Geologic and geomorphic impacts of the 2010-2012 Canterbury earthquake sequence and local evidence for large prehistoric earthquakes

M.C. Quigley

Department of Geological Sciences

University of Canterbury

2013 Hochstetter Lecture

UC
UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

Geoscience Society of New Zealand

THANKS!

Funders

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Collaborators

GNS Science, Te Pū Ao

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University of Ulster

University of Calgary

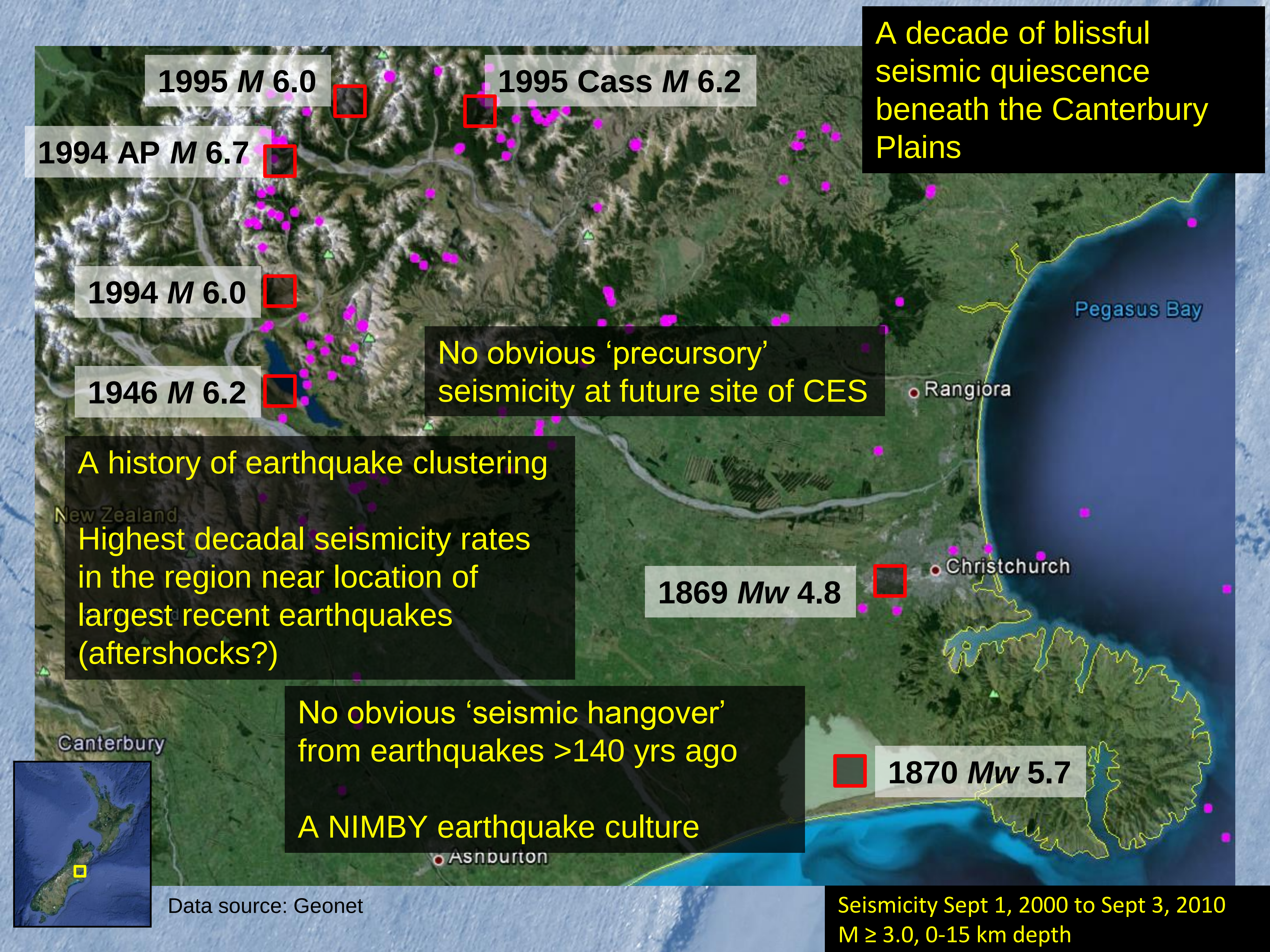
USC University of Southern California

Lincoln University, Te Whare Wānaka o Aoraki, Christchurch New Zealand

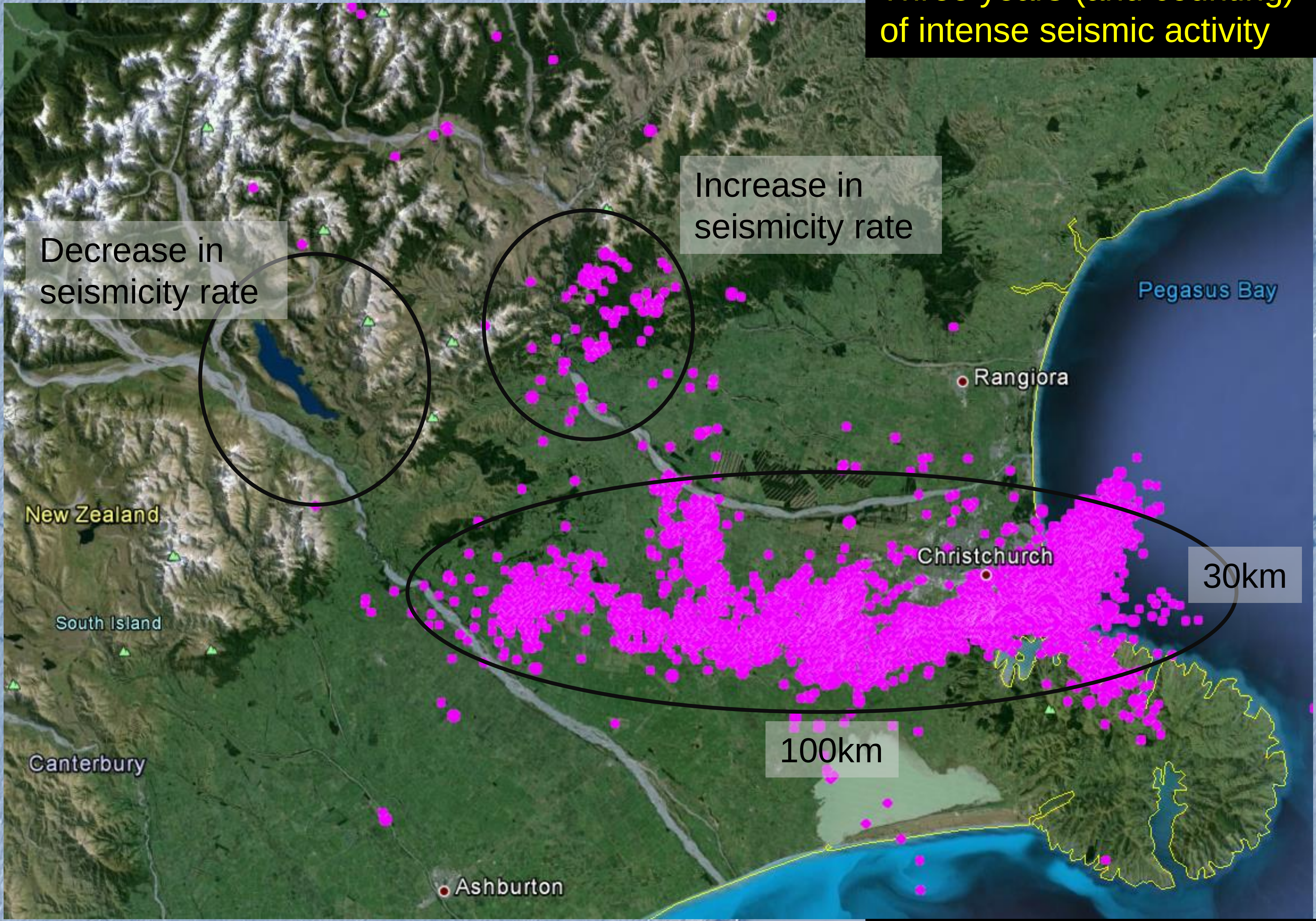
Western University Canada

Students

Dr. Brendan Duffy, Timothy Stahl, Dr. Eric Bilderback, Narges Khajavi, Sarah Bastin, Sharon Hornblow, Gregory De Pascale, Peri Sasnett, and many others!


A decade of blissful seismic quiescence beneath the Canterbury Plains
1995 M 6.0
1995 Cass M 6.2
1994 AP M 6.7
1994 M 6.0
1946 M 6.2
No obvious 'precursory' seismicity at future site of CES
Rangiora
Pegasus Bay
A history of earthquake clustering
New Zealand
Highest decadal seismicity rates in the region near location of largest recent earthquakes (aftershocks?)
Christchurch
1869 Mw 4.8
No obvious 'seismic hangover' from earthquakes >140 yrs ago
A NIMBY earthquake culture
1870 Mw 5.7
Canterbury
Ashburton
Data source: Geonet
Seismicity Sept 1, 2000 to Sept 3, 2010
M ≥ 3.0, 0-15 km depth

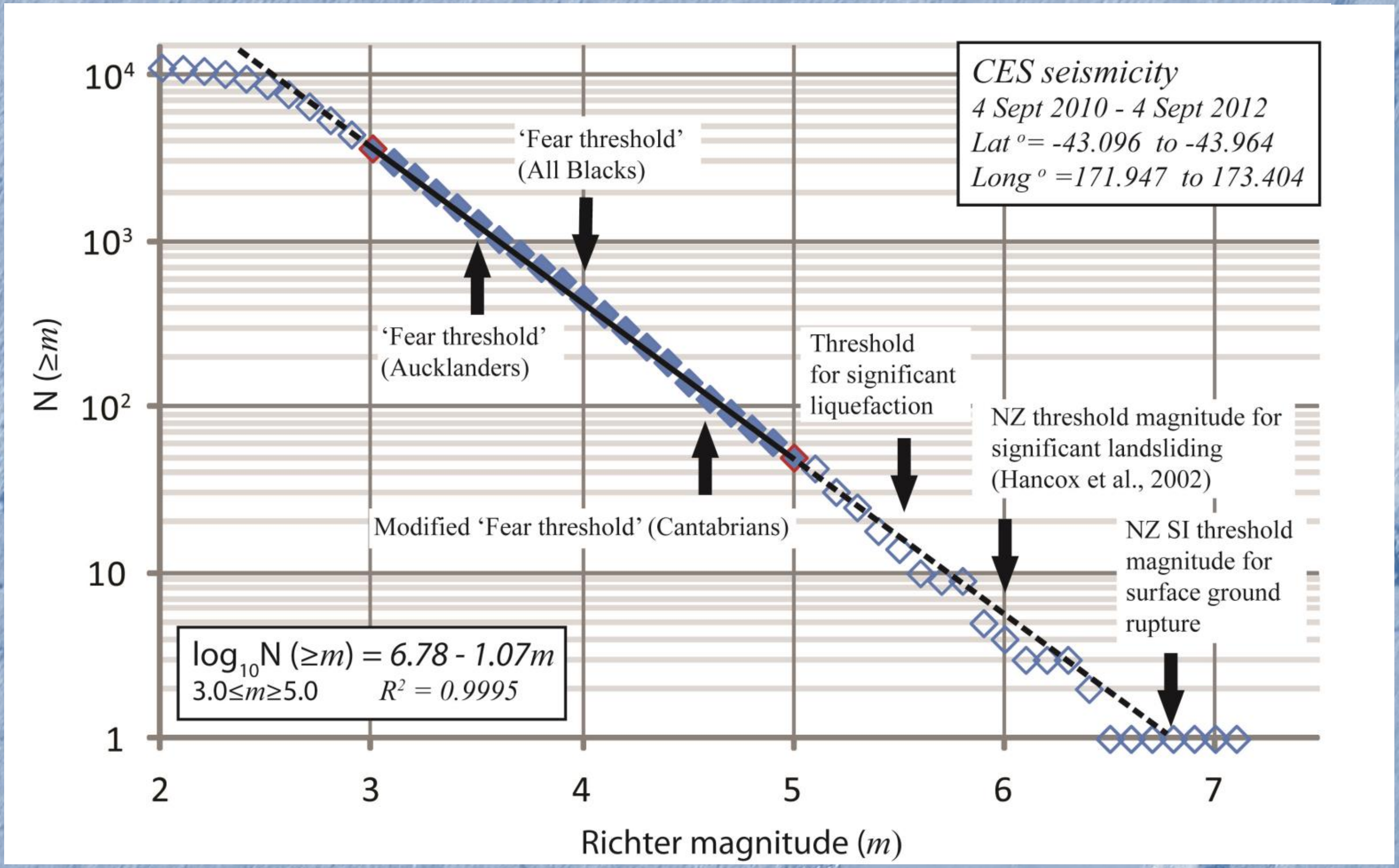
Three years (and counting) of intense seismic activity



Seismicity Sept 4, 2010 to July 1, 2013
M ≥ 3.0, 0-15 km depth

Data source: Geonet

Truth and beauty of earthquakes: The Gutenberg-Richter relationship



1 earthquake sequence

100s of 'heart-in-throat' moments (prolonged stress and anxiety)

10 liquefaction episodes at some locations (4 major)

5 rockfall episodes at some sites (3 major)

Earthquake comparisons: Counting the costs

	4 September 2010	22 February 2011	13 June 13 2011	23 December 2011
Mag (M_w)	7.1	6.2	6.0	5.9
Epicentre[1]	30 km W	10 km SE	10 km SE	10 km E
Time[2]	4:36 am	12.51 pm	2.20 pm	3.18 pm
Max PGA[3]	0.6g (0.3g CBD)	2.2g (0.8g CBD)	2.2g (0.4g CBD)	0.96g[4] (0.25g CBD)
Casualties	0 fatalities	185 fatalities	0 fatalities	0 fatalities
Building Damage	To older brick & URM	All pre-1970s & several modern buildings with eccentric design	Further residential damage in Port Hills & already damaged CBD buildings	Minor, but several instances of progressive failure
Liquefaction	Widespread in eastern suburbs	Extreme damage in many eastern Christchurch suburbs	Further damage in eastern Christchurch suburbs	Minor damage in eastern Christchurch suburbs
Cost[5]	4-5 billion	15-20 billion	c. 1.5 billion	c. 26 million

Loss of life and most damage occurred in an ‘aftershock’ on a previously unknown ‘blind’ fault
Most fatalities in two building collapses – building stock performed well from life safety perspective but poorly from a ‘post-event functionality’ perspective

Berryman, 2012

Earthquake comparisons: Counting the costs

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Notes:

1. Epicentral distances are with respect to Christchurch CBD

More recent cost estimates exceed $40 Billion – this is almost 30% of New Zealand's real GDP

Berryman, 2012

Earthquake comparisons: Counting the costs

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Building Damage	To older brick & URM	All pre-1970s & several modern buildings with eccentric design	Further residential damage in Port Hills & already damaged CBD buildings	Minor, but several instances of progressive failure
Prob	**1/475 yr**	**1/12,000 yr**	**1/1,000 yr**	**1/300 yr**
%	0.2	0.008	0.08	0.3
Cost[5]	4-5 billion	15-20 billion	c. 1.5 billion	c. 26 million

Notes:
1. Epicentral distances are with respect to Christchurch CBD

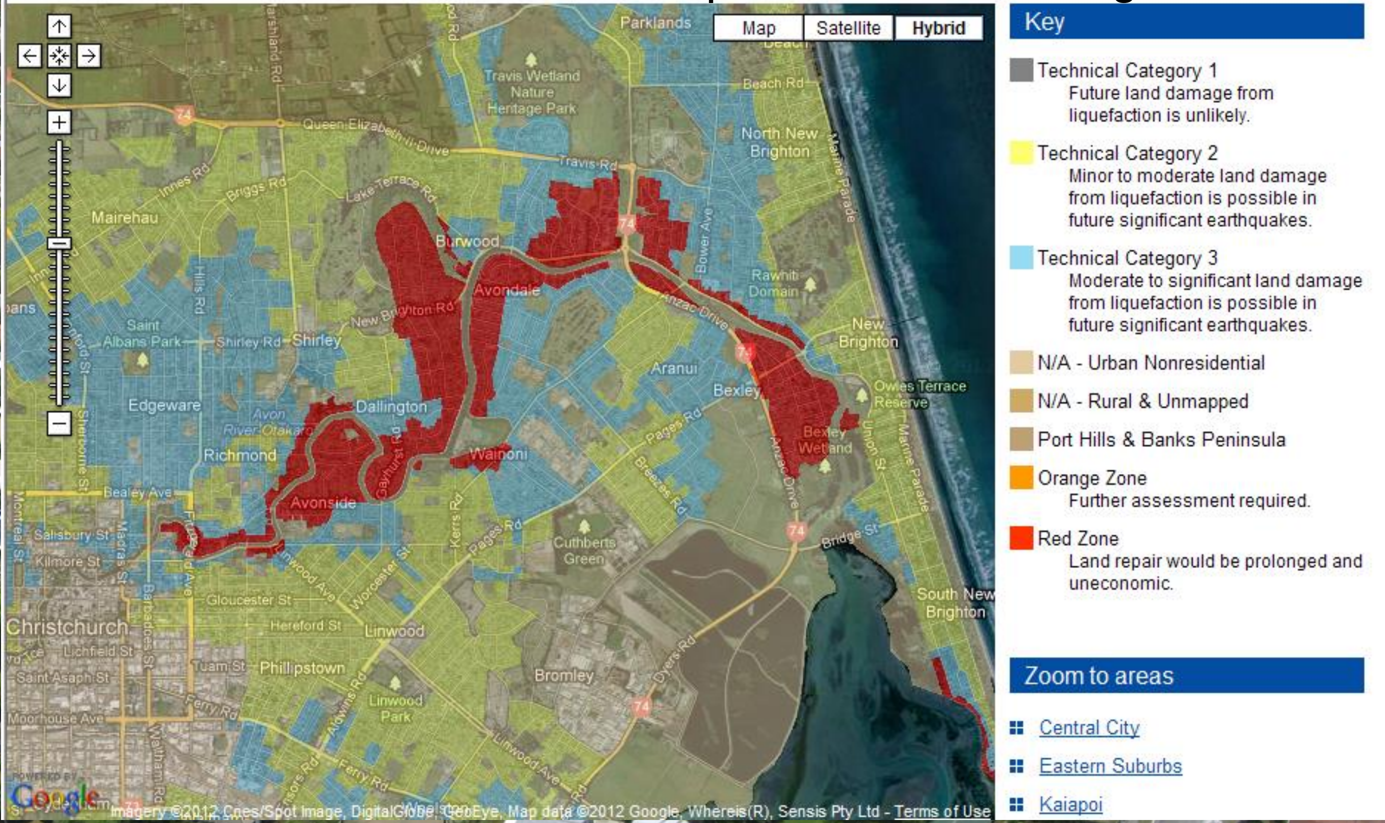
High PGAs and earthquake clustering

Communicating science during a time-evolving hazard: The importance of discussing 'relative probability change' in addition to absolute probabilities

Berryman, 2012

An acceptable risk or an avoidable mistake?

A $1.1 B question for central government

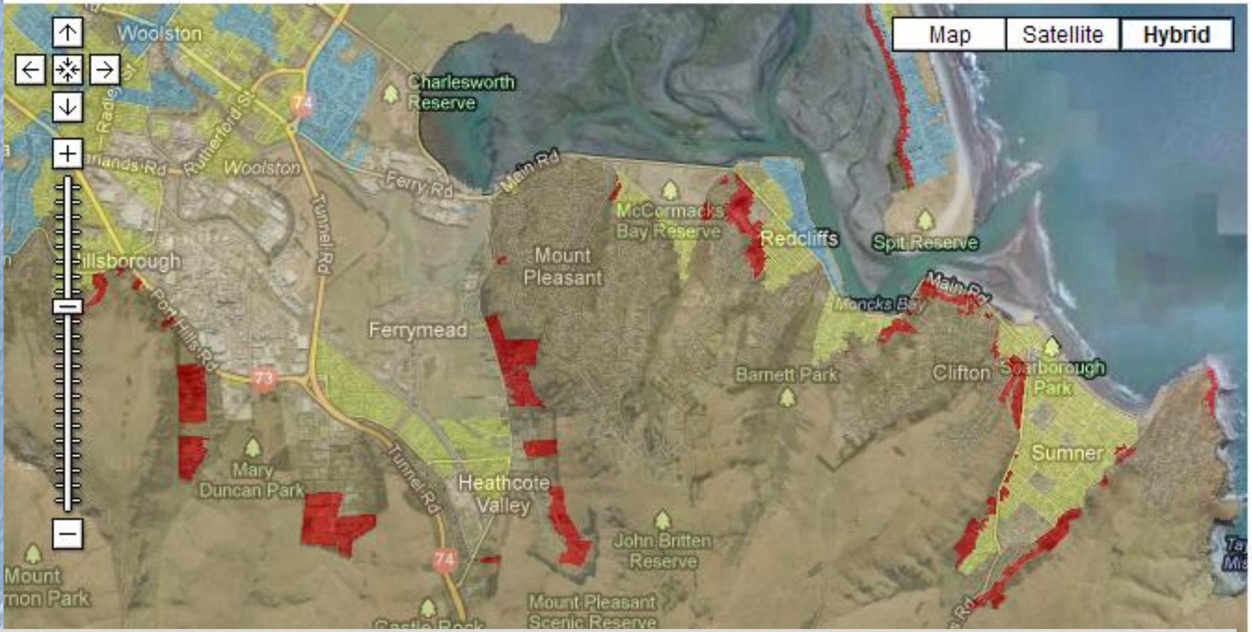


Bexley: A modern suburb built at sea-level in a designated high-risk flood zone on ChCh’s most liquefaction susceptible soils (1/75 to 1/100 yr threshold)

http://www.abc.net.au/news/image/2756902-3x2-940x627.jpg

GEER report 2011

Central City



Key

- Technical Category 1 — Future land damage from liquefaction is unlikely.
- Technical Category 2 — Minor to moderate land damage from liquefaction is possible in future significant earthquakes.
- Technical Category 3 — Moderate to significant land damage from liquefaction is possible in future significant earthquakes.
- N/A - Urban Nonresidential
- N/A - Rural & Unmapped
- Port Hills & Banks Peninsula
- Orange Zone — Further assessment required.
- Red Zone — Land repair would be prolonged and uneconomic.

Modern houses built immediately above and below seacliffs

5 rockfall fatalities, lots of luck, and some lessons learned

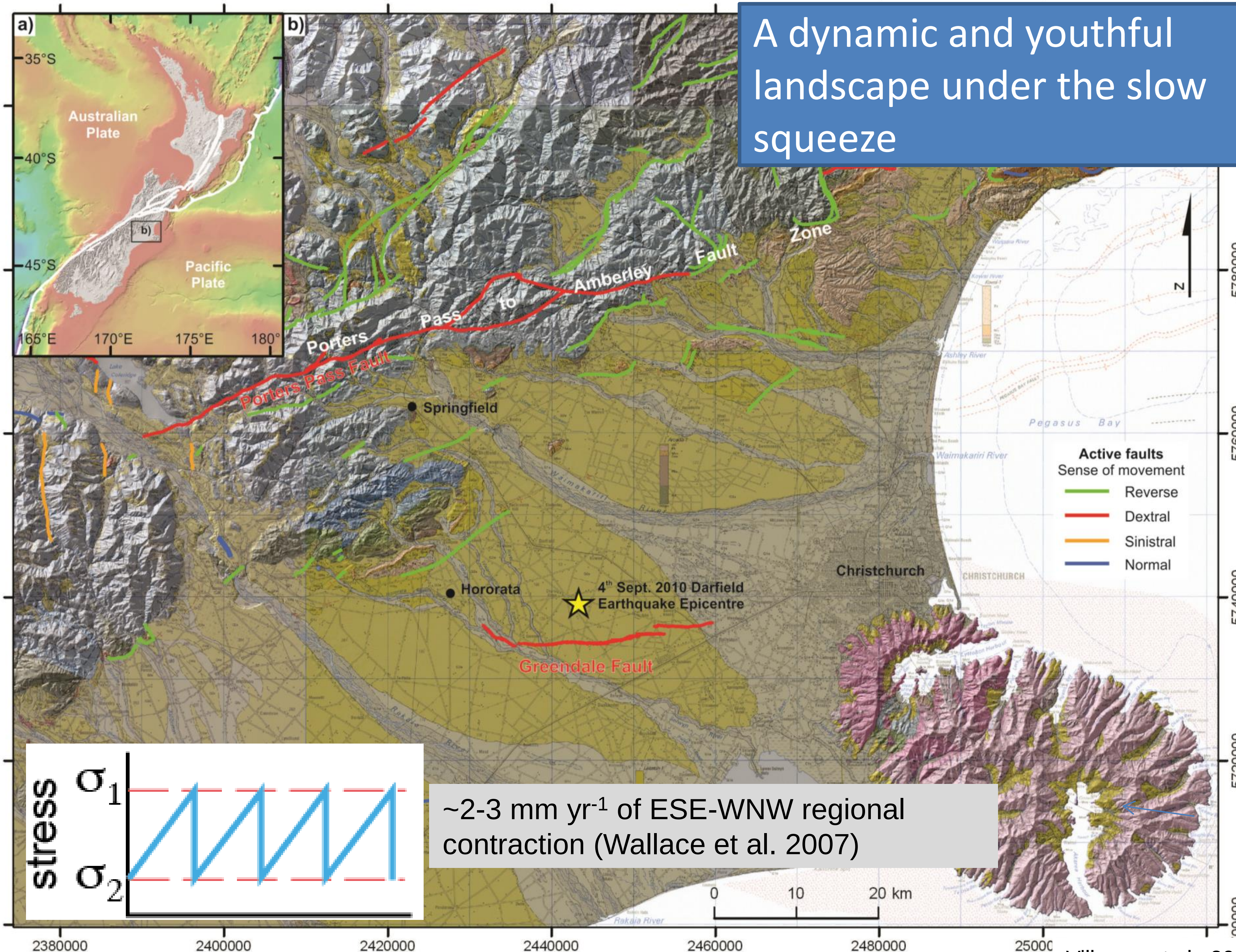
Some starting lessons

- Proactive, science-based land-use planning and structural and lifeline engineering is fundamental to reducing loss
- Reactive approach is more expensive, very complicated (science, politics, community well-being) and takes a large toll on people and the environment
- ‘Personalize your hazard’ (including ‘greenfields’)
- Combining ‘top-down’ and ‘bottom-up’ approaches to science communication will best facilitate good decision making and community acceptance

Kaiapoi resident Brent Cairns says all he wants is transparency.
“I want to see is why my land deemed to be in the red zone, when we've lived there for over a year.” TV3 Sept 2011

Some science

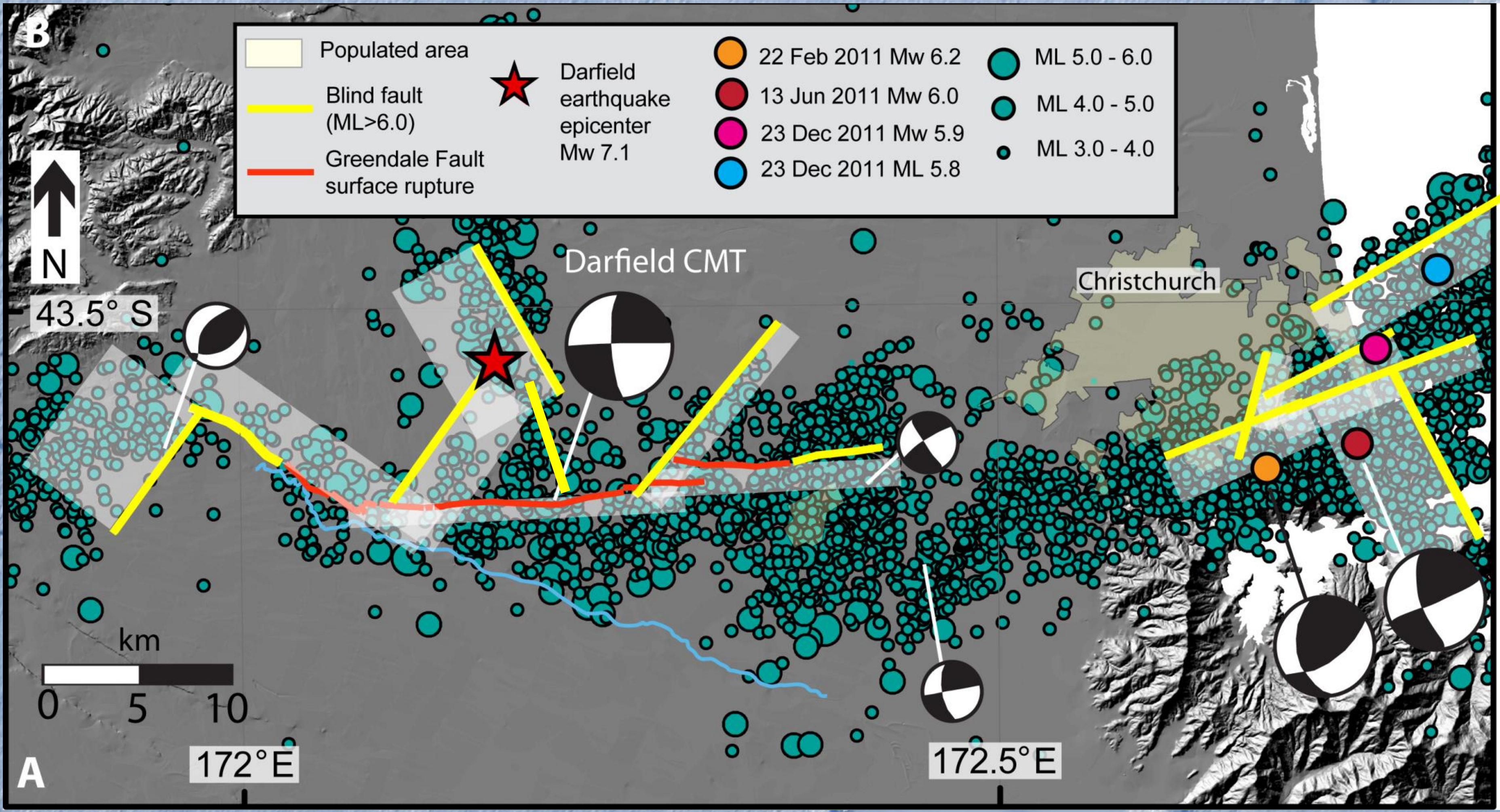
A dynamic and youthful landscape under the slow squeeze



~2-3 mm yr^{-1} of ESE-WNW regional contraction (Wallace et al. 2007)

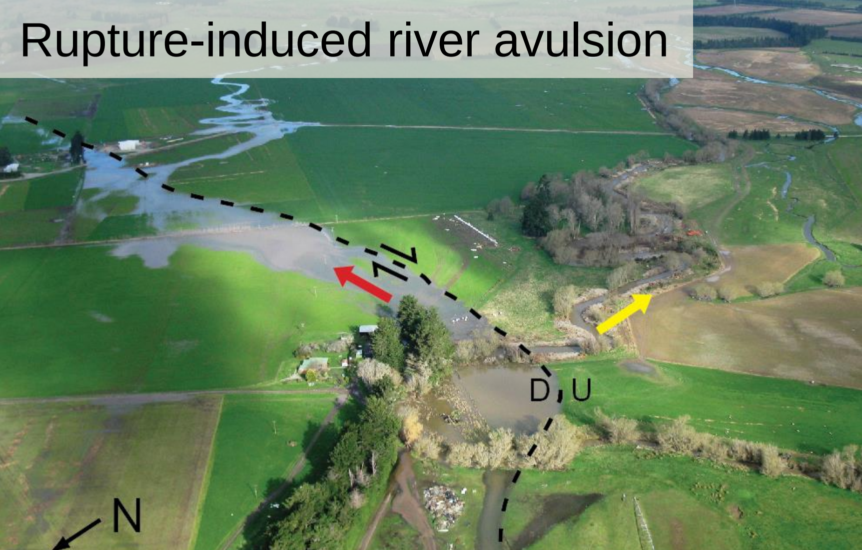
Villamor et al., 2011

The 2010-2012 Canterbury earthquake sequence



Complex faulting (SS_D, SS_S, R, N)

1 surface rupture, at least 12 'blind' faults



Rupture-induced river avulsion

Fault rupture damage: Important questions

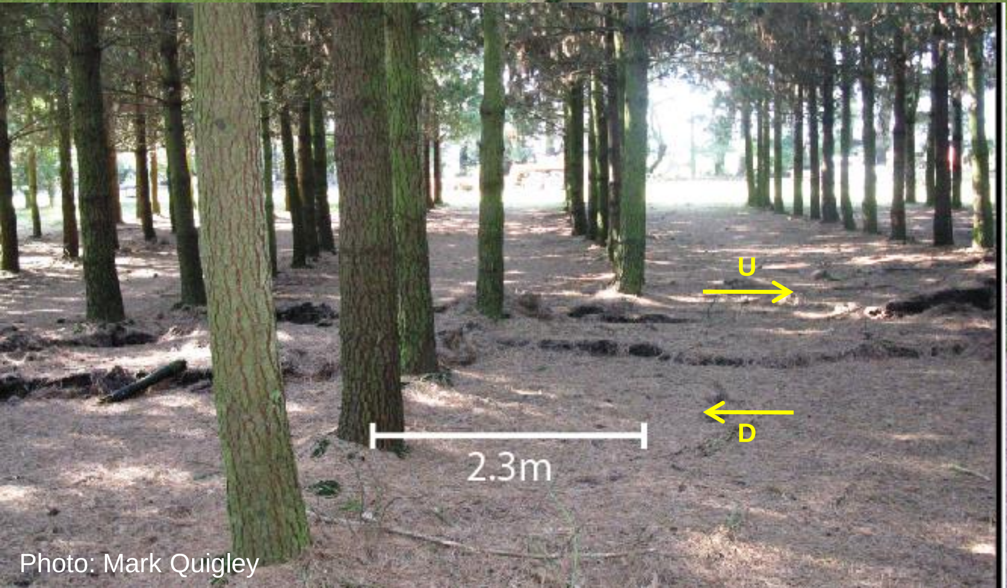
- Relationship between earthquake magnitude, surface displacement, and SRL
- Thresholds between surface cracking and folding
- Width of deformation zone
- Return times (surface rupture and slip on related faults)

→ Forecasting earthquake hazards, designing resilient structures and lifelines, land-use planning (fault set-backs), interpreting paleo-earthquakes from the geologic record

Damage to lifelines

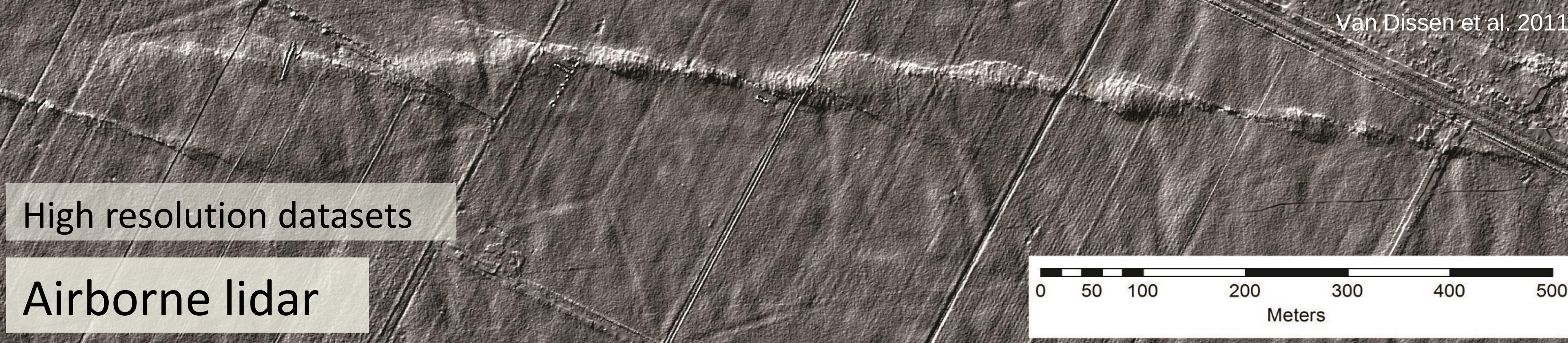
Damage to structures

Surface rupture trace: from the subtle to sublime

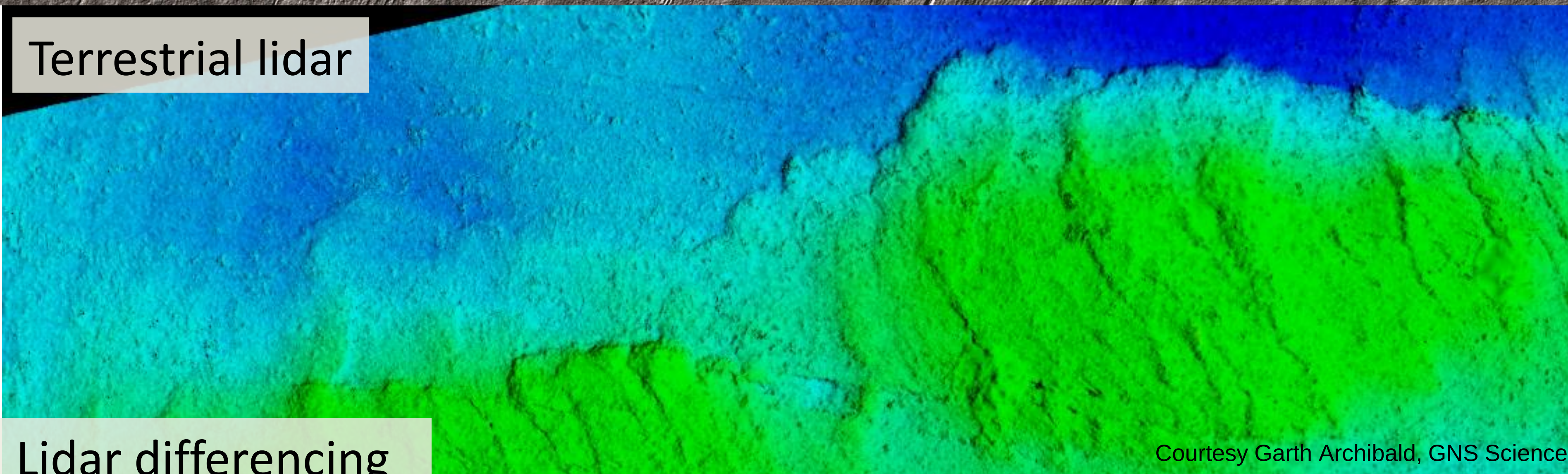


High resolution datasets

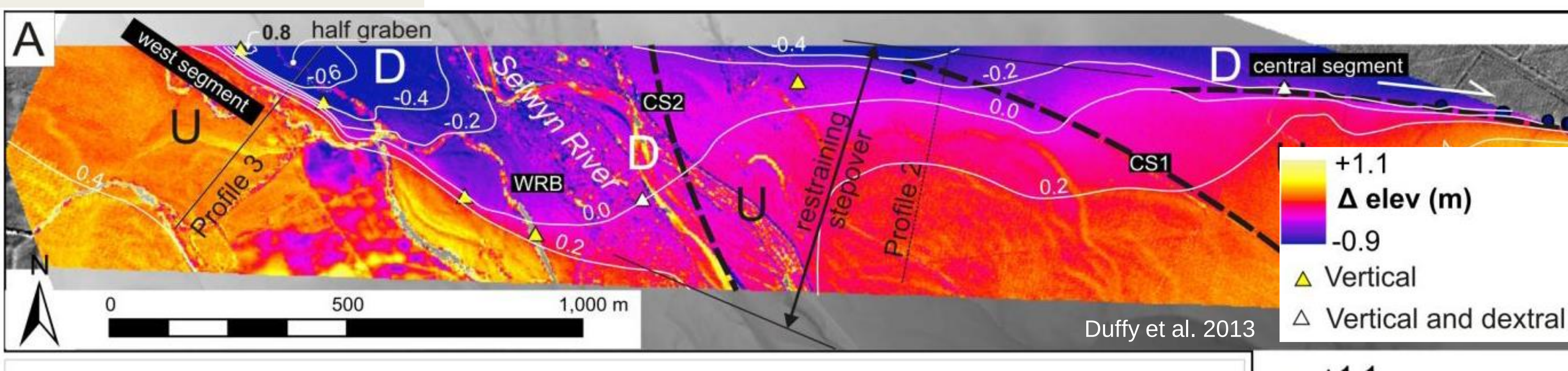
Airborne lidar



Terrestrial lidar



Lidar differencing

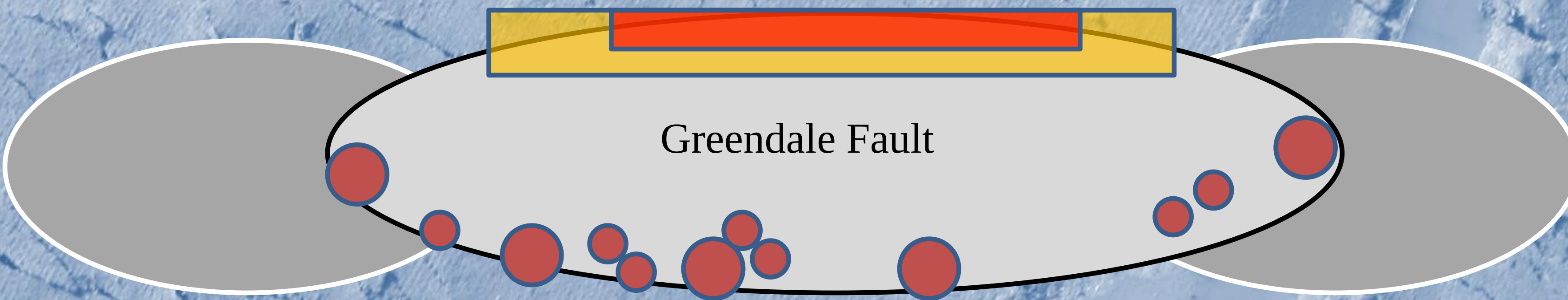


MAPPED SURFACE RUPTURE LENGTH (HISTORIC) = 29.5 ± 0.5 km

Mw 6.8-6.9

IDENTIFIABLE WITHOUT AGRICULTURAL FEATURES (GEOLOGIC) ≤ 20 km

Mw 6.6-6.7



GF SUBSURFACE RUP LENGTH (GEODETIC / SEISMOLOGIC) ~48 km

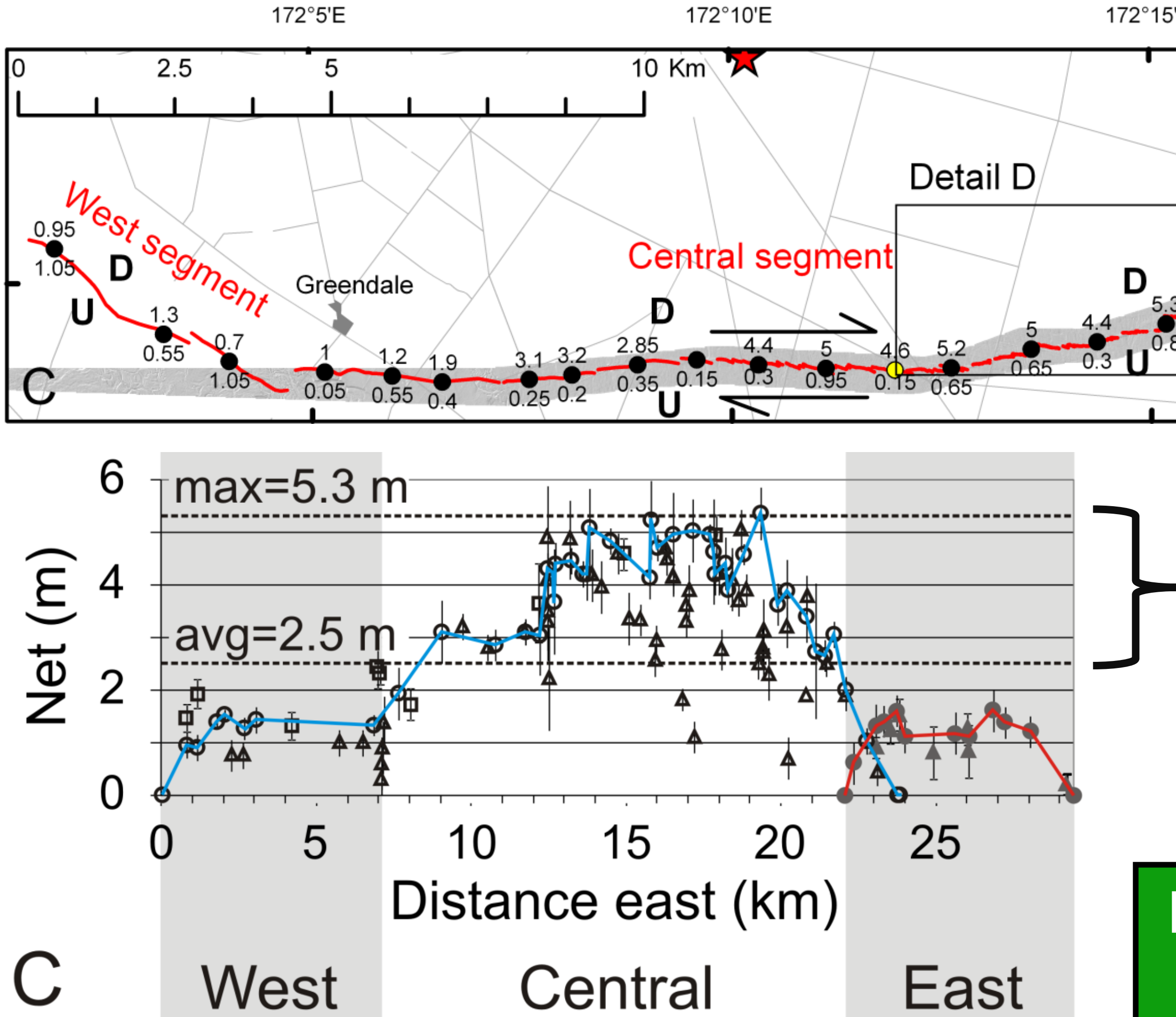
Mw 6.9-7.0

COMBINED SUBSURF RUP LENGTH (GEODETIC / SEISMOLOGIC) ~86 km

Mw 7.1

Importance of understanding how geologic record of active faulting rel to subsurface rupture potential: *E* Mw 7.1 = 6X *E* Mw 6.6

>100 field measurements,
1000s of potential strain markers
-Fault displacements
-Thresholds between bending and breaking
R. Cosgrove



Quigley et al 2012

Mw 7.4 from scaling rel

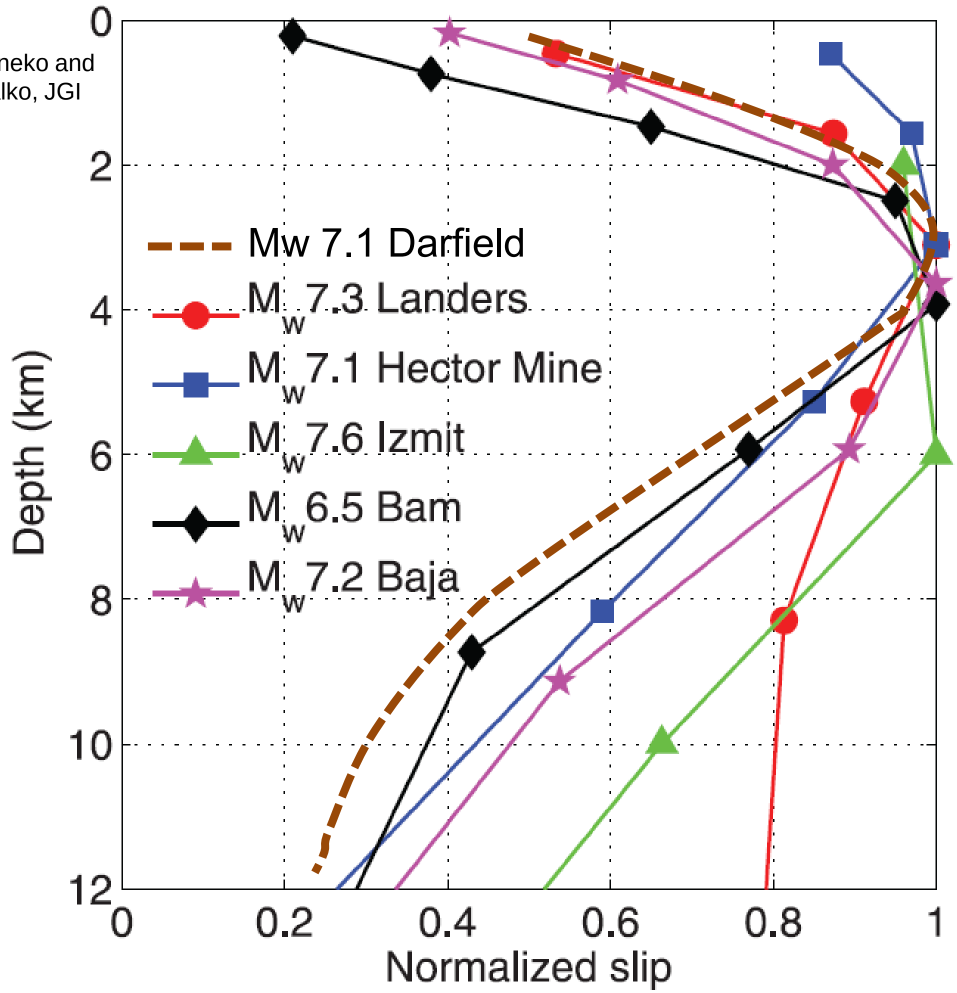
Why?

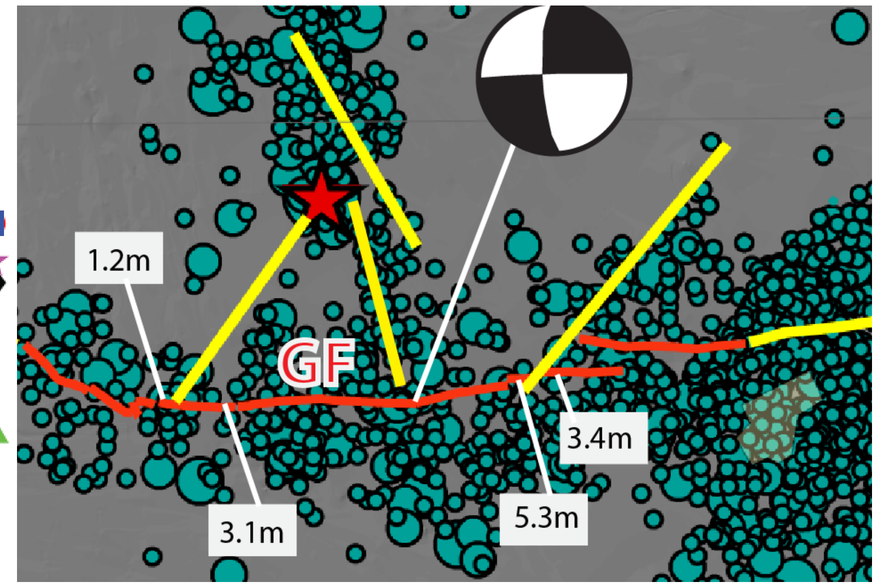
Lots of surface slip?

Slip distribution?

Measurement technique?

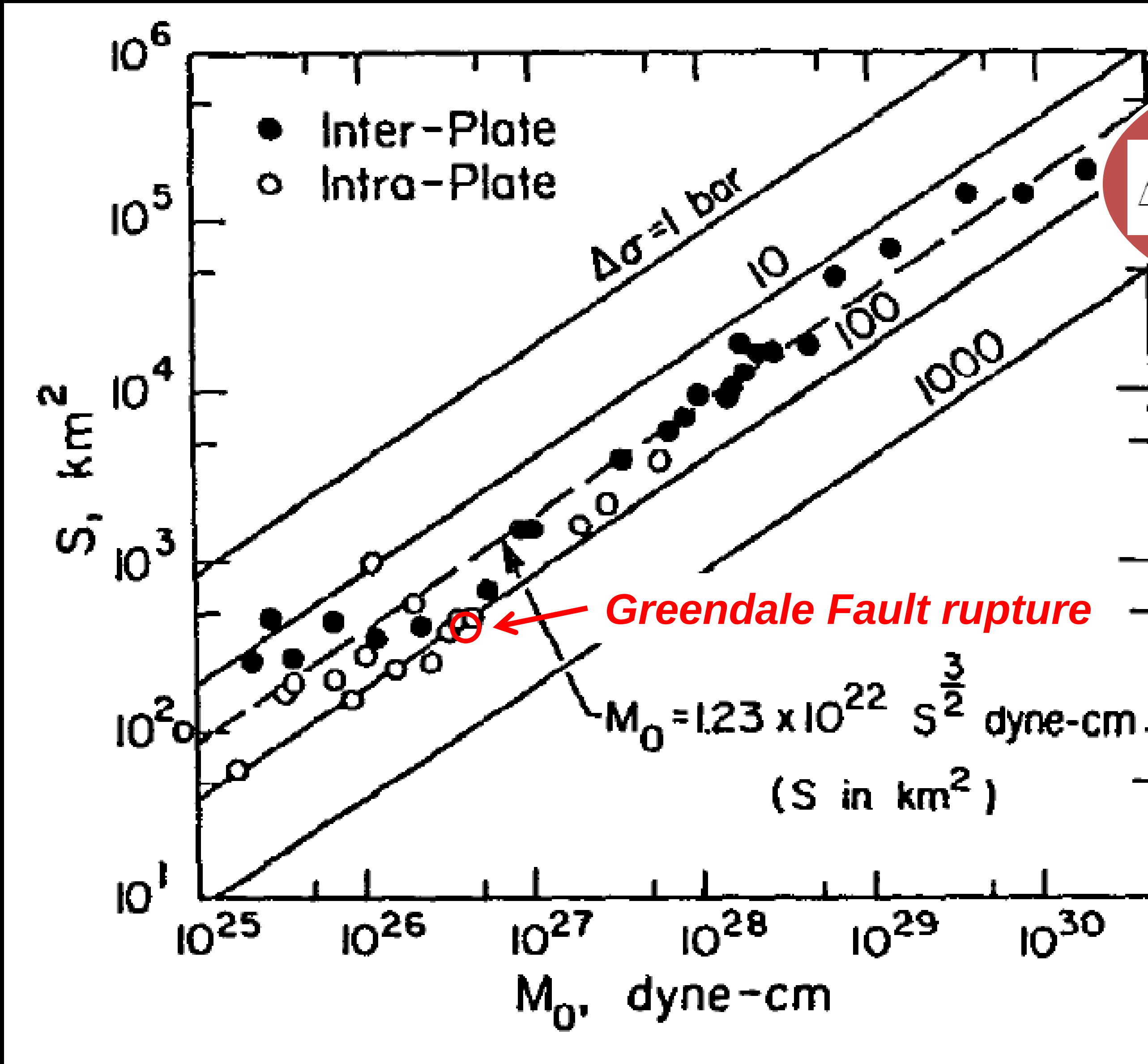
Y. Kaneko and
Y. Fialko, JGI
2011





Some indication that fault interactions may have increased coseismic slip

Nothing really anomalous in slip distribution



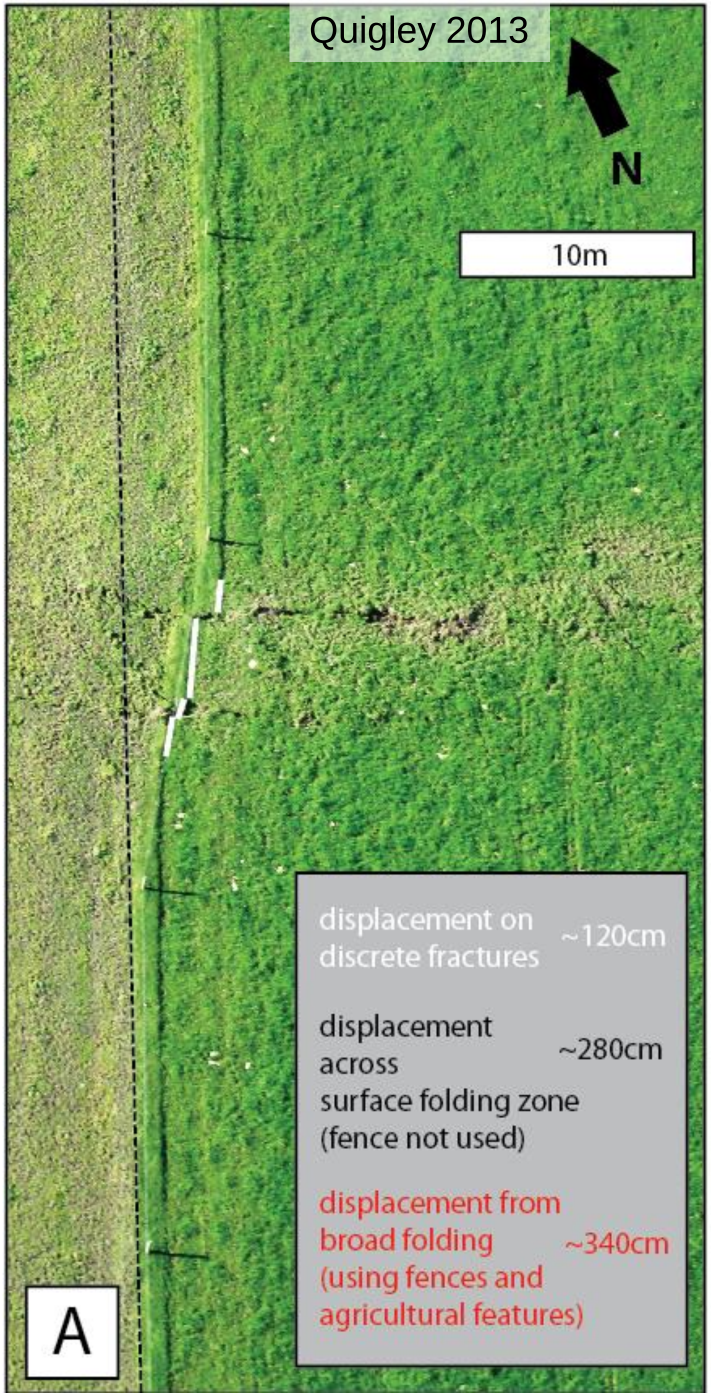
Relation between fault area and seismic moment for large and great earthquakes (Kanamori & Anderson 1975)

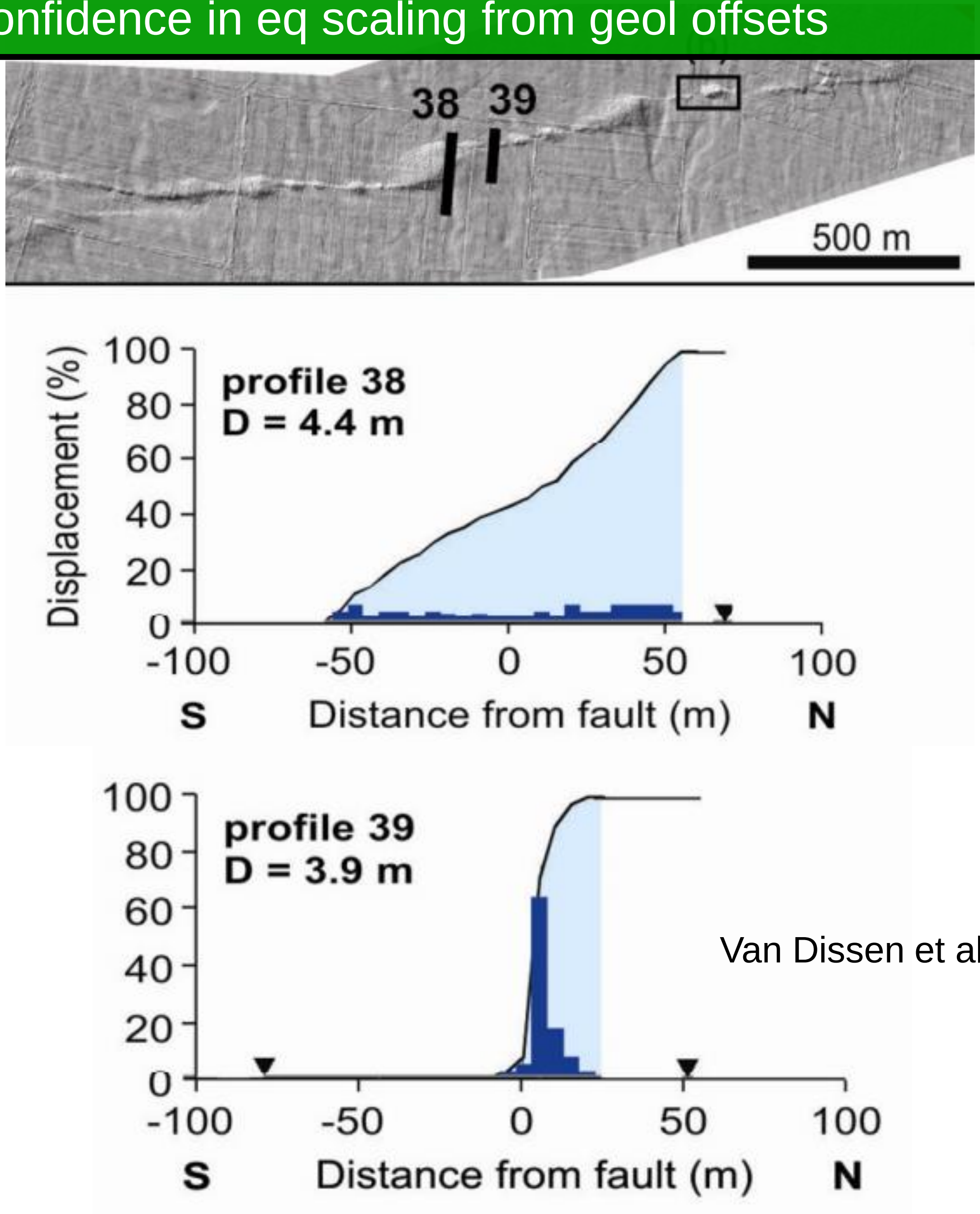
$\Delta\sigma^G = (\mu/C) \times (D/W) = 13.9 \pm 3.7$ MPa

At the high end of stress drop estimates but not surprising for tectonic setting

Higher than 'analogous' earthquakes (8 ± 1 MPa for 1992 Mw 7.3 Landers;10 ± 2 MPa for 1999 Mw 7.1 Hector Mine; Price and Bürgmann, 2002) = higher fault friction due to long recurrence intervals?

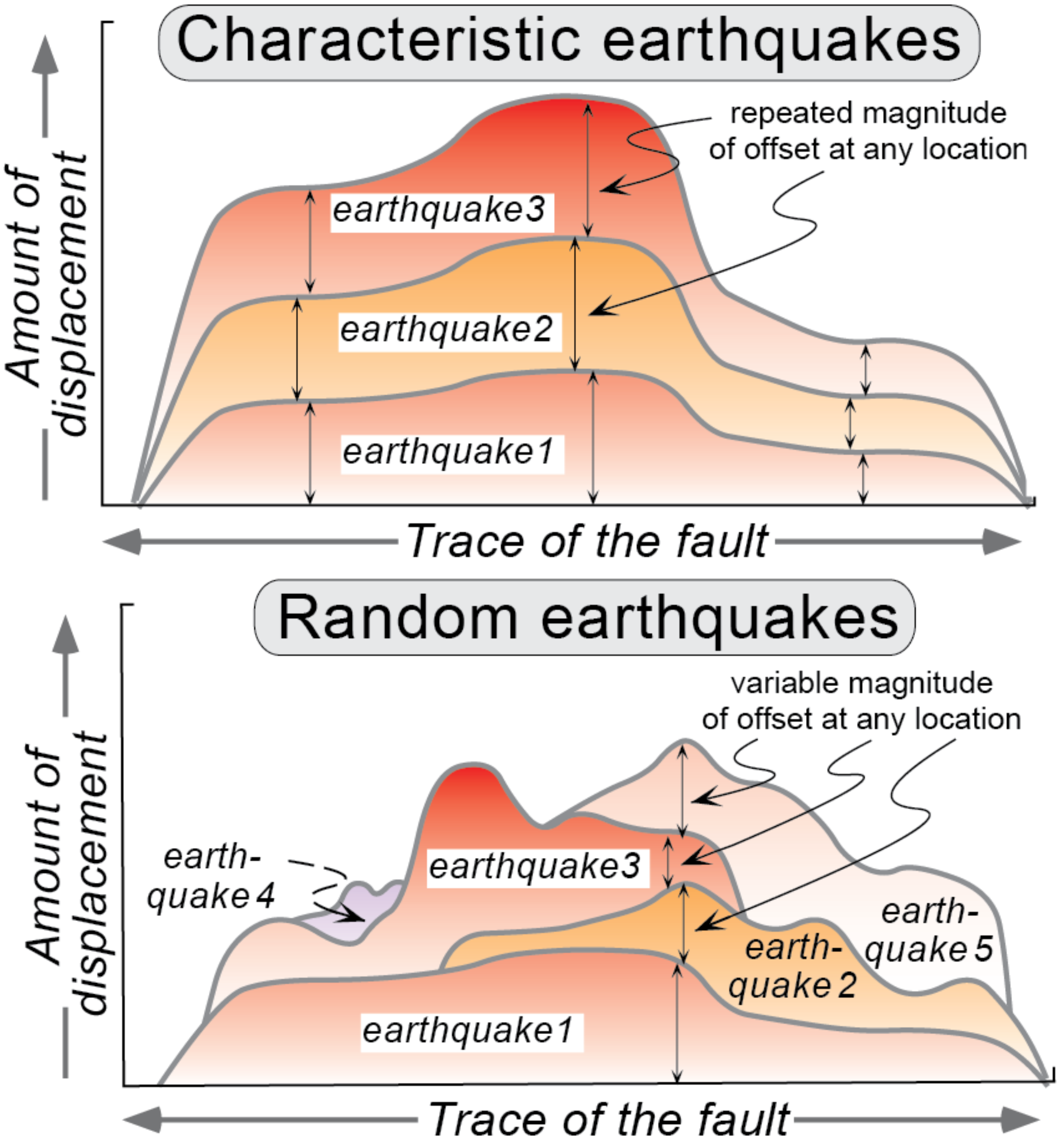
Better documentation of relationships between discrete and distributed deformation – Mw 7.0 estimated from discrete displacements only - confidence in eq scaling from geol offsets





Van Dissen et al 2012

Greendale Fault behaviour in time and space

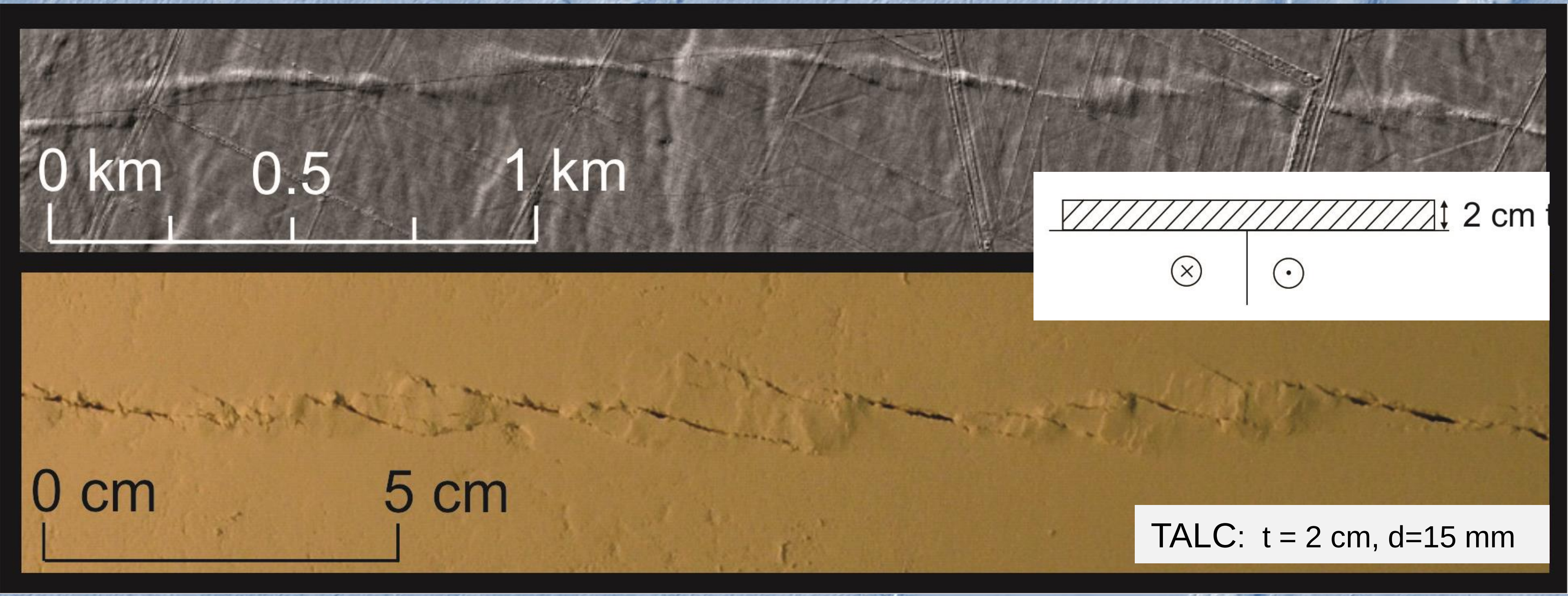


Burbank and Anderson

- Timing and M_w of penultimate eq
- RI, displacement histories, fault behaviour

Analogue modelling of Greendale Fault surface rupture:

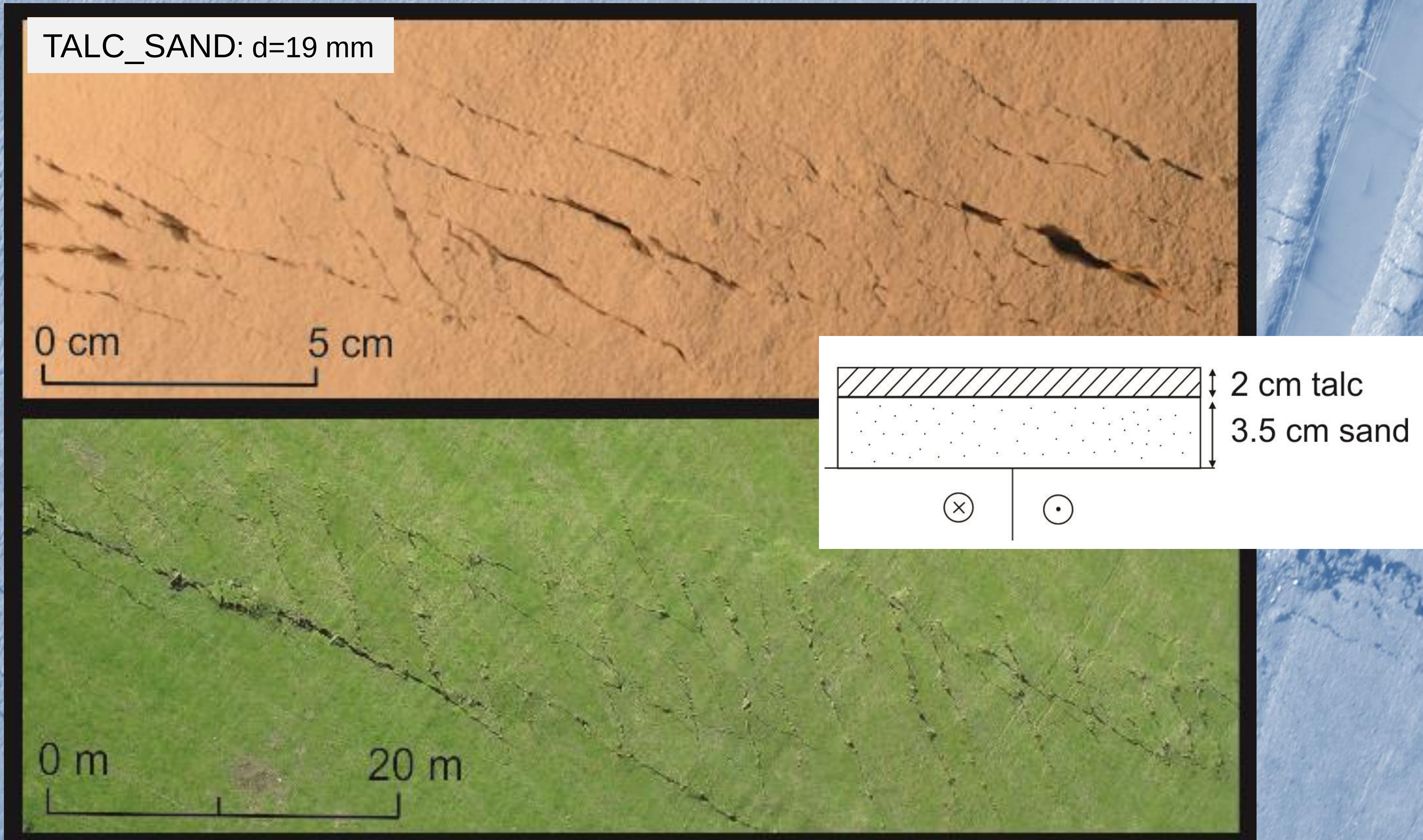
What controls rupture morphology and displacement variations?
Where is the best place to site a trench, and what fractures will most faithfully record prior earthquakes?



Single layer, cohesive material (talc) best replicates km-scale surface rupture morphology

Surface complexities created with simple, planar uniformally dipping basement fault

Sasnett, 2013

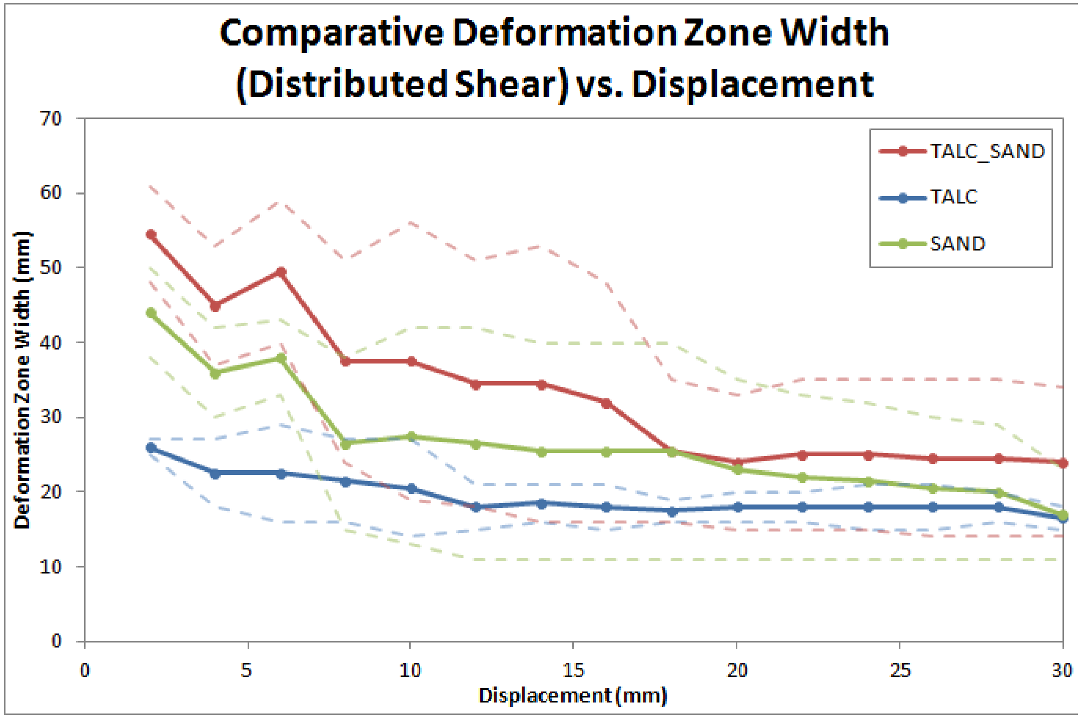


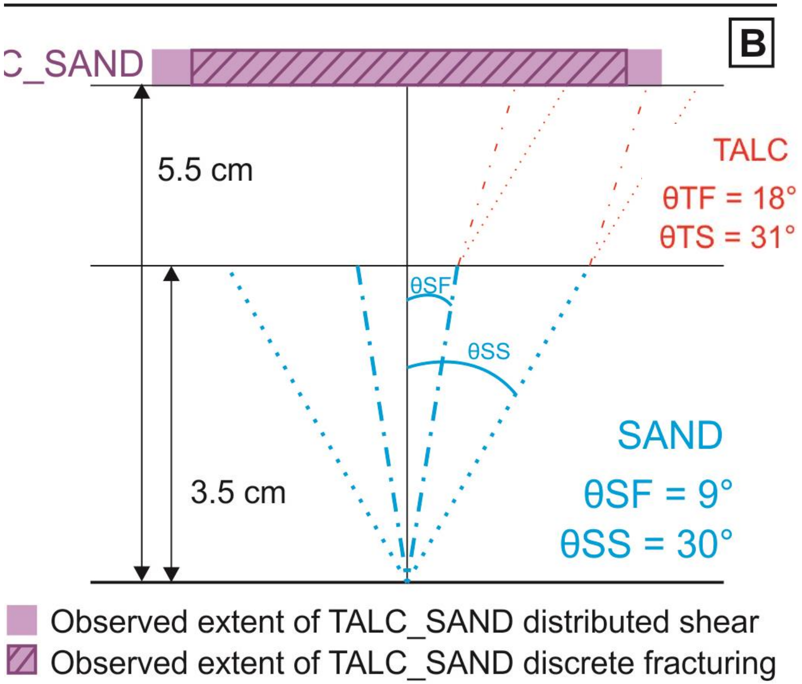
Multi layer model best replicates m-scale surface rupture morphology

Surface complexities created with simple, planar uniformally dipping basement fault beneath layered 'strata'

Sasnett, 2013

• *Need to create a wide deformation zone but with discrete fractures*



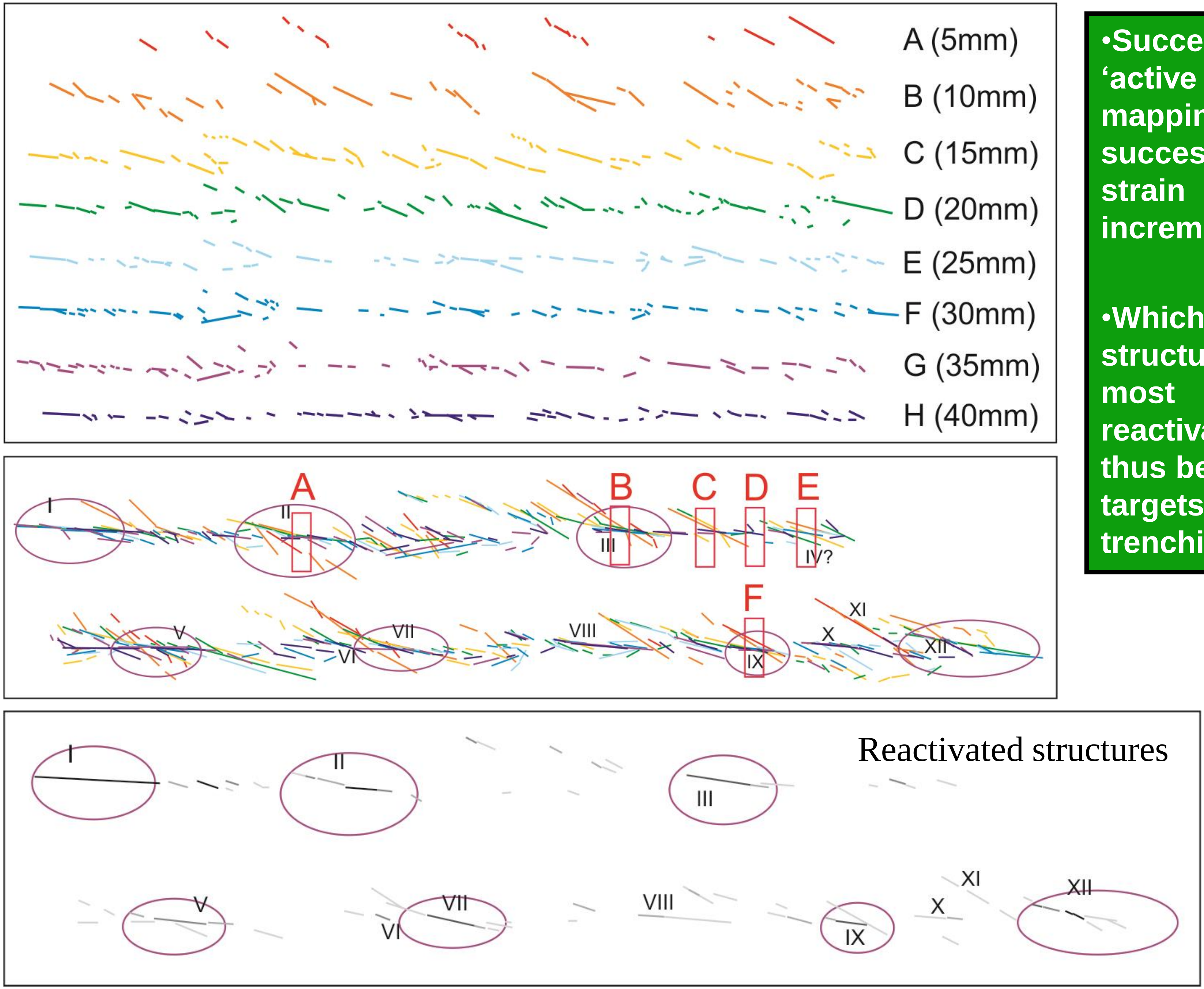


•Presence of granular sand increases shear zone width

•Presence of overlying cohesive layer concentrates distributed strain onto discrete fractures

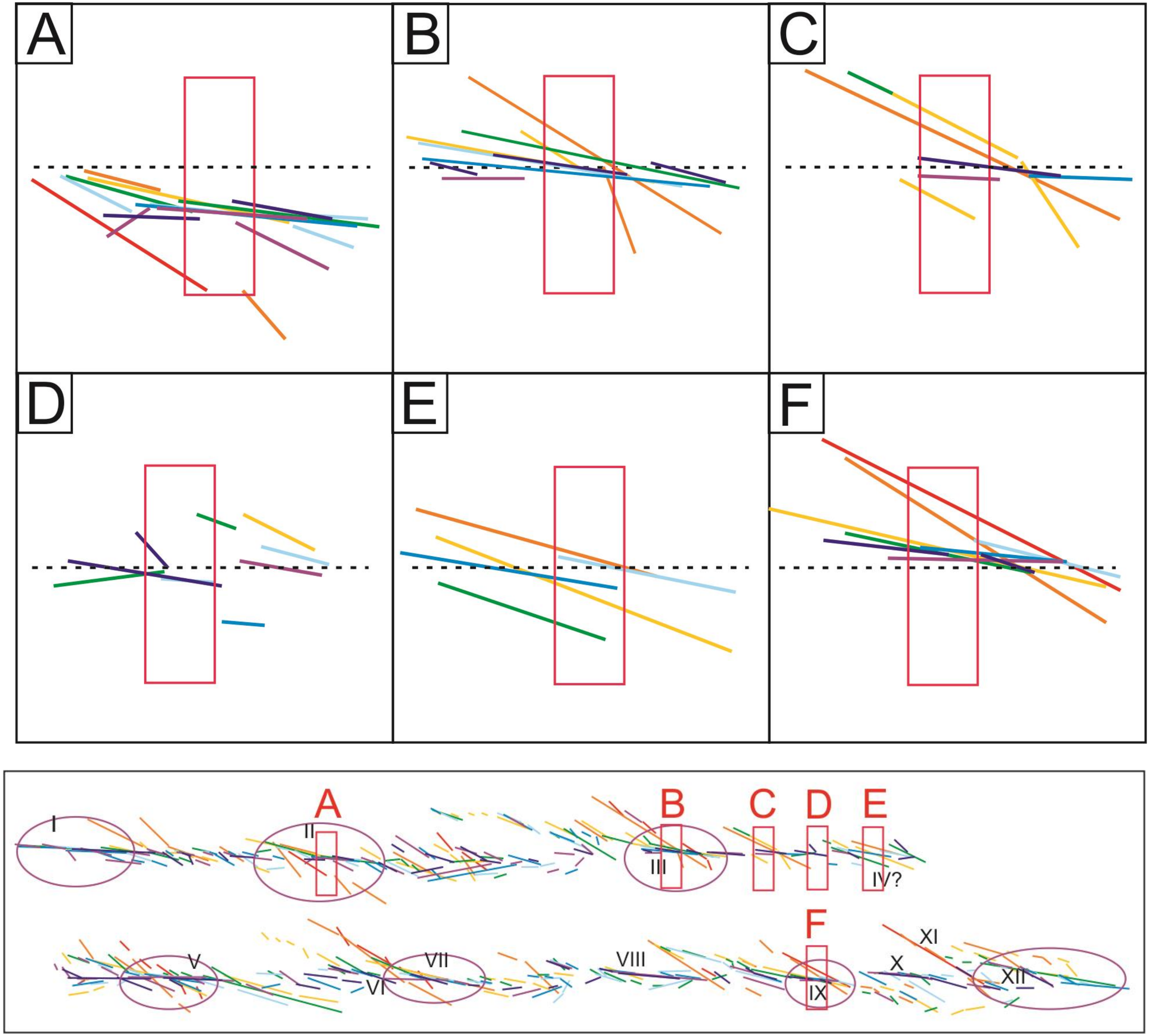
•Best fit for surface rupture characteristics, but is this supported by subsurface geology?

Sasnett, 2013



- **Successive 'active fracture' mapping at successive strain increments**
- **Which structures are most reactivated and thus best targets for trenching?**

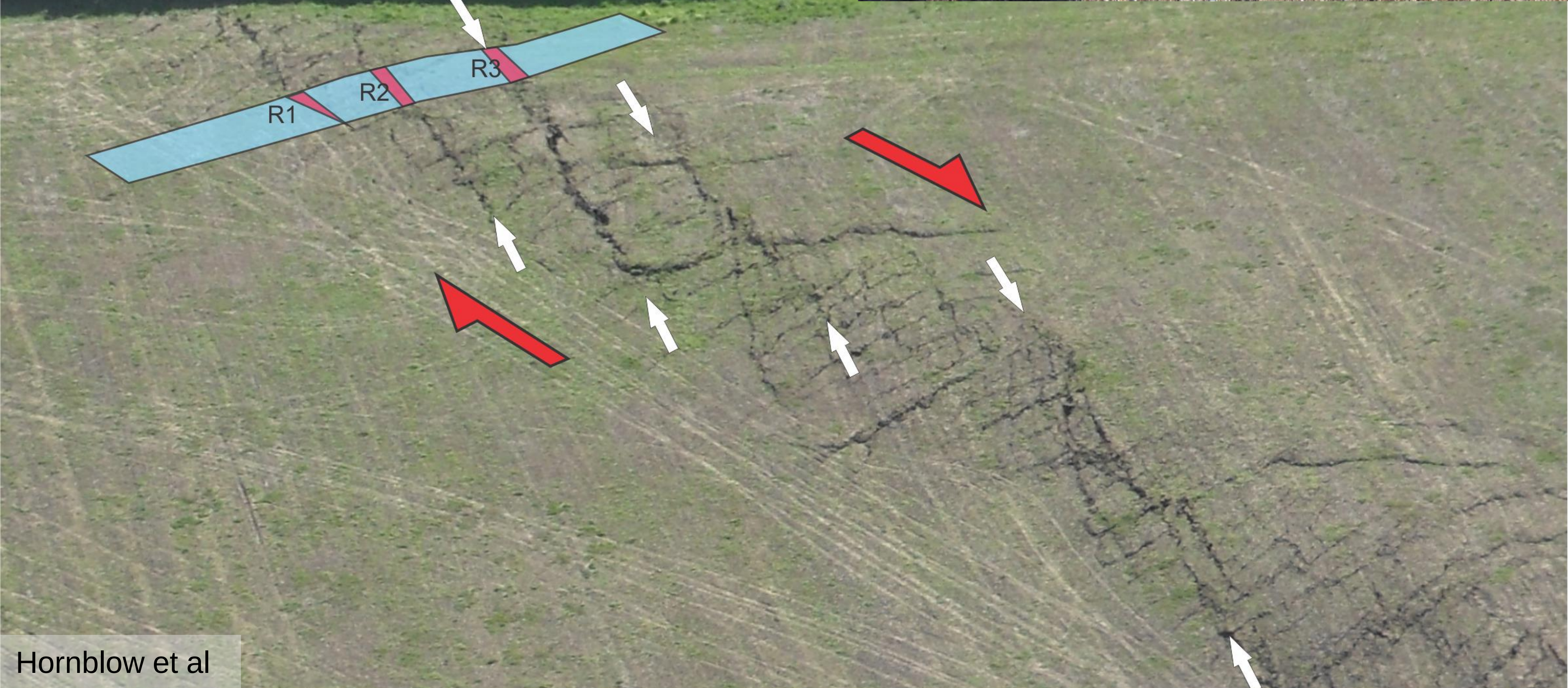
Sasnett, 2013



- **Synthetic trenches – Low angle (Riedel) fractures best targets, but complex relationships possible**
- **Supported by trenching?**

Sasnett, 2013

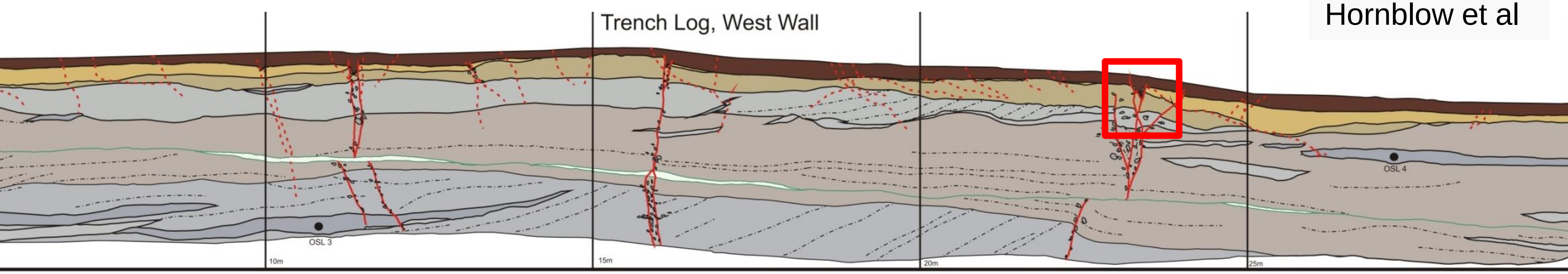
Greendale Fault paleoseismology project



Hornblow et al

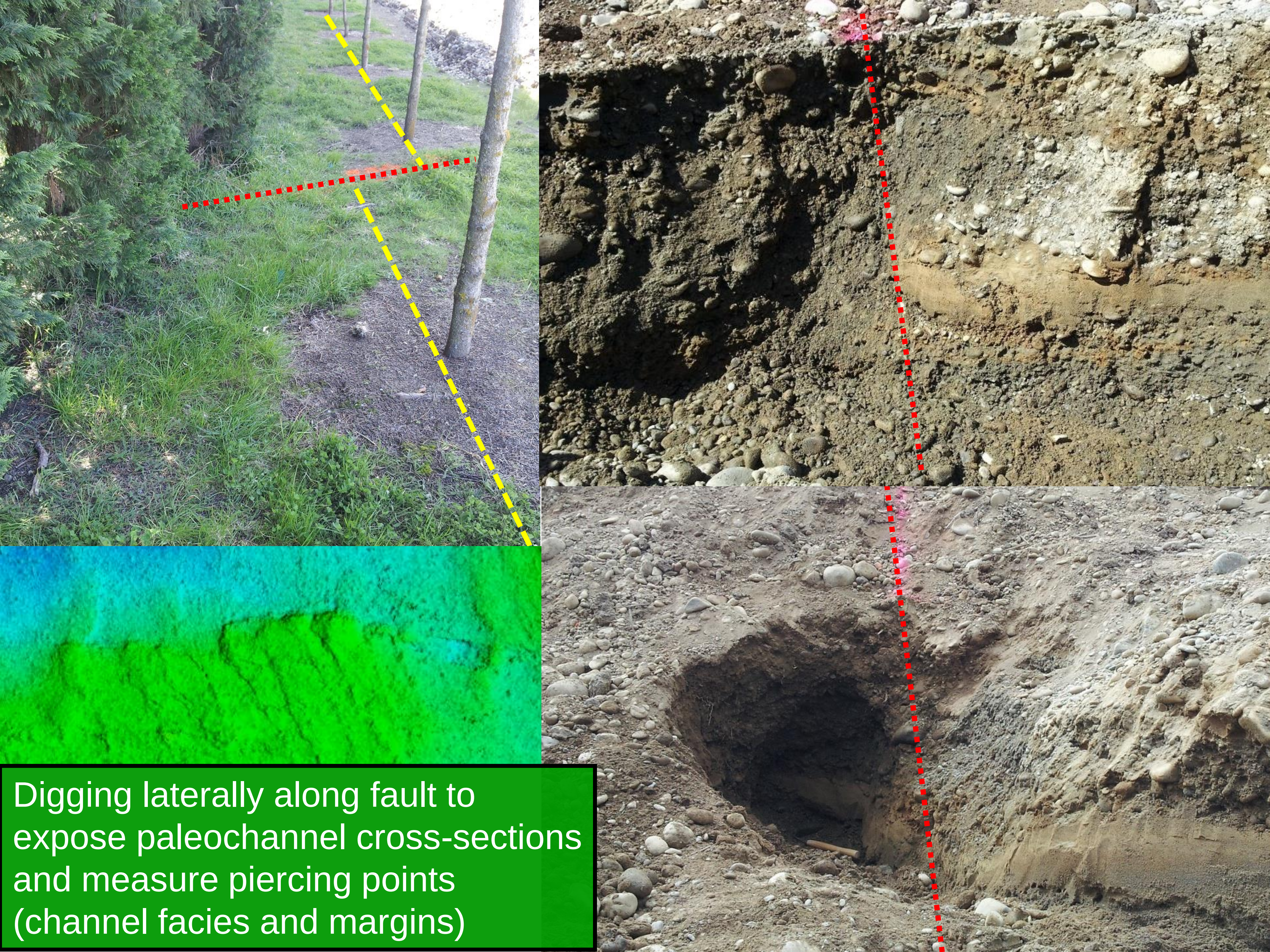
Subsurface mapping and GPR surveying of faulted sediments

Hornblow et al



-Many surface fractures terminate in uppermost 30-50cm (pedogenesis and loess filled channels increases cohesivity and promote fracturing)

-Thoroughgoing R fractures penetrate deeply and appeared to show more subsurface than surface displacement

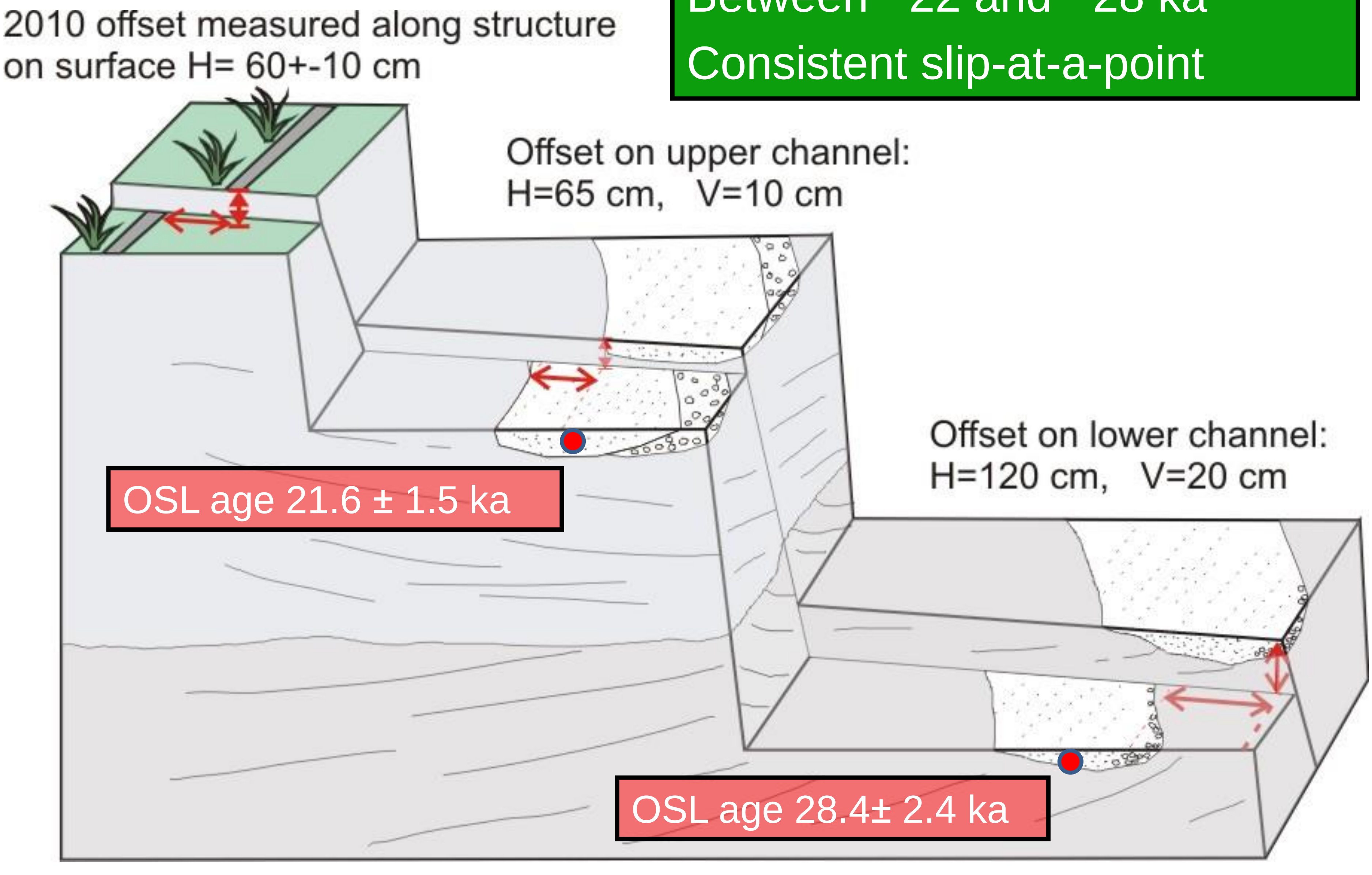


Digging laterally along fault to expose paleochannel cross-sections and measure piercing points (channel facies and margins)

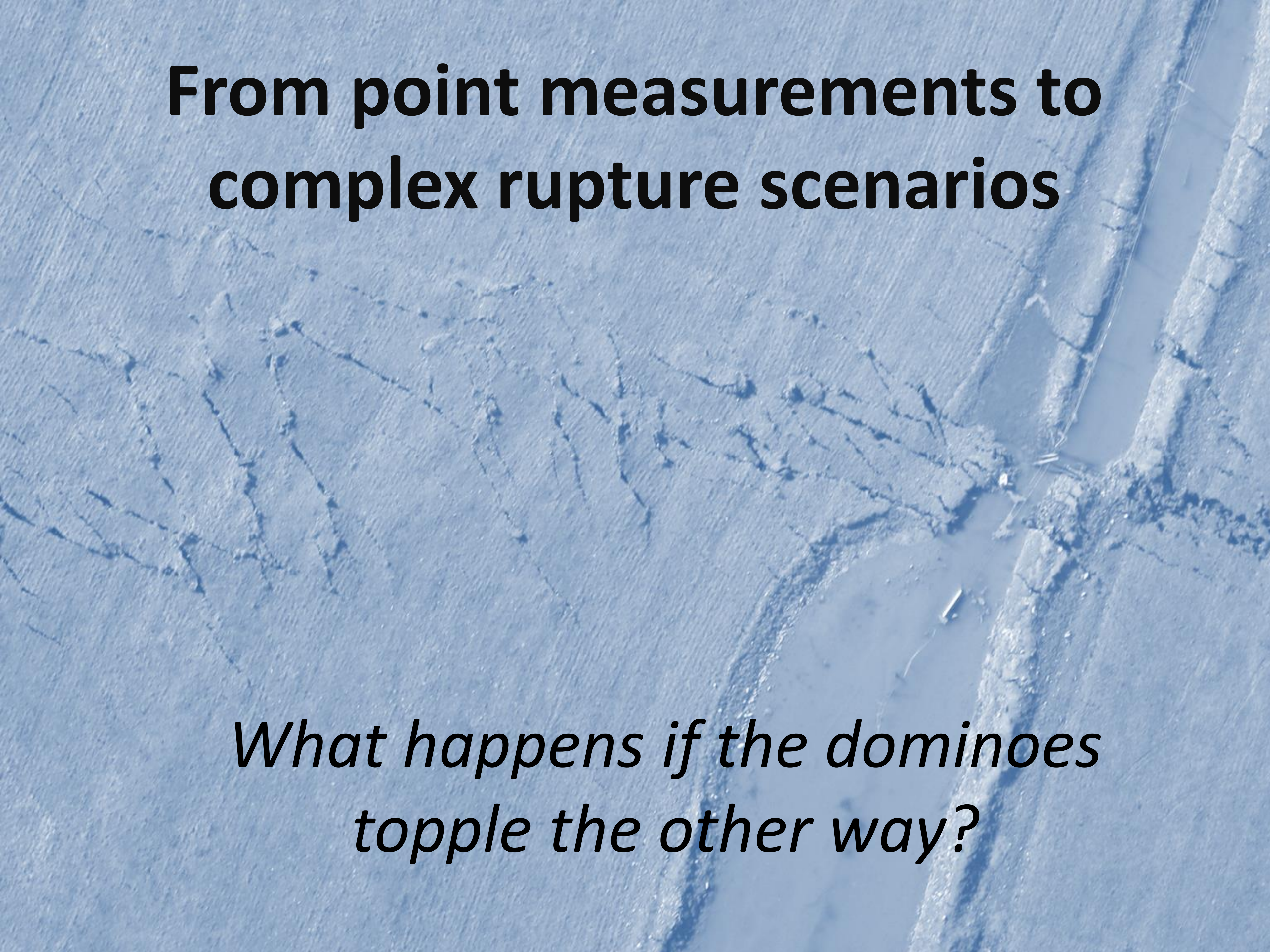
The penultimate earthquake:

Between ~22 and ~28 ka

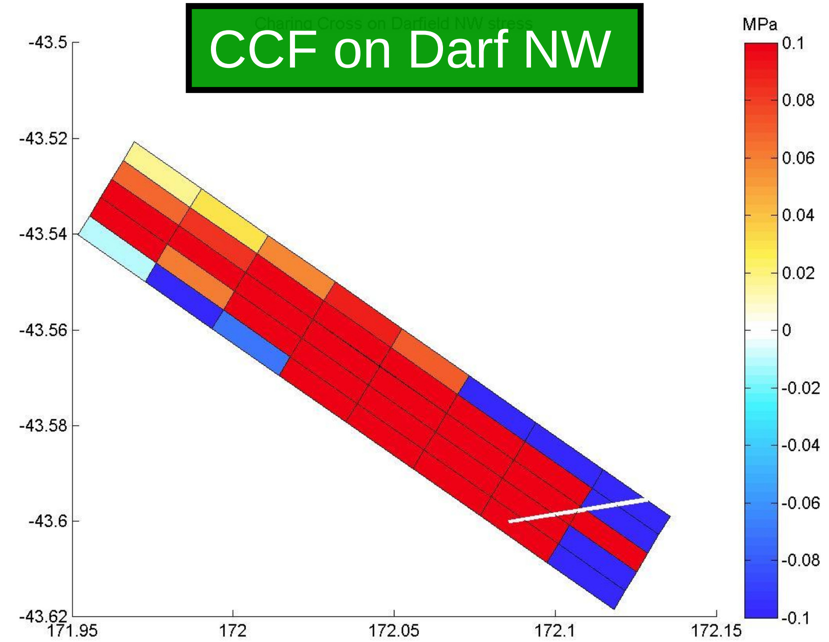
Consistent slip-at-a-point

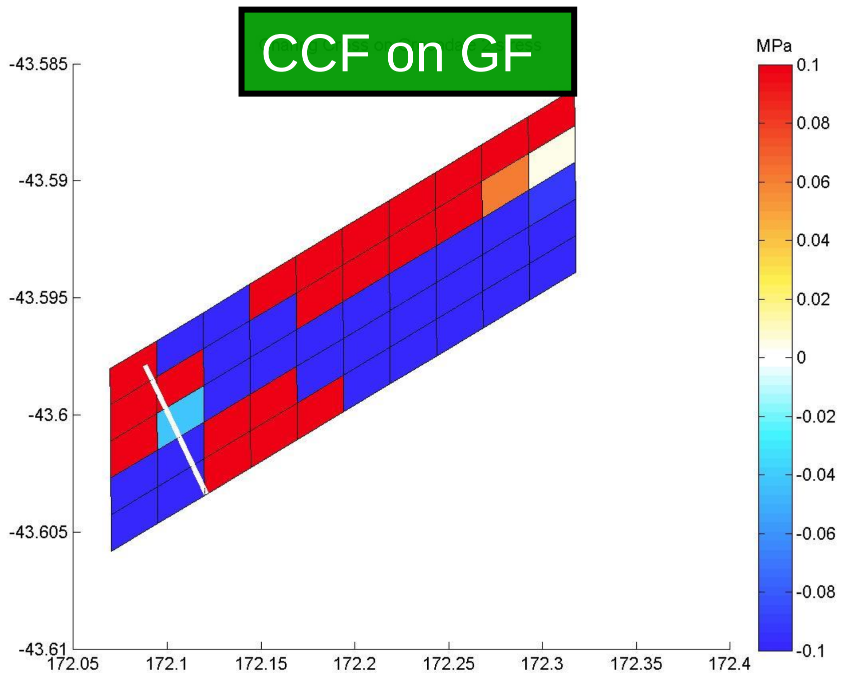


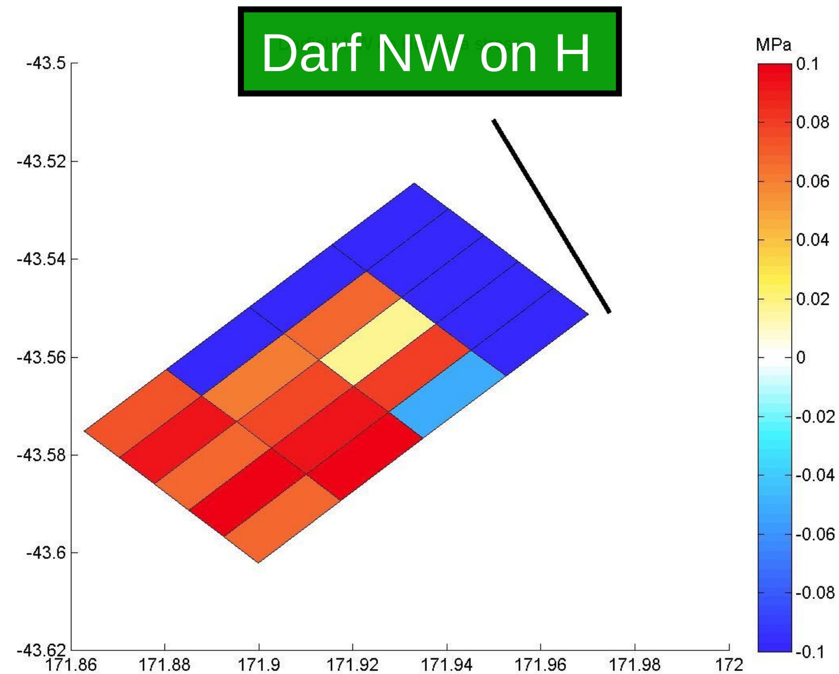
Hornblow et al


From point measurements to complex rupture scenarios
What happens if the dominoes topple the other way?

Coulomb 'static' stress evolution for rupture initiating on CCF

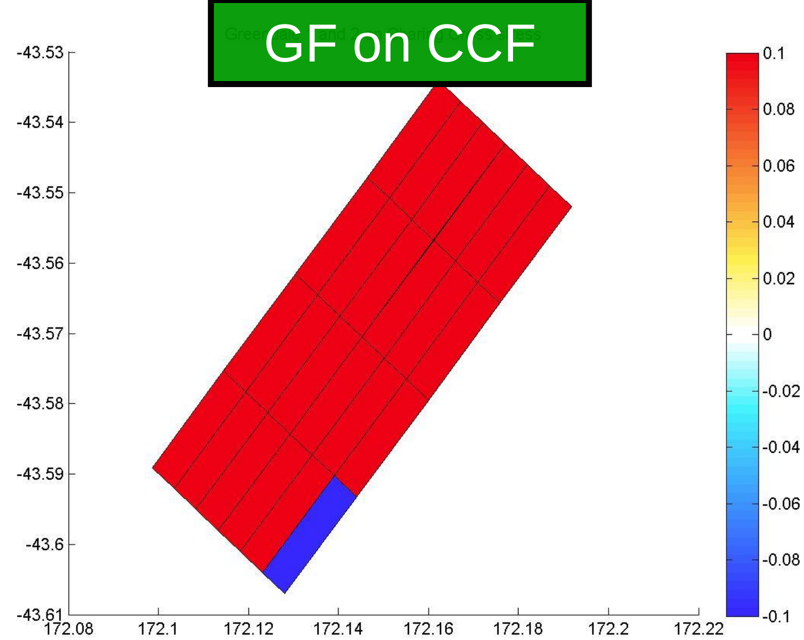


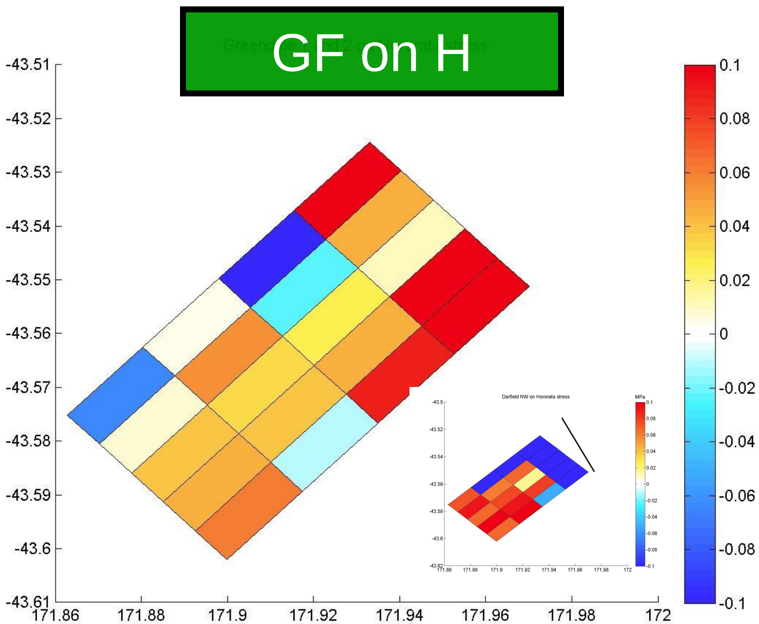


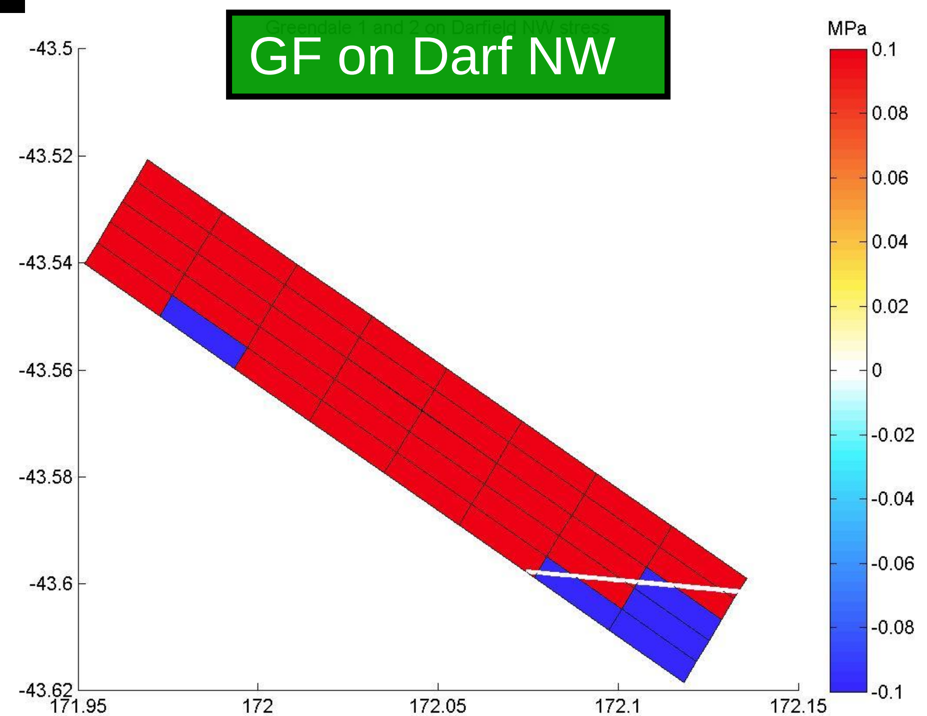


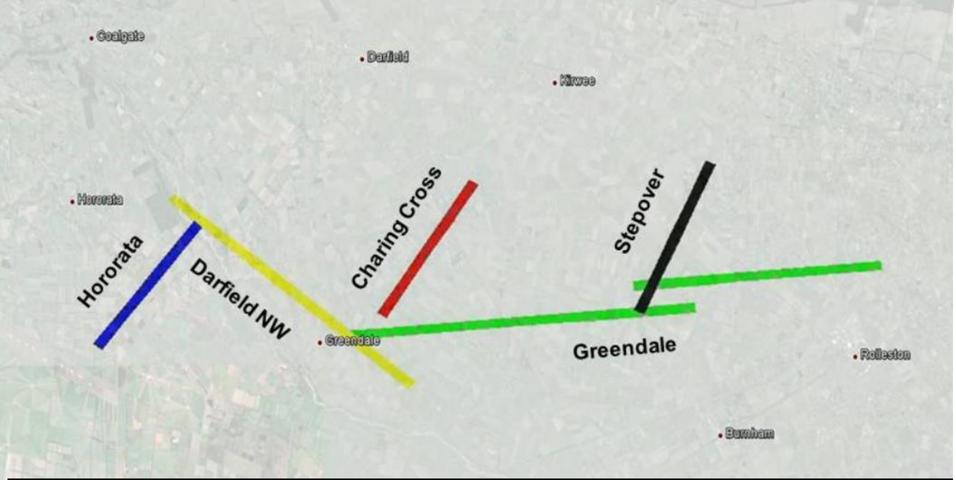
Courtesy: Abigail Jimenez, Sandy Steacy (Ulster)

Coulomb 'static' stress evolution for rupture initiating on GF

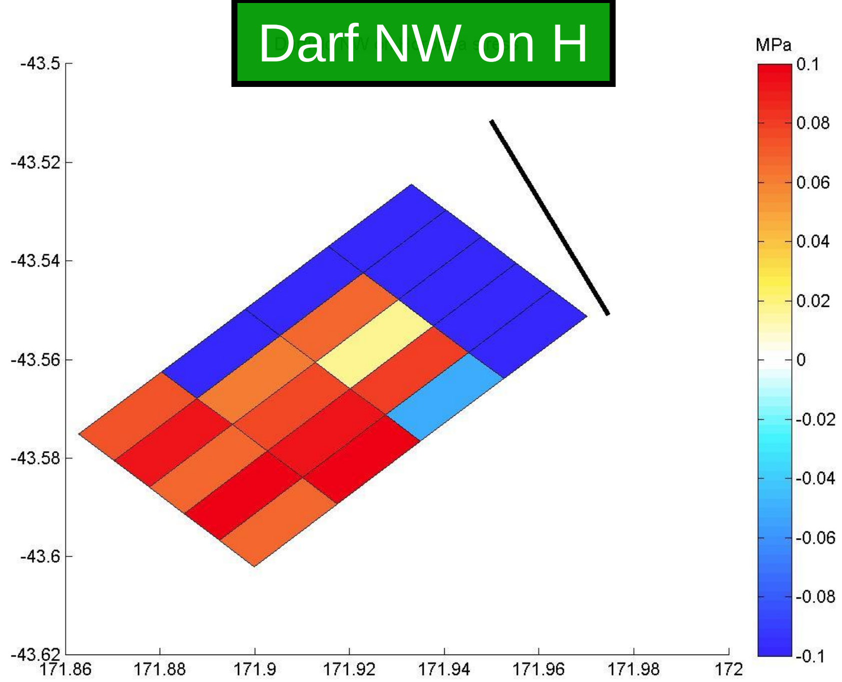


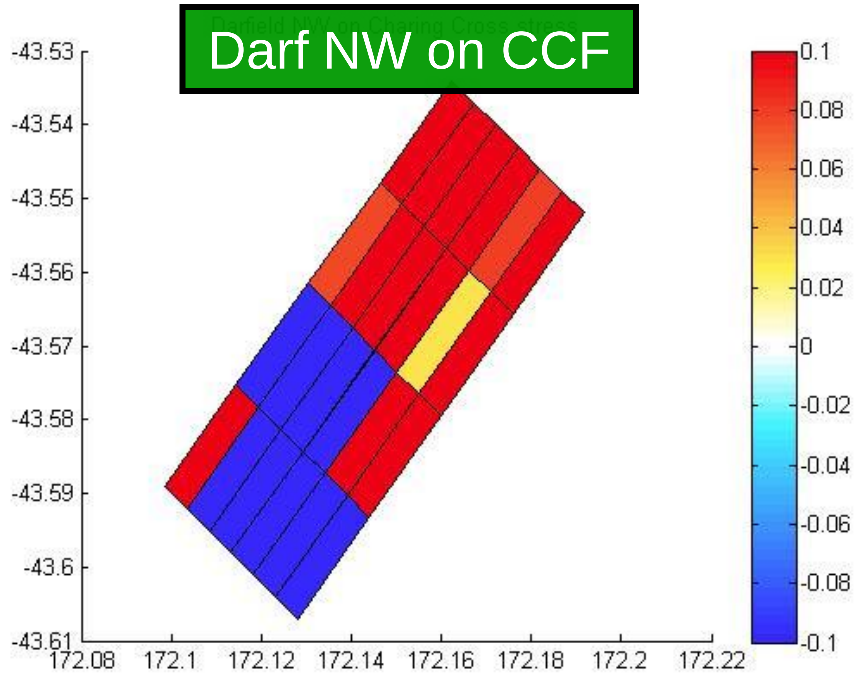


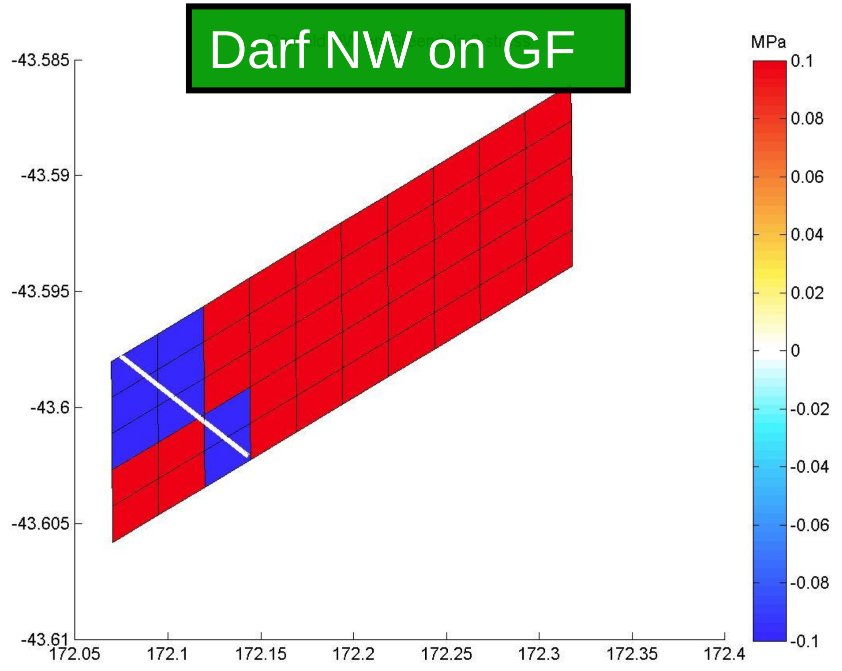




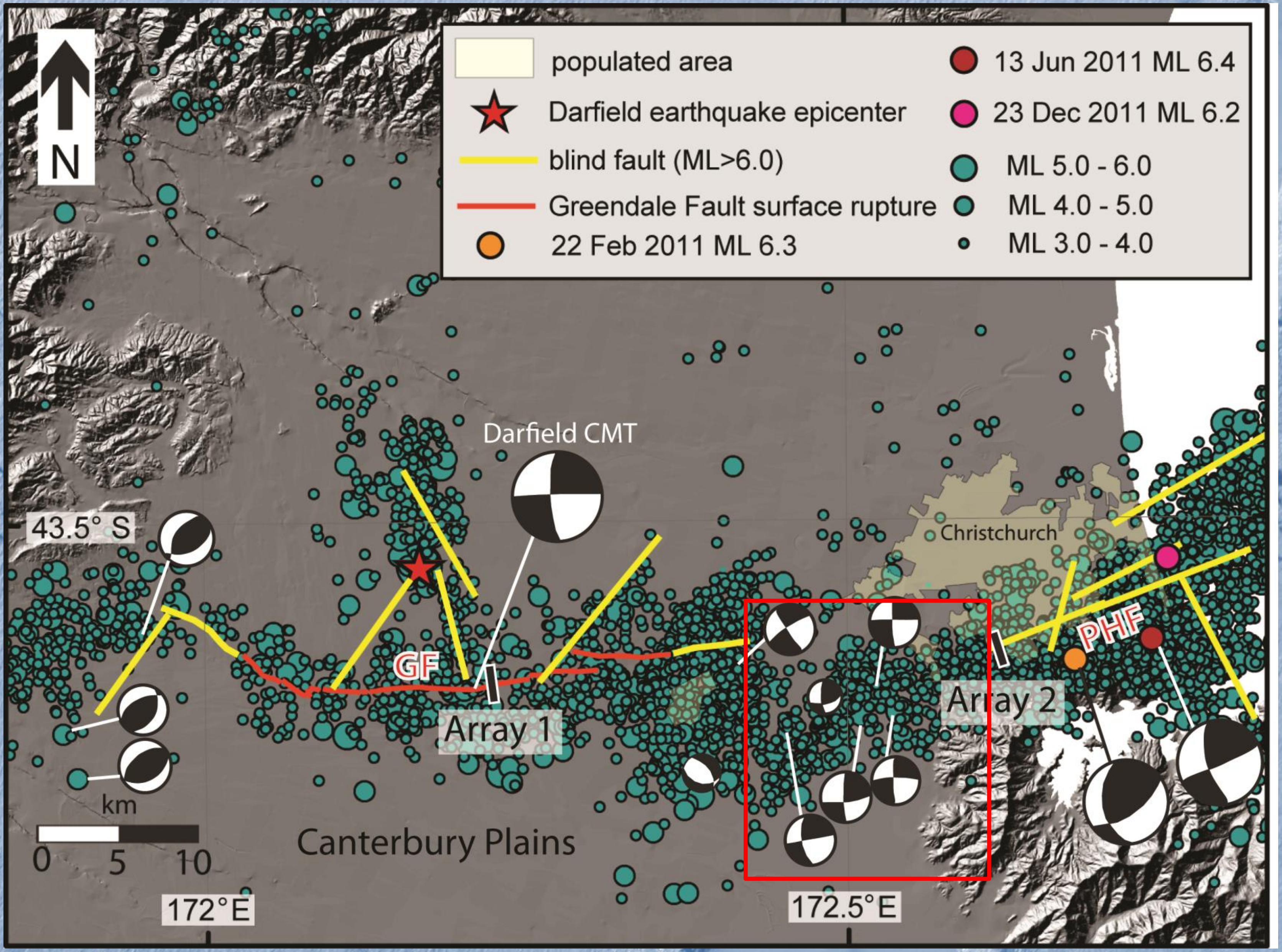
Coulomb 'static' stress evolution for rupture initiating on Darf NW

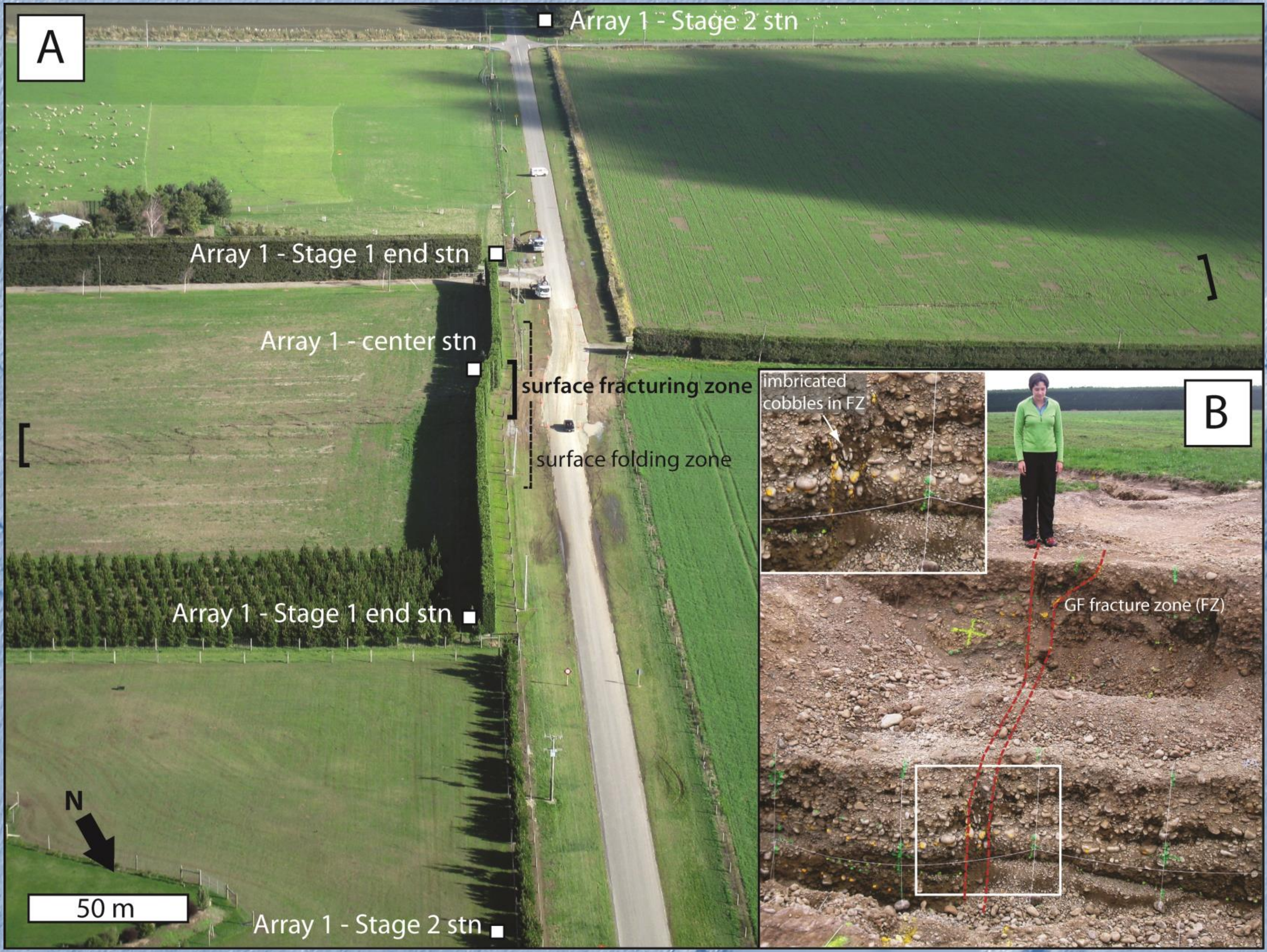






Other rupture scenarios (Mw max): Fault connectivity and rupture potential



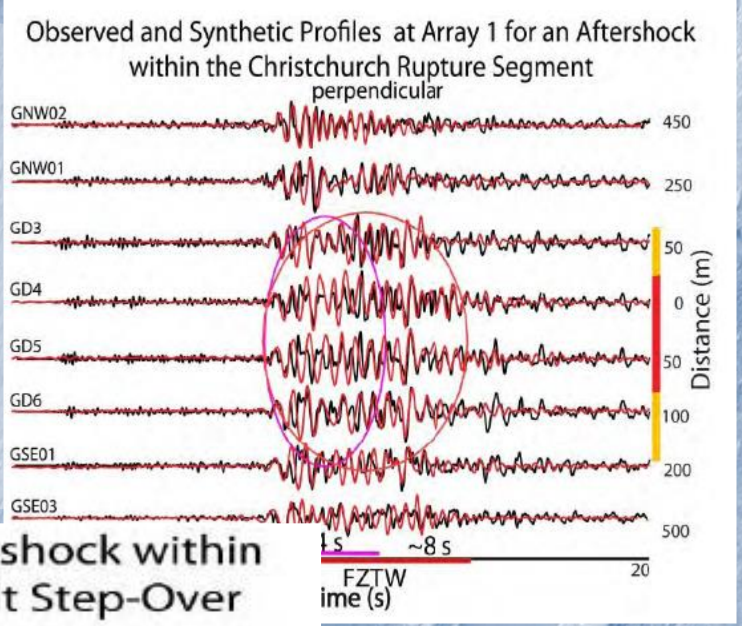


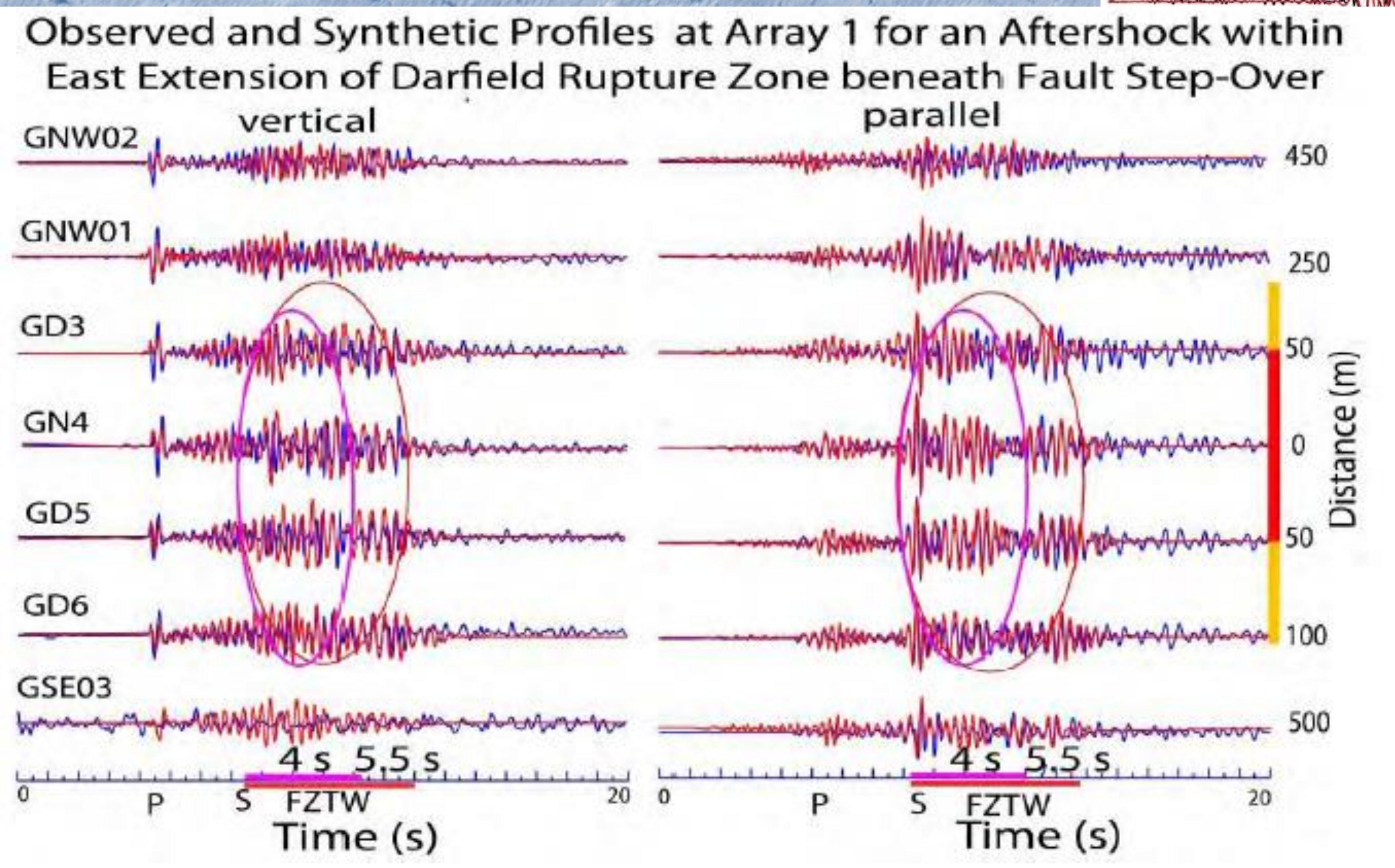
Li et al (in review)

FZTW imaged on GF array for eq in ‘The Gap’ and on PHF

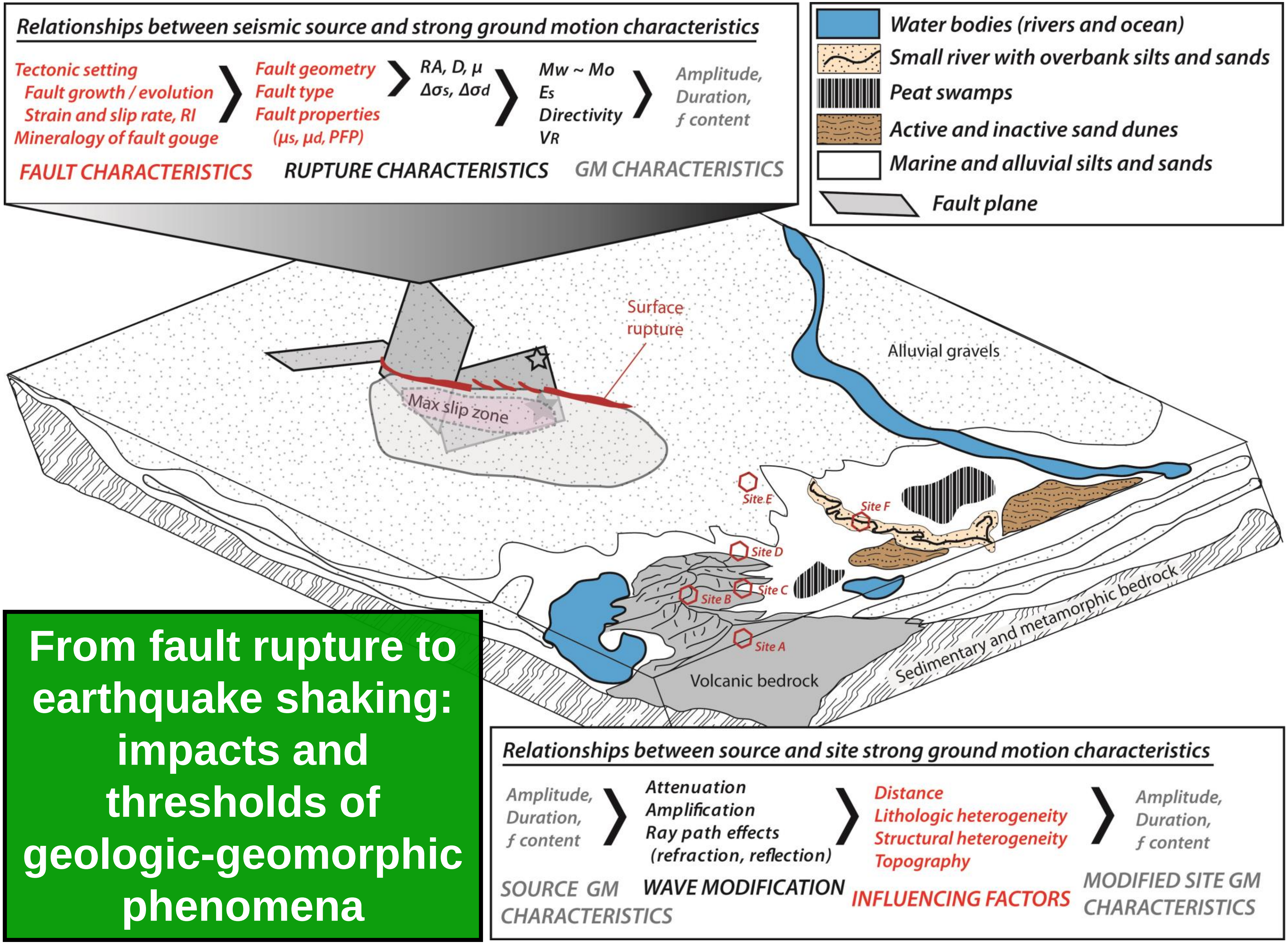
‘Moderate connectivity’ through gap via a complicated fracture mesh of small pre-existing faults and stress-aligned microcracks

Improbable that these faults can rupture together (Mw 7.3 to 7.4) but this provides an example of an incipient system to compare to more mature faults: how do faults grow?



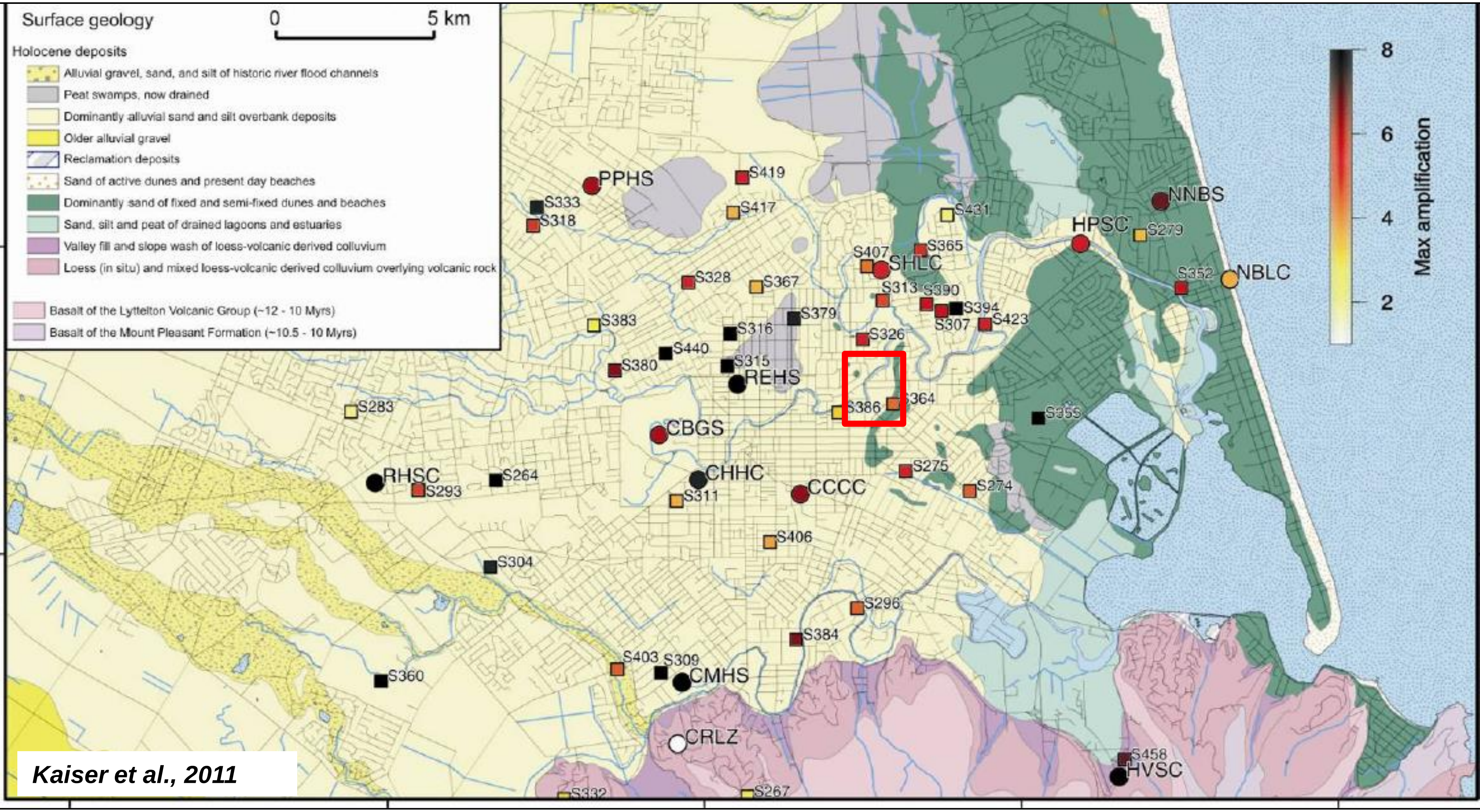


From fault rupture to earthquake shaking: impacts and thresholds of geologic-geomorphic phenomena



Each earthquake tells its own story:

Low frequency seismic amplification in the geologically-variable Christchurch “Jelly Bowl” and adjacent volcanic bedrock hills during the Feb 22 M_w 6.2 earthquake



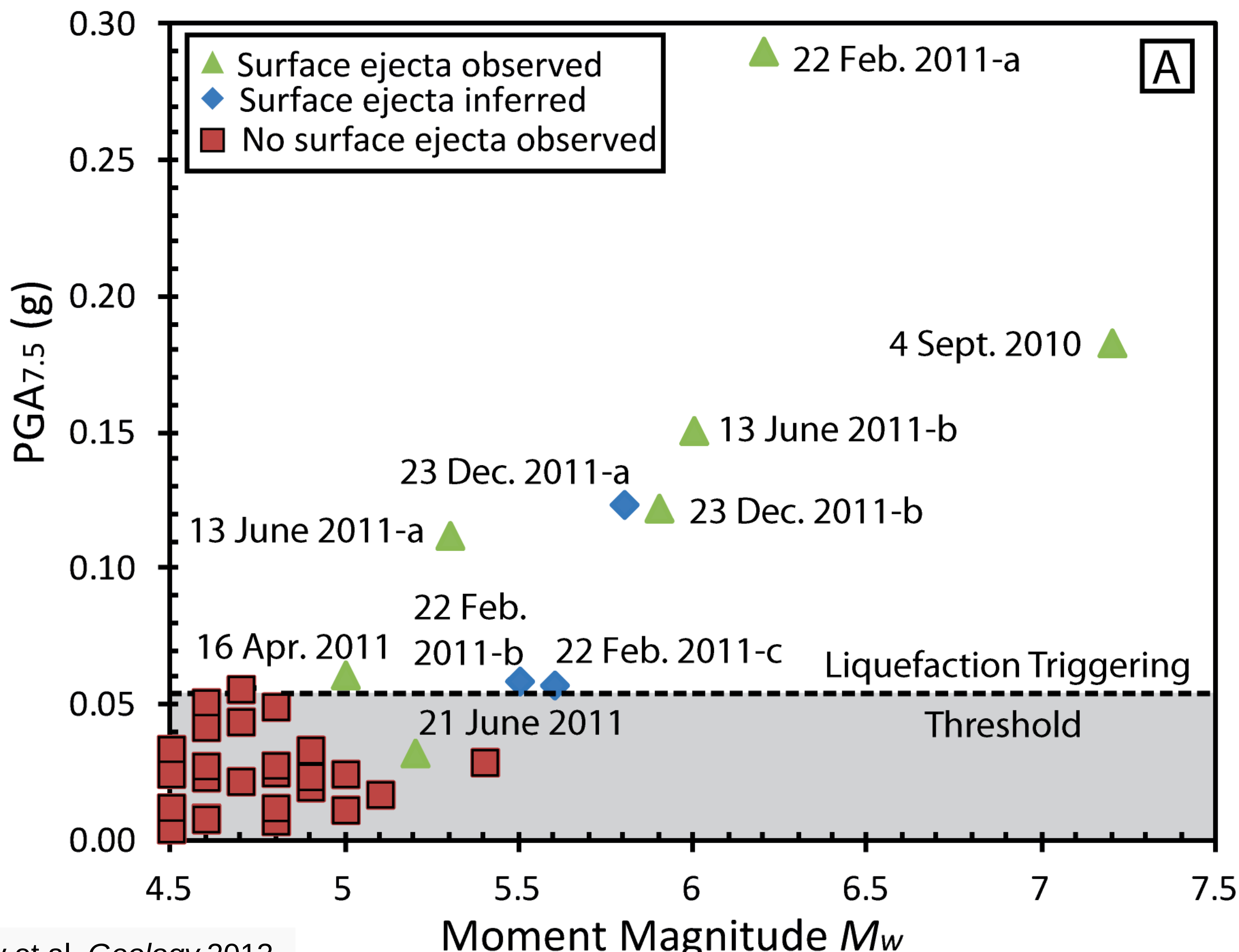
Kaiser et al., 2011

Figure 7. Maximum amplification in the 1 - 9 Hz frequency band derived from spectral ratio calculations at GeoNet stations (circles) and QCN stations (squares). Warmer station colours indicate higher amplifications relative to reference station CRLZ. Background map shows surface geology of the Christchurch area following Brown and Weeber 1992). Coordinates are New Zealand Map Grid given in metres.

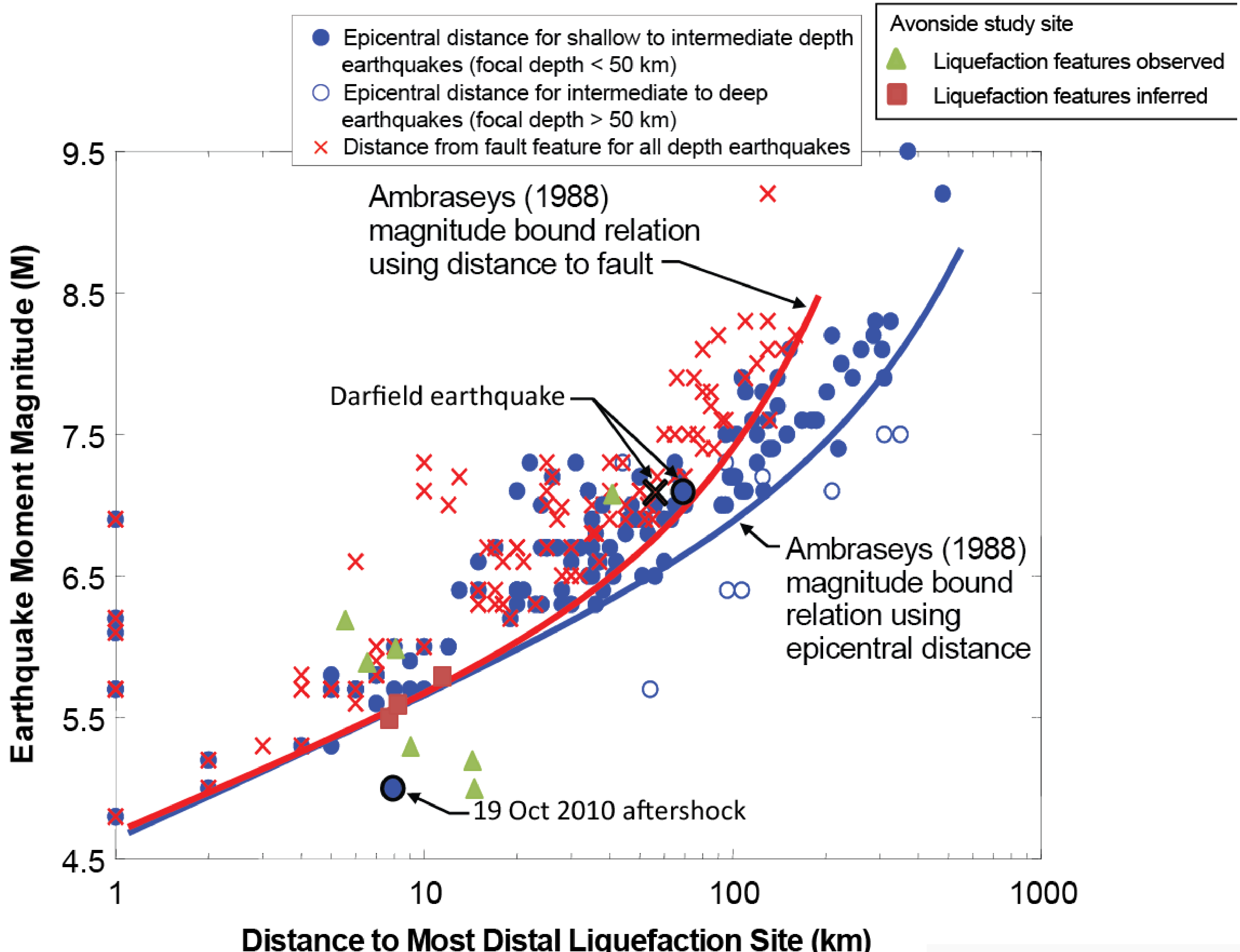
Science in the backyard (literally): Recurrent liquefaction in Christchurch during the Canterbury earthquake sequence

Quigley et al., *Geology* 2013

At least 10 liquefaction episodes, some of which occurred at surprisingly low PGAs

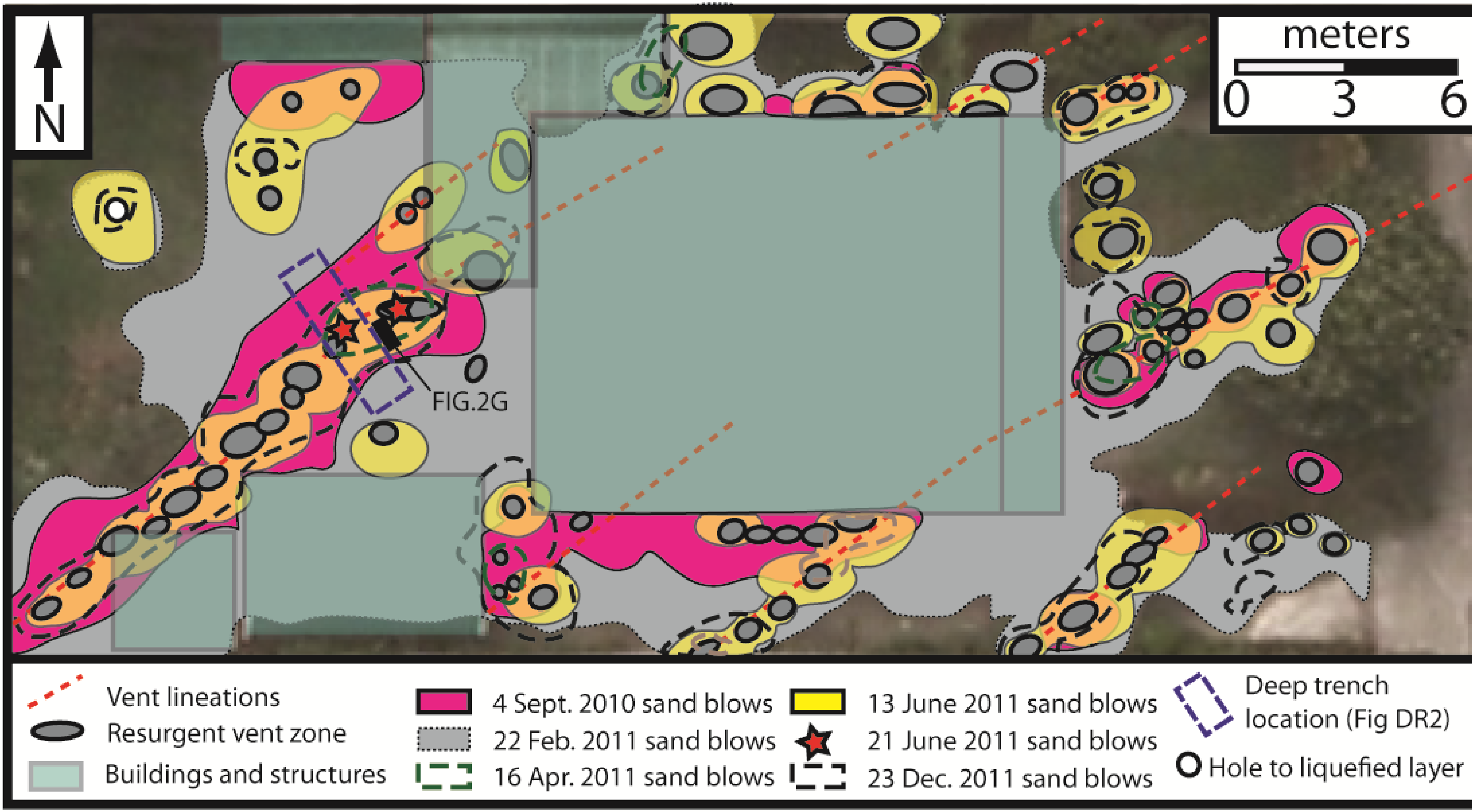


Quigley et al.,*Geology* 2013



Modified from Green et al. 2011

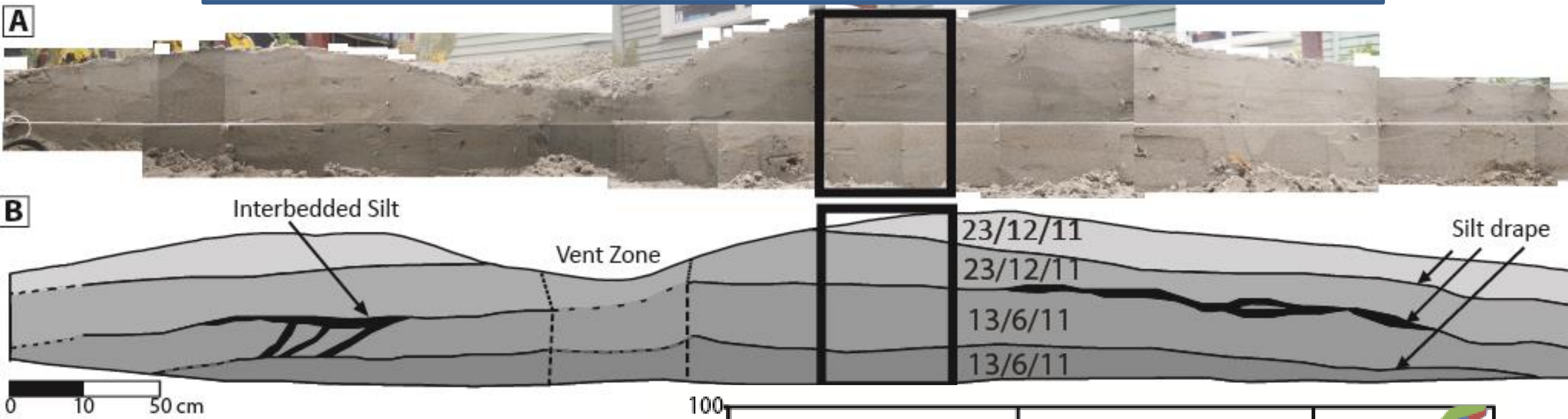
Liquefaction sourced from the same vent structures related to lateral spreading – might prior events have done the same?

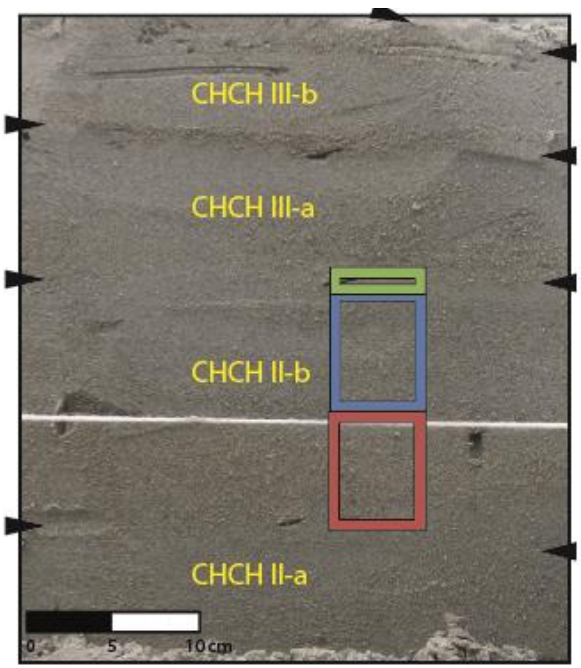


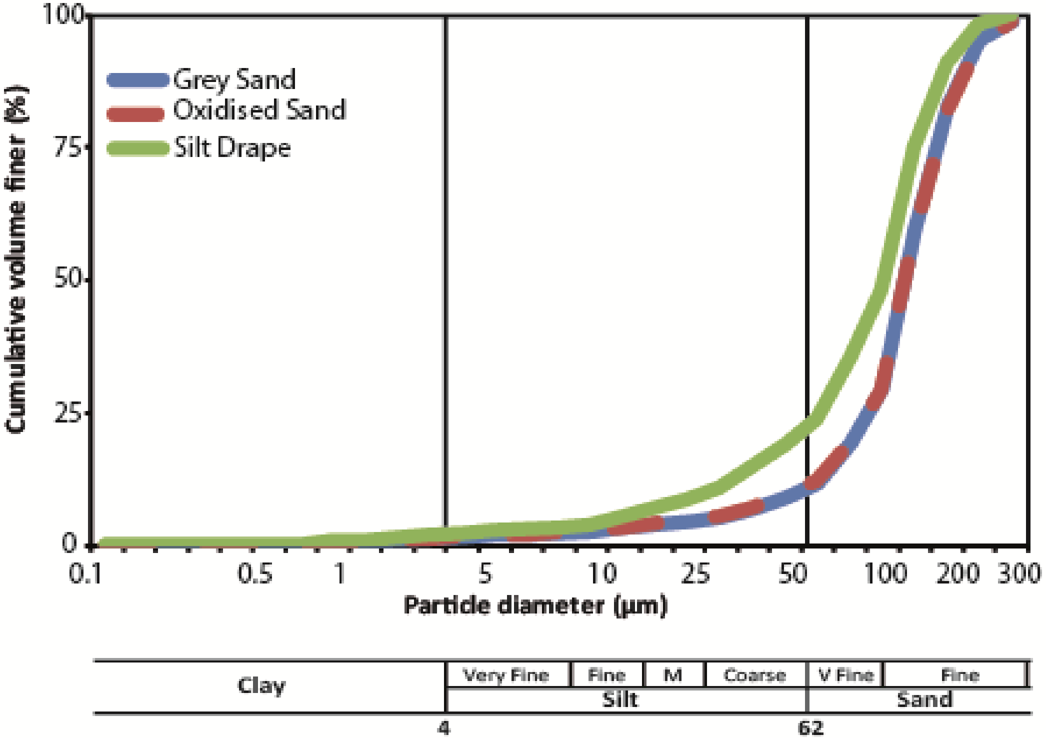
Would we recognize this in the geologic record?

Quigley et al., *Geology* 2013

Surface ejecta trenching – develop relationships between earthquake characteristics and extent / thickness of sand blows

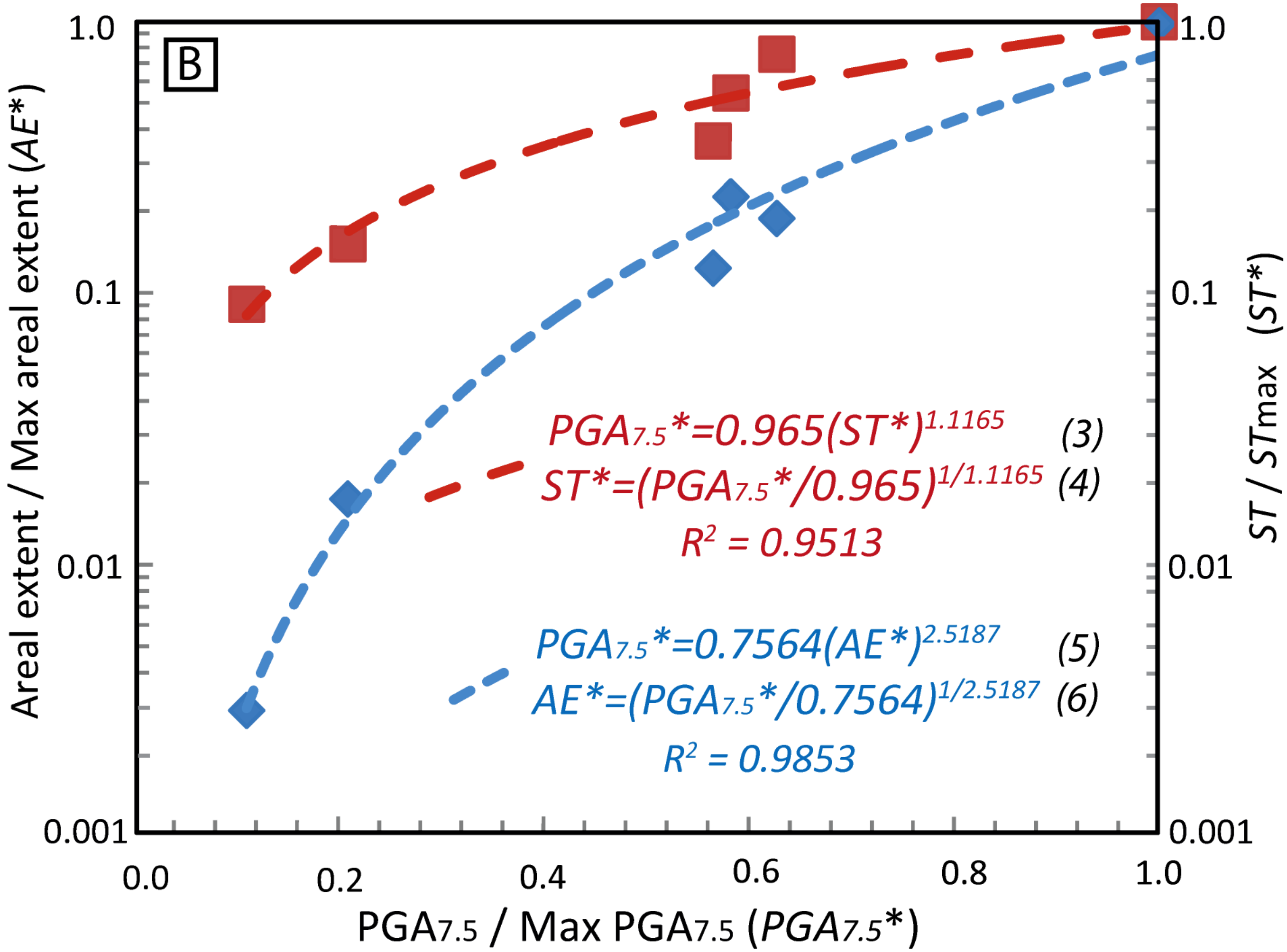






Quigley et al.,*Geology* 2013

Normalize maximum thicknesses, areal extents and PGAs to maximum values: predict future sand blow chacteristics from PGAs and interpret geologic record of paleoearthquakes



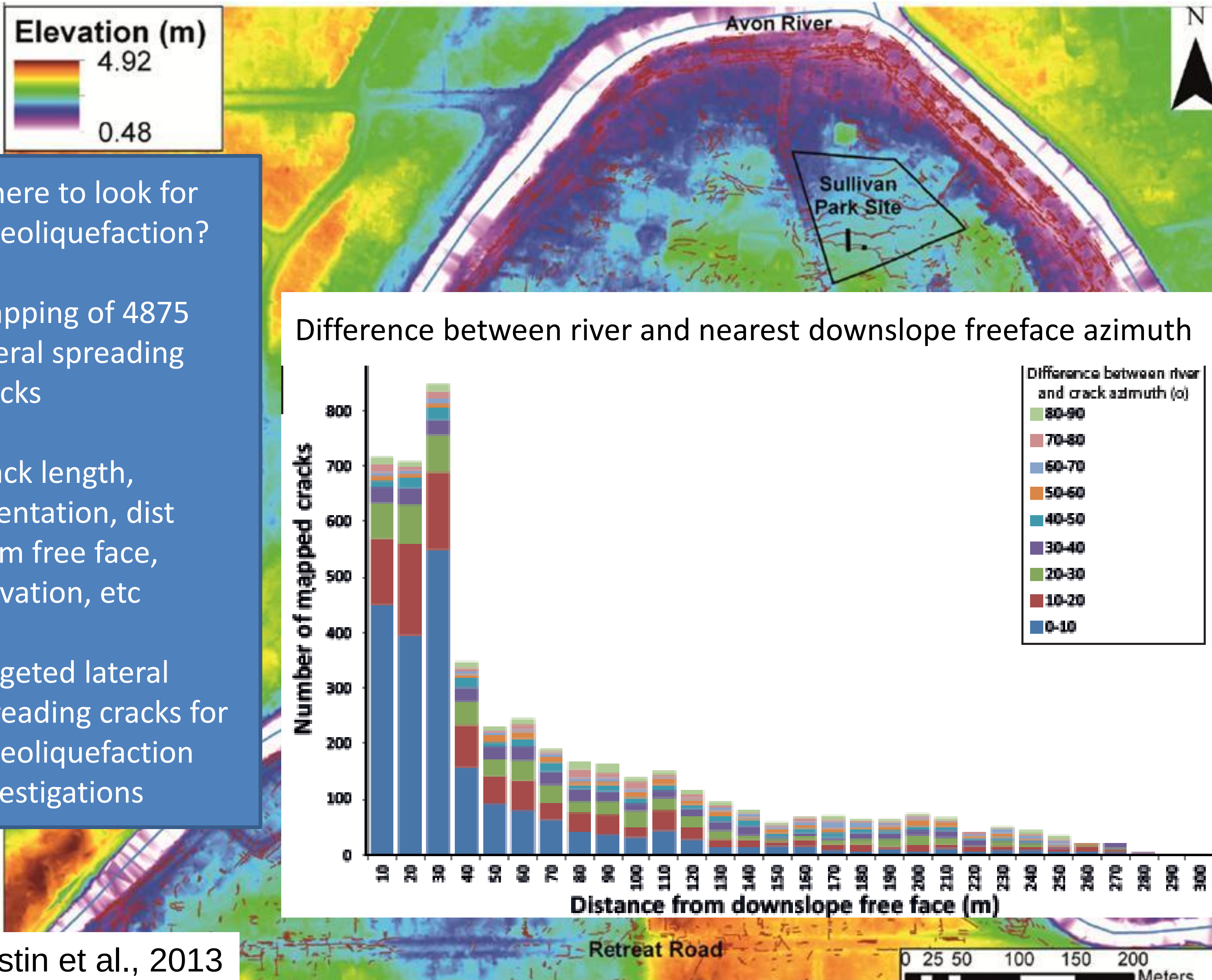
Quigley et al., *Geology* 2013

Where to look for paleoliquefaction?

Mapping of 4875 lateral spreading cracks

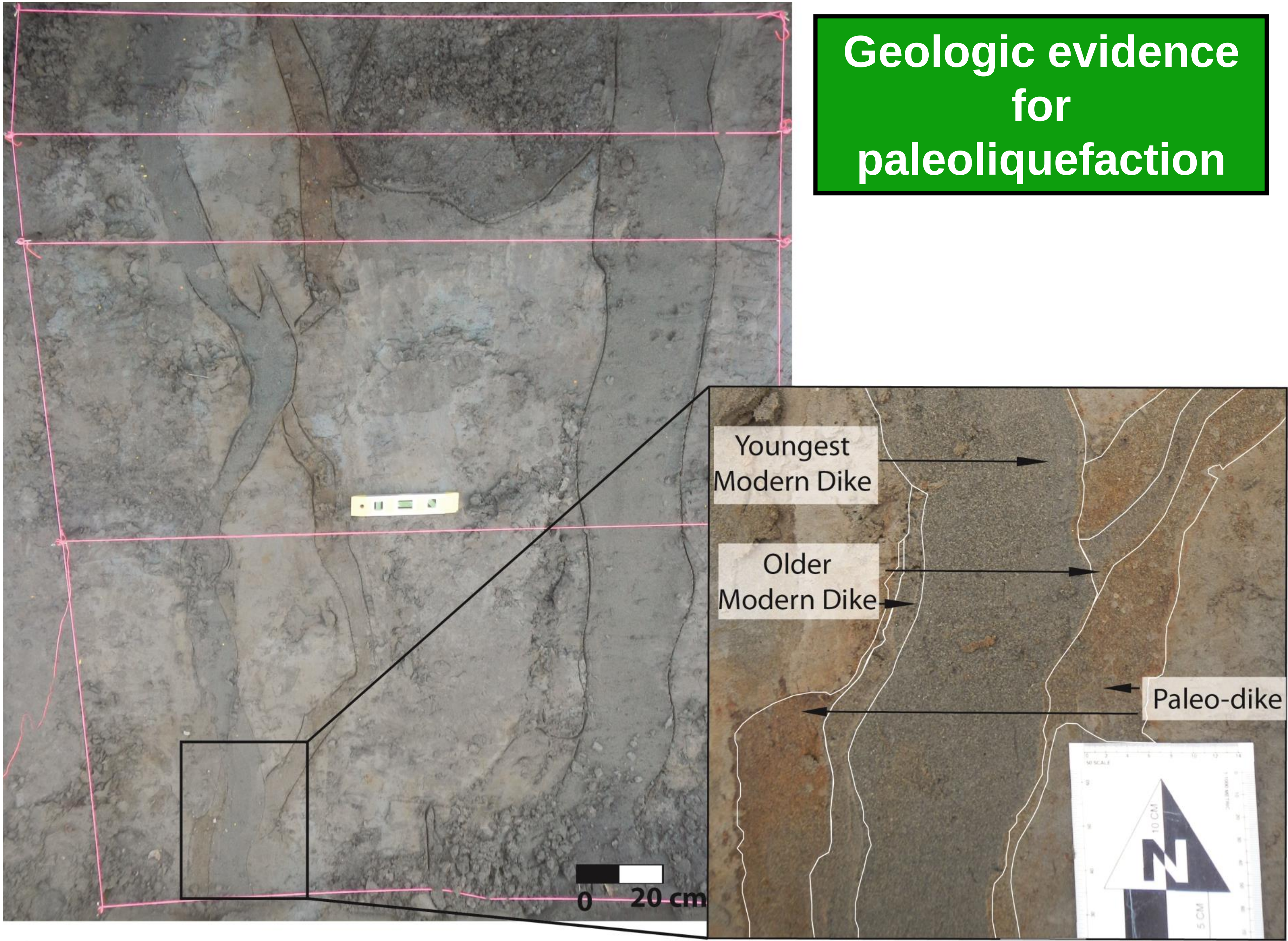
Crack length, orientation, dist from free face, elevation, etc

Targeted lateral spreading cracks for paleoliquefaction investigations



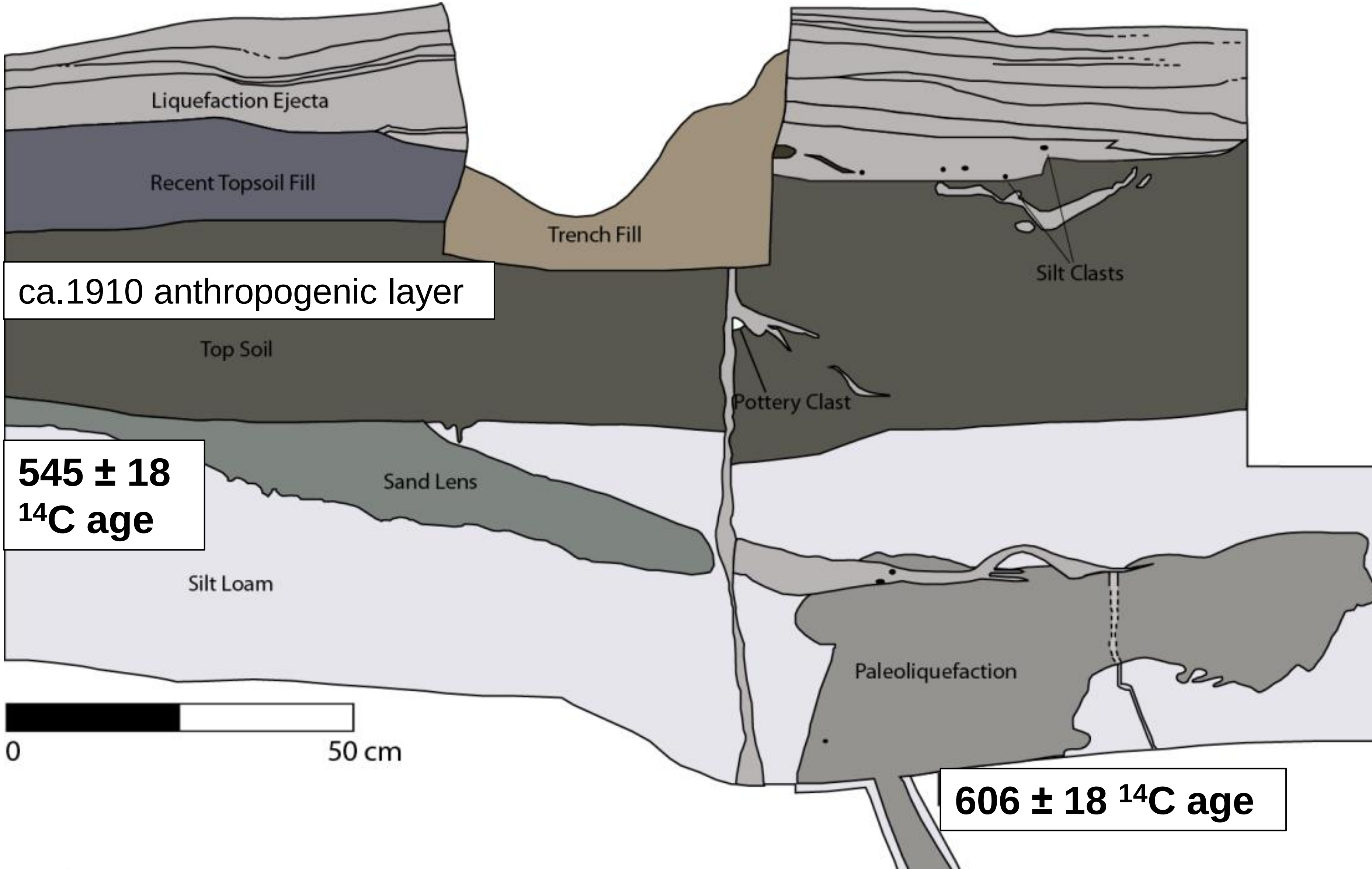
Bastin et al., 2013

Geologic evidence for paleoliquefaction



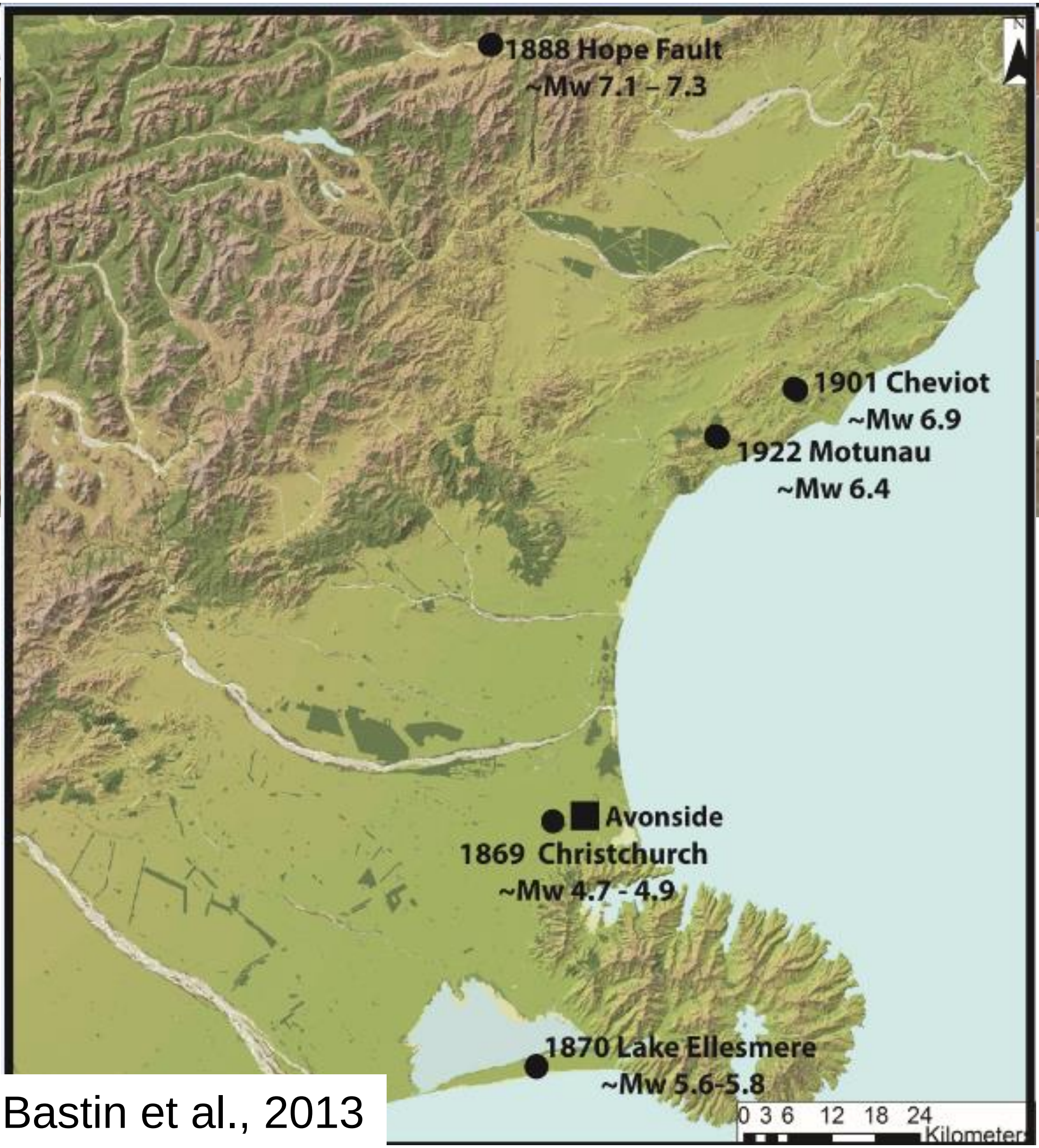
Bastin et al., 2013

Liquefaction of my former backyard sometime between 1910 and ~1470 AD (last ~545 yr)

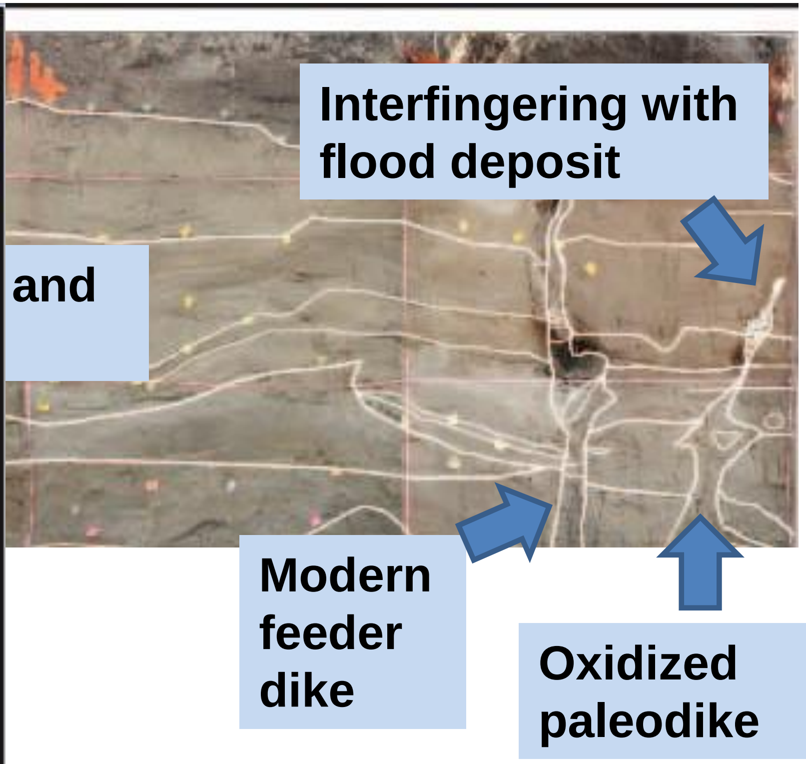


Bastin et al., 2013

Liquefaction of Sullivan's Park sometime between 1880s and 1920s

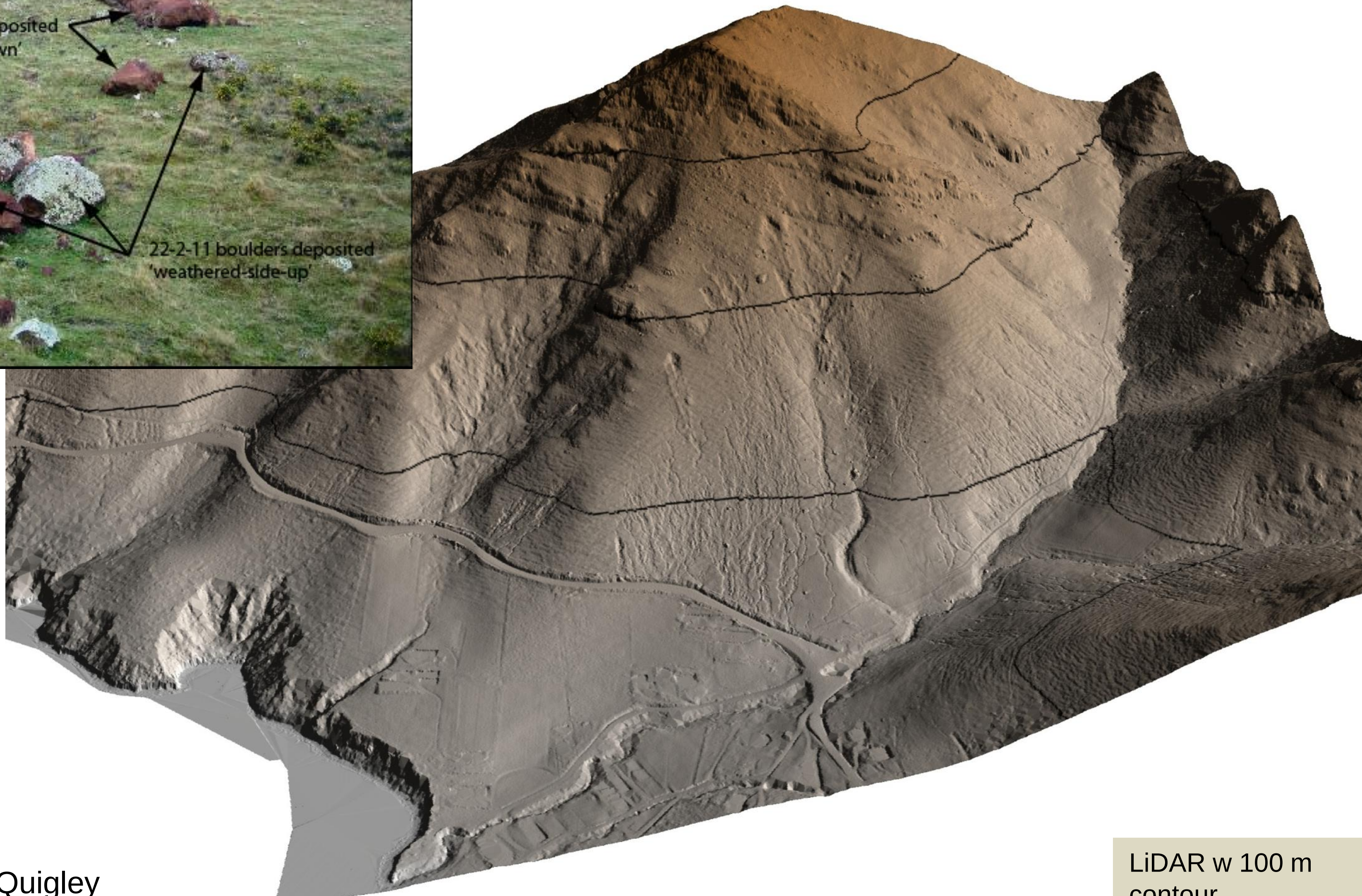


Bastin et al., 2013



Suspects

Rockfall / Boulder Roll Hazard

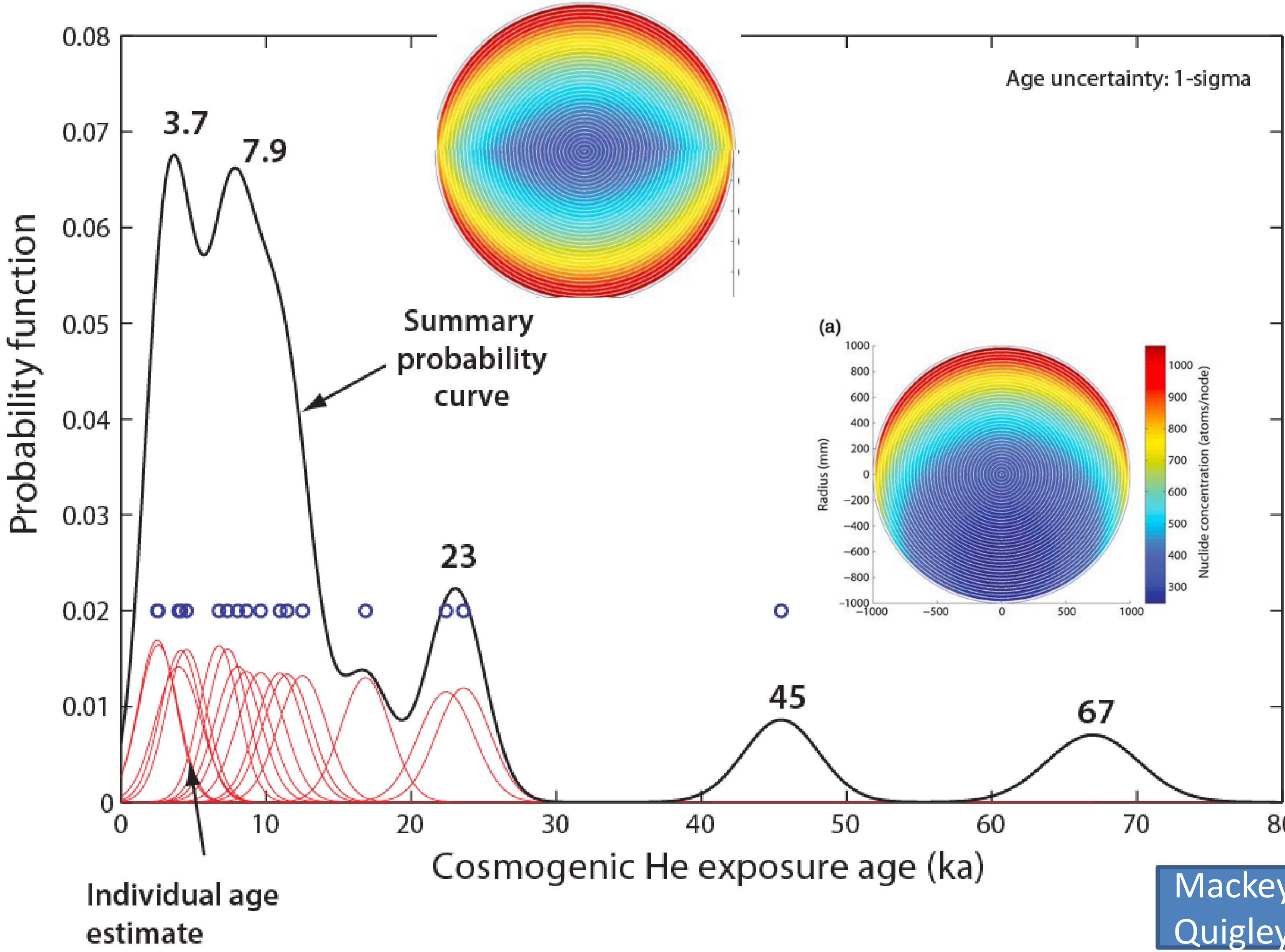


LiDAR w 100 m contour

Mackey and Quigley

Quigley et al

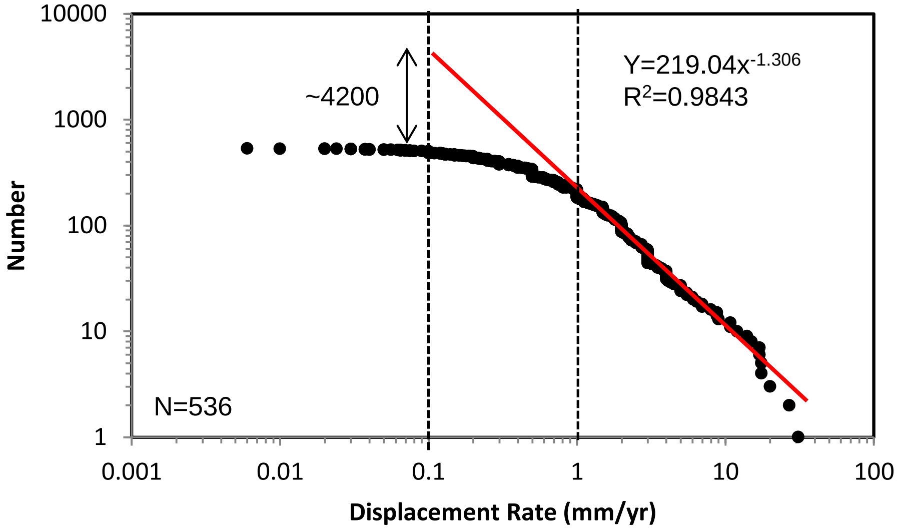
A mid Holocene rockfall event incorporating ‘fresh’ and pre-exposed material ?
No evidence for ‘random’ temporal occurrence
No evidence for Alpine Fault earthquakes

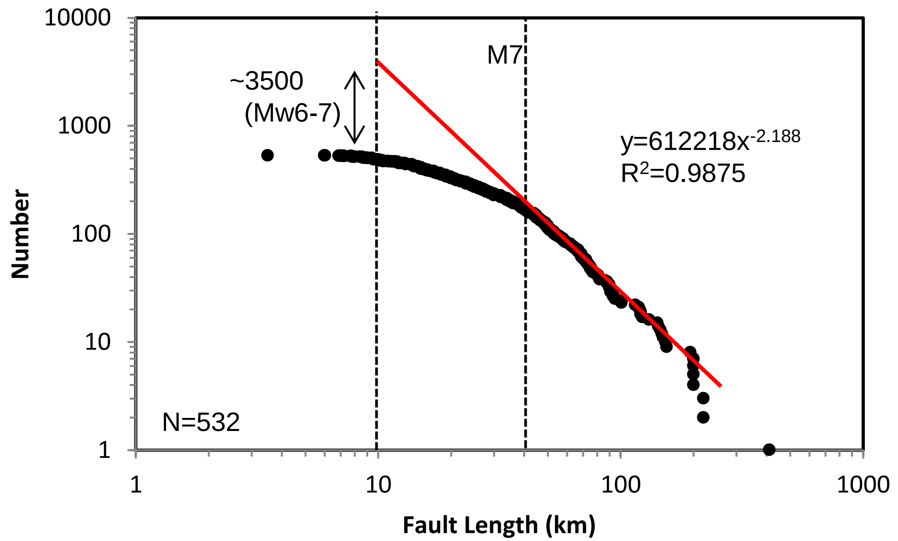


Mackey and Quigley, 2012

Future challenges

An analogous eq (sequence) could happen at any time anywhere else in New Zealand: have you personalized your hazard?

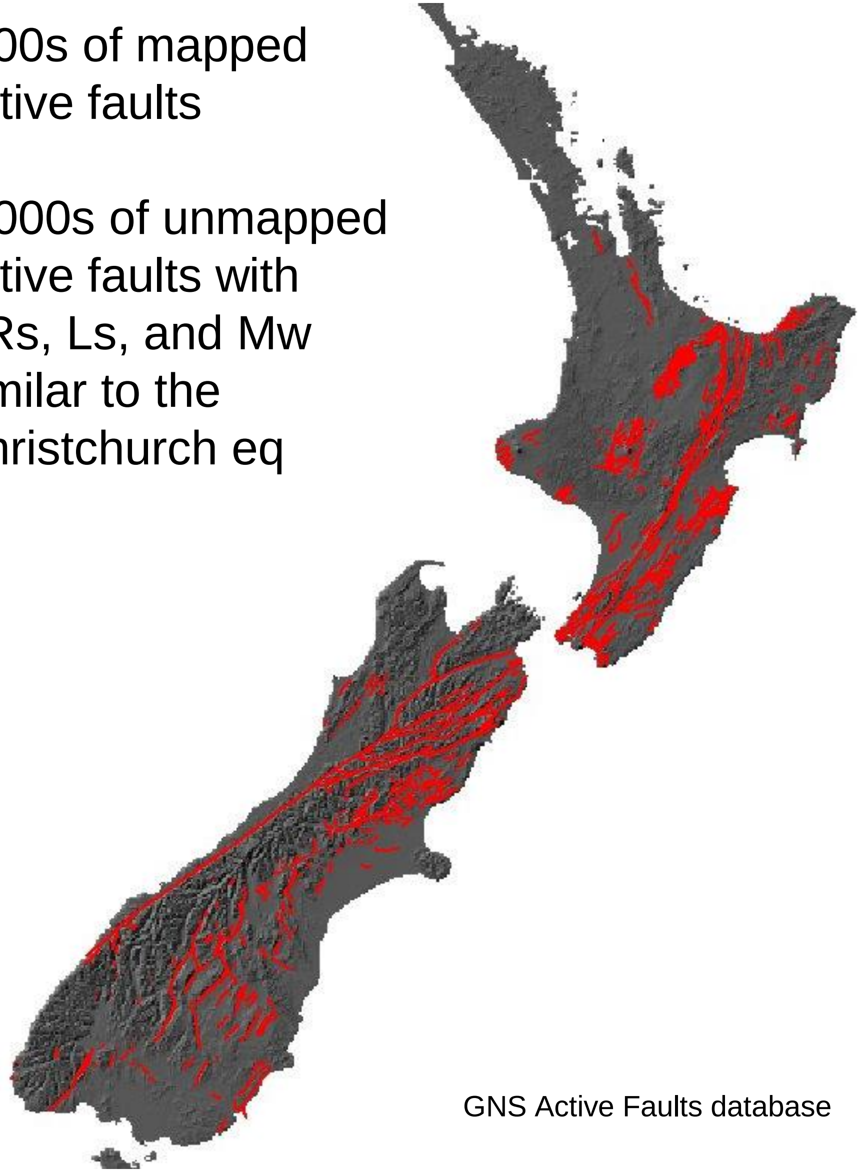




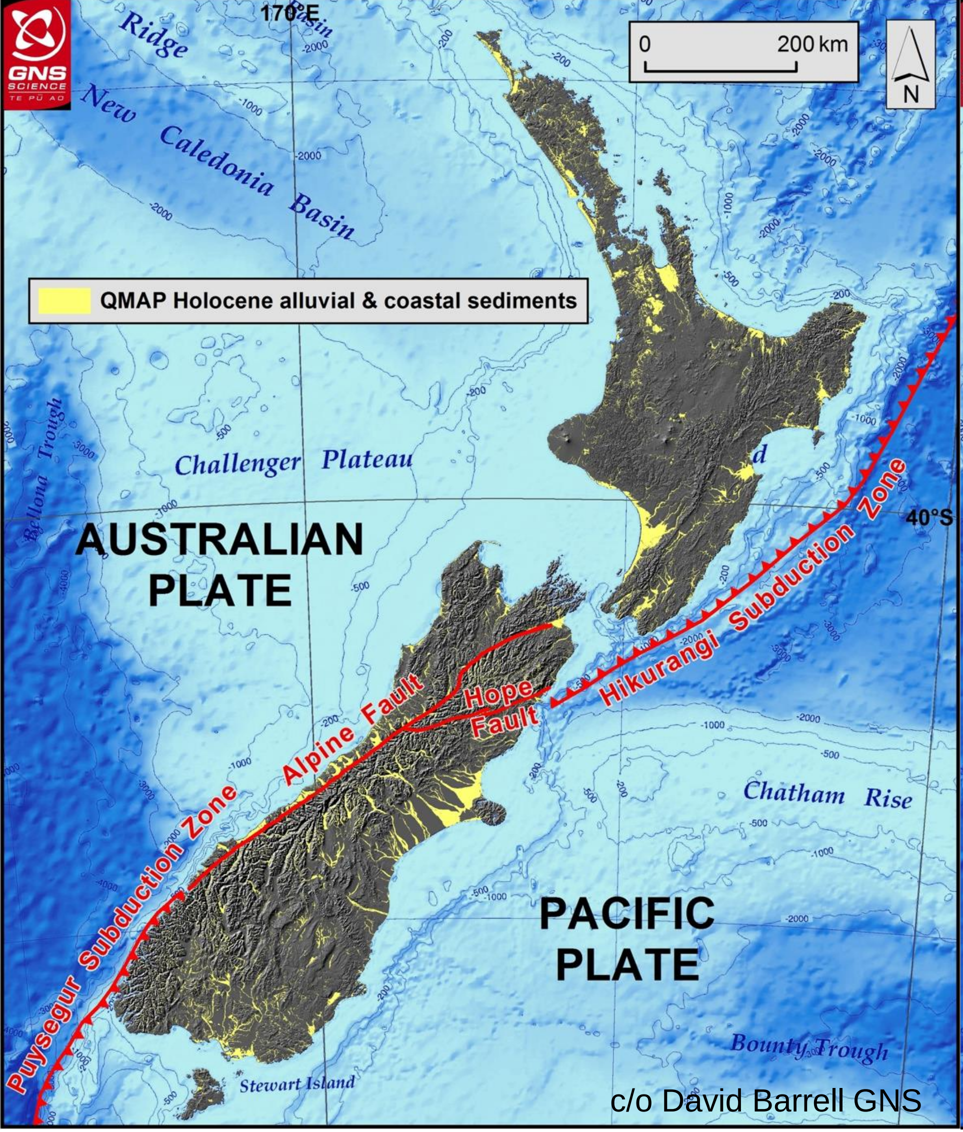
Nicol et al. (2011)

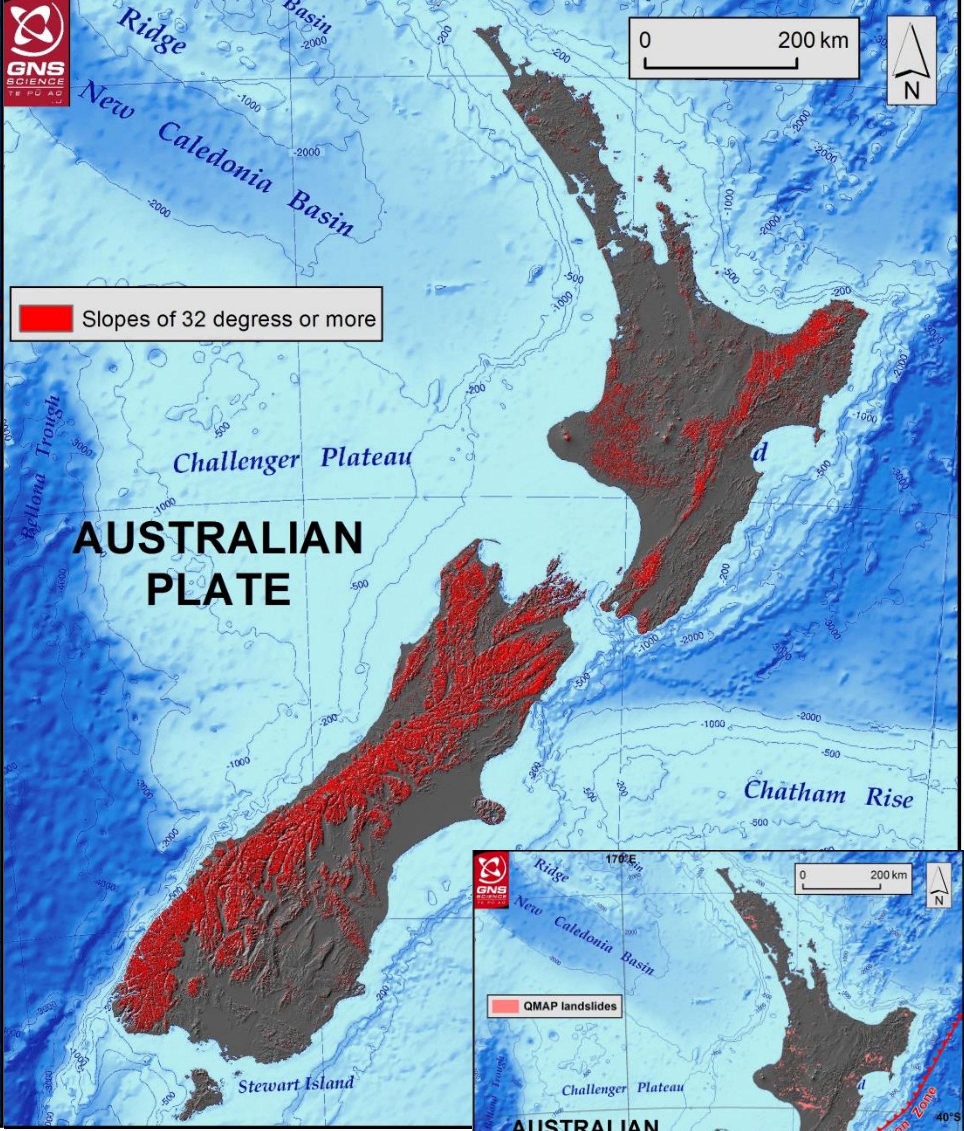
-100s of mapped active faults

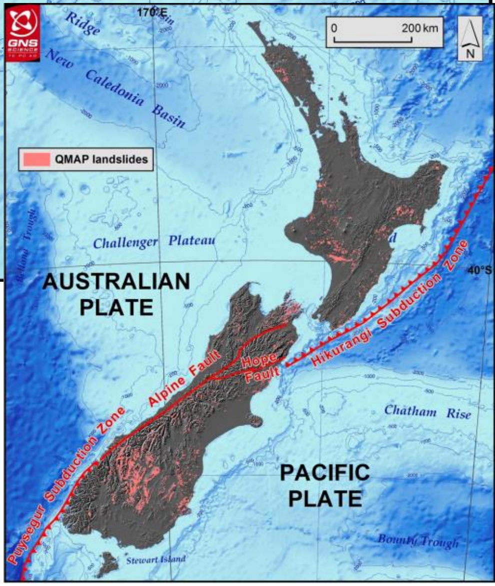
-1000s of unmapped active faults with SRs, Ls, and Mw similar to the Christchurch eq



GNS Active Faults database







A land of potentially liquefiable sediments and landslide-susceptible hillslopes

Conclusions

- Our research is driven by the desire to solve fundamental process-based questions and conduct ‘science for society’
- Earthquakes rupture the surface more than we recognize in the geologic record (*SRL* and *D*) – but discrete displacements provide meaningful Mw estimates when used with existing scaling relationships
- We see geologic evidence for penultimate earthquake rupture on the Greendale Fault ca. 25±3 kyr ago, we infer from stress modelling that the complexity of this earthquake is the norm rather than the exception, we think it is unlikely that GF rupture could have propagated coseismically on to the Feb and June faults, but the fractures between these faults are effective ‘waveguides’
- Everywhere we look, we find geological evidence for pre-CES paleoliquefaction and paleorockfalls – are we listening to the geologic record?
- Personalize your hazard, and support proactive rather than reactive approaches to natural hazards