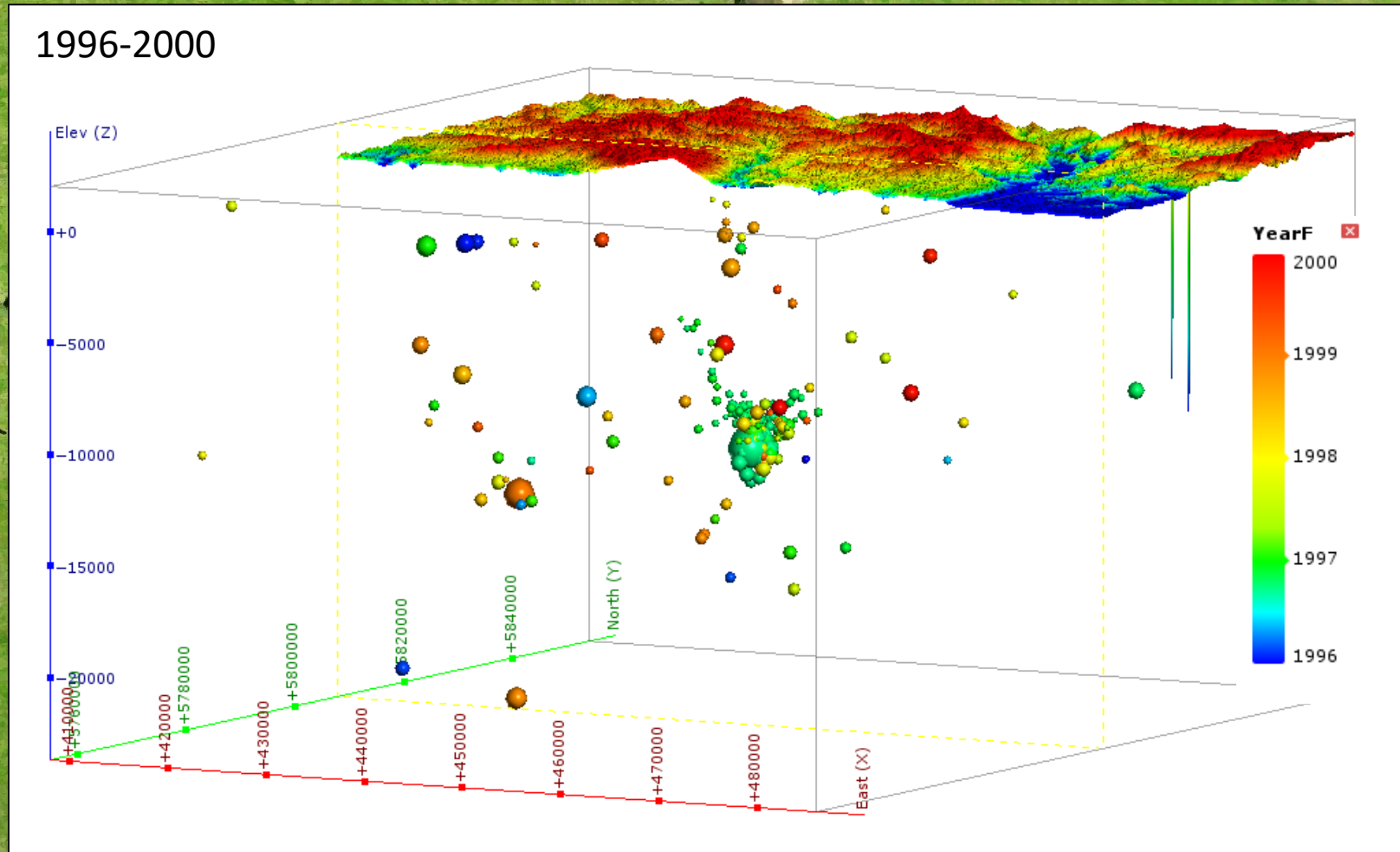
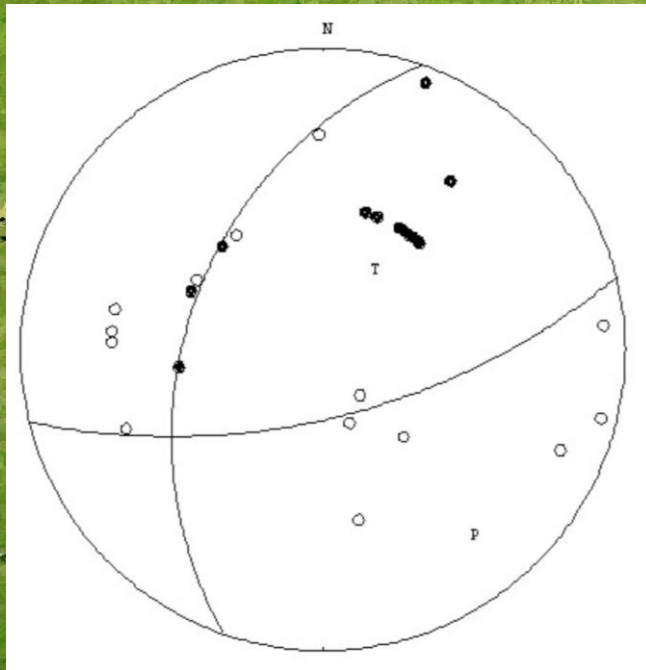
1983 - Dam completed and reservoir filling commences, 1985 shallow earthquake swarms start





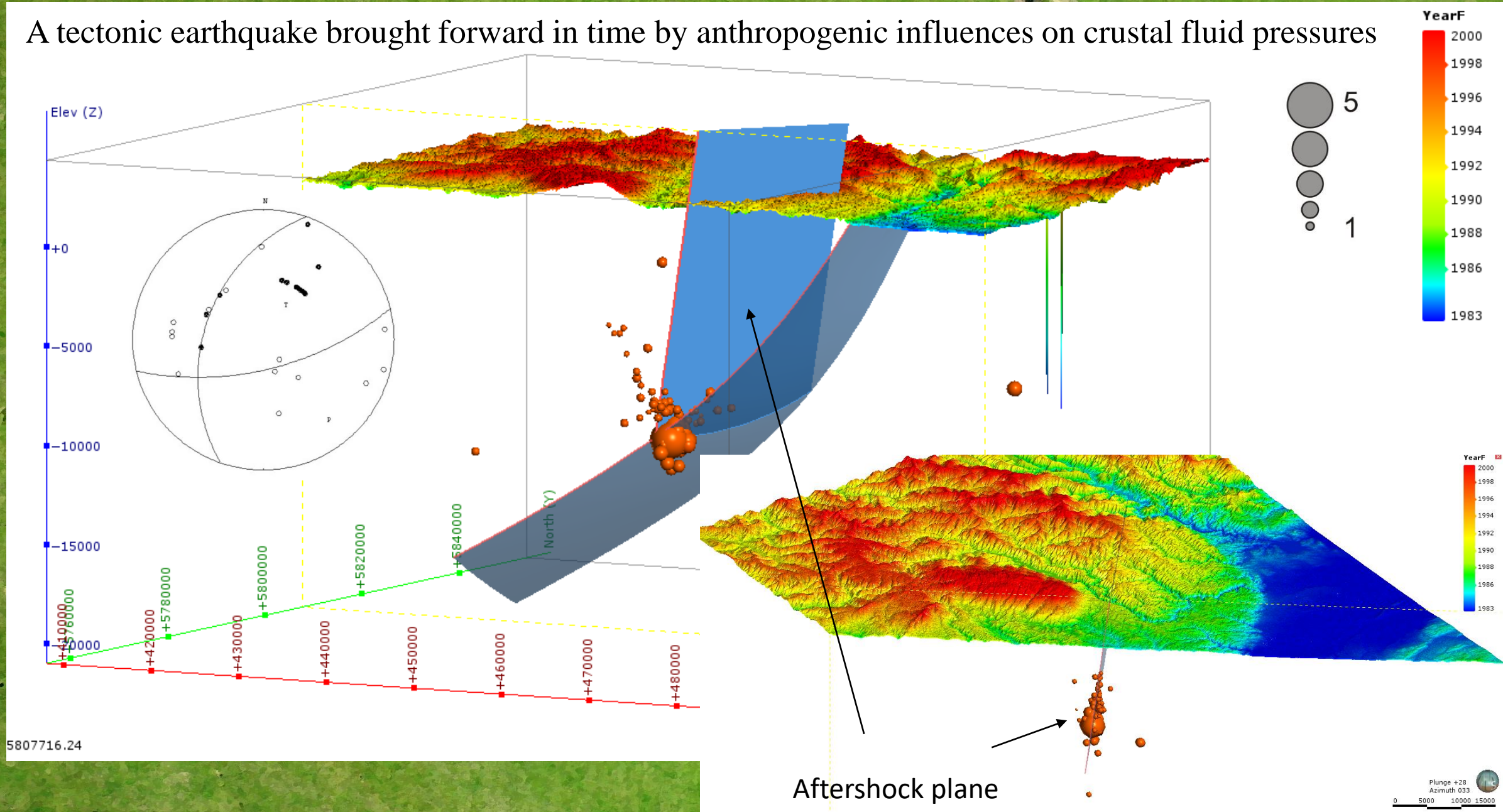
# Thompson Dam, Victoria, Australia

1996 ML 5.0 earthquake



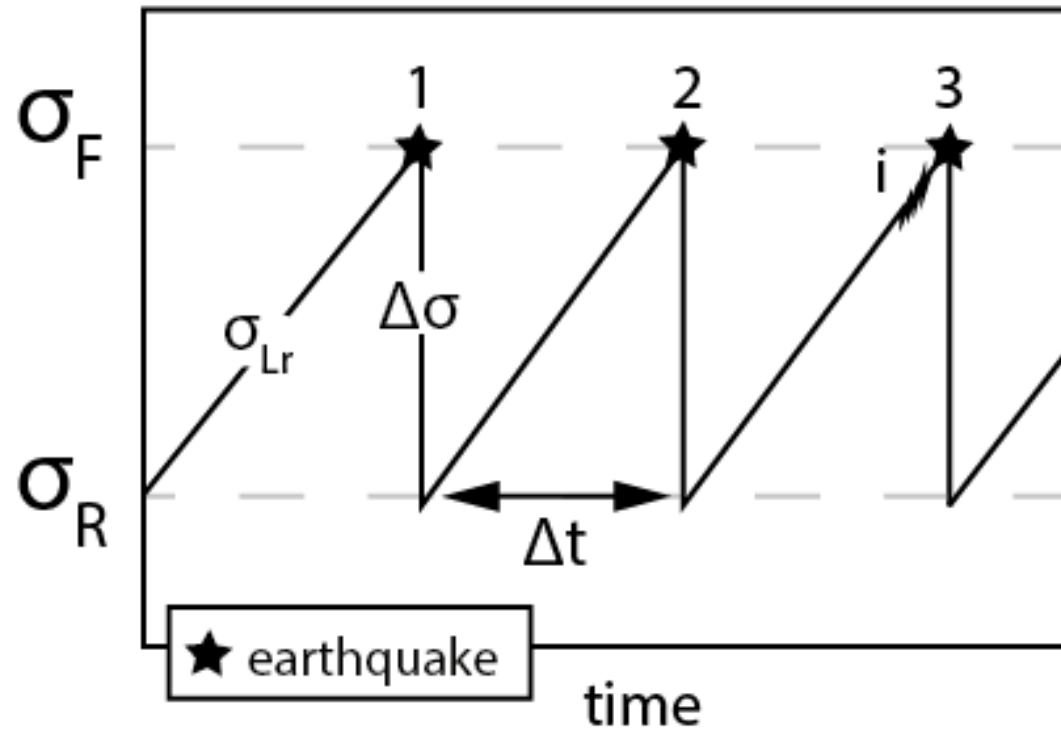


A tectonic earthquake brought forward in time by anthropogenic influences on crustal fluid pressures





# The Seismic Cycle



$$\sigma_F = \tau - \mu (\sigma_N - P)$$

$\tau$  = shear stress on fault

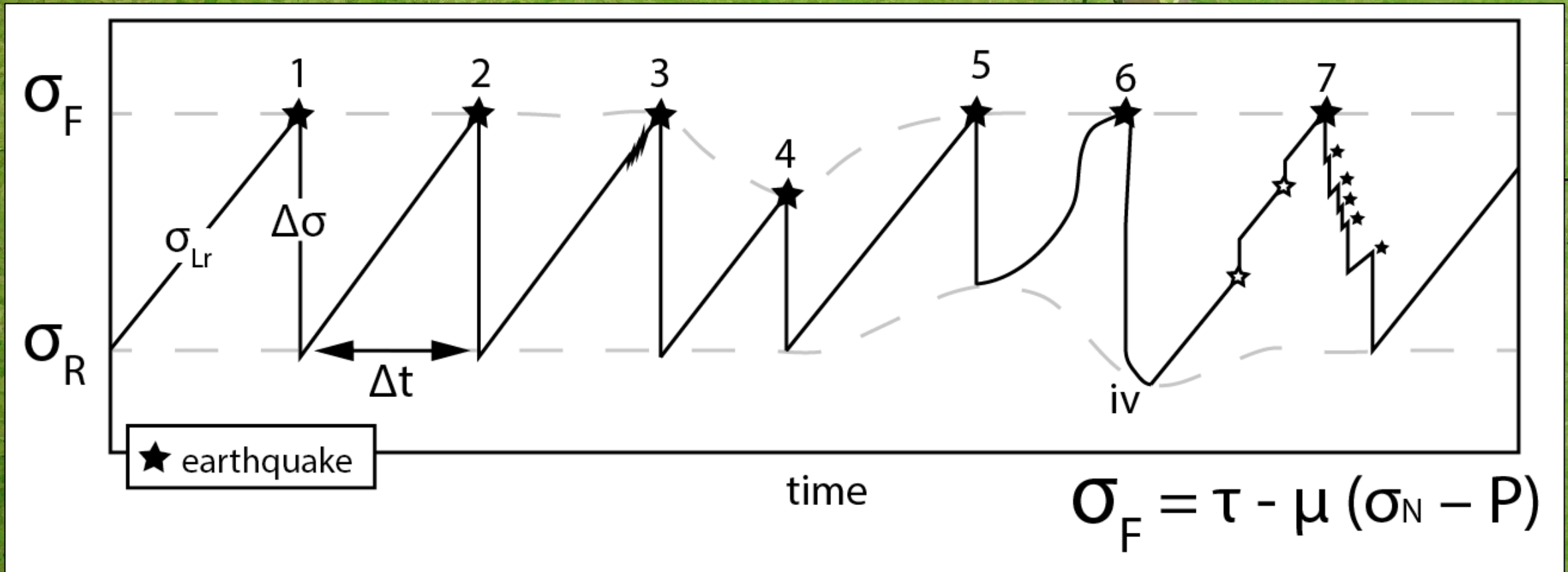
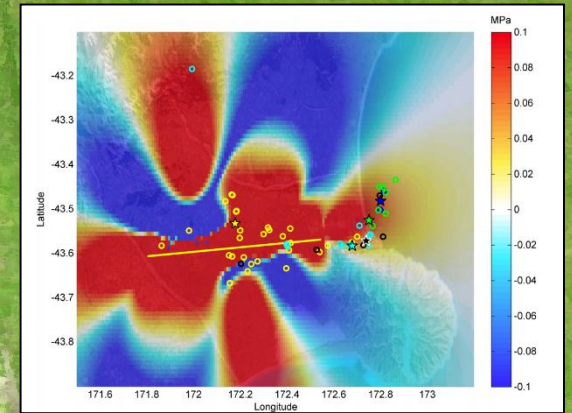
$\mu$  = coefficient of friction of fault

$\sigma_N$  = normal stress on the fault

$P$  = pore fluid pressure in the fault zone



# The seismic cycle and natural earthquake triggering

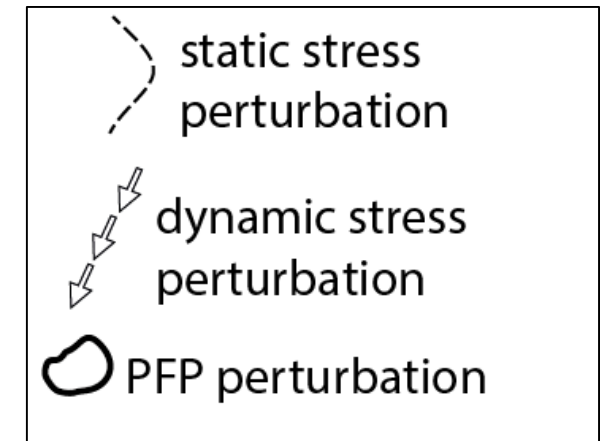
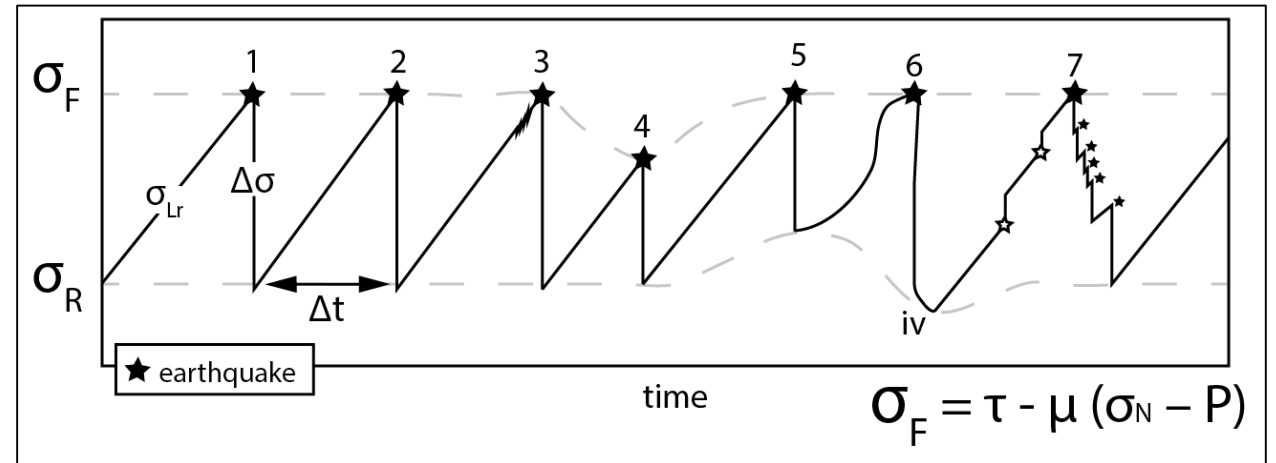
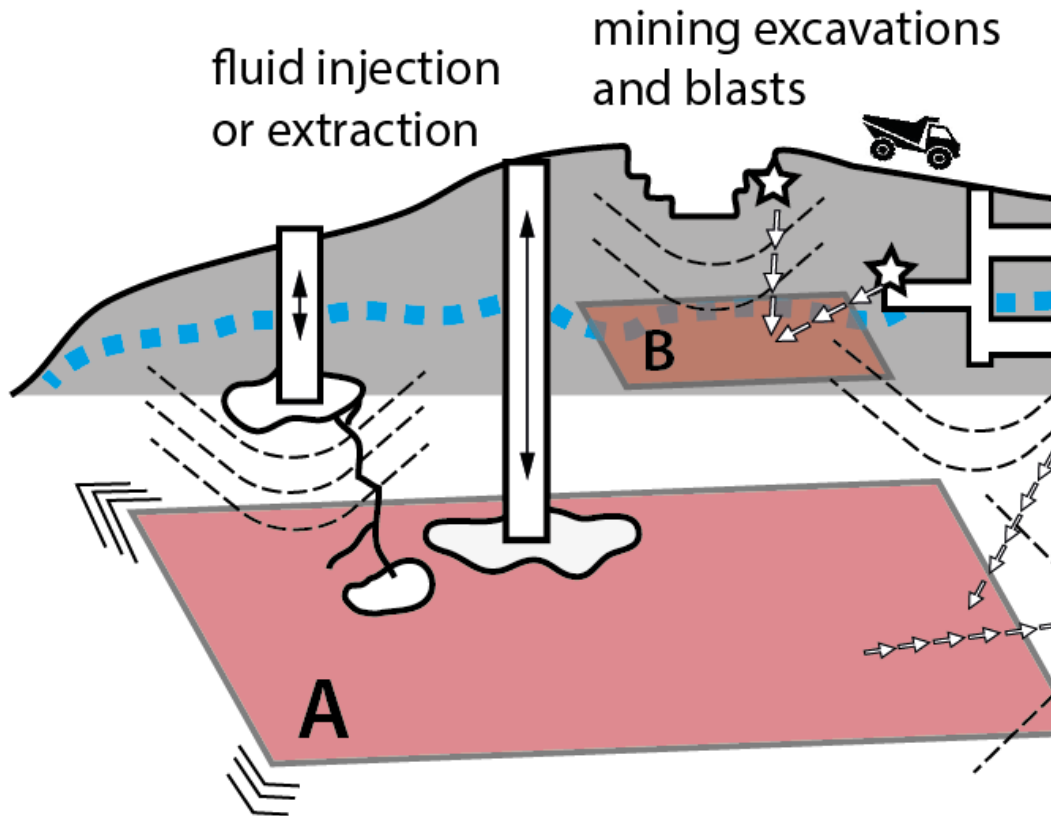




# Anthropogenic earthquake triggering:

Redistributions of mass and fluids

## Anthropogenic earthquakes



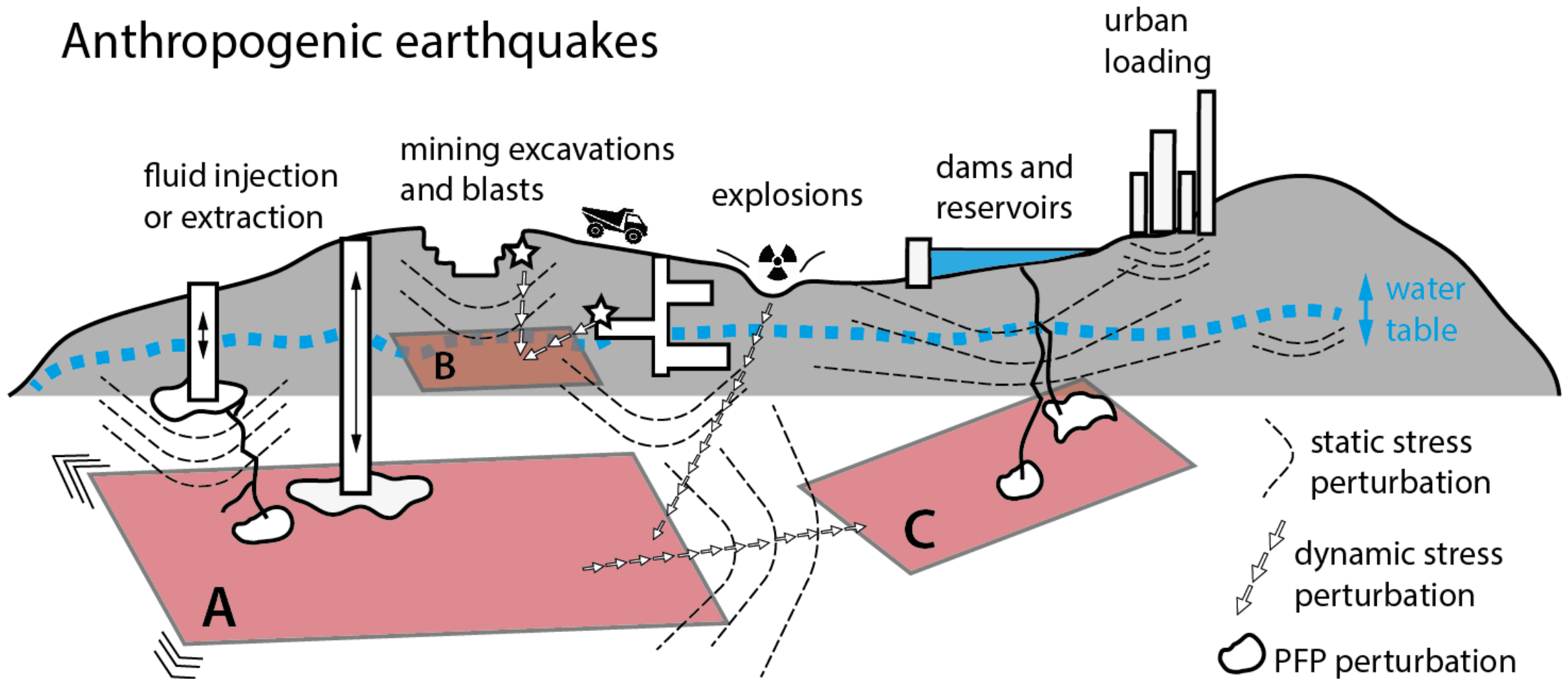


# Anthropogenic earthquakes:

Redistributions of mass and fluids

$$\sigma_F = \tau - \mu (\sigma_N - P)$$

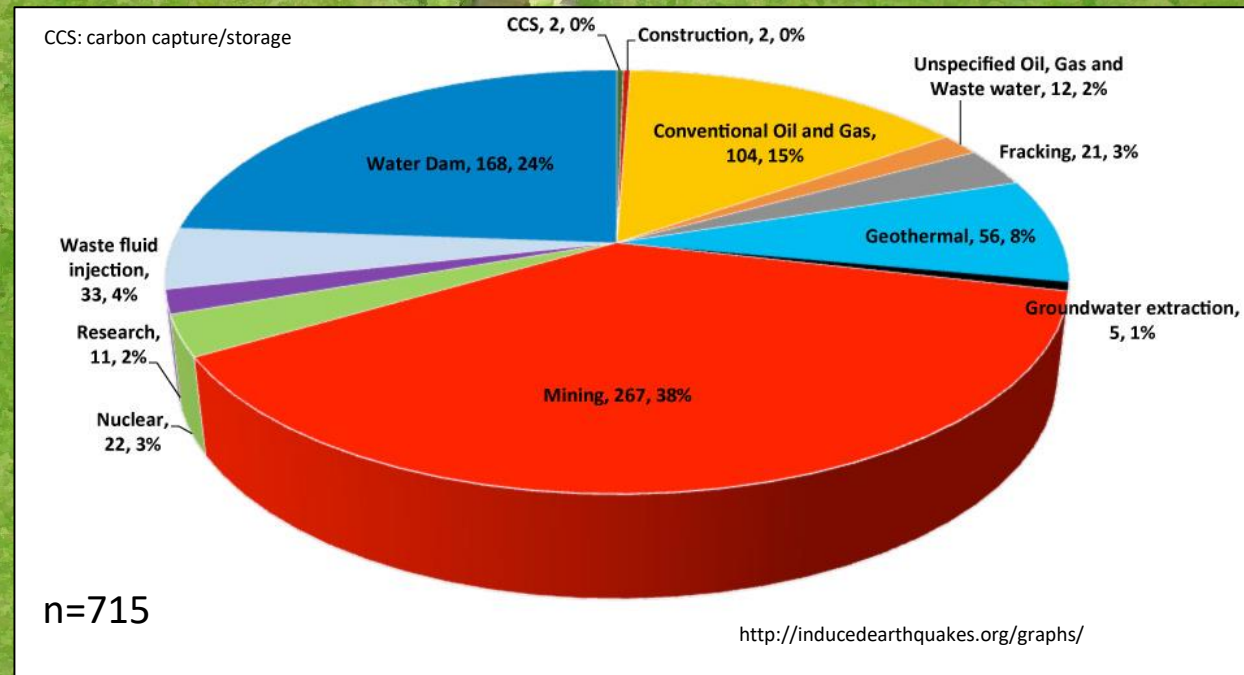
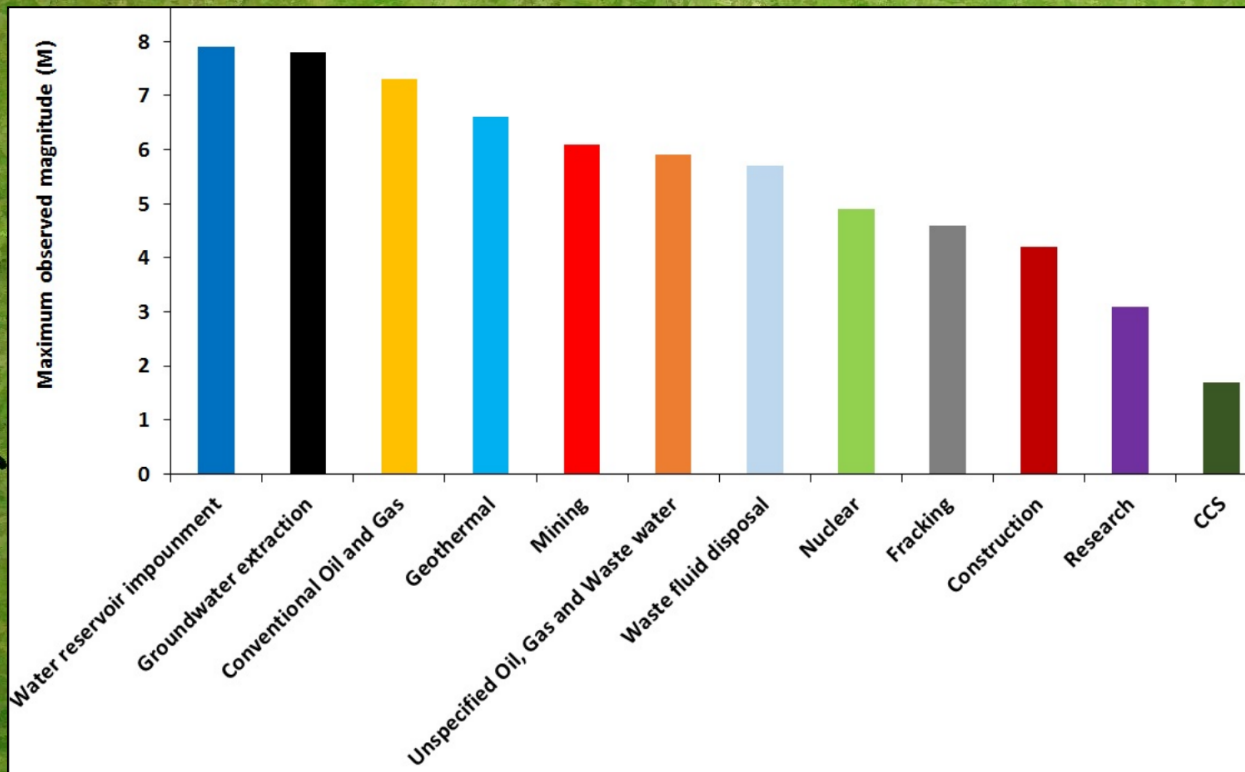
## Anthropogenic earthquakes





# Anthropogenic earthquakes:

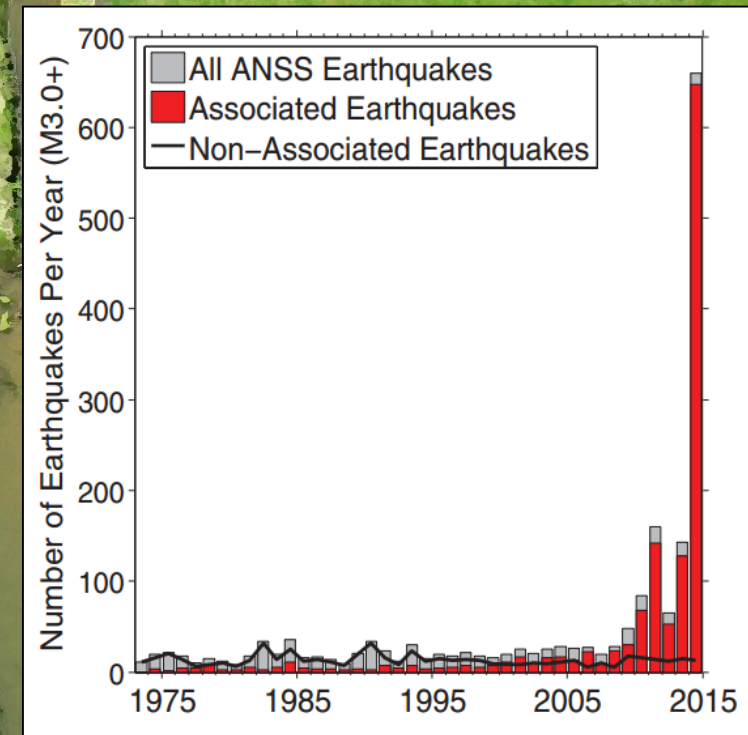
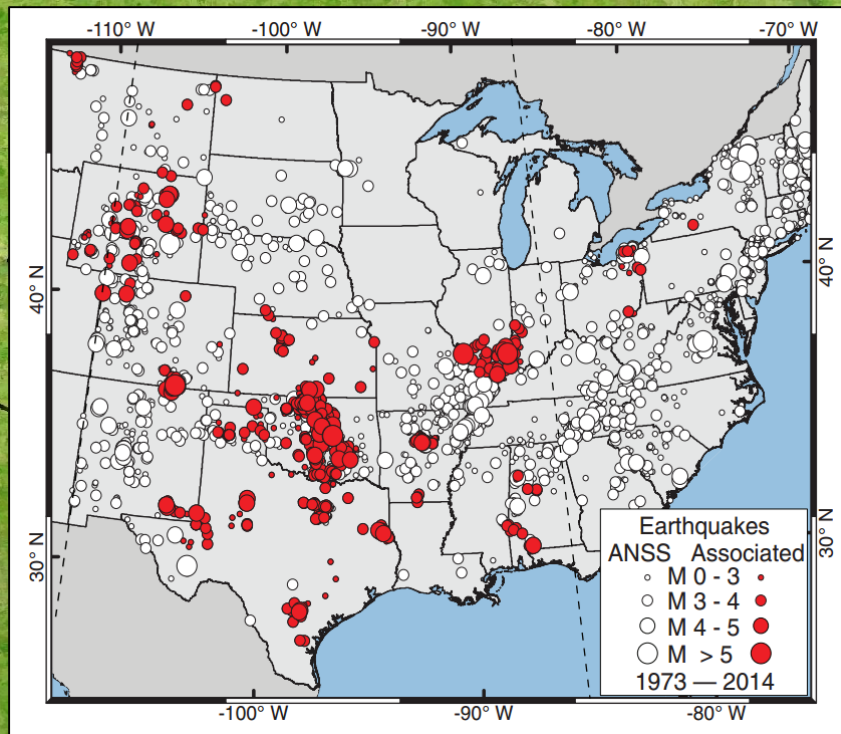
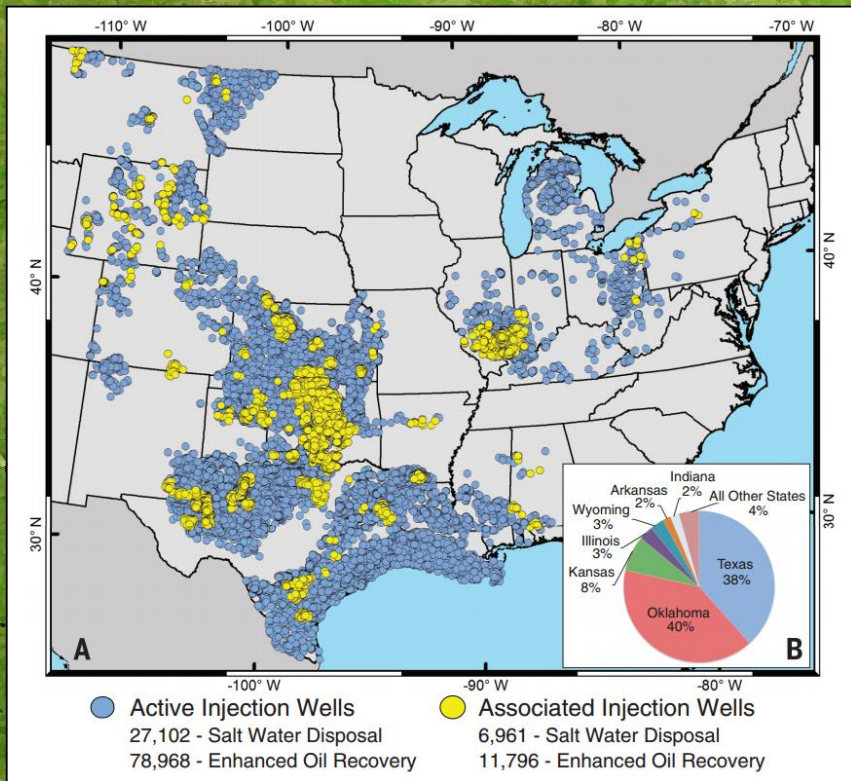
## Magnitudes and attribution to anthropogenic activities





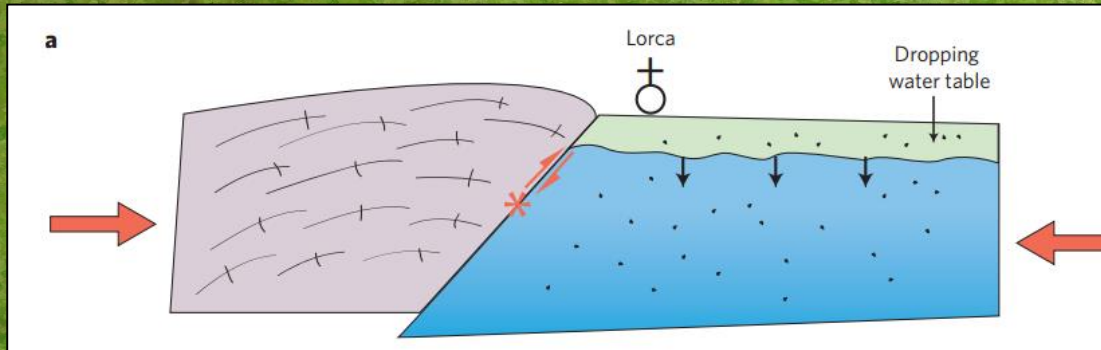
# Anthropogenic earthquakes:

## Changes in seismicity rates and locations

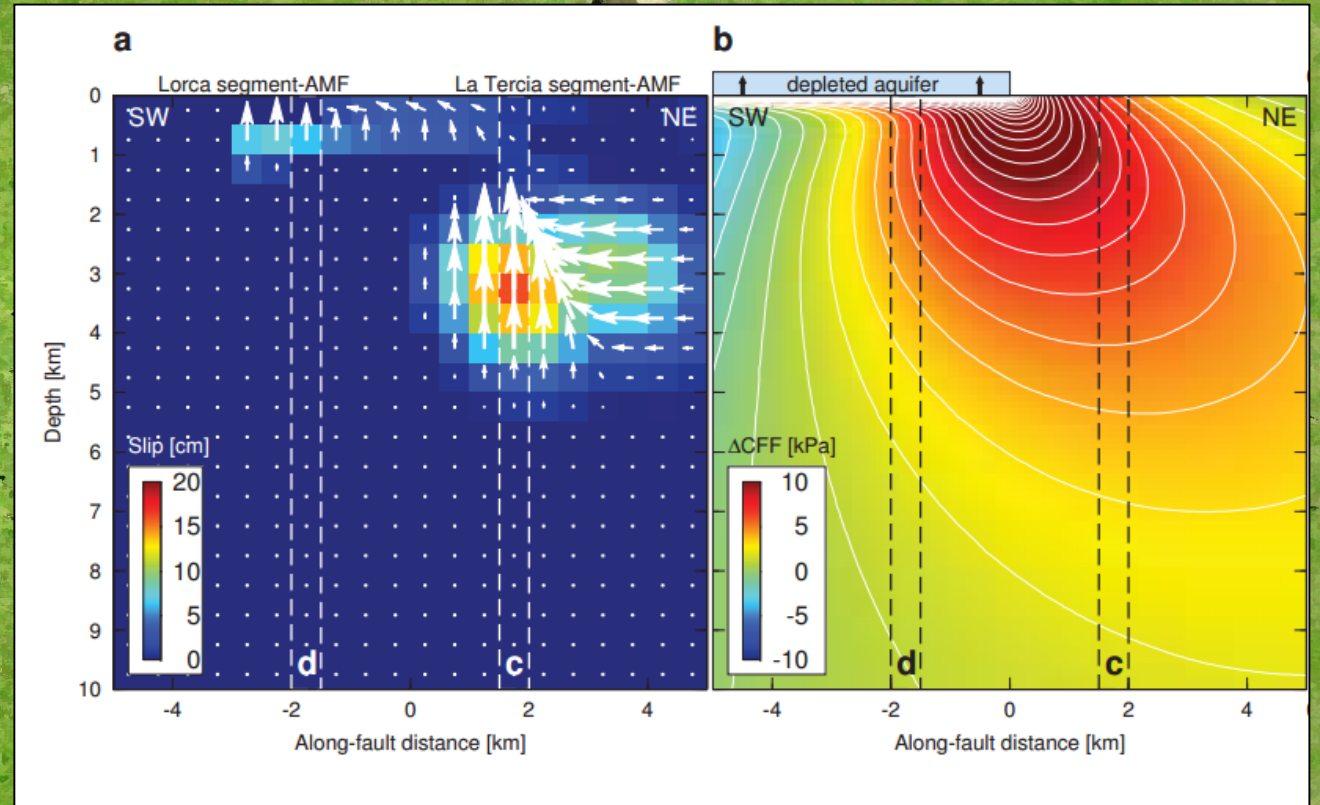




# Anthropogenic activity influences fault slip at depth



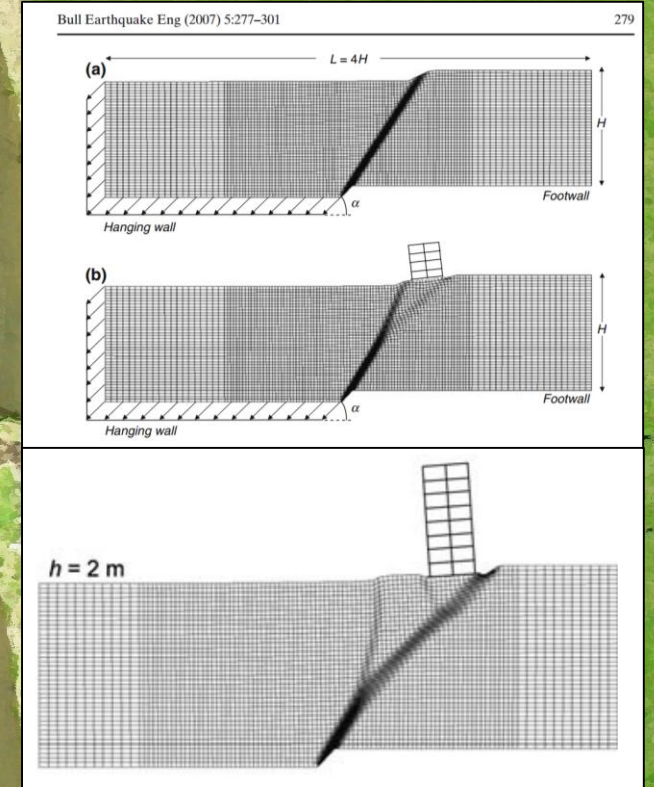
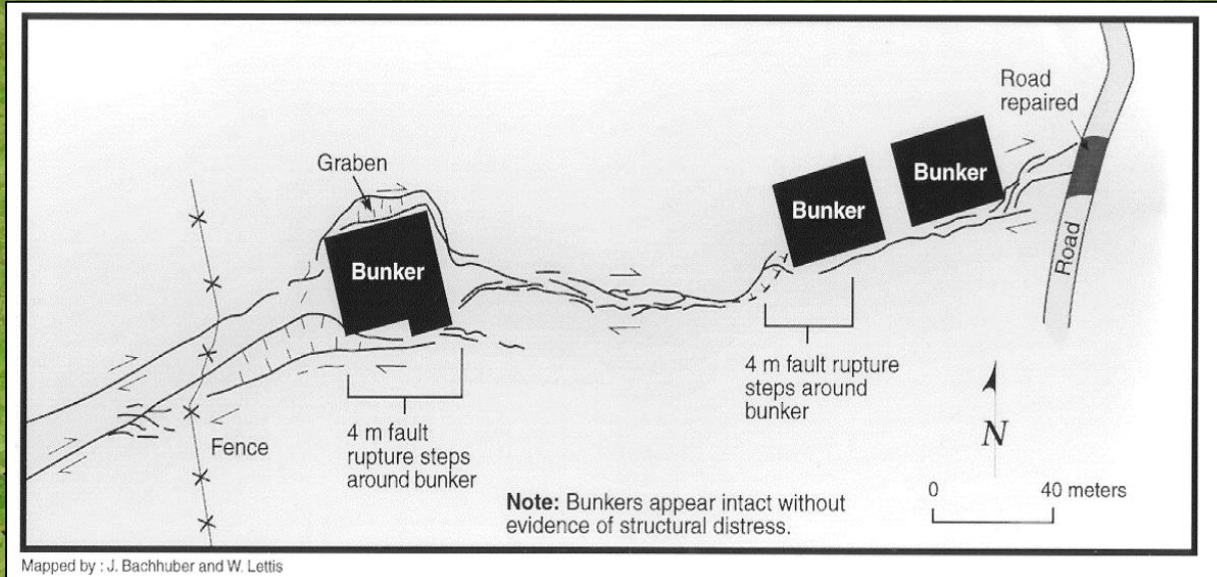
Crustal stress perturbations  
due to groundwater  
withdrawal influence slip  
distributions in 2011 Mw 5.1  
Lorca (Spain) earthquake





# Anthropogenic influences on earthquake surface ruptures

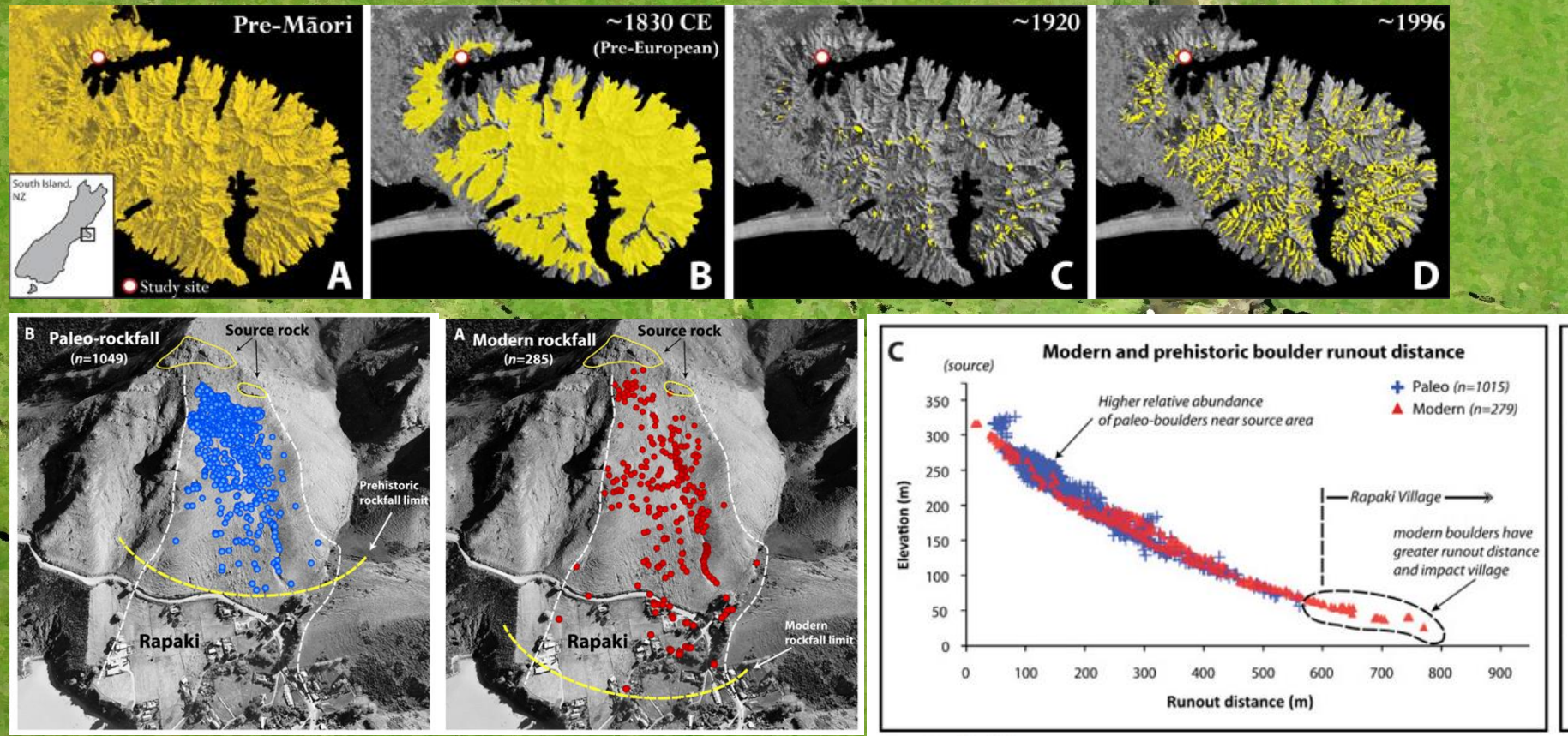
Anthropogenic structures influence surface rupture morphologies in 2007 Kocaeli (Turkey) and 2010 Darfield earthquakes



Numerical modelling shows effects of buildings on surface ruptures



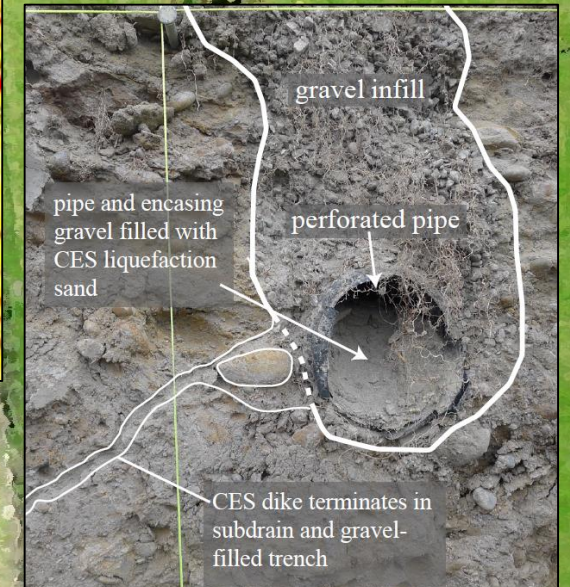
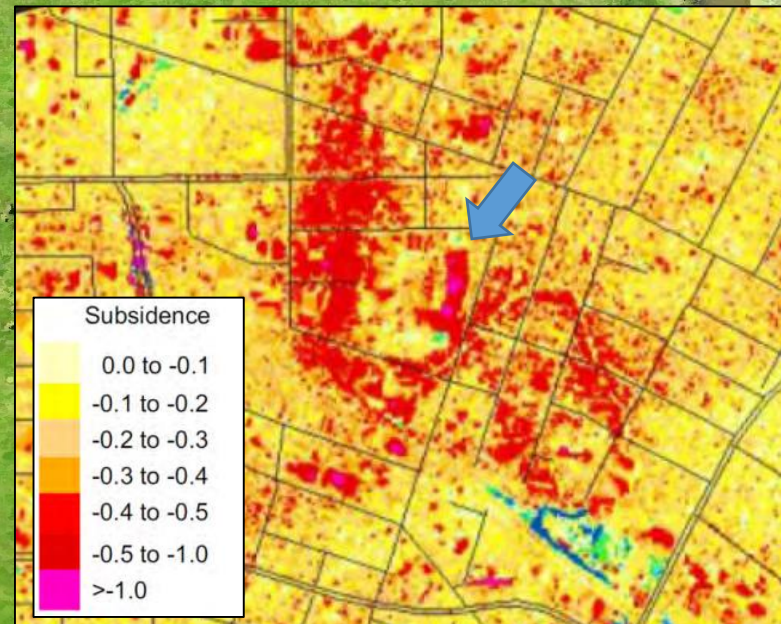
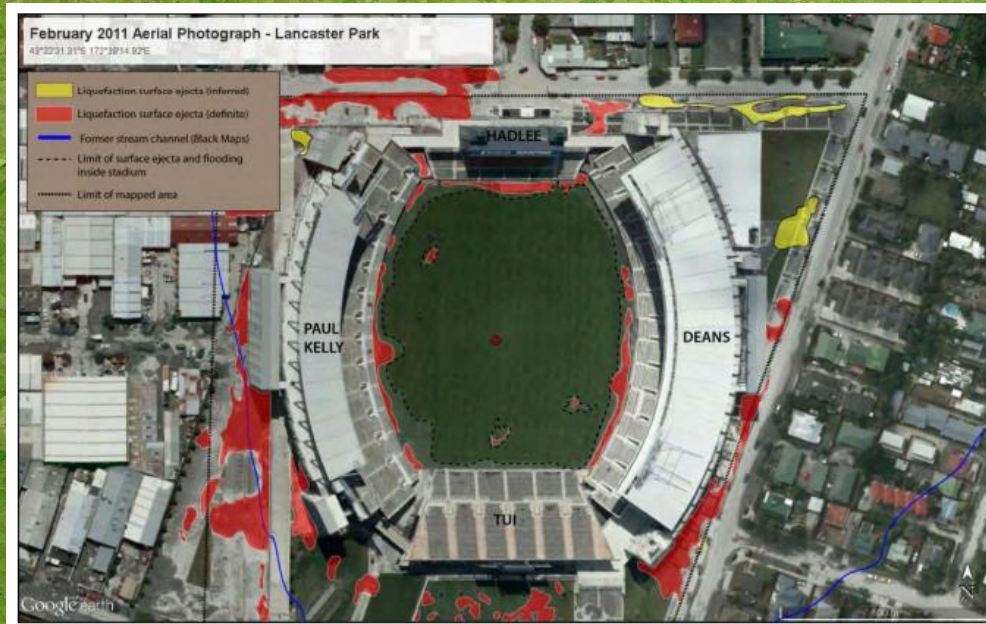
# Anthropogenic earthquake effects: Influences of deforestation on rockfall run-out distances



**SOURCES:** Mackey, B., and Quigley, M. (2014) Strong proximal earthquakes revealed by cosmogenic  $^3\text{He}$  dating of prehistoric rockfalls, Christchurch, New Zealand, *Geology*, 42 (11), 975-978;  
Borella, J., Quigley, M., Vick, L. (2016) Anthropocene rockfalls travel farther than prehistoric predecessors, *Science Advances* Vol. 2, no. 9, e1600969, DOI: 10.1126/sciadv.1600969

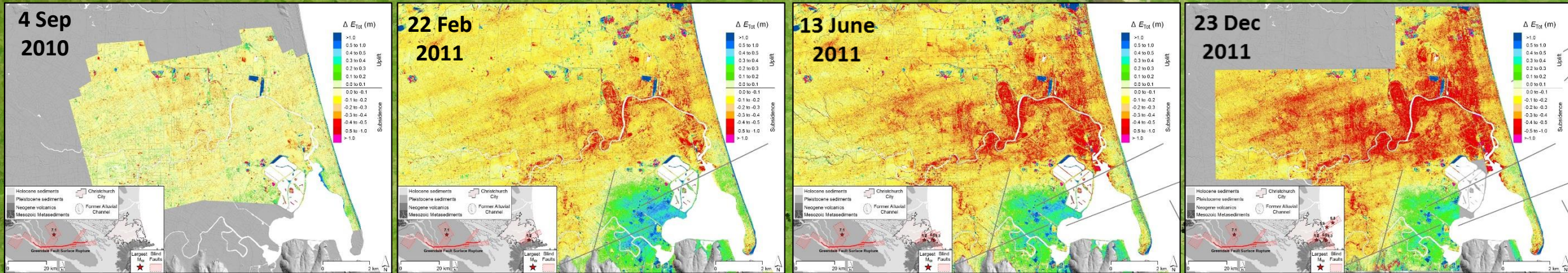


# Anthropogenic earthquake effects: Influences of infrastructure on liquefaction





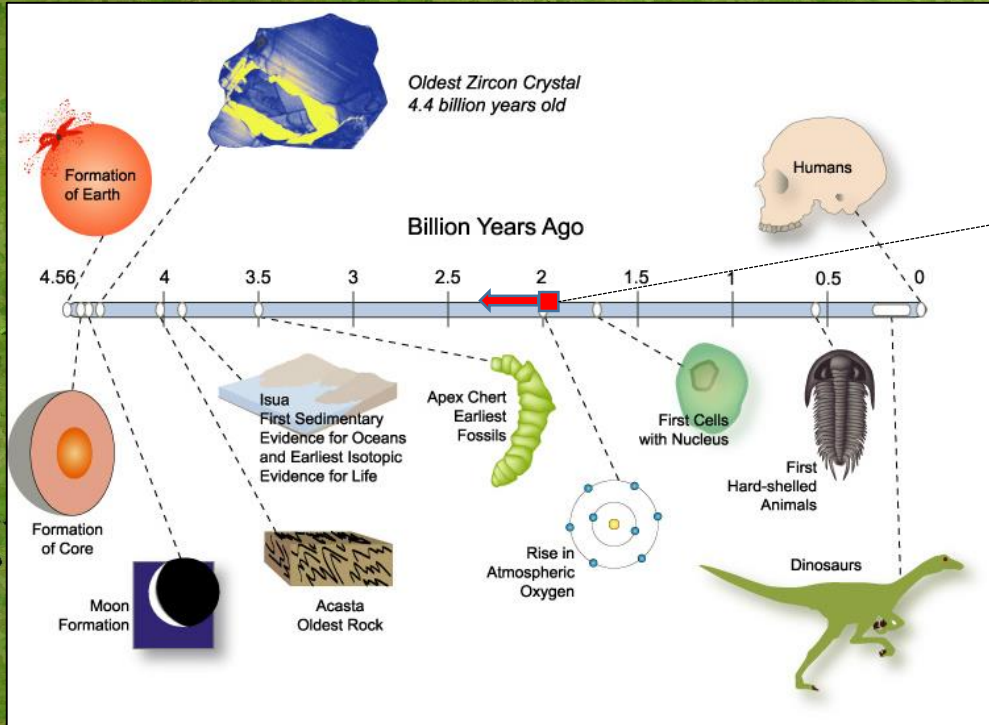
# Anthropogenic post-earthquake geomorphology: Doing Mother Nature's work for her?



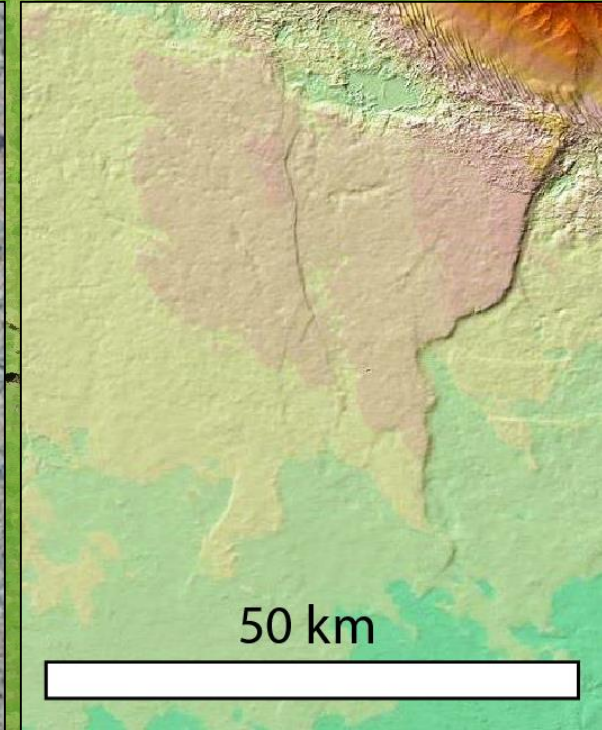


# Earth's first quakes

Earthquakes millions and billions of years before us



$\geq 2$  billion year old seismogenic frictional melts



$\geq 1$ -2 million year old fault scarps

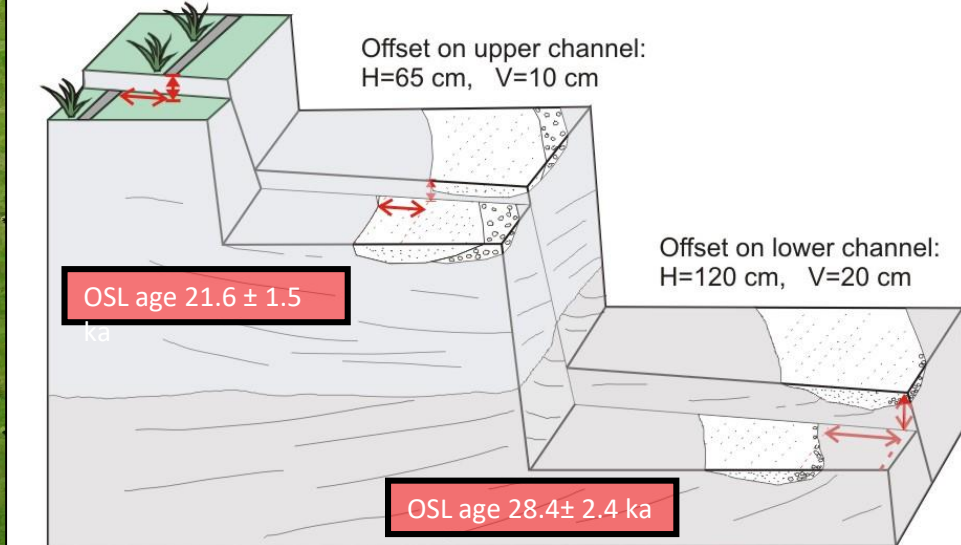


# Historic earthquakes have analogous pre-Anthropocene predecessors

Earthquakes on pre-existing faults

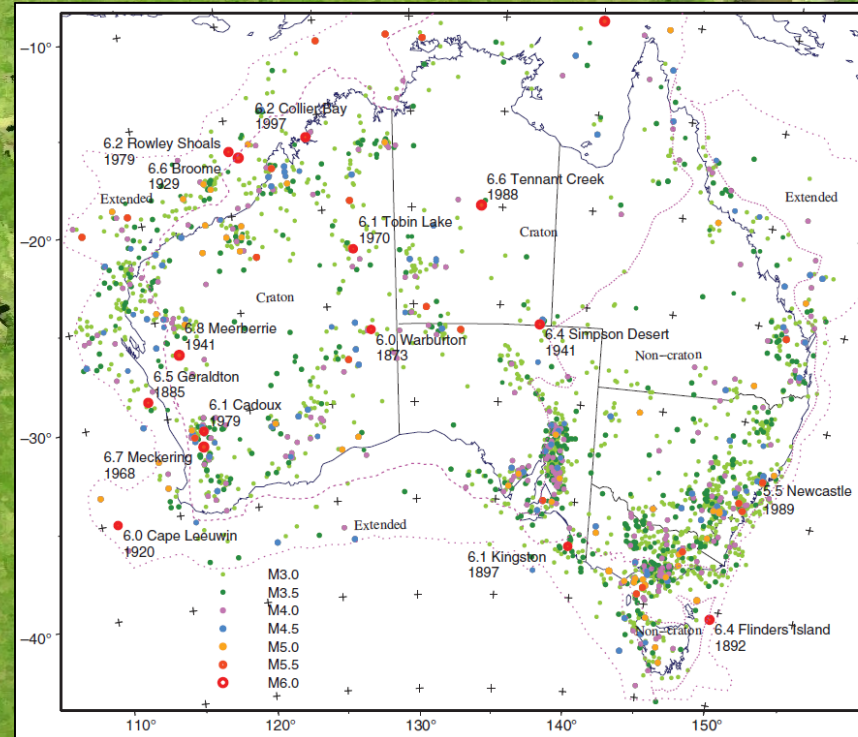


2010 offset measured along structure on surface  $H=60\pm 10$  cm

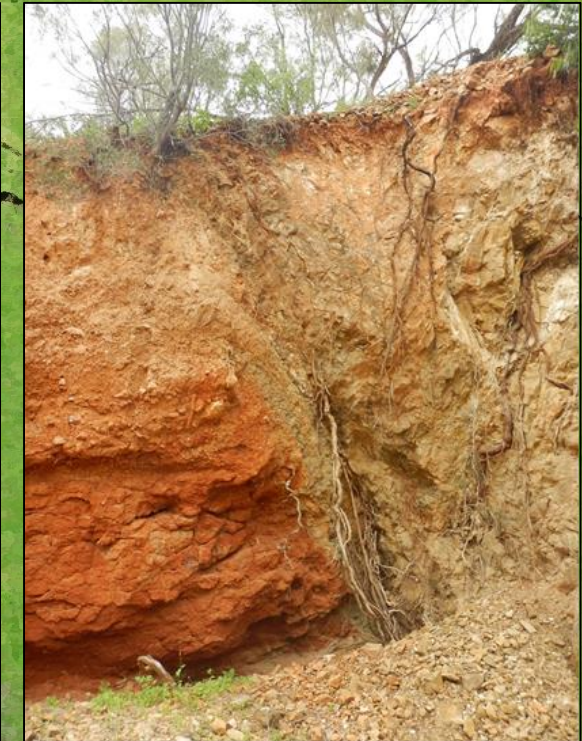


Evidence for the penultimate earthquake on the 2010 Darfield earthquake source fault

Large prehistoric earthquakes in areas of contemporary intraplate seismicity



Intraplate seismicity and active faulting in Australia

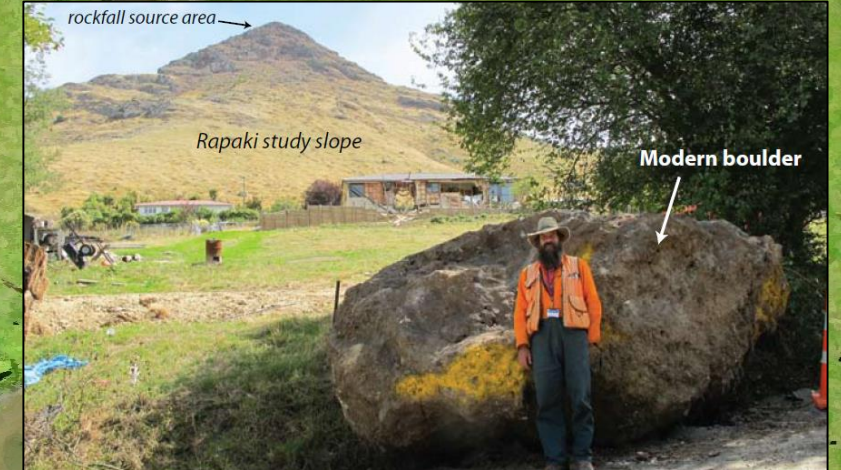
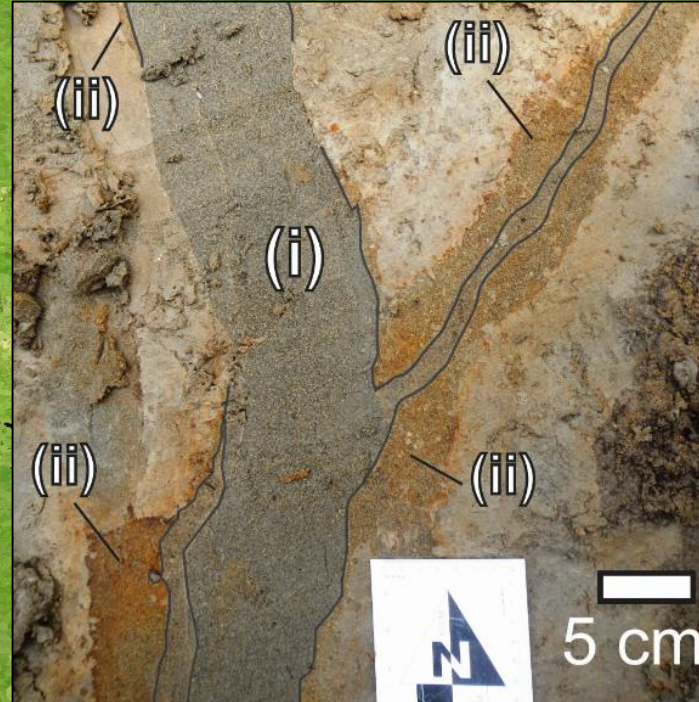




# Historical earthquake effects have analogous pre-Anthropocene predecessors



Contemporary and prehistoric liquefaction in Christchurch, NZ



Contemporary and prehistoric rockfalls in Christchurch, NZ



# Earthquakes in the Anthropocene

The human influence on earthquakes and their environmental effects

- Historical earthquakes have analogous pre-Anthropocene predecessors – the geologic record remains important for forecasting the effects of future earthquakes
- Humans are influencing the locations, rates, and character of earthquakes, the severity of their environmental effects (surface ruptures, rockfalls, liquefaction), and the geologic legacy of these effects
- When using the attributes of past earthquakes to forecast future ones, one must be mindful of these potentially intervening anthropogenic influences

Thanks: Brendan Duffy, Josh Borella, Gary Gibson

PowerPoint of this presentation available at [www.drquigs.com](http://www.drquigs.com)

